JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.73, April 2009, pp.489-518

The Eastern Ghats Belt ..A Polycyclic Granulite Terrain

DHRUBA MUKHOPADHYAY and KRISHNAPRIYA BASAK
Department of Geology, University of Calcutta, Kolkata - 700 019
Email: dhruba_38@yahoo.co.uk

Abstract: The Eastern Ghats Belt is a polycyclic granulite terrain along the east coast of India whose western boundary is marked by a shear zone along which the granulites are thrusted over the cratonic units of the Indian shield, and its northern margin is marked by the presence of a number of fault-bounded blocks. Recent work has convincingly brought out that there are domains within the belt having different evolutionary histories. The segment south of the Godavari Rift went through a high grade thermo-tectonic event at ~1.6-1.7 Ga. North of the Godavari Rift in a narrow zone along the western boundary the last high-grade metamorphic event is of late Archaean age. A series of alkaline plutons along the western boundary zone testifies to a rifting episode at ~1.3-1.5 Ga. In the major part of the EGB the metamorphism is broadly of Grenvillian age, with two major thermo-tectonic pulses at ~1.1-1.2 Ga and ~0.95-1.0 Ga. But high grade conditions persisted for a long period and younger thermal events of ~0.65 Ga to ~0.80 Ga are locally recorded. There are differences in the tectonometamorphic histories of different domains, but the tectonic significance of these differences remains uncertain. Pan-African (0.50-0.55) thermal overprints are common and become conspicuous along the western boundary zone. The thrusting of the Eastern Ghats granulites in a hot state over the cratons to the west is of Pan-African age. In the Rodinia assembly (~0.9 Ga) the Eastern Ghats and the Rayner-Napier Complexes of Antarctica were contiguous, but the pre-Rodinia configuration of these terrains remains unclear. At ~0.8 Ga during the Rodinia break up Greater India rifted apart from East Antarctica, and only later it docked with Australia-East Antarctica at 530-550 Ma. The continuation of the East Antarctic Pan-African orogenic belts into the Eastern Ghats is yet to be ascertained.

Keywords: Granulite terrain, Rodinia assembly, Pan-African events, Eastern Ghats.

INTRODUCTION

The Eastern Ghats Belt (EGB) is a high grade terrain along the east coast of India, and is bounded to the north by the Singhbhum craton and to the west by the Bastar craton, the Dharwar craton and the Nellore-Khammam Schist Belt (Fig.1). The cratons are of Archaean age and are composed of tonalite-trondhjemite-granite gneiss hosting supracrustal belts. To the south the EGB disappears into the Indian Ocean a little south of Ongole in Andhra Pradesh (Ramakrishnan et al. 1998, Dasgupta and Sengupta, 2003, and references therein). The EGB is split into two segments by the Godavari Rift north of Ongole (Fig. 1). It is also dissected by the Mahanadi Rift near the northern margin. Before the Gondwanaland break-up the EGB was contiguous with the high grade terrains of Napier and Rayner Complexes of East Antarctica. Understanding the tectonometamorphic history of the Eastern Ghats is vital for reconstruction of the supercontinent assembly during the Precambrian and the early Palaeozoic. Till the middle of the twentieth century very little was known about the regional geological history of the Eastern Ghats. An early work by Crookshank (1938) described the western boundary of the EGB with the Bastar craton as an intrusive contact. In the tectonic synthesis of Krishnan (1961) the Eastern Ghats trend was described as a product of the Eastern Ghats orogeny (1570 Ma) and he mentioned that over a large part of the Eastern Ghats the strike is NE-SW which slightly veers to N-S and NNW-SSE near the southern extremity. He also noted that at the northern end, near the Mahanadi valley, the strike sharply swings to the east and becomes ESE-WNW to E-W. Intensive petrological studies during the last twenty years combined with isotopic dating have brought in a lot of new information which has advanced our understanding of the architecture and evolution of the EGB, though many problems still remain. This paper presents a critical review of the current state of knowledge on the EGB.

LITHOTECTONIC PROVINCES IN THE EASTERN GHATS BELT

Nanda and Pati (1989) and Ramakrishnan et al. (1998) compiled a geological map of the EGB and suggested that on the basis of dominant lithological assemblages (Fig.1) the EGB can be longitudinally subdivided into four zones, which are as follows from west to east:

1. Western Charnockite Zone (WCZ)
2. Western Khondalite Zone (WKZ)
3. Central Migmatite Zone (CMZ)
4. Eastern Khondalite Zone (EKZ)

They endorsed the earlier proposal Narayanaswami (1975) about the existence of a Transition Zone (TZ) between the EGB and the Bastar craton, a zone containing diverse cratonic components with metamorphism grading to granulite facies. However, as shown by Gupta and Bhattacharya (2000), Gupta et al. (2000), Neogi and Das (2000) and Bhadra et al. (2003, 2004), the rocks in the Transition Zone are similar to the EGB rocks and the boundary with the craton lies west of it. While differences in the broad lithological associations in the four zones do exist, recent studies suggest that in terms of tectonometamorphic pattern and chronology of events the picture is more complex. Chetty and his coworkers (Chetty, 2001; Chetty et al. 2003; and the references therein) identified several mega-lineaments in satellite imageries and interpreted them as shear zones which subdivide the EGB into several structural domains. The most prominent of these is the Sileru Shear Zone (SSZ), marking the eastern boundary of the WCZ (Fig.2). Another major lineament, the NNW-SSE trending Nagavalli-Vamasadhara Shear Zone, divides the EGB into eastern and western blocks. The nearly E-W trending Mahanadi Shear Zone (MSZ) in the north (also named as the Ranipathar Shear zone, Crowe et al. 2003) separates the northernmost part of the EGB from the rest of the belt (Fig.2). There are scanty data on the details of structures in the shear zones and the claimed structural distinctions between the domains are to be substantiated by detailed structural mapping. There is little information on the ages of the shear zones. The real tectonic significance of the lineaments identified in the imageries remains unclear.

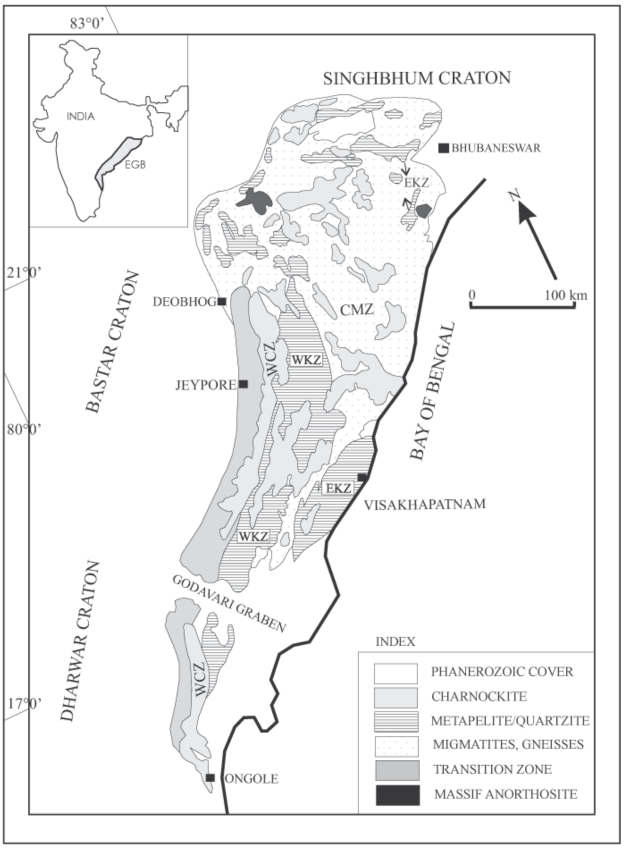

Fig.1. Generalised Lithological map of the Eastern Ghats Belt (*after* Ramakrishnan et al. 1998).

Rickers et al. (2001a) attempted to identify different domains on the basis of Nd model ages combined with Rb-Sr and Pb isotopic data. They recognised the following four domains (Fig.3):

1. *Domain 1*: This broadly coincides with the WCZ and is subdivided into two domains.
   Domain 1A: This domain lies to the south of the Godavari Rift and is characterized by homogeneous Nd model ages. The crustal residence times for the orthogneisses range from 2.3 to 2.5 Ga and for the paragneisses from 2.6 to 2.8 Ga. The age of the metamorphism is between 1.6 and 1.7 Ga. The metasediments were derived from a source containing Archaean granitoid and greenstone materials.
   Domain 1B: In the part of the WCZ north of the Godavari Rift the Nd model ages of enderbitic orthogneisses range from 3.2-3.9 Ga. Preliminary U-Pb data from zoned zircon grains indicate a high-grade metamorphic event at ~2.8 Ga, and the Pb isotopic data show no evidence of 1.6-1.7 Ga high grade event recorded in the Domain 1A.
2. *Domain 2*: This is bounded to the west by the Sileru Shear Zone (SSZ) and to the east by the Nagavalli-Vamasadhara lineament. The metasediments have rather homogeneous Nd model ages of 2.1-2.5 Ga. The orthogneisses have highly variable model ages of 1.8-3.2 Ga. The Sm-Nd and Pb isotopic data are consistent with the model of reworking of inhomogeneous Archaean crust during later granulite facies metamorphism, with variable input of juvenile material.
3. *Domain 3*: This is bounded by the Nagavalli-Vamasadhara lineament and the Mahanadi lineament and shows homogeneous Nd model ages of 1.8 to 2.2 Ga for

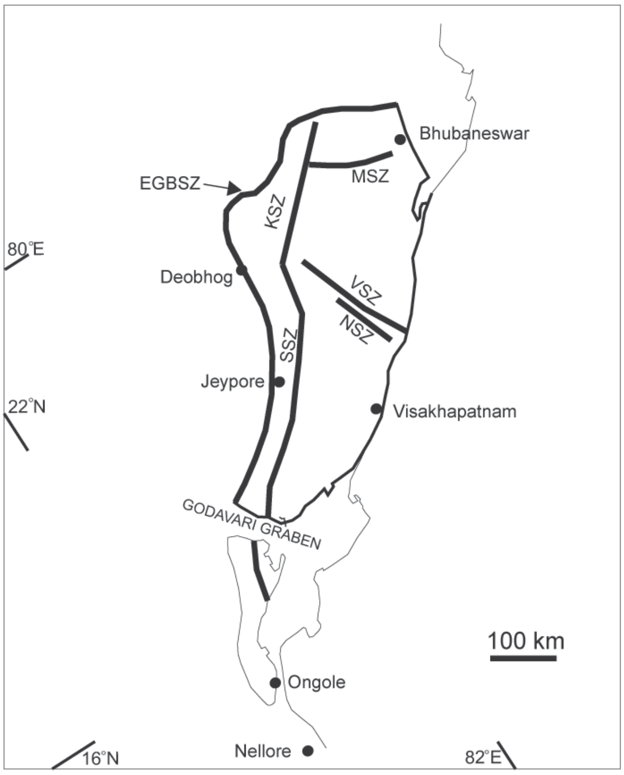

Fig.2. Major shear zones in the Eastern Ghats Belt (*after* Chetty, 2001). EGBSZ – Eastern Ghats boundary shear zone, SSZ – Sileru shear zone, KSZ – Koraput-Sonpur shear zone, NSZ,VSZ – Nagavalli-Vamasadhara shear zone, MSZ – Mahanadi shear zone.

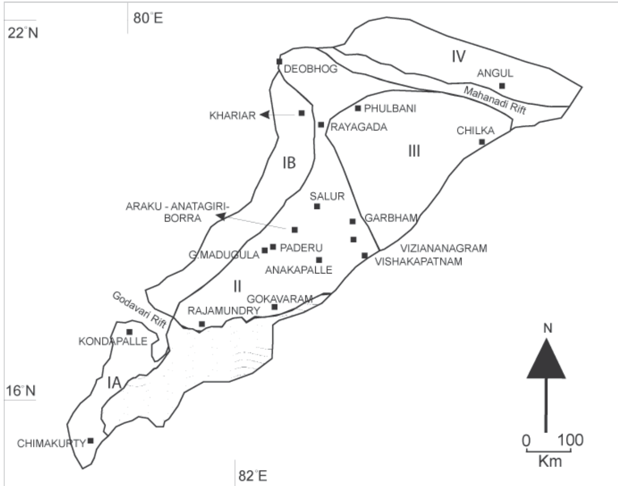

Fig.3. Domains based on isotopic data in the Eastern Ghats Belt (*after* Rickers et al. 2001a).

both the orthogneisses and the metasediments. It is interpreted that this domain represents reworked (during Grenvillian orogeny), homogeneous early Proterozoic material. Domain 3 had more juvenile additions and Domain 2 had more Archaean components. Rickers et al. (2001a) opine that either the Domains 2 and 3 are totally unrelated blocks or Domain 3 represents a position away from the orogenic front and Domain 2 close to it.

4. *Domain 4*: In this domain lying to the north of the Mahanadi lineament the metasediments display Nd model ages of 2.2-2.8 Ga and the orthogneisses have Nd model ages of around 3.2 Ga, indistinguishable from the model ages from the Eastern Indian craton.

It is to be noted that except for Domain 1 the other domains cut across the boundaries of the zones delineated by Ramakrishnan et al. (1998). It is also to be noted that according to Rickers et al. (2001a) there was only minor juvenile addition to the crust during the Neoproterozoic tectonothermal episodes.

Dobmeier and Raith (2003) presented a subdivision of the EGB into 4 provinces, each with a distinct geological history. The provinces are subdivided into a total of 12 domains, each being characterized by specific lithology, structure and metamorphic grade. The four provinces are (Fig.4):

1. *Jeypore Province (JP)*: Its western contact is with the Bastar craton, and it includes the WCZ and the TZ north of the Godavari Rift, i.e., the Domain 1B of Rickers et al. (2001a). The rocks are charnockite-enderbite, mafic granulite, with minor pelitic gneiss.

2. *Krishna Province (KP)*: This includes the Ongole Domain (equivalent to southern part of WCZ or Domain 1A of Rickers et al. 2001a), and the low- to medium-grade Nellore-Khammam Schist Belt (Udayagiri Domain and Vinjamuru Domain). In the Ongole Domain the dominant rocks are mafic granulite and large bodies of enderbitic gneiss and leptynite. The metasedimentary rocks occurring as rafts within the meta-igneous rocks are stromatic to diatexitic metapelitic granulite containing profuse garnetiferous quartzofeldspathic leucosomes, high-Mg-Al granulite, quartzite and calc-silicate gneiss. Layered mafic-ultramafic complexes, such as the one at Kondapalle, intrude the metasedimentary rocks and are themselves invaded by the enderbite. The other two domains of this province, the Udayagiri Domain and the Vinjamuru Domain, are in greenschist and amphibolite facies metamorphic states respectively, but the inclusion of these within the EGB is questionable.

3. *Eastern Ghats Province (EGP)*: This constitutes the major part of EGB and includes the WKZ, the CMZ and the EKZ, i.e., the Domains 2, 3 and part of 4 of Rickers et al. (2001a). The principal rock types are diatexitic pelitic gneiss

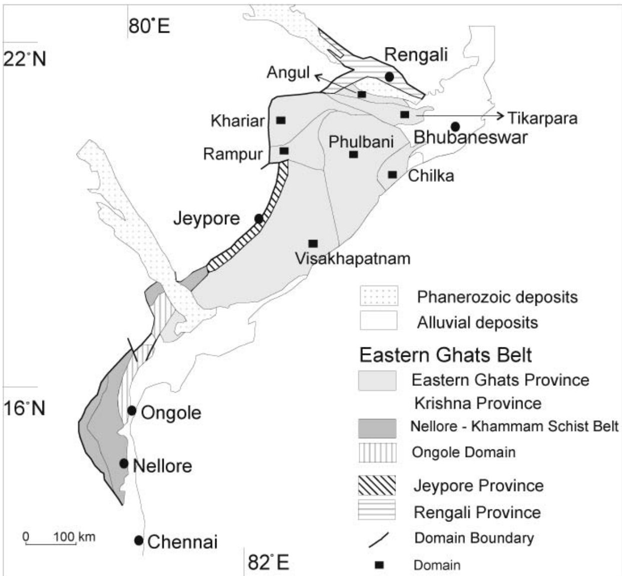

Fig.4. Provinces and Domains in the Eastern Ghats Belt according to Dobmeier and Raith (2003). Domains in the Eastern Ghats province are: Visakhapatnam, Phulbani, Rampur, Khariar, Tikarpara and Angul.

(khondalite), small bodies of high-Mg-Al granulite, calc-silicate gneiss, mafic granulite and enderbite, interspersed with massif-type anorthosite and intrusive granite-charnockite complexes. It is subdivided into seven domains, the biggest of which are the Phulbani and the Visakhapatnam Domains on either side of the Nagavalli-Vamasadhara mega-lineament.

4. Rengali Province (RP): This is the northernmost province of the EGB. It is fragmented into several fault bounded blocks (Fig.5) and the regional trend of foliation is WNW-ESE. The rocks are low to medium grade volcano-sedimentary sequences and medium to high grade orthogneisses. There was extensive felsic magmatism at ~2.8 Ga. Mahalik (1994) assigned the high grade gneiss assemblages to the Eastern Ghats Belt and the low to medium grade supracrustal sequences to the Singhbhum craton. Nash et al. (1996) and Fachmann (2001, quoted in Dobmeier and Raith, 2003) assigned the assemblage north of the Kerajang Fault to the Singhbhum Craton while the gneisses to the south were assigned to the Eastern Ghats Belt. Crow et al. (2001, 2003) pointed out that an amphibolite facies assemblage resembling the package of the Rengali Domain, extends south of the Kerajang Fault up to the Eastern Ghats Boundary Fault and on the other hand a block of granulite facies rocks occurs north of the Kerajang Fault (Fig.5). The overall character of the Rengali province favours its exclusion from the Eastern Ghats belt.

The scheme of Dobmeier and Raith (2003) is an admirable attempt to lay the groundwork for classification of a complex high grade terrain, but more work needs to be done to unravel the temporal and tectonic relations between the provinces and to bring out the exact distinctions between the domains. The inclusion of units of contrasted metamorphic grade and structural style within the Krishna Province may be questioned (Gupta, 2004).

Though Dobmeier and Raith (2003) have recommended abandoning the term Eastern Ghats Belt (EGB) because of the different ages of tectonometamorphic episodes of the different provinces, in this review we shall use the term EGB in the traditional sense of including the granulite terrain along the Eastern Coast of India extending from Angul and Bhubaneswar to Ongole and separated from the Singhbhum, Bastar, Dharwar cratons and the Nellore-Khammam schist belt by tectonic boundaries.

BOUNDARIES OF THE EGB AND OF THE DOMAINS WITHIN IT

South of the Godavari Rift

The granulites of the Ongole Domain are in contact with the amphibolite facies rocks of the Vinjamuru Domain of the Nellore-Khammam Schist Belt. The contact is tectonic, the Ongole Domain being thrusted over the Vinjamuru Domain (Dobmeier and Raith, 2003). Along the western margin the granulites of the Ongole Domain are retrogressed to amphibolite facies.

North of the Godavari Rift

The tectonic discontinuity along the western boundary of the EGB is referred to as the Eastern Ghats Frontal Thrust (EGFT) (Neogi and Das, 2000), or Eastern Ghats Boundary Shear Zone (EGBSZ) (Dobmeier and Raith, 2003), or Terrain Boundary Shear Zone (TBSZ) (Biswal et al. 2007). It is marked by a steep gravity gradient (Subrahmanyam and Verma, 1986).

The western boundary of the Jeypore Province (JP) with the Bastar craton is a shear zone (EGBSZ) characterised by a wide mylonitic belt (Bhadra et al. 2003, 2004; Gupta and Bhattacharya, 2000; Neogi and Das, 2000). The mylonitic foliation with downdip stretching lineation has 50°-60° dip towards SE; it is parallel to the terrain boundary. The mylonites are largely derived from the cratonic gneisses. Away from the contact zone narrow mylonitic shear zones transect the gneissic foliation in the rocks. Within the EGB granulites a shear foliation is developed overprinting the earlier gneissic foliations.

North of the northern termination of the JP in the

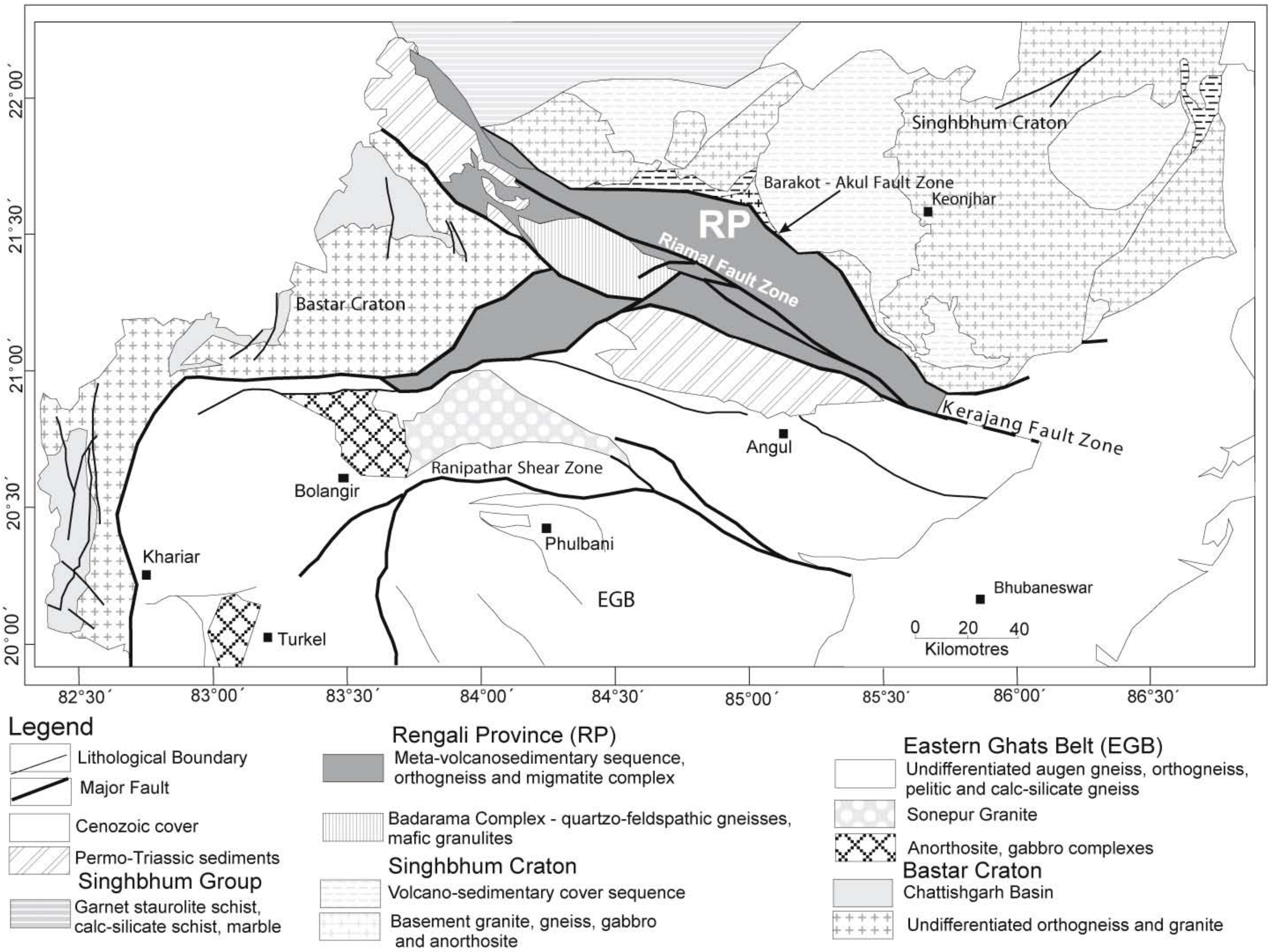

Fig.5. Generalised geological map of the Rengali Province, and the northern part of the Eastern Ghats province (*after* Crowe et al. 2003).

Deobhog-Bhawanipatna area the rocks of the CMZ (EGP of Dobmeier and Raith, 2003) overlap those of the JP and come directly in contact with the Bastar craton along the EGBSZ (Bhadra et al. 2003, 2004; Das et al. 2008, Gupta et al. 2000; Gupta and Bhattacharya, 2000; Neogi and Das, 2000) (Figs.3 and 4). The northern termination of the JP is not clearly delineated, and the rocks of the JP may continue northward buried under the EGP thrust sheet. The shear zone related foliation overprints the earlier foliations in both the cratonic rocks and the EGP rocks. The microstructures consistently indicate top to the west (i.e. thrust) sense of movement. Though Nanda and Pati (1989) reported that the shearing caused retrogression of granulites to amphibolites and hydrated gneisses along the boundary zone, careful study of texture and mineral assemblages (Bhadra et al. 2004; Bhattacharya, 2004; Das et al. 2008; Gupta and Bhattacharya, 2000; Gupta et al. 2000; Neogi and Das, 2000) prove that granulite facies conditions prevailed during the thrusting of EGP over the craton, though mineralogical changes caused by hydration are discernible. Gupta et al. (2000) and Bhadra et al. (2003, 2004) invoked the model of thrusting of hot granulites over the cold craton, causing post-thrusting heating of the craton, while the granulites underwent cooling and decompression. Biswal and his coworkers (Biswal et al. 2007, and the references therein) considered the boundary thrust as a listric frontal thrust or the basal decollément of the EGB, which was visualized by them as a fold-and-thrust belt with a number of stacked thrust sheets. Monazite dating (discussed later) indicates ~500-550 Ma to be the age of the ductile shearing in the boundary zone.

The nature of the northern boundary of the EGB is less well understood. North of Khariar the EGBSZ veers to the east and continues north of the Bolangir anorthosite pluton, but its continuation further east is unclear; it probably continues to Rairakhol to terminate against the Kerajang Fault (Fig.5) (Crowe et al. 2003). A number of faults are reported from this region which bound different blocks (Crowe et al. 2003; Nash et al. 1996). The northernmost fault is the Barakot-Akul Fault. Little detail is available on the nature of this fault. South of this, is the Kerajang Fault, which is the longest fault in this region and can be traced for over 250 km and which, for a part of its length, is the Gondwana Boundary Fault. The block bounded by the Kerajang and Barakot-Akul Faults was considered by Nash et al. (1996) to entirely belong to the Singhbhum craton, while Crowe et al. (2001) described it as a distinct transitional belt containing an amphibolite facies sequence with intercalated basement gneiss and meta-volcanosedimentary lithologies. In this review the Kerajang Fault is considered to mark the northern boundary of the EGB as it separates the bulk of the granulite facies rocks from the amphibolite facies rocks.

There is scanty information on the nature and timing of movement on these faults. Repeated reactivation on these faults at semiductile and brittle conditions has been suggested (Crowe et al. 2001, 2003; Fachmann, 2001 quoted in Dobmeier and Raith, 2003; Lisker and Fachmann, 2001). Nash et al. (1996) mentioned that a •precursor Kerajang shear zone with dextral movementŽ was instrumental in bringing the Singhbhum craton and EGB into juxtaposition and the fault •has demonstrable Palaeozoic-Mesozoic dextral motion associated with coal basin formationŽ Crowe et al. (2001, 2003) suggested that the movement on the fault was initiated at 0.9 – 1.0 Ga, and there was dextral-reverse reactivation along the fault afterwards and possibly prior to ~700 Ma, which was associated with regional shortening within the EGP and the Rengali Province. From ^{40}Ar/^{39}Ar data they concluded that renewed reactivation took place within the same shortening regime at ~500–550 Ma. Our unpublished work and the observations of Sarkar et al. (2007) in the Angul region suggest that in the northern part of the Angul Domain an earlier fabric is dragged to ENE-WSW trend due to simple shear deformation with a dextral sense of movement under high grade condition.

Another shear zone, the Mahanadi Shear Zone (MSZ, Chetty, 2001), or the Ranipathar Shear Zone (Crowe et al. 2003) having ESE-WNW trend marks the boundary between the Tikarpara Domain and the Phulbani Domain of the EGP. West of Phulbani a splay from this shear zone turns to the south and probably joins up with the Nagavalli-Vamasadhara lineament (Dobmeier and Raith, 2003). It is reported that ultramylonites are present in the MSZ and that the sense of movement is dextral (Chetty, 2001), but the evidence is insufficient.

Biswal and his coworkers (Biswal et al. 2001, 2007 and references therein) interpreted the northern boundary of the EGB as the lateral ramp of the advancing EGB thrust sheet. However, this sector of the EGB with overall E-W strike of foliation is a broad zone nearly a hundred kilometer wide and the structural style indicates shortening perpendicular to it. A more reasonable model would be to consider it as a syntaxial bend due to oblique collision of an indentor in the EGB with the craton, analogous to the syntaxial bend of the NW Himalayas showing bending of the geological formations and the structural trends.

The western boundary of the EGP (WKZ of Ramakrishnan et al. 1998, Domain 2 of Rickers et al. 2001a) with the JP coincides with a well defined mega-lineament named as the Sileru Shear Zone (SSZ). The northern continuation of SSZ north of the JP is unclear; it may link up with the EGBSZ, or with another shear zone within the EGP, the Koraput-Sonpur Shear Zone (KSZ, Fig. 2). The foliation within the SSZ has an average dip of 50° towards SE. Both thrust and dextral movements along the shear zone are reported (Chetty, 2001 and references therein; Gupta and Bose, 2004). There is no detailed study elucidating the age and kinematics of the SSZ.

The NNW-SSE trending Nagavalli-Vamasadhara lineament (Chetty, 2001; Chetty et al. 2003) marks the approximate boundary between the Domains 2 and 3 of Rickers et al. (2001a) (Visakhapatnam and Phulbani Provinces of Dobmeier and Raith, 2003). It is reported to show dextral sense of movement (Chetty et al. 2003 and references therein). However it is not clear how this motion fits in the regional framework of EGB, because this dextral motion is not kinematically compatible with thrusting on KSZ or dextral motion on MSZ (Fig.2). Chetty et al. (2003) thought that it joins up with the Napier-Rayner boundary shear zone in the Antarctica. More detailed work is to be done on the geometry and kinematics of the shear zone.

STRUCTURAL FRAMEWORK

The least studied aspects of the EGB are regional structural geometry and deformational history. Structural data are available only from discrete parts of the belt. In many areas three major episodes of deformation (summarized in Bhattacharya, 1996; Bhattacharya, 1997; Bhattacharyya and Gupta, 2001; Gupta, 2004) are identified. The bedding is mostly obscure but the contact surfaces between metapelite and calc-granulite probably represent original sedimentary interfaces which were folded to F_1

reclined isoclinal folds during D_1. The gneissic banding (S_1) is axial planar to these folds and is defined by granulite facies mineral assemblages. The compositional banding (S_1) is accentuated by the intrusion of layer-parallel garnet-bearing leucosomes. S_2 is also a gneissic foliation formed during D_2 under high grade condition. The foliation in the charnockitic, enderbitic and granitoid gneisses defined by pyroxene and/or pyroxene-garnet segregations alternating with felsic bands is in most instances S_2, because a discordant early foliation (S_1) is preserved in the included xenoliths. The persistence of high temperature during D_2 is evidenced by continued neosome generation and stable high temperature mineral assemblages in S_2 fabrics. However, from the Kondapalle region that lies to the south of the Godavari Rift, Sengupta et al. (1999) reported retrogression in the fabrics related to post-F_1 folds. The second-generation folds (F_2) in EGB are commonly overturned, tight to isoclinal and occur on various scales. Coaxial relation between F_1 and F_2 folds is documented in several areas (Bhattacharya, 1996; Mukhopadhyay and Bhattacharya, 1997; Sarkar et al. 2007). At many places S_2 has transposed the S_1 and the regional tectonic trend within the EGB is defined by composite S_1/S_2.

A third, tight to open folding event, F_3, is associated with an axial planar fabric, most prominently displayed at F_3 fold hinges. F_3 folds are commonly open, upright with variably oriented axial planes (E-W trending near Chilka, N-S trending at Salur). At Chilka arrested charnockitization has taken place along the axial planes (Dobmeier and Raith, 2000). Locally developed shear cleavage with a strike-slip component, micro faults and shear bands are commonly associated with F_3 folding. Sheath folds in khondalite produced by intense shearing are reported from NE of Visakhapatnam, near Ramadri coast (Takamura et al. 2000). The time relation between this shearing and folding episodes remains unspecified.

Mention has already been made about thrusting/shearing along the western boundary of the EGB, with the EGB riding over the craton to the west. Das et al. (2008) documented that away from the boundary zone three sets of pre-thrust foliations are developed in the Eastern Ghats granulites, and a shear zone related fabric cuts across them. The intensity of development of the shear fabric increases towards the shear zone and within the shear zone the earlier fabrics and the penetrative shear fabric are all drawn into parallelism with the shear zone. On the basis of petrological evidences which will be discussed later, Das et al. (2008) suggested that the Eastern Ghats granulites were emplaced along imbricate thrusts with successively younger thrusts being emplaced on the hinterland side.

Biswal and his coworkers (Biswal et al. 2001, 2007 and the references therein) visualized the structural architecture within the EGB to be similar to that of a fold-and-thrust belt with a number of stacked thrust sheets and nappes. However, their identification and delineation of thrust sheets, windows and klippes are not backed by rigorous mapping and structural analysis. For example, no convincing reason is given for considering the rocks within the designated Dharamgarh window as belonging to the basement (Biswal et al. 2007), or why the rocks within the •Turkela klippeŽare correlated with the main •Turkela thrust sheetŽ(Biswal et al. 2001). Further, some lithological units appear to cut across the boundaries of the supposed nappes (compare maps of Das et al. 2008 and Biswal et al. 2007). Contrary to the ideas of Bhadra et al. (2004), Das et al. (2008), Gupta and Bhattacharya (2000), Gupta et al. (2000), that high grade condition prevailed during thrusting, Biswal et al. (2001, 2007) thought that the EGB rocks were metamorphosed to granulite facies prior to thrusting and were retrograded to amphibolite facies along the thrust zone. However, geochronological and petrological data do not support this contention. Biswal et al. (2007) contends that the thrusting is synkinematic with the second phase of folding (F_2). Many other workers on the contrary have demonstrated that the shear foliation related to thrusting/shearing transects the earlier S_1 and S_2 gneissic fabrics (Bhadra et al. 2004; Gupta et al. 2000; Das et al. 2008). The geochronological data suggest a considerable temporal gap between the shearing (Pan-African, ~0.50-0.55 Ga) and the timing of the main tectonothermal event within the EGP (Grenvillian, ~0.9-1.0 Ga).

The overall E-W to ESE-WNW regional foliation trends in areas north of MSZ (Jenapore, Angul, Bolangir) are different from the NE-SW trend in rest of the EGP and the structures in the northern region indicate N-S shortening. Kar (2001, 2007) reported that at Jenapore the pervasive gneissic foliation (S_1) in khondalites and charnockites is axial planar to the first generation of reclined isoclinal folds. The leptynitic foliation (S_2) is axial planar to folds on S_1; S_2 has commonly transposed S_1 and the two are generally parallel. The third generation folds are the regional broad warps. At Angul granulite facies conditions prevailed during two successive episodes (D_1 and D_2) of fabric forming deformation (Sarkar et al. 2007); these were followed by several shearing events. Our observations in this region show that the gneissosity in khondalites formed earlier than that in the charnockitic gneisses, though the two are generally parallel. These formed during D_1 and D_2 deformations respectively. A later phase of dextral shearing has dragged the composite gneissic foliation to WNW-ESE orientation in a shear zone broadly parallel to the MSZ and the Kerajang Fault Zone (cf. Sarkar et al. 2007). Folds/broad warps with N-S trending axial traces and steep southerly plunging axes are later than this shearing. A thrust-shear dominated deformational regime with N-S directed shortening is recognized in Bolangir anorthosite and its country rocks (Dobmeier, 2006).

Correlation of the deformational events identified in different areas is problematic, and the folds of a particular generation in one area are not necessarily coeval with the folds of the corresponding generation in another area. Therefore, unified deformation history for the entire EGB cannot be constructed from the data available from widely separated regions. As pointed out by Gupta (2004), if the EGB is made up of several domains (Rickers et al. 2001a; Dobmeier and Raith, 2003) having different tectonometamorphic histories, it would be neither feasible nor desirable to attempt to build up a single deformational history for the entire belt.

METAMORPHIC HISTORY

Metamorphic Events

Ongole Domain

A succession of different metamorphic events has been deciphered in the EGB rocks. (Dasgupta and Sengupta, 2003 and references therein). In the Ongole Domain an ultra-high-temperature (UHT) granulite facies metamorphism with peak temperature >1000°C and pressure >10kb, and a deep crustal heating and isobaric cooling trajectory are documented (Bhui et al. 2007; Sengupta et al. 1999) from rocks in the contact zone of the Kondapalle Layered Complex (Leelanandam, 1997; Leelanandam, 2004; Leelanandam and Vijaya Kumar, 2007). Partial melting took place in the prograde phase and the peak metamorphism produced garnet+spinel+corundum+sillimanite assemblage in the high-Mg-Al granulites. From rocks at Chimakurthy Dasgupta et al. (1997) also deduced similar P-T path at a shallower crustal level, attaining T > 950° C and P ~6 kb at the peak metamorphic stage. This UHT metamorphism at different crustal levels has been ascribed to heat supplied by the mafic-ultramafic magmatism (Dasgupta et al. 1997; Sengupta et al. 1999). There is no evidence of decompression following the isobaric cooling that is observed in the other domains of the EGB north of the Godavari Rift. This led Sengupta et al. (1999) to conclude that while UHT metamorphism affected the terrains north and south of the Godavari Rift, the decompression related tectonic event affected only the domains to the north. However, the UHT metamorphic events in the two regions are not coeval as indicated by the isotopic data discussed later.

Eastern Ghats Province

North of the Godavari Rift also an early UHT (~1000°C) metamorphic event (M_1) at crustal depths of 30-35km (8-10 kb) is reported from high-Mg-Al granulites in several areas (Fig.6), like Anantagiri (Sengupta et al. 1990), Anakapalle (Dasgupta et al. 1994; Rickers et al. 2001b; Sanyal and Fukuoka, 1995), Araku (Sengupta et al. 1991), Paderu (Bhattacharya and Kar, 2002; Lal et al. 1987; Pal and Bose, 1997), Rayagada (Shaw and Arima, 1996a, 1996b, 1998), G. Madugula (Mohan et al. 1997), Vizianagram (Kamineni and Rao, 1988a), Sunkarametta (Bose et al. 2000), Rajamundry (Dasgupta et al. 1995), Kakanuru (Kamineni and Rao, 1988b), Deobhog (Gupta et al. 2000; Neogi and Das, 2000), from calc-granulites of Borra (Bhowmik et al. 1995), Garividi and Rajamundry (Dasgupta et al. 1992; Dasgupta, 1993), Anakapalle (Sengupta et al. 1997a) and also from mafic granulites from Araku-Anantagiri areas (Dasgupta et al. 1991; Dasgupta et al. 1993).

The prograde path of this M_1 metamorphism could be reconstructed only in a few areas. Dasgupta and Sengupta (2003, and the references therein) argued for an anticlockwise trajectory for the prograde M_1 event under a fluid absent/deficient condition. From the considerations of petrogenetic grid they inferred that in the high-Mg-Al granulites, in the prograde path prior to the peak temperature, dehydration melting of biotite produced spinel+cordierite and cordierite+garnet assemblages in restites coexisting with the melt; sapphirine+ilmenite was produced by continuous reaction from spinel+quartz+rutile (Dasgupta et al. 1995; Sengupta et al. 1990). Peak M_1 P-T of 8-10 kb and ~1000° C led to, (a) breakdown of early cordierite in high-Mg-Al granulites and stabilization of sapphirine+quartz and spinel+quartz in appropriate bulk compositions and under suitable f_{O2} conditions (Sengupta et al. 1991; Dasgupta and Sengupta, 1995), (b) stabilization of wollastonite+ scapolite+garnet (grandite)+calcite and wollastonite+ plagioclase+garnet (grandite) in calc-silicate granulites (Dasgupta and Sengupta, 1995, 2003), and (c) stabilization of spinel+plagioclase+clinopyroxene+orthopyroxene+ olivine in mafic granulites (Dasgupta et al. 1991; Dasgupta et al.. 1993). Shaw and Arima (1996a, 1996b) deduced peak P-T conditions of 12 kb and 1100°C for the rocks at Rayagada, followed by decompression to 9 kb, though Dasgupta and Sengupta (2003) argued that the assemblages could be interpreted in other ways which did not require the extreme pressure. At G. Madugula, after attaining

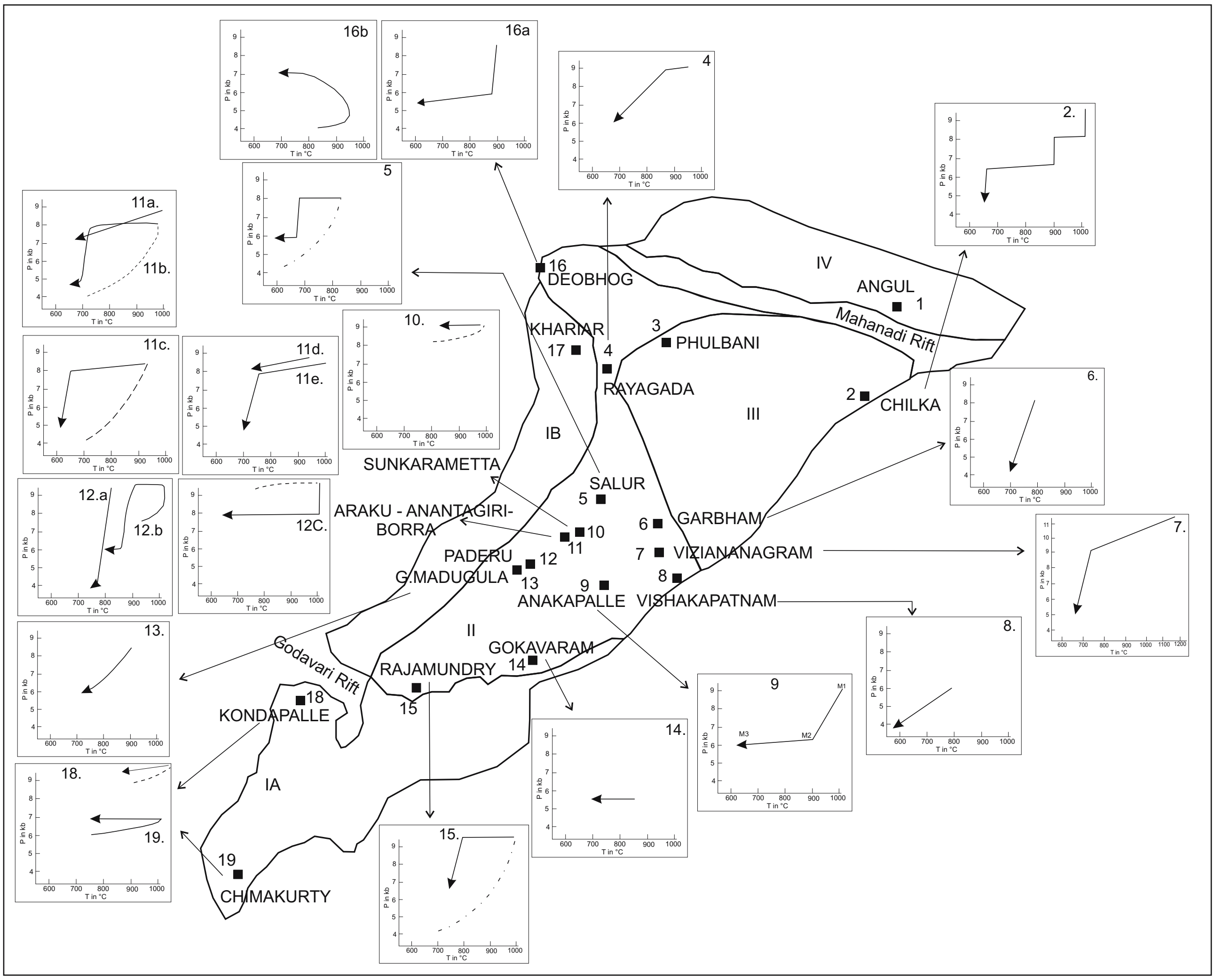

Fig.6. P-T trajectories at different localities in the Eastern Ghats belt. **2** – Chilka, Sen et al. (1995), **4** – Rayagada, Shaw and Arima (1996), **5** – Salur, Mukhopadhyay and Bhattacharya (1997), **6** – Garbham, Dasgupta et al. (1992), **7** – Vizianagram, Sarkar et al. (2003), **8** – Visakhapatnam, Fonarev et al. (1995), **9** – Anakapalle, Dasgupta et al. (1994), Sanyal and Fukoaka (1995), **10** – Sankarimetta, Bose et al. (2000). **11** – A: Borra – Bhowmik et al. (1995), B: Borra – Bhowmik et al. (1997), C: Anantagiri: Sengupta et al. (1991), D: Araku, Sengupta et al. (1991), E: Dasgupta et al. (1991), **12** – A: Paderu, Lal et al. (1987), B: Pal and Bose (1997), C: Bhattacharya et al. (2003), **13** – G. Madugula, Mohan et al. (1997), **14** – Gokavaram, Dasgupta et al. (1999), **15** – Rajamundry - Dasgupta and Sengupta (1995), **16** – A: Deobhog, Gupta et al. (2000), B: Bhawanaipatna, Das et al. (2006), **18** – Kondapalle, Sengupta et al. (1999).**19** – Chimakurty, Dasgupta et al. (1997). Domains as defined by Rickers et al. (2001a) are also shown.

the peak UHT conditions (8.4 kb, >900°C) the rocks experienced substantial decompression (by up to 3 kb) and moderate cooling (of 150°-200°C) (Mohan et al. 1997). In the Salur area Mukhopadhyay and Bhattacharya (1997) documented that the pre- to syn-D_1 low-P-high-T prograde phase first led to vapour-absent incongruent melting of biotite and formation of cordierite+orthopyroxene+garnet-bearing leucosomes in metatexites. Syn- to post-D_1 heating and loading led to decomposition of cordierite to orthopyroxene+sillimanite+biotite+quartz symplectites in the leucosomes. In the metasediments the peak temperature of >850°C at ~7.0-8.0 kb was reached syn- to post-D_2, and garnet+orthopyroxene-bearing diatexites and anastomosing veins were produced. This was followed by near isobaric cooling. In the early tectonic orthopyroxene-bearing granitoid gneisses the highest temperature of 950°-1020°C is recorded using the robust Al-in-orthopyroxene thermometry. This temperature was attained at a deeper level in the prograde phase in the granitoid gneiss prior to its emplacement at a shallower level during D_1 deformation.

A slightly different scenario was presented by Das et al. (2006) who demonstrated that low-P prograde heating (T > 800°C, P < 5 kb) led to anatexis, and in the restites sapphirine stabilization was induced at ~900° C and ~4.5 kb through the reaction corundum + cordierite + spinel = sapphirine. Minor amounts of sillimanite were produced by the ancillary reaction corundum + cordierite = sapphirine + sillimanite. They ascribed this heating to asthenospheric upwelling below a thinned crust. The near-peak temperature was attained prior to the attainment of P_{max} value resulting from orogenic loading. Subsequent cooling due to thermal relaxation at high pressure (700°C at 8 kb) produced decomposition of sapphirine+cordierite to enstatite+ sillimanite symplectites; occasional spinel in the symplectite may have been formed by the reaction sapphirine = spinel+sillimanite+enstatite.

Although the UHT assemblages are not recorded throughout the Eastern Ghats Province (EGP), the geochronological data discussed later suggest that the early UHT metamorphic event affected the entire EGP. The absence of UHT assemblage may be due to absence of suitable bulk composition and/or thorough reworking during the later episode of granulite facies metamorphism at lower temperature. Most workers consider that the M_1 UHT metamorphic episode had an anticlockwise P-T path, the retrograde path being characterized by isobaric cooling to 750°-850°C (Dasgupta and Sengupta, 2003 and references therein). The cooling produced orthopyroxene+sillimanite+ garnet bearing assemblages in high-Mg-Al rocks by reactions involving spinel, saphirine, cordierite. It is inferred that post-peak isobaric cooling also produced K-feldspar+cordierite+orthopyroxene symplectites in high-Mg-Al granulites through breakdown of osumilite (Dasgupta and Sengupta, 1995). The cooling produced coronal grossular-rich garnet and anorthite+calcite symplectite at the expense of scapolite+wollastonite+calcite assemblage in calc-silicate gneisses and coronal garnet over pyroxene in mafic granulites and enderbites (Dasgupta and Sengupta, 2003, and references therein; Mukhopadhyay and Bhattacharya, 1997).

In the Anakapalle area Dasgupta et al. (1994) documented an early high temperature decompression of 1.5 kb from peak condition followed by isobaric cooling. According to them this does not imply a clockwise P-T trajectory (cf. Mohan et al. 1997), but the decompression is probably part of an overall anti-clockwise trajectory. It is to be noted that the Anakapalle granulites do not record the extreme thermal conditions at peak metamorphism, though sapphirine inclusions in garnet porphyroblasts suggest an earlier event of UHT metamorphism (Dasgupta et al. 1994; Dasgupta and Sengupta, 1995). The above trajectory does not start from UHT condition, and thus it is possible that the clockwise P-T path at Anakapalle may reflect the trajectory for the M_2 metamorphism.

According to several workers (Dasgupta and Sengupta, 2003; Dasgupta et al. 1992, 1995; Dobmeier and Raith, 2003; Rickers et al. 2001b; Sengupta et al. 1990, 1999; Simmat and Raith, 2008) the isobarically cooled M_1 granulites were reworked by a second granulite grade metamorphism (M_2) and partial melting, whose peak condition is estimated to be 8-8.5 kb and 800°-850°C, as constrained by the thermobarometric data. The gap between the M_1 and M_2 metamorphisms is marked by the intrusion of enderbite-charnockite into the supracrustal rocks. Leptynite and megacrystic garnetiferous gneiss are linked with the M_2 partial melting. The prograde path of M_2 could not be worked out. The retrograde path of M_2 is characterized by near isothermal decompression to ~5 kb as constrained by thermobarometric data. The formation of second generation of cordierite in pelitic gneisses at the expense of orthopyroxene+sillimanite+garnet+quartz, and of decomposition of garnet to plagioclase+ orthopyroxene/ ilmenite/biotite is generally attributed to this decompression (Dasgupta et al. 1992, 1994, 1995; Gupta et al. 2000; Kamineni and Rao, 1988a; Mohan et al. 1997; Mukhopadhyay and Bhattacharya, 1997; Sengupta et al. 1990). However, Das et al. (2008) argued that in the mafic granulites from the western boundary shear zones the reactant phases for the production of orthopyroxene+ plagioclase symplectites are hornblende, plagioclase and garnet, and the symplectites are formed due to post-thrust reheating rather than decompression. From a study in the Bolangir anorthosite Prasad et al. (2005) suggested that the corona around garnet formed at 750°±50°C, 6.0±1.0 kb, through the break down reaction grossularite+plagioclase$_1$ (±quartz) = orthopyroxene+plagioclase$_2$ in the NCFMAS system rather than the reaction grossularite+quartz = orthopyroxene+plagioclase in the CFMAS system, which has a low –dP/dT slope. Therefore the interpretation of orthopyroxene-plagioclase symplectite around garnet as a near-isothermal decompression may be an oversimplification and a critical evaluation of the •decompression• reactions in other areas is warranted.

Two separate episodes of metamorphism are also inferred by Kar (2007) in the Jenapore area in North Orissa, close to the boundary with the Rengali Province. An earlier metamorphism, coeval with D_1, had a peak P-T regime of 9.5 kb at 950°C, followed by post-peak isobaric cooling through 200°-350°C at 8.5-9.5 kb. He considered this early metamorphism to be of Archaean age, but the evidence in support is weak. A later metamorphism, probably of Grenvillian age and coeval with D_2, had P-T condition of ~6 kb at 600°C with either up-pressure or cooling trajectory.

Rickers et al. (2001b) reported multistage evolution of xenoliths of high-Mg-Al granulite in mafic granulite from Anakapalle, starting with first phase deformation and UHT metamorphism (>1000°C, ~10 kb) that produced orthopyroxene+garnet+sapphirine+spinel+rutile assemblage. In the second stage high temperature decompression caused replacement of garnet and orthopyroxene porphyroblasts by lamellar orthopyroxene+sapphirine symplectites. This was followed by a period of felsic intrusion accompanied by local-scale metasomatism and subsequent deformation-metamorphism (? = M_2 in other areas) still under granulite facies condition. Finally, there was a period of cooling and decompression to ~800^0 C, 4-7 kb (? = M_2 decompression in other areas), giving rise to growth of late garnet at the expense of orthopyroxene+sapphirine+plagioclase.

From the Chilka area Sen et al. (1995) also documented a multistage evolutionary model for high-Mg-Al granulites with peak P-T conditions of >12kb and 1000°C, followed by three stages of decompression punctuated by two isobaric cooling (IBC) segments. This estimate of peak metamorphic condition is disputed by Dasgupta and Sengupta (2003) who recorded a much lower P of 8 kb and T ~900°C. Later detailed work (Dobmeier and Simmat, 2002) has brought into light a protracted tectonometamorphic history in the Chilka area. The supracrustal assemblage along with the mafic layers and lenses were intruded by concordant bodies of tonalite (now enderbite) prior to the earliest discernible deformation. The intrusion was probably linked with an unspecified early event of metamorphism and partial melting. The rocks were all deformed (D_1) and affected by UHT/HT metamorphism, and migmatization. Probably at this time the massif type anorthosite pluton intruded at mid-crustal levels (~7 kb). Leucogranitic crustal melts (now leptynite, K-feldspar bearing augen gneiss) also intruded the supracrustal rocks and enderbitic granulites. The entire ensemble was subjected to renewed granulite facies tectonometamorphic reworking (D_2-D_3). UHT (T>1000°C) contact metamorphism is documented in high Fe-Al granulites and in calc-silicate rocks from the narrow contact aureole of anorthosite (Raith et al. 2007; Sengupta et al. 2008). The granulite facies condition (~800°C, ~8 kb) continued through all the phases of deformation (D_1-D_4), and this was followed by cooling and decompression to ~650°C, ~5 kb.

The proposition that in the region north of the Godavari Rift an UHT event predates a lower temperature granulite facies event is contradicted by Bhattacharya and Gupta (2001). They favour a model of a single granulite facies metamorphic event and multiphase deformation events D_1, D_2, D_3 forming a continuum. During the prograde phase there was prolific migmatization under granulite facies condition, and the emplacement of regional scale granitoids was synchronous with D_1 shortening; thus deformation was initiated on a crust that was already thermally perturbed and partially molten. Thereafter melt productivity decreased during D_2-D_3, but the granulite facies conditions persisted and the peak conditions of T = 900°-950°C and P = 8-9 kb were attained after D_3. They also pointed out that the sapphirine has varying relation to the fabric elements and suggested that in spatially separated domains the UHT events may not be of the same age; alternatively the deformation events may be diachronous.

In many areas of the Eastern Ghats sporadic amphibolite facies metamorphism (M_3) accompanying hydration and carbonation has overprinted the earlier assemblages with P-T condition estimated at 4-5 kb, ~600° C. This is often localized along shear zones. In the Salur area Mukhopadhyay and Bhattacharya (1997) documented decomposition of garnet during such a low pressure cooling path following the isothermal decompression. This cooling trajectory is constrained by the following reactions,

almandine + K-feldspar + H_2O → muscovite + annite + quartz

anorthite + K-feldspar + H_2O + CO_2 → muscovite + calcite + quartz

Western Boundary Shear Zone

In contrast to the low grade metamorphism along the shear zones in the central parts of the EGP, near the EGBSZ in the neighbourhood of Deobhog the peak P-T conditions reaching up to UHT stage were reached after the formation of the D_3 shear foliation. This metamorphism led to generation of garnet+orthopyroxene bearing leucosomes and stabilization of orthopyroxene+ clinopyroxene+plagioclase assemblage in mafic granulites and sapphirine+cordierite+ orthopyroxene in high-Mg-Al granulites (Gupta et al. 2000; Neogi and Das, 2000). In a slice of cratonic granite-migmatite within the hanging wall granulites located to the south of Deobhog Bhadra et al. (2007) demonstrated that melting took place during shear deformation at 800°±50°C and 8.0±1 kb. Gupta et al. (2000) and Bhadra et al. (2004) invoked the model of thrusting of hot granulites over the cold craton, causing post-thrusting heating of the craton, while the granulites underwent cooling and decompression. The mineral assemblages within the autochthonous craton document progressive increase in grade towards the contact while cooling in the granulites is documented by the development of coronal garnet and subsequent decompression by the breakdown of coronal garnet to orthopyroxene+plagioclase. Concomitant H_2O influx caused retrogression of orthopyroxene to hornblende+biotite aggregates. Gupta et al. (2000) further pointed out that the preservation of the thrust-induced thermal gradients in the rocks would imply rapid exhumation of the craton-mobile belt assembly closely following the juxtaposition of the two units. As mentioned earlier, Das et al. (2008), however, prefer to interpret the breakdown of garnet to orthopyroxene+plagioclase symplectite as being due to post-thrust heating rather than decompression.

Das et al. (2008) suggested that the syn- and post-thrusting mineral assemblages in the rocks in and close to the shear zone represent a distinct metamorphic event which is younger than the Grenvillian granulite facies event within the EGP. They record two stages (M_1 and M_2) of pre-thrust metamorphism in the granulites. The syn-thrusting M_3 metamorphic stage is represented by the shear foliation defining grains of hornblende and associated plagioclase+clinopyroxene± orthopyroxene assemblage. They postulated that after its emplacement over the craton, the hot EGB thrust sheet first underwent cooling as a result of thermal relaxation. They also suggested that the stabilization of hornblende in the precisting granulites may be correlated with the cooling event aided by influx of fluids released by concomitant prograde metamorphic reactions in the heated footwall cratonic gneisses. This was followed by loading and subsequent reheating (M_4) caused by the burial of the granulite facies gneisses neighbouring the shear zone under the west-vergent imbricated thrust sheets which were emplaced from the hinterland EGB and were stacked one above the other. This reheating caused the decomposition of garnet mentioned above, and the resultant symplectite overgrew the shear fabric. Das et al. (2008) presented a well-argued case, but their model is contrary to the commonly observed phenomenon of progressively younger thrusts developing closer to the foreland (cf. relation between MCT, MBT, and HFT in the Himalayas, Hodges, 2000), and if this model is accepted all the thrusts will have to be accepted as being out-of-sequence thrusts. Further, there is no record in the mineral assemblages of the nearly isothermal loading prior to reheating as proposed by them and there is no support for this model from geothermobarometric measurements.

P-T Trajectories

The P-T trajectories from different sectors of the Eastern Ghats are shown in Fig.6. The trajectories are of diverse types, but Dasgupta and Sengupta (2003 and references therein) argued that in most parts of EGB, M_1 shows a general anti-clockwise trajectory, in which the UHT metamorphic peak is followed by near isobaric cooling (IBC). Lal et al. (1987) had earlier suggested a clockwise path with decompression following the UHT peak condition for the rocks in the Paderu area. However, Pal and Bose (1997) and Sengupta et al. (1997b) reinterpreted the petrographic data of Lal et al. (1987) to make them consistent with a general anticlockwise path; the prograde path reached peak values of P = 9.5 kb, T = ~1000°C and was followed by near isobaric cooling to P = 9 kb, T = 900°C. At Paderu, Bhattacharya and Kar (2002) and Bhattacharya et al. (2003) also proposed a clockwise path, in which peak P-T condition of ~10 kb and ~1000°C was followed by high temperature decompression and subsequent isobaric cooling. However, Sengupta et al. (2004) have questioned some of their textural interpretations and thermodynamic calibrations. They suggest that the data are consistent with decompression from a lower pressure of 7-8 kb and T = 850°C. This decompression postdated cooling from the UHT conditions. The pattern would thus be similar to the anticlockwise pattern in other areas. The retrograde path of M_2 metmorphism is marked by near isothermal decompression followed by cooling. Bhattacharya and Gupta (2001) suggested that the differences in the post-peak P-T paths in different areas may indicate the existence of spatially disparate metamorphic sectors within the granulite belt.

For the M_3 and M_4 metamorphism (? Pan-African) along the western boundary zone Das et al. (2008) proposed a clockwise P-T path starting from M_2. This needs corroboration by quantitative P-T determinations.

Deformation and Metamorphism

An outstanding problem is the correlation of the metamorphic events with the deformation events. The mineral assemblages in the segregation bands formed during both D_1 and D_2 indicate that the deformation took place in granulite facies environment. Foliation parallel leucosomes and emplacement of syn-deformation granites point to extensive melt production during D_1 and D_2 deformations. The minerals in the granulites generally show recrystallized granoblastic fabric with little evidence of internal strain, thus testifying that the high temperature persisted even after the culmination of the deformation events (Bhattacharya and Gupta, 2001). The structures of the different phases indicate protracted compressional deformation, but it is not certain whether these formed in a continuum during one cycle or discontinuously. In some areas at least (our unpublished observation at Angul, Dobmeier and Raith, 2000, at Chilka, Rickers et al. 2001b, at Anakapalle), a break between D_1 and D_2 is testified by the emplacement of felsic rocks in between. At Jenapur also Kar (2001, 2007) inferred a break between D_1 and D_2. This is important in the context of the question of whether there is one cycle of metamorphism, or whether rocks metamorphosed in an earlier phase are reworked during a later phase of metamorphism.

The timing of the attainment of peak condition of UHT/HT metamorphism is unclear. At Anantagiri in the central part of EGB, UHT minerals like sapphirine define the penetrative foliation (D_1/D_2) (Sengupta et al., 1990), which implies syntectonic growth. Rickers et al. (2001b) also report UHT metamorphism accompanying the first deformation at Anakapalle. From the same region Dasgupta et al. (1994) describe that sapphirine occurs in coronas or symplectitic aggregates with random orientation and overprinting the main gneissic foliation, suggesting post-tectonic growth. On the contrary along the western boundary zone the UHT metamorphic condition (≥ 900°C, ~9 kb) was attained during or after the D_3 deformation, i.e., during or after the thrusting of EGB over the craton (Gupta et al. 2000; Neogi and Das, 2000; Bhadra et al. 2004). In contrast, in the central part of the EGB the retrogressive event M_3 is often correlated with D_3. Therefore either the metamorphic events or the deformation events or both were diachronous over the extent of the EGB (Gupta, 2004). Clearly more detailed structural observations combined with textural analysis are needed to better understand the deformation-metamorphism relation.

META-IGNEOUS ROCKS

Mafic-Ultramafic Rocks

Bands, and lenses of mafic granulite, interlayered with metapelitic rocks or occurring as enclaves within quartzo-feldspathic gneiss are common throughout the EGB (Sengupta et al. 1996). The mafic granulites have tholeiitic affinity (Subba Rao and Divakara Rao, 1999). Xenoliths of high-Mg-Al granulite occur within the mafic granulites at places, which in turn are intruded by charnockite and enderbite. Sengupta et al. (1996) pointed out their geochemical similarity to continental flood basalts and suggested that they probably originated in an extensional setting. Whether any of the mafic bands represent volcanic flows remains to be ascertained.

At Kondapalle that lies south of the Godavari Rift, a layered complex of gabbro-norite- pyroxenite-anorthosite has intruded the metapelitic granulites (Leelanandam, 1990, 1997, 2004; Sengupta et al. 1999). The parental magma was high-Mg basalt, and the geochemical characteristics suggest emplacement in an arc-related environment (Leelanandam and Vijaya Kumar, 2007). The layered complex and the surrounding felsic granulites are interpreted to be parts of root complex of a continental magmatic arc. Leelanandam (2004) estimated liquidus temperatures of the parental liquid to range up to 1500°C on the basis of olivine compositions, while Sengupta et al. (1999) reported that the emplacement and fractionation of the suite took place at >8 kb and ≥1100°C. Subsolidus temperatures of 850°-1100°C are inferred from olivine-orthopyroxene exchange equilibria, and the subsolidus re-equilibration was estimated to be at 700°–810°C for olivine-spinel pairs (Leelanandam and Vijaya Kumar, 2007). Post-emplacement near-isobaric cooling to 700° C produced coronal garnet and exsolution of spinel from aluminous pyroxene (Sengupta et al. 1999). Similar mafic-ultramafic complex is present at Chimakurthy south of the Godavari Rift (Dasgupta et al. 1997), which was emplaced at a shallower level (~6 kb). From the central part of the complex a temperature of 1100°C is estimated from two-pyroxene thermometry. The clinopyroxenite, gabbro and anorthosite of the suite are thought to be derived from a high-Al tholeiitic parental magma (Vijaya Kumar et al. 2007). The emplacement of the layered complexes is inferred to be coeval with and to be causally connected with the UHT metamorphism.

Quartzo-feldspathic Gneisses

A major constituent of the EGB is orthopyroxene-bearing quartzo-feldspathic gneiss (charnockite and enderbite) which forms large massifs. Dasgupta and Sengupta (2003, and references therein) have pointed out that most of the massifs are made up of enderbite rather than charnockite *sensu stricto*, and these have intruded the khondalite-mafic granulite-leptynite ensemble. The latter were already high grade migmatitic gneisses at the time of intrusion, as indicated by the presence of xenoliths of the migmatitic gneiss with internal foliation that is discordant to that in the host. The intrusion of enderbite is generally regarded to be post-D_1, and pre- or syn-D_2 (Dobmeier and Raith, 2003, our own unpublished observations from Angul). It has been suggested from the calc-alkaline affinity of the rocks that these were generated in an Andean-type active continental margin setting (Dobmeier and Raith, 2003). A high grade overprint (M_2) accompanied by partial melting and ductile deformation is discernible in the charnockites and enderbites (Murthy et al. 1998; Charan et al. 1998). From the Chilka area Dobmeier and Raith (2000) describe that enderbite intruded the pelitic gneiss prior to the earliest recognizable deformation (D_1), but the possibility of the supracrustal rocks being already in a high grade and deformed state could not be excluded. Therefore it is possible that what they describe as D_1 is really D_2. Kar et al. (2003) suggested that the massif-type enderbite is crystallized from a tonalitic magma that is produced by hornblende-dehydration melting of hornblende-granulite.

Patchy charnockitic domains within leptynitic gneiss are seen at several places within the EGB (Angul: Halden et al. 1982; Chilka: Bhattacharya et al. 1993; Dobmeier and Raith, 2000; Jenapur: Kar, 2007; Vizianagram: Datta et al. 2001). These have been interpreted by Bhattacharya et al. (1993) and Kar (2007) as boudinaged charnockite layers or caught up xenoliths within quartzo-feldspathic melt; Bhattacharya et al. (2002) have cited structural relations and geochemical dissimilarities with the host to indicate that the charnockite is older than the leptynitic host. In their view there is a genetic connection between the enderbite and the patchy charnockite. The zircon $^{207}Pb/^{206}Pb$ dates from the host are 975 Ma and 1000 Ma, while dominant dates of zircons from patchy charnockite are around 900 Ma, though a few older dates of 2694 Ma and 1722 Ma are also found. Thus the dates provide no confirmatory evidence of older age of the charnockite patches. Contrary to Bhattacharya et al. (1993), Dobmeier and Raith (2000) hold that the patchy charnockite is younger than the enderbite, and was formed during what they describe as D_3. They presented evidence in favour of in situ synkinematic formation of charnockite domains through breakdown of biotite and garnet due to local fluid migration along steep foliation planes. Datta et al. (2001) interpreted the patchy charnockite near Vizianagram to be produced by influx of CO_2-rich fluid along the foliation in the host leptynite. They envisaged that the fluid was derived from the crystallization of the enderbitic magma that intruded the leptynite. Therefore, according to them enderbite and patchy charnockite are broadly contemporaneous and both are younger than leptynite.

Leptynite is garnet-bearing quartzo-feldspathic gneiss (leucogranite) with a typical platy granoblastic (•plättungŽ, Sen, 1987) texture. It is intimately associated with khondalite and is interpreted to have been formed by biotite-dehydration melting of a pelitic source (Karmakar and Fukuoka, 1992; Sen and Bhattacharya, 1997). Probably a major part of the leptynites was formed during M_1, earlier than the enderbite intrusion. However, from Chilka area Dobmeier and Raith (2000) describe that the precursor melt of leptynite intruded the enderbite and was later metamorphosed and deformed during D_2-D_3. It is likely that partial melting took place at different times to give rise to leptynites of different ages.

Porphyritic granitoids, with garnet and/or orthopyroxene, form batholithic bodies and are younger than both enderbite and leptynite. Many of the batholitihic bodies occur along mega-lineaments (Nash et al. 1996; Ramakrishnan et al. 1998). These are not affected by the early deformation. They have S-type characters and their bulk compositions and isotopic data suggest derivation from crustal sources (Krause, 1998, quoted in Dobmeier and Raith, 2003).

The sequence of emplacement of the diverse types of felsic gneisses in different areas of the EGB, their mutual relation, and their relation to the tectonometamorphic events need to be worked out in details.

Anorthosite

Massif-type anorthosite complexes of varying size occur in the EGB (Leelanandam, 1990; Leelanandam and Reddy, 1998; Bolangir: Bhattacharya et al. 1998; Dobmeier, 2006; Chilka: Dobmeier and Simmat, 2002; Krause et al. 2001; Sarkar et al. 1981; Jugsayapatna: Nanda and Panda, 1999; Turkel: Maji et al. 1997). The age of these anorthosite plutons is around ~0.9 Ga (Bolangir Complex: Krause et al. 2001; Chilka Lake Complex: Chatterjee et al. 2008). South of the Godavari Rift anorthosite is present in the layered complexes, and a small layered-type anorthosite complex (Pangidi anorthosite) (Dharma Rao et al. 2004) is reported to have older age (~1.7 Ga).

The anorthosites are deformed and metamorphosed, but there are divergent views on the time of emplacement of the plutons *vis-à-vis* deformation episodes. Ferrodiorite occurs at places in the immediate contacts of anorthosite; it intrudes the anorthosite as dykes and sheets. The anorthosite is thought to have formed by plagioclase fractionation from high alumina basaltic melts during lithospheric thinning. The ferrodiorite is interpreted as interstitial residual melts which suffered contamination through interaction with adjacent felsic melts. Chilka anorthosite magma had temperature in excess of ~1000^0 C. No chilled margin is seen because the anorthosite intruded into the country rocks which were hot and had suffered deformation and granulite facies metamorphism prior to and during the emplacement of anorthosite.

Different workers have described the emplacement of anorthosite as being prior to, at the beginning of, or during ductile regional deformation and granulite facies metamorphism at mid-crustal levels (750–800°C, 7–6 kb). According to Dobmeier (2006) the Bolangir anorthosite was emplaced during the main episode of isoclinal folding of the country rocks (D_2-D_3), but after the development of migmatitic foliation and extensive leucosome formation. According to Bhattacharya et al. (1994) the Chilka anorthosite was emplaced after D_2 and prior to D_3; it is younger than the leptynites which has a well-preserved D_2

foliation. However, Dobmeier and Raith (2000) and Dobmeier and Simmat (2002) described the emplacement of Chilka anorthosite to be post-D_1 and post-UHT metamorphism and pre-D_2. It was deformed (D_2-D_3) and metamorphosed later along with its host rocks.

The Pangidi anorthosite south of Godavari Rift is associated with leuconorite and pyroxenite and the association is similar to the nearby Kondapalle Complex (Dharma Rao et al. 2004), but has higher proportion of hydrous minerals.

Alkaline Rocks

The plutons of alkaline rocks are confined to a belt adjacent to the boundary between the EGB and the neighbouring Bastar, Singhbhum and Eastern Dharwar cratons (Fig.7) (Leelanandam, 1998;Upadhyay, 2008 and references therein). In the northern segment, the alkaline complexes of Kankrakhol, Baradangua, Kharsoli and Rairakhol are present along the southern edge of the Rengali Province. Further south the Khariar alkaline rocks are

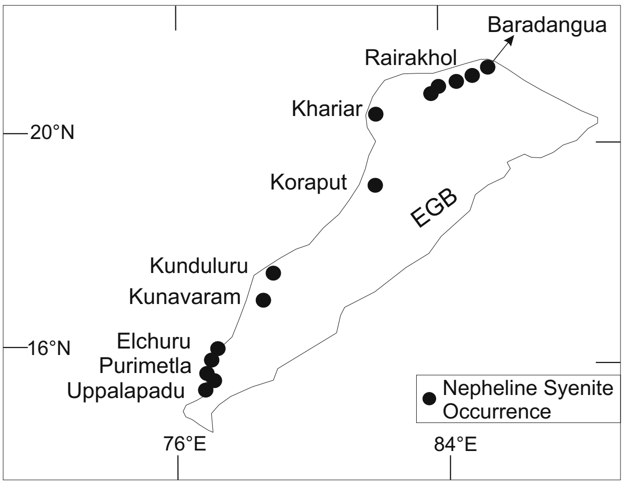

Fig.7. Locations of alkaline plutons in the Eastern Ghats Belt.

exposed along the western contact of the Eastern Ghats Province with the Bastar craton (Upadhyay et al. 2006b and references therein; as et al. 2008;Biswal et al. 2007), while at Koraput the alkaline pluton occurs within the sheared metapelitic gneisses of the Eastern Ghats Province, about 6 km east of its contact with the Jeypore Province (Bhattacharya and Kar, 2004;Gupta et al. 2005;Nanda et al. 2008 and references therein). The recent work by Nanda et al. (2008) suggests that the post-intrusion metamorphic history of the Koraput alkaline pluton is different from that in the other alkaline plutons in the boundary zone. The Kunavaram complex is located along the southern tip of the Sileru Shear Zone. Its western boundary is marked by a prominent shear zone (Gupta and Bose, 2004;Upadhyay and Raith, 2006a and references therein). The rocks to the west of the shear zone are designated as cratonic rocks by Upadhyay and Raith (2006a), but if the shear zone is correlated with the Sileru Shear Zone the western rocks are expected to belong to the Jeypore Province. The description of Gupta and Bose (2004) that the amphibolites in this region appear to be retrograded granulites lends support to this idea. South of the Godavari Rift the alkaline complexes (Elchuru, Uppalapadu, Purimetra) (Upadhyay et al. 2006a;Vijaya Kumar et al. 2007) belong to the Prakasam Igneous Province (Leelanandam, 1989) straddling the western boundary of the Ongole Domain with the Vinjamuru Domain of the Krishna Province.

The principal rocks in the alkaline plutons are nepheline syenite, hornblende syenite, syenite and quartz syenite. In addition to the alkaline syenites quartz-bearing monzo-syenitic bodies are also present (Upadhyay and Raith, 2006a). At Khariar the rocks of the alkaline complex are interlayered with tholeiitic mafic rocks which may be the remnants of an ocean floor (Upadhyay et al. 2006b). Vijaya Kumar et al. (2007) referred to the spatial and temporal association of both tholeiitic and alkaline end-members of continental rift magmatism within the Prakasam Igneous Province.

Though magmatic foliation is occasionally recognized in the alkaline rocks (Gupta et al. 2005; Das et al. 2008), the dominant planar fabric is commonly a solid-state deformation structure (Gupta et al. 2005; Das et al. 2008; Nanda et al. 2008; Upadhyay, 2008 and references therein). The magmatic foliation is seen at places to be folded (Biswal et al. 2007), and an axial plane foliation cuts across it. The shear zone related fabric overprints this solid state fabric and is parallel to the shear foliation in the country rocks of both the craton and the EGB (Upadhyay, 2008 and references therein, Das et al. 2008). The microstructures related to shearing indicate top-to-west (thrust) sense of movement, a dextral component of motion is also recorded at Kunavaram (Gupta and Bose, 2004).

The alkaline complexes are all metamorphosed. At Khariar while the post-shearing peak P-T condition in the *overlying* EGB granulites is T = ~750°C, P = ~7 kb, (Das et al. 2008), the metamorphic imprint in the alkaline complex below the thrust was of amphibolite facies and in the *underlying* cratonic rocks the syn-thrusting metamorphism caused by loading and heating from the overlying hot granulite block was of greenschist facies. At Koraput the host EGP gneisses suffered an earlier granulite facies metamorphism and deformation. Post-metamorphic emplacement of the alkaline pluton was followed by retrogression-deformation event producing biotite-defined foliation. Subsequent prograde metamorphic event involved heating along an anticlockwise path (heating followed by loading) and produced anhydrous granulite facies assemblage (garnet+clinopyroxene+K-feldspar± orthopyroxene) both in the country rocks and in the pluton (Nanda et al. 2008). Nanda et al. (2008) consider this later event to represent an intracrustal orogeny unrelated to the process of amalgamation of the granulite belt with the Archaean Bastar/Dharwar craton (? Pan-African Orogeny). At Kunavaram there was a decrease in the grade of metamorphism in the country rocks during shearing to greenschist-lower amphibolite facies (Gupta and Bose, 2004). For the Jojuru quartz-monzosyenite in the Prakasam Igneous Province near the western boundary zone of the Ongole Domain, Upadhyay and Raith (2006b) have estimated the P–T to be 5.5–7.0 kb and 600°–700°C from coronal garnet formed at the interface between clino-pyroxene–orthopyroxene–ilmenite clusters and plagioclase.

Upadhyay (2008) and Vijaya Kumar et al. (2007) suggested that the parental magma for the alkaline complexes were of basanitic composition produced by partial melting of enriched mantle sources in sub-continental lithospheric mantle; fractionation, with or without crustal assimilation produced the different rock suites.

Some workers (Biswal et al. 2007; Bose, 1970; Bose et al. 1971; Chetty, 2001 and references therein) are of the view that the alkaline rocks were emplaced syntectonically during thrusting and shearing along the western and northern contact zone of the EGB. On the other hand Czygan and Goldenberg (1989), Gupta and Bose (2004), Gupta et al. (2005), Upadhyay and Raith (2006a, 2006b), Upadhyay et al. (2006a, 2006b) and Upadhyay (2008) show that the rocks are deformed and metamorphosed and the shearing has overprinted a solid-state metamorphic fabric in the rocks. Bhattacharya and Kar (2004, 2005) suggested that the series of plutons represent a hot-spot trace as the Indian plate moved over a hot spot/plume. But as Upadhyay (2008) pointed out there is no systematic change in the ages of the plutons from one end to the other as expected in this model, and no explanation is offered as to why the plutons are confined to the craton-EGB boundary. From the point of view of geological setting and petrography these alkaline complexes resemble the deformed alkaline rocks and carbonatites (DARC) of southeastern Africa for which Burke et al. (2003) proposed a model of emplacement during rifting and basin formation and deformation during closure and basin inversion. Leelanandam (1998) and Leelanandam et al. (2006) also proposed intracontinental rifting for the formation of the complexes. On the basis of similar ages (~1300 Ma to ~1500 Ma) and the rift-related geochemical signatures of the alkaline rocks Upadhyay (2008) suggested that the linear chain of alkaline complexes mark the location of a palaeo-rift at the cratonic margin, and these were later deformed during the collisional event associated with the thrusting of the EGB over the cratonic foreland.

GEOCHRONOLOGICAL CONSTRAINTS

Age of the Alkaline Plutons

The U-Pb data of zircon from a pegmatite in the Khariar alkaline complex within the northern part of EBSBZ give an upper intercept age of 1500+3/-4 Ma and a lower intercept age of 540±20 Ma (Aftalion et al. 2000). The SHRIMP $^{207}Pb/^{206}Pb$ age of zircon interiors is 1480±17 Ma (Upadhyay et al. 2006b). Therefore, it may be concluded that the intrusion age of the alkaline complex is ~1.5 Ga and the later tectonothermal imprint is of Pan-African age. The Pan-African age is corroborated by K/Ar cooling ages of nepheline (550±11 Ma) and amphibole (531±11 Ma), $^{206}Pb/^{238}U$ age of apatite (494±8 Ma) (Aftalion et al. 2000), Rb/Sr biotite-whole rock isochron ages (487.1±0.6 and 499.0±1.6 Ma) and $^{207}Pb/^{206}Pb$ age of sphene (~593 Ma) (Upadhyay et al. 2006b). A spectrum of SHRIMP dates of zircon ranging from 3174 Ma to 511 Ma has been reported by Biswal et al. (2007). According to them a cluster of ages at 511-576 Ma represents the intrusion age, and the older zircons are regarded as xenocrystic. The rationale for this conclusion is not clearly stated. The zircons have complex zoning patterns and the interpretation by Biswal et al. (2007) of the isotopic data may be questioned.

A preliminary report of U-Pb dates of zircon in alkaline rocks of Koraput suggests that the age of the post-intrusion granulite facies metamorphism to be in the range of ~0.70–0. 87 Ga (Nanda et al. 2008). These dates cannot be reconciled with the idea that the EGP and JP were juxtaposed due to thrusting in the Pan-African time (~0.5 Ga), because Nanda et al. (2008) report that the retrogression-deformation event (inferred to be coeval with thrusting) that predated the post intrusion metamorphism (0.70–0.87 Ga) affected the EGP and the JP alike indicating their contiguity at this earlier time.

The combined SHRIMP and TIMS analyses of interiors of zircon grains from the Kunavaram alkaline complex located in the southern tip of the Sileru Shear Zone define a discordia with the upper intercept age of 1384±63 Ma (intrusion age) and a lower intercept age of 632±62 Ma (metamorphism age) (Upadhyay and Raith, 2006a). The age of the later metamorphic overprint is corroborated by the near-concordant $^{207}Pb/^{206}Pb$ date of ~611 Ma from titanite and 484.0±2.3 Ma to 500.9±0.6 Ma cooling ages determined from biotite-whole rock Rb/Sr isochrons (Upadhyay and Raith, 2006a). The Rb-Sr whole rock isochron age of the alkaline complex is 1265±58 Ma (Clark and Subba Rao, 1971), expectedly younger than zircon age.

U–Th–Pb SHRIMP dating of zircons from the alkaline complexes within the Ongole Domain yields dates ranging from 1263 Ma to 1352 Ma (Upadhyay et al. 2006a; Upadhyay and Raith, 2006b; Vijaya Kumar et al. 2007). The Rb/Sr whole rock isochron ages for the alkaline complexes range from 1242Ma to 1369 Ma (Sarkar and Paul, 1998; Subba Rao et al. 1989; Upadhyay et al. 2006a).

The Rairakhol Complex of alkaline rocks, located near the boundary with the Rengali Province, has been dated by the Rb/Sr whole rock isochron method to be 1413±23 Ma (Sarkar et al. 2000).

Ongole Domain

In the Ongole Domain the Nd model ages of the sediments representing the mean crustal age of the provenance areas range between 2.6 to 2.8 Ga (Rickers et al. 2001a); this is the age of the granitoids of the eastern Dharwar craton, suggesting that at the time of sedimentation the Ongole Domain was probably adjacent to the Eastern Dharwar craton. The T_{DM} age of enderbites and charnockites is 2.3-2.5 Ga. These orthogneisses developed by assimilation of as much as 40% Archaean crust with mantle derived basaltic melt (Rickers et al. 2001a). The melt derivation was at an unspecified time between 1.7-2.4 Ga and the mixing was either at the time of differentiation or at 1.7 Ga at the latest. U-Pb ages of near-concordant magmatic zircon fix their time of crystallization at 1.70-1.72 Ga (Kovach et al. 2001). U-Pb dates of zircon fix the time of partial melting in charnockitic gneisses and in diatexitic granulites at 1672±3 Ma. (Kovach et al. 2001) and 1.61-1.63 Ga respectively (Upadhyay et al. quoted in Simmat and Raith, 2008), which fix the age of the UHT/HT metamorphism in this domain. U-Pb dates of monazites from charnockitic orthogneisses and their garnetiferous leucosomes are ~1.60 Ga (Kovach et al. 2001; Simmat and Raith, 2008), and from late- to post-tectonic pegmatite are 1672±4 Ma (Kovach et al. 2001), and 1672-1512 Ma (Mezger and Cosca, 1999). $^{207}Pb/^{206}Pb$ allanite ages from pegmatite dykes are 1598 Ma and 1350 Ma (Mezger and Cosca, 1999). From these dates it may be concluded that the main metamorphism was at ~1.6-1.7 Ga.

The metamorphosed Pangidi anorthosite complex has yielded a Sm-Nd isochron age of 1739±220 Ma (Dharma Rao et al. 2004). This is described as the intrusion age, which is similar to the above age of metamorphism. A younger Rb-Sr whole rock age of 1507±59 Ma (Sarkar and Paul, 1998) of a mangeritic granulite is probably due to later resetting of the isotopic system.

Chemical dating of monazite (Simmat and Raith, 2008) gives distinct populations at 1645 Ma, 1590 Ma, 1560 Ma and 1450 Ma, with the oldest ages being preserved in the monazite inclusions in garnet and in the core domains of zoned matrix monazites. According to Simmat and Raith (2008) the age of the fabric-defining high to ultrahigh metamorphism is between 1590 and 1650 Ma. Imprints of later ductile to brittle deformation accompanied by hydration are recorded in the monazite chemical dates of 1350-1450 Ma (Simmat and Raith, 2008). This event has been correlated with the crustal extension, rifting and alkaline plutonism along the margin of the EGB. EPMA single spot ages between 1200 and 600 Ma are measured in some samples from the Ongole Domain, but the significance of these ages is uncertain.

Mezger and Cosca (1999) reported that $^{40}Ar/^{39}Ar$ age of amphibole indicates cooling below ~500°C at 1111 Ma. Therefore the Ongole Domain had cooled down when the neighbouring Eastern Ghats Province was undergoing Grenvillian high grade metamorphism. It is important to note that no Grenvillian or Pan-African dates of metamorphism have been obtained from the Ongole Domain.

The Ongole Domain is thrusted westward over the Vinjamuru Domain of Nellore-Khammam Schist Belt, in which the granites intrusive into granitic gneisses yield U-Pb zircon upper intercept ages of 1589.7±5.7 Ma and 1588.4±7.1 Ma (Dobmeier et al. 2006). Rb-Sr age of synkinematically grown phengitic white mica indicate a low grade metamorphic overprint at 474-501 Ma, which Dobmeier et al. (2006) correlate with the westward thrusting.

Jeypore Province

Geochronological information from this province is meagre. The relation between the different lithotectonic units at the southern tip of the Jeypore Province and the relation between the Jeypore Province and the Ongole Domain are unclear. The enderbites in the Jeypore Province have Nd model ages (T_{DM}) of 3.0-3.9 Ga; this along with the strongly retarded Pb isotopic signatures of feldspars suggests formation of the igneous protoliths before 3.0 Ga (Kovach et al. 2001, Rickers et al. 2001a). The age of the metamorphism is not adequately constrained, but preliminary U-Pb data from complexly zoned zircons indicate granitoid emplacement at ~2.7 Ga, and granulite facies metamorphism at ~2.5 Ga (Kovach et al. 2001, Simmat and Raith, 2008).

At Kunavaram, beyond the southern tip of the Jeypore Province, the granulites are shown as belonging to the Ongole Domain in the map of Dobmeier and Raith (2003), and to the WKZ (? Jeypore Province) in the map of Ramakrishnan et al. (1998). Chemical dates using EPMA of monazites from the granulites to the east of the Kunavaram alkaline complex have a large range of 457 Ma to 1542 Ma (Upadhyay and Raith, 2006a). Three main populations are noticed: (a) 1447±9 Ma and 1449±31 Ma from cores of monazite inclusions in garnet, (b) 1017±47 Ma and 1087±46 Ma from small monazite grains in garnet, and (c) 526±25 Ma from overgrowths and rims on older monazite cores. The monazites residing in the mylonitic foliation of a garnet-sillimanite enclave in the nepheline syenite yield a uniform chemical date of 510±19 Ma. Clearly the monazites have a complex history but the dates suggest that the rocks went through a Grenvillian (~1.0-1.1 Ga) high grade metamorphism and a Pan-African (~0.5 Ga) overprint related to the development of the shear zone.

Rengali Province

North of the Kerajang Fault ^{207}Pb-^{206}Pb ages of zircon in granite gneiss indicate magmatism at ~2.8 Ga (Crowe, 2003 quoted in Dobmeier and Raith, 2003; Mishra et al. 2000). Mishra et al. (2000) opined that this gives a minimum age for the granulite facies metamorphism because xenoliths of granulite are present within the gneisses. The Sm-Nd whole rock isochron age of charnockite-mafic granulites from Jenapore close to the boundary of the Rengali Province is 3030±200 Ma and the ^{207}Pb/^{206}Pb age of zircon from charnockite of this area is 2930±42 Ma (Bhattacharya et al. 2001). The Rb/Sr whole rock isochron ages of charnockites at Riamal and Rengali north of the Kerajang Fault are 2743±103 and 2735±44 respectively (Sarkar et al. 2000). There are no U-Pb age data from these granulite occurrences, but on the basis of the available dates it is reasonable to conclude that the granulite facies metamorphism in RP is of Archaean age.

Eastern Ghats Province

Age of Anorthosites

For the Bolangir pluton, the U-Pb dates for zircon from the bordering ferrodiorite are discordant. From the upper intercept of the constructed discordia in the U-Pb concordia diagram Krause et al. (2001) fixed the time of intrusion to be 933±32 Ma.

Sarkar et al. (1981) determined a Rb/Sr whole rock isochron age of 1404±89 for the Chilka anorthosites. However Krause et al. (2001) argued on the basis of field and geochemical evidence that the linear data array in the Rb/Sr evolution diagram represents a mixing line between two components, the •pristine• anorthosite and a felsic melt generated in the aureole. They fixed the time of final stages of anorthosite emplacement as 792±2 Ma on the basis of concordant U-Pb age of abraded zircons from ferrodiorite which is a late stage crystallization product. Recently Chatterjee et al. (2008) have determined the upper intercept age of nearly concordant zircon to be 983.0±2.5 and the lower intercept age to be 704±10 Ma. They reinterpreted the 792 Ma date as the timimg of a separate tectonothermal event. Chemical dating of monazite yielded two age populations: 714±11 Ma for the core domains, and 655±12 for the rim domains. These are thought to represent two episodes of metamorphic monazite growth. The lower intercept age of zircon may be an average of these two age populations. Monazite rimming apatite yields a young date of 463±22Ma representing Pan-African thermal activity.

Age of Metamorphic Events

In the eastern part of the Eastern Ghats Province (EGP), near Visakhapatnam, the T_{DM} whole rock model ages of charnockites range from 2349 Ma to 2610 Ma (Paul et al. 1990). These are interpreted to represent the time of extraction of the protolith from the mantle. The whole-rock Sm-Nd isochron dates of 1455±80 Ma for the mafic granulites, and of 1464±63 Ma for the felsic rocks (leptynites) of Rayagada in the western sector of EGP are interpreted to represent the age of intrusion by Shaw et al. (1997). However the possibility that these represent the time of extraction of the melt and not the intrusion age cannot be ruled out. If these are indeed the intrusion ages the sedimentation must be older than this. Shaw et al. (1997) reported SHRIMP ^{207}Pb/^{206}Pb ages of 2747 Ma and 1450 Ma of detrital subrounded to rounded zircon grains in metapelitic granulites. U-Pb ages of 1801-1369 Ma of detrital zircon grains from pelitic and high-Mg-Al granulites have also been reported by Jarick (1999, quoted in Simmat and Raith, 2008). Hence the youngest sediments must be younger than ~1.37 Ga. We have already discussed that at Khariar and at Kunavaram the alkaline complexes having intrusion age of ~1.4-1.5 Ga are hosted by the granulites. Hence unless the present disposition of the alkaline complexes is due to thrust wedging the sedimentation must have started at >1.5 Ga. With our present information the age of sedimentation cannot be more precisely defined. Broadly these ages are consistent with the T_{DM} model ages which lie within the range 1.8-2.5 Ga (Rickers et al. 2001a).

The available geochronological data lend support to the conclusions discussed earlier about a UHT metamorphism being followed by a second episode of high temperature granulite facies metamorphism. The results from conventional dating methods are discussed first, followed by the results obtained in recent years from chemical dating of monazite.

An early episode of felsic magmatism at 1150-1200 Ma is indicated by U-Pb zircon date of (?charnockitic) augen gneiss (Angul: 1159±59/-30, Aftalion et al. 1988), and zircon age of intrusive granitoid complex near Berhampur (U-Pb upper intercept age: 1186±38 Ma, $^{207}Pb/^{206}Pb$ age of zircon: 1074 Ma, Krause, 1998, quoted in Simmat and Raith, 2008) and Sm-Nd whole rock isochron age of granitoid gneisses thought to be the product of high temperature melting during prograde metamorphism (Paderu: 1162±20 Ma, Bhattacharya et al. 2003).

The timing of the early UHT metamorphism is inferred to be ~1100 Ma on the basis of Pb-Pb whole rock - feldspar isochron age of sapphirine-bearing granulites (1099±56 Ma) and zircon U-Pb age (1139±24, Jarick, 1999, quoted in Simmat and Raith, 2008) and SHRIMP $^{207}Pb/^{206}Pb$ age of zircon (1105$\pm$9 Ma) in partial melt product (Crowe, 2003, quoted in Dobmeier and Raith, 2003), Sm-Nd whole rock-mineral (feldspar-garnet) isochron age (1067±43 Ma) of metapelites and Rb-Sr whole rock isochron age (1069±84 Ma) of metapelites (Shaw et al. 1997). The geochronological data cannot resolve the question of whether the felsic magmatism was a separate event or was linked to the UHT metamorphism and was a product of it.

The large data base generated by Simmat and Raith (2008) on chemical dating of monazites in samples collected throughout the EGB indicates a complex polycyclic evolution of the EGB. Older EPMA spot ages of monazite are obtained from small grains armoured in porphyroblastic garnets or in the interiors of such grains and also in the cores of the grains in the matrix. The host garnet porphyroblasts also contain inclusions of sillimanite, spinel and rutile at several places and therefore these old dates are considered to represent the prograde stage of the early UHT metamorphism. Significantly the older dates are very rare in charnockites and enderbites, probably suggesting that these crystallized either after or during the cooling stage of the first cycle of deformation-metamorphism. Some of the determined values of the older dates are (Simmat and Raith, 2008):

(a) In the western sector extending from Vijaywada to Khariar the range is 1159-1181 Ma from khondalites and 1065 Ma from high-Mg-Al granulites. The older ages in khondalites are interpreted to date the prograde stage and the younger age in high-Mg-Al granulite the peak stage of UHT metamorphism.
(b) In the central sector near Phulbani the range of the oldest apparent spot ages in khondalites are 1020 – 1067 Ma (Mean: 1061±48 Ma).
(c) In the eastern sector skirting the east coast, at Anakapalle the oldest spot ages in xenoliths of high-Mg-Al granulites (Rickers et al. 2001b) range from 1100 to 1300 Ma (Mean: 1100±27 Ma). In garnetiferous augen gneiss at Berhampur the oldest spot ages are 1008 to 1037 Ma (Mean: 1017±10 Ma).
(d) In the Chilka region the oldest spot ages are 1030-1090 Ma in khondalites and metasomatised khondalites.
(e) In the Angul area age populations of 1200-1260 Ma have been obtained from the interiors of monazite grains in the matrix of restites and leucosomes and as inclusions in garnet.

There is strong evidence that the main fabric-defining M2 granulite facies metamorphism and anatexis was of Grenvillian age, ~950-1000 Ma. The significant dates obtained through conventional methods are given in Table 1. This event was contemporaneous with generation of voluminous felsic melts which were emplaced as syn- to post-tectonic felsic plutons. Field and petrological evidence and the gochronological data indicate that there are several cycles of deformation and metamorphism, anatexis and emplacement of felsic plutons.

Chemical dates of monazite confirm this conclusion. The most prominent populations of the chemical dates of monazite fall within the span of 950-980 Ma in pelitic granulites, high-Mg-Al granulites, charnockites-enderbites, leptynites and augen gneiss (Simmat and Raith, 2008). The dates come from either overgrowth or individual grains in both restitic and leucosomal layers. In most of the samples the peak of the age population distributions fall within this range, and this date fixes the timing of the fabric-defining HT metamorphism and anatexis. At Anakapalle the dominant domains of monazite grains included in porphyroblastic garnet in high-Mg-Al granulites have age populations of 980-1000 Ma which Simmat and Raith (2008) interpret to constrain the growth of porphyroblastic garnet in the UHT assemblages.

However, a prolonged tectonothermal activity with HT metamorphism, melting and leucosome generation is indicated by U-Pb zircon age (792±2 Ma, Krause et al. 2001; 764±35 Ma, Crowe, 2003, quoted in Dobmeier and Raith, 2003, 769±29Ma and 701±12 Ma, Nanda et al. 2008), Sm-Nd whole rock-mineral isochron ages (815±9 and 808±64 Ma) and Rb-Sr whole rock-mineral isochron ages (833±10 Ma, 781±39 Ma) (Shaw et al. 1997).

Table 1. Grenvillian dates in the Eastern Ghats Province

Rock/Mineral	Locality	Method	Age (Ma)	Reference
Mafic granulite	Rayagada	Sm-Nd WR-Mineral (pyr-hbl-plag) isochron	946 ± 30	Shaw et al. (1997)
Charnockites/Enderbites	Rayagada	Sm-Nd WR isochron Rb-Sr WR isochron	1023 ± 93 958 ± 16	Shaw et al. (1997)
Metapelite - Zircon	Rayagada	$^{207}Pb/^{206}Pb$ weighted mean on concordia	945 ± 11 936 ± 13	Shaw et al. (1997)
Charnockite - Zircon	Phulbani	U-Pb	985 ± 5	Paul et al. (1990)
Charnockite -Zircon	Visakhapatnam	U-Pb	979	Grew and Manton (1986)
Leptynite/Charnockite - Zircon	Angul	U-Pb	1088+26/-17	Aftalion et al. (1988)
Porph. Charnockite - Zircon		U-Pb	~950	Kovach et al. (1998)
Granite - Zircon	Angul	U-Pb	957+8/-4	Aftalion et al. (1988)
Porph. Granitoid-Zircon	Salur	Concordia upper intercept	954 ± 12	Krause 1998)**
Garnet granite -Zircon	Bolangir	$^{207}Pb/^{206}Pb$	918 ± 20	Crowe (2003)*
Sapphirine Granulite - Zircon		Pb-Pb single zircon evaporation	946-952	Jarick (1999)*
Sapphirine Granulite - Zircon	Paderu	U-Pb Upper Intercept	988 ± 18	Bhattacharya et al. (2003)
Sapphirine Granulite - Monazite	Paderu	$^{207}Pb/^{206}Pb$ Concordant	900	Bhattacharya et al. (2003)
Charnockite - Monazite	Phulbani	U-Pb	965 ± 7	Paul et al. (1990)
Sapphirine Granulite - Perrierite	Anakapalle	U-Pb Th-Pb	989 993	Grew and Manton (1986)
Augen gneiss - Monazite	Angul	U-Pb	964 ± 4	Aftalion et al. (1988)
Leptynite – Monazite	Angul	U-Pb	953 ± 4	Aftalion et al. (1988)
Granite - Monazite	Angul	U-Pb	956 ± 4	Aftalion et al. (1988)
Metapelite - Monazite	Angul	$^{207}Pb/^{206}Pb$ concordant		Mezger and Cosca (1999)
Calc-silicate rock - Titanite	Angul	U-Pb Concordia upper intercept	935 ± 25	Mezger and Cosca (1999)
Pegmatite - Allanite	ENE of Bhubaneshwar	$^{207}Pb/^{206}Pb$ Nearly concorant	885 ± 9	Mezger and Cosca (1999)

* Quoted in Dobmeier and Raith, 2003; ** Quoted in Simmat and Raith, 2008

Minor EPMA monazite age populations at ~900 Ma, ~800 Ma and ~600 Ma throughout EGP confirm the persistence of the high grade conditions for an extended period. Metamorphic overgrowths on zircons from orthogneisses at Phulbani have U-Pb SHRIMP ages of 789-826 Ma (Crowe, 2003, quoted in Simmat and Raith, 2008). These ages have been correlated by Simmat and Raith (2008) with an episode of ductile deformation and associated fluid infiltration that produced a mylonitic fabric in the granulites and partially retrograded the granulite facies assemblages. In the Chilka Domain the age populations of monazite grain interiors in khondalites and high-Mg-Al granulites are at 970 Ma, 964 Ma and 943 Ma, indicating that the Grenvillian high grade metamorphism affected this domain also. However, the frequency distribution of the monazite ages from khondalites, high-Mg-Al granulites and the rocks of the anorthosite complex suggests that the major episode of growth and recrystallization of monazite in these rocks occurred between 700 Ma and 800 Ma during a period of granulite facies reworking (Dobmeier and Simmat, 2002; Simmat and Raith, 2008). A prolonged duration of this high grade event is indicated by age populations at 660-690 Ma. This has been correlated with D_2-D_3 deformations. Similar ages are recently reported for the post-alkaline-pluton granulite facies metamorphism close to the boundary zone at Koraput (Nanda et al. 2008).

A cluster of dates testify to the Pan-African overprint. The dates from conventional methods are given in Table 2. A well-defined cluster of chemical dates of monazite within the range of 500-530 Ma is recorded throughout the EGP, though no signature of this Pan-African event is recorded in the EPMA monazite age distributions at some localities. It is more pronounced in the western part which is affected by shear deformation and syn- to post-kinematic high grade recrystallization.

$^{40}Ar/^{39}Ar$ dates of different minerals bring out the

Table 2. Pan-African dates in the Eastern Ghats Province

Rock/Mineral	Locality	Method	Age (Ma)	Remark
Nepheline Syenite	Khariar	Rb-Sr WR-Mineral (biotite) isochron	487.1 ± 0.6 499 ± 1.6	Upadhyay et al. (2006a)
Neph. Syn. – Titanite	Khariar	$^{207}Pb/^{206}Pb$	593	Upadhyay et al. (2006a)
Neph. Syen. - Amphibole	Khariar	K-Ar	530 ± 11	Aftalion et al. (2000)
Neph. Syn. – Nepheline	Khariar	K-Ar	550 ± 11	Aftalion et al. (2000)
Neph. Syenite - Apatite	Khariar	$^{206}Pb/^{238}U$	494 ± 8	Aftalion et al. (2000)
Foliated Porphyriric Granite - Biotite	East of Khariar	$^{39}Ar/^{40}Ar$	533 ± 2	Crowe et al. (2001)
Amphibolite - Hornblende	North of Bolangir - EGBF	$^{39}Ar/^{40}Ar$	521 ± 3	Crowe et al. (2001)
Calc-silicate rock - Titanite	Angul	U-Pb Concordia lower intercept	504 ± 20	Mezger and Cosca (1999)
Opx-Felds Gneiss - Biotite	East of Angul	$^{39}Ar/^{40}Ar$	530 ± 2	Crowe et al. (2001)
Mylonitic Augen Gneiss - Biotite	West of Angul Ranipathar Shear	$^{39}Ar/^{40}Ar$	504 ± 2	Crowe et al. (2001)
Leptynite	Rayagada	Sm-Nd WR-Mineral (garnet-feldspar) (garnet) isochron	573 ± 12 567 ± 63	Shaw et al. (1997)
Metapelite	Rayagada	Sm-Nd WR-Mineral (garnet-feldspar) isochron	613 ± 20 554 ± 52 500 ± 54	Shaw et al. (1997)
Metapelite	Rayagada	Rb-Sr WR-Mineral (feldspar - biotite) isochron	498 ± 40 543 ± 3	Shaw et al. (1997)
Megacrystic granite gneiss	Visakhapatnam	Sm-Nd WR-Mineral (garnet) isochron	535 ± 50	Paul et al. (1990)
Apatite-Magnetite Vein - Zircon	Visakhapatnam	U-Pb Concordant	516 ± 1	Mezger and Cosca (1999)
Apatite-Magnetite Vein - Zircon	Visakhapatnam	U-Pb	502	Kovach et al. (1997)
Pitchblende in Pegmatite	Srikakulam	U-Pb	503 ± 2	Simmat and Raith (2008)

cooling history of the rocks because the different minerals have different closure temperatures. From the Angul domain in the northern sector of the EGP U-Pb titanite age (935±25 Ma, Mezger and Cosca, 1999) from the calc-silicate gneisses and $^{40}Ar/^{39}Ar$ age of amphibole (854±4 Ma, Lisker and Fachmann, 2001) and Rb/Sr muscovite age (850 Ma, Halden et al. 1982) indicate that uplift and cooling of the segment soon followed the granulite facies metamorphism. Crowe et al. (2001) repoted that in the Angul Domain and the Rengali Province the $^{40}Ar/^{39}Ar$ data define two groups of dates with distinct cooling histories between ca. 700 and 420 Ma. The older group of ages defines a slow apparent cooling path (~1.0^0 C/Ma), whereas the younger group of $^{40}Ar/^{39}Ar$ dates from the western and northern margin of the Eastern Ghats Belt and along the southern margin of the Rengali Province defines a more rapid cooling path (4°C-2.5° C/Ma). The younger $^{40}Ar/^{39}Ar$ dates are interpreted to reflect a variable and locally intense thermal event at ca. 500–550 Ma associated with reactivation of major shear zones.

Age of Shear Zones

Near Deobhog close to the EGBSZ the EPMA U-Th-Pb dates of interior domains of zircons in metapelitic granulites are 906±46 Ma, whereas from the margins the dates are 539±72 Ma and 530±74 Ma (Hofmann, 2001, quoted in Das et al. 2008). An even younger population of 472± 44 Ma has been obtained from monazite grains in the mylonitized fabric of khondalite along the thrust zone.

Consistency between the $^{39}Ar/^{40}Ar$ hornblende ages in the Rengali Province and the Angul Domain show that the two were juxtaposed at similar crustal levels at ~700 Ma, but in the Grenvillian period the Angul Domain was at a deep level (granulite facies), while the Rengali Province was at a shallower level (amphibolite facies). This indicates movement along the boundary zone (Kerajang Fault) after

~950 Ma but before 700 Ma. On the other hand the adjacent Chilka Domain to the south shows evidence of high grade reworking between 800 and 500 Ma (Dobmeier and Simmat, 2002), and on this basis Simmat and Raith (2008) have concluded that the Angul Domain must have been tectonically and thermally decoupled from the rest of the Eastern Ghats Province. This suggests that the Mahanadi Shear Zone was active in Neoproterozoic time. Mylonites in a porphyritic granite in this zone are dated at 780±7 Ma ($^{207}Pb/^{206}Pb$ SHRIMP zircon age) (Crowe, 2003, quoted in Dobmeier and Raith, 2003). Biotite $^{40}Ar/^{39}Ar$ plateau age from mylonitic gneiss along the Mahanadi Shear Zone (Ranipathar Shear Zone) is 504±2 Ma, and an amphibolite sample close to the EGBSZ gives $^{40}Ar/^{39}Ar$ age of 521±3 Ma (Crowe et al. 2001).

Monazite grains of sheared khondalite of the Angul domain adjacent to the Kerajang Fault yield an apparent population age of 662±43 Ma (Simmat and Raith, 2008). $^{40}Ar/^{39}Ar$ plateau ages of white mica and biotites from shear zone rocks indicate reactivation along the Kerajang Fault at 473-488 Ma (Crowe et al. 2001). Exhumation of Angul Domain and Rengali Province to surface levels occurred by ca. 300 Ma as constrained by unconformable Gondwana coal-bearing sediments overlying these rocks. Younger fission track dates (152±12 Ma, 119±6 Ma) along the fault zones suggest repeated reactivation on these till as late as Cretaceous (Lisker and Fachmann, 2001).

GEODYNAMICAL MODEL

The Rengali and Jeypore Provinces are Archaean metamorphic terrains bordering the Singhbhum and Bastar cratons. If there was any reworking in the Proterozoic it must have been in greenschist facies because it did not affect the Pb isotopic signature in feldspar (Rickers et al. 2001a). However, the palaeotectonic evolution of these two terrains cannot be adequately constrained because of lack of sufficient data. These terrains were either accreted to Proto-India in an unspecified time prior to the amalgamation of the Eastern Ghats Province or they represent the older crust of Proto-India reworked by Neoarchaean thermo-tectonic processes. The original extension of these provinces remains unknown, but a large tract in the northern part of the South Indian granulite terrain is also of similar age.

Dobmeier and Raith (2003) opined that the Ongole Domain and the adjacent lower grade Nellore-Khammam Schist Belt (Udayagiri Domain and Vinjamuru Domain) have a common geological history. The volcano-sedimentary sequences in them were deposited at around ~1.8-1.9 Ga and the Ongole Domain went through a high grade tectonothermal event at around ~1.6-1.7 Ga. Similar dates (~1.5-1.6 Ga) are obtained from the rocks of the neighbouring Vinjamuru Domain. Dobmeier and Raith (2003) argued that an E-W convergence caused a thrust stacking of the three domains giving rise to inverse metamorphic superposition with the granulite facies Ongole Domain being stacked over the amphibolite facies Vinjamuru Domain and the latter over the greenschist facies Udayagiri Domain. They further suggested that this resulted from the collision of the Napier Complex with the Eastern Dharwar craton between 1.7 and 1.5 Ga. The continental arc setting of the Kondapalle Complex lends support to this scenario of continental collision. Because of the Pan-African ages along the western thrust zone it appears reasonable to conclude that though the above-mentioned collision was at ~1.7 Ga, the present disposition of the blocks in the Krishna Province was attained at the time of the Pan-African collision of the EGP with the western landmass. However, the Ongole Domain has no northward extension, and hence whether the Mesoproterozoic collision zone extended north of the Godavari Rift remains unclear.

The ~1.7 Ga collision is possibly related to the assembling of the Columbia supercontinent, which is believed to have taken place at around ~1.8 Ga (Li et al. 2008; Rogers and Santosh, 2002; Zhao et al. 2004). In all commonly accepted reconstructions (Li et al. 2008; Rogers and Santosh, 2002; Zhou et al. 2002) coastal East Antarctica is joined with India (Greater India), while the rest of East Antarctica (Mawson Craton) is joined with South Australia. However, how coastal East Antarctica became juxtaposed to India remains unclear. Events of ~1.6 Ga age are encountered in the Rayner-Napier Complexes (Kelly et al. 2002; Owada et al. 2003), but their relation to any collisional process or to the process of assembling of the Columbia supercontinent is yet to be elucidated. There are no palaeomagnetic data which could throw light on this problem. It is possible that the 1.6 – 1.7 Ga old granulite belt extended north of the Godavari Rift too along the margin of the Bastar craton, but is now hidden under the younger granulites of the Eastern Ghats Province, or is thoroughly reworked during the Grenvillian orogeny. This older belt could have been contiguous with the Napier-Rayner terrain to form an Indo-Napier crustal segment at ~1.6 Ga (Kelly et al. 2002). There is no confirmatory proof for the above, though Rickers et al. (2001a) suggest reworking of older material in their Domains 2 and 3. If it was already an exhumed terrain it could provide the 1.6 Ga detritus in the Belt-Purcell basins of western North America in the reconstruction of Rogers and Santosh (2002).

The distribution of the alkaline plutons suggests rifting along the craton margin at ~1.3-1.5 Ga. The rifting might have started from north to south as indicated by the older dates north of the Godavari Rift. This rifting was probably related to the break up of Columbia prior to the Rodinia assembly. The Godavari Rift might have developed as a failed rift or aulacogen at this time, though it was again reactivated during Gondwana sedimentation. Upadhyay (2008) argued that rifting took place along the passive margin of the Indian protocontinent, and it developed into an ocean which opened towards southeast, and in this ocean the sediments (dominantly argillaceous) of the Eastern Ghats Province were deposited. The age of the youngest detrital zircons fixes the time of the sedimentation to have continued after ~1.4 Ga but before the earliest metamorphism at ~1.2 Ga (Upadhyay, 2008). However, the basement or the provenance of the sediments cannot be identified. The mafic rocks associated with the metasediments may partly represent segments of oceanic crust. However what was on the other side of the rift is an unsolved question. It could conceivably be the East Antarctica landmass of Rayner-Napier Complexes. The sedimentary basins of Chhattisgarh, Khariar, Pranhita-Godavari and several other small basins developed at the Indian craton margin during this rifting.

The final breakup of Columbia (Condie, 2002) at about 1.2–1.3 Ga was soon followed by the assembly of Rodinia supercontinent along globally distributed Grenvillian orogens at ~1.0 Ga (Dalziel, 1995; Dalziel et al. 2000; Meert, 2003). Several alternative models of Rodinia assembly have been proposed, such as, SWEAT (Moores, 1991), AUSWUS (Karlstrom et al. 1999) and AUSMEX (Wingate et al. 2002). However, there are difficulties with all of them, and neither geological nor palaeomagnetic data are fully compatible with these models (Harley, 2003; Li et al. 2008 and references therein; Pisarevsky et al. 2003a, b; Zhao et al. 2004; Zhao et al. 2006). In most Rodinia reconstructions India is attached to East Antarctica with the combined Eastern Ghats Belt and the Napier-Rayner Complexes comprising one block. However, the geochronological evidence shows that there is no continuous Grenvillian belt in coastal East Antarctica; instead there are three distinct Grenvillian provinces of which Rayner Complex is one (Fitzsimons, 2000, 2003; Harley, 2003). Pisarevsky et al. (2003a) contended that India (together with the Rayner Block of Antarctica) was not a part of Rodinia, but collided obliquely with the rest of East Gondwanaland (West Australia and the Mawson craton of Antarctica-Australia) between 610 and 680 Ma. Later, Li et al. (2008) revised this idea taking into account multiple lines of evidence and stated that India became part of Rodinia by ~900 Ma through Grenvillian continental collision along the ~950-1000 Ma Eastern Ghats Belt and the corresponding Rayner Province in East Antarctica. Prior to the Grenvillian orogeny, the Rayner complex and the EGP had contrasting evolutionary histories. While the Rayner complex was affected by a Palaeoproterozoic (1.60–1.65 Ga) thermal event (Kelly et al. 2002), the EGP sediments underwent their first high-grade metamorphism only during the late Mesoproterozoic (1.2 Ga). Therefore, the pre-Grenvillian configuration of the EGP and the Rayner Complex and their coming together during the Rodinia assembly remains a burning question.

The isotopic data indicate that a large part of the crust in the EGP evolved during Neoproterozoic times through continent-continent collision process related to Rodinia assembly. It is thoroughly reworked by multiple episodes of deformation and metamorphism, together with partial melting both synchronous with and outlasting these episodes and voluminous emplacement of felsic intrusions.

It is important to note that no significant Grenvillian tectonothermal imprint is recognizable in the Ongole or Jeypore Domains, nor in the Bastar, or Eastern Dharwar cratons. On the contrary the Ongole Domain had cooled down to ~500°C by ~1.0 Ga (Mezger and Cosca, 1999). So the Grenvillian orogenic front must have been far removed from Ongole Domain and the western cratons. It is only during the Pan-African time that the granulites were juxtaposed to the craton and the alkaline plutons. The exact location of the Grenvillian Front or the Grenvillian suture is a matter of debate (Dasgupta and Sengupta, 2003). The original Grenvillian suture may be now buried under the EGP thrust sheet (Upadhyay, 2008).

The break-up of Rodinia started at about 825 Ma (Li et al. 2008); Greater India started to break away from East Antarctica and Australia at ~775 Ma. Li et al. (2008) proposed that this rifting was due to the activity of a superplume sited below Rodinia with episodic plume events at ~825 Ma, ~780 Ma and ~750 Ma. By about ~720 Ma the rifting had stopped and the rift zone was replaced by a convergence zone. Thermo-tectonic events of similar ages have been documented in the Chilka Domain of EGP (Dobmeier and Simmat, 2002, Simmat and Raith 2008). By 700 Ma Central Madagaskar was joined to Greater India. Subsequently India started to converge towards Antarctica and Australia, and by ~530 Ma India had collided with Antarctic and Australia, leading to the development of Pan-African orogenic belt along the junction. This was the period of the assembling of the Gondwanaland with the amalgamation of Greater India, East Antarctica (Mawson continent) and Australia with the African and South American blocks (Boger et al. 2001).

Pan-African ages in the EGB rocks are recorded in a wide variety of minerals having high closure temperatures such as zircons (U–Pb TIMS, Kovach et al., 1997; Mezger and Cosca, 1999), monazites (U–Th–Pb EPMA, Simmat and Raith, 2008, Upadhyay, 2008 and references therein), titanites (U–Pb, Mezger and Cosca, 1999), and hornblende (^{40}Ar–^{39}Ar, Mezger and Cosca, 1999). This indicates that the Neoproterozoic–Paleozoic thermal imprint reached significantly high grades (upper amphibolite to granulite) in several regions. As discussed earlier, along the western contact zone the peak of UHT-HT metamorphism was attained after the Pan-African shear fabric was impressed on the rocks. Although there is no doubt that many parts of the EGB had been affected by a Pan-African thermal event, there is no consensus on the extent to which Pan-African tectonism had reworked the Paleo-, Meso- to Neoproterozoic granulites of the Jeypore province, Ongole domain and the EGP. Dobmeier and Raith (2003) suggested that in contrast to East Antarctica, Pan-African tectonics in the EGB was largely focused on shear zones and thrusts reflecting localized intracontinental deformation. Pan-African ages are very common along the western boundary zone of EGB, and the thrusting of the granulites over the western craton has been described as a Pan-African event (Das et al. 2008, Simmat and Raith, 2008). Along the western boundary zone Das et al. (2008) argued in favour of a clockwise P-T path signifying onset of the Pan-African orogeny that overprinted the Grenvillian orogeny of the main EGP. Significantly Pan-African dates are absent in the Rayner complex, but on either side of it are the Lützow-Holm and Prydz Bay Belts (Fitzsimons, 2000, 2003) which are Pan-African belts. How these are to be fitted to the scenario in the EGP remains to be worked out.

CONCLUDING REMARKS

One of the most important outcomes of the recent researches in the Eastern Ghats is the understanding that the belt is subdivided into different domains. The classification into four provinces as defined by Dobmeier and Raith (2003) provides a good working model, though it may have to be refined as more data come in. However, the nature of the boundaries between the provinces and the domains is still not fully established through detailed observations. If they represent movement zones, this has to be confirmed by careful structural studies on their geometry and kinematics. Tectonometamorphic events of diverse ages have affected the different sectors of the belt. The geochronological data are insufficient to firmly establish the correlation of the tectonometamorphic events in the different domains. For example, the available geochronological data suggest that the Chilka Domain was tectonically decoupled from the Angul Domain during 800 Ma to 500 Ma (Simmat and Raith, 2008). Further detailed work may modify this conclusion or may bring out such information for other domains also. There is a general consensus that pre-Grenvillian, Grenvillian and Pan-African events have affected the EGB, but the relative importance of these events and the extent of the areas affected by them are unclear. How the different crustal blocks within the EGB formed during the orogenies, what was the nature of relative movements between these domains and how they behaved during the tectonic movements and became joined in Greater India are questions which remain to be answered.

The India-Antarctica connection during Meso- and Neoproterozoic is another intriguing problem. The Rayner Complex in East Antarctica shows thermal events at ~1.6 Ga and at ~1.0 Ga. The part of the Eastern Ghats south of the Godavari Rift shows the main tectonothermal event at ~1.6-1.7 Ga similar to the Rayner Complex, and the two were probably contiguous at that time but might have separated during Columbia break-up. North of the Godavari Rift the Eastern Ghats Province does not show the ~1.6 Ga event; only ~1.2 Ga, ~1.0 Ga and ~0.5 Ga events are documented. Thus it seems probable that at the end of the Grenvillian orogeny the EGP and the Rayner Complex formed a continuous belt in Rodinia, but prior to this the two were disparate terrains. There is very little paleomagnetic information to constrain the position of India in Columbia and Rodinia, though Pisarevsky et al. (2003a) opine that India was not a part of Rodinia. How India and Antarctica was joined in Columbia and Rodinia is still an unsettled question.

Acknowledgements: We have been greatly benefited through discussions with Professor Michael Raith and Dr. Pulak Sengupta. Dr. Saibal Gupta kindly provided us with a preprint of their article on the Koraput alkaline pluton. The comments of Dr. Gupta and another reviewer have helped us to improve the original manuscript. D.M. acknowledges assistance from the Indian National Science Academy through the Senior Scientist Scheme. We are grateful to Professor H. K. Gupta and the Editorial Board of the Geological Society of India for inviting us to write this review.

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. Jour. Geol., v.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. Geol. Surv. India, Sp. Publ., v.57, pp.26-33.

BHADRA, S., BANERJEE, M. and BHATTACHARYA, A. (2003) Tectonic restoration of a polychromous mobile nelt-craton assembly: constraints from corridor study across the western margin of the Eastern Ghats Belt. Mem. Geol. Soc. India, no.52, pp.109-130.

BHADRA, S., DAS, S. and BHATTACHARYA, A. (2007) Shear zone hosted polyphase migmatites (Eastern India): the role of dynamic melting in the generation of REE-depleted felsic melts, and implications for disequilibrium melting. Jour. Petrol., v.48, pp.433-457.

BHADRA, S., GUPTA, S. and BANERJEE, M. (2004) Structural evolution across the Eastern Ghats Mobile Belt-Bastar craton boundary, India: hot over cold thrusting in an ancient collision zone. Jour. Struct. Geol., v.26, pp.233-245.

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.), v.110, pp.369-383.

BHATTACHARYA, A., RAITH, M., HOERNES, S. and BANERJEE, D. (1998) Geochemical evolution of the massif type anorthosite complex at Bolangir in the Eastern Ghats Belt of India. Jour. Petrol., v.39, pp.1169-1195.

BHATTACHARYA, S. (1996) Eastern Ghats granulite terrain of India: an overview. Jour. Southeast Asian Earth Sci., v.14, pp.165-174.

BHATTACHARYA, S. (1997) Evolution of Eastern Ghats granulite belt of India in a compressional tectonic regime and juxtaposition against Iron Ore Craton of Singhbhum by oblique collision-transpression. Proc. Indian Acad. Sci. (Earth Planet. Sci.), v.106, pp. 65-75.

BHATTACHARYA, S. (2004) High-temperature crustal scale shear zone at the western margin of the Eastern Ghats granulite belt, India: implications for rapid exhumation. Jour. Asian Earth Sci., v.24, pp.281-290.

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., v.143, pp.175-191.

BHATTACHARYA, S. and KAR, R. (2004) Alkaline intrusion in a granulite ensemble in the Eastern Ghats belt, India: Shear zone pathway and a pull-apart structure. Proc. Indian Acad. Sci. (Earth Planet. Sci.), v.113, pp.37-48.

BHATTACHARYA, S. and KAR, R. (2005) Petrological and Geochemical Constraints on the Evolution of the Alkaline Complex of Koraput in the Eastern Ghats Granulite Belt, India. Gondwana Res., v.8, pp.596-602.

BHATTACHARYA, S., DEOMURARI, M.P. and TEIXERIA, W. (2002) Grenvillian thermal event and remnant charnockite: Isotopic evidence from the Chilka Lake granulite–migmatite suite in the Eastern Ghats belt. India. Proc. Ind. Acad. Sci. (Earth Planet. Sci.), v.111, pp.391-399.

BHATTACHARYA, S., SEN, S.K. and ACHARYYA, A. (1993) Structural evidence supporting a remnant origin of patchy charnockites in the Chilka Lake area, India. Geol. Mag., v.130, pp.363-368.

BHATTACHARYA, S., SEN, S.K. and ACHARYYA, A. (1994) The structural setting of the Chilka Lake granulite-migmatite-anorthosite suite with emphasis on the time relation of charnockites. Precambrian Res., v.66, pp.393-409.

BHATTACHARYA, S., KAR, R., MISRA, S. and TEIXEIRA, W. (2001) Early Archaean continental crust in the Eastern Ghats granulite belt, India: Isotopic evidence from a charnockite Suite. Geol. Mag., v.138, pp.609-618.

BHATTACHARYA, S., KAR, R., TEIXEIRA, W. and BASEI, M. (2003) High-temperature crustal anatexis in a clockwise P–T path: isotopic evidence from a granulite-granitoid suite in the Eastern Ghats belt, India. Jour. Geol. Soc. London, v.160, pp.39-46.

BHOWMIK, S.K., DASGUPTA, S., HOERNES, S. and BHATTACHARYA, P.K. (1995) Extremely high temperature calcareous granulites from the Eastern Ghats, India: Evidence for isobaric cooling, fluid buffering and terminal channelized fluid flow. Eur. Jour. Min., v.7, pp.689-703.

BHUI, U.K., SENGUPTA, P. and SENGUPTA, P. (2007) Phase relations in mafic dykes and their host rocks from Kondapalle, Andhra Pradesh, India: Implications for the time–depth trajectory of the Palaeoproterozoic (late Archaean?) granulites from southern Eastern Ghats Belt. Precambrian Res., v.156, pp.153-174.

BISWAL, T.K., DE WAELE, B. and AHUJA, H. (2007) Timing and dynamics of the juxtaposition of the Eastern Ghats Mobile Belt against the Bhandara Craton, India: a structural and zircon U-Pb SHRIMP study of the fold-thrust belt and associated nepheline syenite plutons. Tectonics, v.26, TC4006, doi:10.1029/2006TC002005.

BISWAL, T.K., SEWARD, D. and JENA, S.K. (2001) Eastern Ghats Mobile Belt is an epitome of Mesoproterozoic fold-thrust belt: a study from its NW margin. Gondwana Res., v.4, pp.579-581.

BOGER, S.D., WILSON, C.J.L. and FANNING, C.M. (2001) Early Palaeozoic tectonism within the East Antarctic craton: the final suture between east and west Gondwana? Geology, v.29, pp.463-466.

Bose, M.K. (1970) Petrology of the intrusive alkaline suite of Koraput, Orissa. Jour. Geol. Soc. India, v.11, pp.99-126.

BOSE, M.K., CHAKRAVARTI, S. and SARKAR, A. (1971) Petrological Observations on Alkali Syenites of Kunavaram, A.P., India. Geol. Mag., v.108, pp.273-280.

BOSE, S., FUKUOKA, M., SENGUPTA, P. and DASGUPTA, S. (2000) Evolution of high Mg-Al granulites from Sunkarametta, Eastern Ghats, India: evidence for a lower crustal heating cooling trajectory. Jour. Meta. Geol., v.20, pp.212-227.

Burke, K., Ashwal, L.D. and Webb, S.J. (2003) New way to map old sutures using deformed alkaline rocks and carbonatites. Geology, v.31, pp.391-394.

Charan, S.N., Subba Rao, M.V. and Divakara Rao, V. (1998) Prograde-retrograde mineralogy and geochemical variation trends in the charnockites of Gamparai region, Visakhapatnam district, Andhra Pradesh. Geol Surv. India Spec. Publ., v.44, pp.220-231.

Chatterjee, N., Crowley, J. L., Mukherjee, A. and Das, S. (2008) Geochronology of the 983-Ma Chilka Lake Anorthosite, Eastern Ghats Belt, India: Implications for Pre-Gondwana Tectonics. Jour. Geol., v. 116, pp. 105–118.

Chetty, T.R.K. (2001) The Eastern Ghats Mobile Belt, India: A collage of Juxtaposed Terranes (?). Gond. Res., v.4, pp.319-328.

Chetty, T.R.K., Vijaya, P., Narayana, B.L. and Giridhar, G.V. (2003) Structure of the Nagavali shear zone, Eastern Ghats Mobile Belt, India: correlation in the East Gondwana reconstruction. Gondwana Res., v.6, pp.215-229.

Clark, G.S. and Subba Rao, K.V. (1971) Rb-Sr isotopic age of the Kunavaram Series, a group of alkaline rocks from India. Can. Jour. Earth Sci. v.8, pp.1597-1602.

Condie, K.C. (2002) Breakup of a Paleoproterozoic supercontinent. Gondwana Res., v.5, pp.41–43.

Crookshank, H. (1938) The western margin of the Eastern Ghats in southern Jeypore. Rec. Geol. Surv. India, v.73, Pt.3, pp.398-434.

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

Crowe,W.A., Nash, C.R., Harris, L.B., Leeming, P.M. and Rankin, L.R. (2003) The geology of the Rengali Province: implications for the tectonic development of northern Orissa, India. Jour. Asian Earth Sci., v.21, pp.697-710.

Czygan,W. and Goldenberg, G. (1989) Petrography and geochemistry of the alkaline complexes of Sivamalai, Elchuru and Uppalapadu, India. Mem. Geol. Soc. India, no.15, pp.225-240.

Dalziel, I.W.D. (1995) Earth before Pangea. Sci. Am., v.272, pp.58-63.

Dalziel, I.W.D., Mosher, S. and Gahagan, L.M. (2000) Laurentia-Kalahari collision and the assembly of Rodinia. Jour. Geol., v.108, pp.499-513.

Das, S., Bhattacharya, A., Raith, M.M., Bhadra, S. and Banerjee, M. (2006) 7-9-3 sapphirine granulites: Phase relations and relevance to high-T CCW orogeny in the Eastern Ghats Belt. Eur. Jour. Min., v.18, pp.35-48.

Das, S., Nasipuri, P., Bhattacharya, A. and Swaminathan, S. (2008) The thrust-contact between the Eastern Ghats Belt and the adjoining Bastar craton (Eastern India): evidence from mafic granulites and tectonic implications. Precambrian Res., v.160, pp.70-85.

Dasgupta, S. (1993) Contrasting mineral parageneses in high-temperature calcsilicate granulites: examples from the Eastern Ghats, India. Jour. Meta. Geol., v.11, pp.193-202.

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. Jour., v.30, pp.307-318.

Dasgupta, S. and Sengupta, P. (2003) Indo-Antarctic correlation: a perspective from the Eastern Ghats Belt. *In*: M. Yoshida, B.F. Windley and S. Dasgupta (Eds.), Proterozoic East Gondwana: supercontinent assembly and breakup. Geol. Soc. London Spec. Publ., v.206, pp.131-143.

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

Dasgupta, S., Sengupta, P., Fukuoka, M. and Bhattacharya, P.K. (1991) Mafic granulites from the Eastern Ghats, India: further evidence for extremely high crustal metamorphism. Jour. Geol., v.99, pp.124-133.

Dasgupta, S., Sengupta, P., Fukuoka, M. and Chakraborti, S. (1992) Dehydration melting, fluid buffering and decompressional P–T path in a granulite complex from the Eastern Ghats, India. Jour. Meta. Geol., v.10, pp.777-788.

Dasgupta, S., Sengupta, P., Mondal, A. and Fukuoka, M. (1993) Mineral chemistry and reaction textures in metabasites from the Eastern Ghats belt, India and their implications. Min. Mag., v.57, pp.113-120.

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

Dasgupta, S., 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 the roles of ZnO and Fe_2O_3. Jour. Petrol., v.36, pp.435-461.

Datta, N.R., Sengupta, P., Gangopadhyay, A. and Sarkar, S. (2001) Incipient charnockite formation in leptynite from Vizianagram, Andhra Pradesh: implication for Pan-African (?) crustal reworking in the Eastern Ghats Belt. Gondwana Res., v.4, pp.603-604.

Dharma Rao, C.V., Vijaya Kumar, T. and Bhaskar Rao, Y.J. (2004) The Pangidi Anorthosite Complex, Eastern Ghats Granulite Belt, India: Mesoproterozoic Sm–Nd isochron age and evidence for significant crustal contamination. Curr. Sci., v.87, pp.1614-1618.

Dobmeier, C. (2006) Emplacement of Proterozoic massif-type anorthosite during regional shortening: evidence from the Bolangir anorthosite complex (Eastern Ghats Province, India). International Jour. Earth Sci., v.95, pp.543-555.

Dobmeier, C. and Raith, M.M. (2000) On the origin of •arrested• charnockitization in the Chilka Lake area, Eastern Ghats Belt, India: a reappraisal. Geol. Mag., v.137, pp.27-37.

Dobmeier, C. and Raith, M.M. (2003) Crustal architecture and evolution of the Eastern Ghats Belt and adjacent regions of India. *In*: M. Yoshida, B.F. Windley and S. Dasgupta (Eds.), Proterozoic East Gondwana: Supercontinent Assembly and Breakup, Geol. Soc. London, Spec. Publ., v.206, 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. v.113, pp.243-268.

DOBMEIER, C., LÜTKE, S., HAMMERSCHMIDT, K. and MEZGER, K. (2006) Emplacement and deformation of the Vinukonda meta-granite (Eastern Ghats India),, implications for the geological evolution of peninsular India and for Rodinia reconstructions. Precambrian Res., v.146, pp.165-178.

FITZSIMONS, I.C.W. (2000) A review of tectonic events in the East Antarctic Shield and their implications for Gondwana and earlier supercontinents. Jour. Afr. Earth Sci., v.31, pp.3-23.

FITZSIMONS, I.C.W. (2003) Proterozoic basement provinces of southern and southwestern Australia, and their correlation with Antarctica. *In*: M. Yoshida, B.F. Windley and S. Dasgupta (Eds.), Proterozoic East Gondwana: Supercontinent Assembly and Breakup, Geol. Soc. London, Spec. Publ., v.206, pp.93-130.

FONAREV, V.I., RAO, A.T. and KONILOV, A.N. (1995) Evaluation of pressure-temperature of metamorphism and tectonothermal history of granulites from the Visakhapatnam area in the Eastern Ghats, India. *In*: M. Yoshida and M. Santosh (Eds.), India and Antarctica during the Precambrian, Mem. Geol. Soc. India, no.34, pp.111-124.

GREW, E.S. and MANTON,W.I. (1986) A new correlation of sapphirine granulites in the Indo-Antarctic metamorphic terrane: late Proterozoic dates from the Eastern Ghats. Precambrian Res., v.33, pp.123-139.

GUPTA, S. (2004) The Eastern Ghats Belt, India - a new look at an old orogen. Geol. Surv. India Spec Publ., v.84, pp.75-100.

GUPTA, S. and BHATTACHARYA, A. (2000) Granulites of the •Transition Zone•: implications for the western reach of the Eastern Ghats Belt. Geol. Surv. India Spec. Publ., v.57, pp.57-66.

GUPTA, S. and BOSE, S. (2004) Deformation history of the Kunavaram complex, Eastern Ghats Belt India: implications for alkaline magmatism along the Indo-Antarctica Suture. Gondwana Res., v.7, pp.1235-1241.

GUPTA, S., BHATTACHARYA, A., RAITH, M. and NANDA, J.K. (2000) Contrasting pressure-temperature-deformation history across a vestigial craton-mobile belt boundary: the western margin of Eastern Ghats belt at Deobhog, India. Jour. Met. Geol., v.18, pp.683-697.

GUPTA, S., NANDA, J., MUKHERJEE, S.K. and SANTRA, M. (2005) Alkaline magmatism versus collisional tectonics in the Eastern Ghats Belt India: constraints from structural studies in the Koraput complex. Gondwana Res., v.8, pp.403-419.

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. Roy. Soc. Edin., Earth Sci., v.73, pp.109-118.

HARLEY, S.L. (2003) Archaean-Cambrian crustal development of East-Antarctica: metamorphic characteristics and tectonic implications. *In*: M. Yoshida, B.F. Windley and S. Dasgupta (Eds.), Proterozoic East Gondwana: Supercontinent Assembly and Breakup. Geol. Soc. London, Spec. Publ., v.206, pp.203-230.

HODGES, K.V. (2000) Tectonics of the Himalaya and southern Tibet from two perspectives. Geol. Soc. Amer. Bull., v.112, pp.324-350.

KAMINENI, D.C. and RAO, A.T. (1988a) Sapphirine-bearing quartzite from the Eastern Ghats granulite terrain, Vizianagaram, India. Jour. Geol., v.96, pp.209-220.

KAMINENI, D.C. and Rao, A.T. (1988b) Sapphirine granulites from Kakanuru area, Eastern Ghats, India. Am. Mineral., v.73, pp.692-700.

KAR, R. (2001) Evidence of Structural reworking in the Eastern Ghats Granulite belt, India: Implication for a Contiguous Supercontinent in the Proterozoic. Gondwana Res., v.4, p.650.

KAR, R. (2007) Domainal fabric development, associated microstructures and *P–T* records attesting to polymetamorphism in a granulite complex of the Eastern Ghats granulite belt, India. Jour. Earth Syst. Sci., v.116, pp.21-35.

KAR, R., BHATTACHARYA, S. and SHERATON, J. W. (2003) Hornblende dehydration melting in mafic rocks and the link between massif-type charnockite and associated granulites, Eastern Ghats granulite belt, India. Contrib. Mineral. Petrol., v.145, pp 707-729.

KARLSTROM, K. E., HARLAN, S.S., WILLIAMS, M.L., MCLELLAND, J., GEISSMAN, J.W. and ÅHALL, K. I. (1999) Refining Rodinia: geologic evidence for the Australia-Western U. S. connection in the Proterozoic. GSA Today, v.9, pp.1-7.

KARMAKAR, S. and FUKUOKA, M. (1992) Genesis of leptynites: evidence from Araku Valley, Eastern Ghats, India. Indian Minerals, v.46, pp.247-258.

KELLY, N.M., CLARKE, G.L. and FANNING, C.M. (2002) A two-stage evolution of the Neoproterozoic Rayner Structural Episode: new U–Pb sensitive high resolution ion microprobe constraints from the Oygarden Group, Kemp Land, East Antarctica. Precambrian Res., v.116, pp.307-330.

KOVACH, V.P., SALNIKOVA, E.B., KOTOV, A.B., YAKOVLEVA, S.Z. and RAO, A.T. (1997) Pan-African U-Pb zircon age from apatite-magnetite veins of Eastern Ghats granulite belt, India. Jour. Geol. Soc. India, v.50, pp.421-424.

KOVACH,V.P., BEREZHNAYA, N.G., SALNIKOVA, E.B., NARAYANA, B.L., DIVAKARA RAO, V., YOSHIDA, M. and KOTOV, A.B. (1998) U–Pb zircon age and Nd isotope systematics of megacrystic charnockites in the Eastern Ghats Granulite Belt, India, and their implication for East Gondwana reconstruction. Jour. Afr. Earth Sci., v.27 (supplement 1), pp.125-127.

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., v. 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., v.109, pp.25-38.

Krishnan, M. S. (1961) The structure and tectonic history of India, (Revised Edition). Geol. Surv. India, Mem., v.81, pp.1-137.

Lal, R.K., Ackermand, D. and Upadhyay, H. (1987) P–T–*x* relationships deduced from corona textures in sapphirine–spinel–quartz assemblages from Paderu, Southern India. Jour. Petrol., v.28, pp.1139-1168.

Leelanandam, C. (1989) The Prakasam Alkaline Province in Andhra Pradesh, India. Jour. Geol. Soc. India, v.34, pp.25-45.

Leelanandam, C. (1990) The anorthosite complex and Proterozoic mobile belt of Peninsular India: a review. *In*: S.M. Naqvi (Ed.), Precambrian Continental Crust and Its Economic Resources, Elsevier, Amsterdam, pp.409-436.

Leelanandam, C. (1997) The Kondapalli layered Complex, Andhra Pradesh, India: a synoptic overview. Gondwana Res., v.1, pp.95-114.

Leelanandam, C. (1998) Alkaline magmatism in the Eastern Ghat Belt,, a critique. Geol. Surv. India, Spec. Publ., v.44, pp.170-179.

Leelanandam, C. (2004) The Kondapalli layered Complex and its mantle connections. DST Newsletter, Deep Crustal Studies, v.14, pp.2-5.

Leelanandam, C. and Reddy, M.N. (1988) Precambrian anorthosites from Peninsular India: problems and perspectives. Indian Jour. Geol., v.60, pp.111-136.

Leelanandam, C. and Vijaya Kumar. (2007) Petrogenesis and tectonic Setting of the chromitites and chromite-bearing ultramafic cumulates of the Kondapalli layered complex, Eastern Ghats Belt, India: evidences from the textural, mineral-chemical and whole-rock geochemical Studies. *In*: C. Leelanandam, I.B. Rama Prasada Rao, Ch. Sivaji and M. Santosh, (Eds.), Indian Continental Crust and Upper Mantle, IAGR Memoir, v.10, pp.89-107.

Leelanandam, C., Burke, K., Ashwal, L.D. and Webb, S.J. (2006) Proterozoic mountain building in Peninsular India: an analysis based primarily on alkaline rock distribution. Geol. Mag., v.143, pp.195-212.

Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub, D.P., Jacobs, J., Karlstrom, K.E., Lul, S., Natapovm, L.M., Pease, V., Pisarevsky, S.A., Thrane, K. and Vernikovsky, V. (2008) Assembly, configuration, and break-up history of Rodinia: A synthesis. Precambrian Res., v.160, pp.179-210.

Lisker, F. and Fachmann, S. (2001) The Phanerozoic history of the Mahanadi region, India. Jour. Geophys. Res., B. Solid Earth, v.106, pp.22027-22050.

Mahalik, N.K. (1994) Geology of the contact between the Eastern Ghats Belt and the North Orissa Craton, India. Jour. Geol. Soc. India, v. 44, pp. 41-51.

Maji, A., Bhattacharya, A. and Raith, M. (1997) The Turkel anorthosite complex revisited. Proc Indian Acad. Sci. (Earth Planet. Sci.), v.106, pp.313-325.

Meert, J. (2003) A synopsis of events related o the assembly of eastern Gondwana. Tectonophysics, v.362, pp.1-40.

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

Mishra, S., Moitra, S., Bhattacharya, S. and Sivaraman, T.V. (2000) Archaean granitoids at the contact of Eastern Ghat granulite belt and Singhbhum-Orissa craton, in Bhuban-Rengali sector, Orissa. Gondwana Res., v.3, pp.205-213.

Mohan, A., Tripathi, P. and Motoyoshi, Y. (1997) Reaction history of sapphirine granulites and a decompressional P–T path in a granulite complex from the Eastern Ghats. Proc. Ind. Acad. Sci. (Earth Planet. Sci.), v.106, pp.115-129.

Moores, E.M. (1991) Southwest U.S. –East Antarctic (SWEAT) connection: a hypothesis. Geology, v.19, pp.425-428.

Mukhopadhyay, A.K. and Bhattacharya, A. (1997) Tectonothermal evolution of the gneiss complex at Salur in the Eastern Ghats granulite belt of India. Jour. Met. Geol., v.15, pp.719-734.

Murthy, D.S.N., Chetty, T.R.K., Balaram, V. and Govil, P.K. (1998) Palaeotectonic environment of pyroxene granulite rocks of Gokavaram-Gangavaram area of the Eastern Ghats granulite terrain of Andhra Pradesh. Geol. Surv. India, Spec. Publ., v.44, pp.286-296.

Nanda, J.K. and Pati, U.C. (1989) Field relations and petrochemistry the granulites and associated rocks in the Ganjam–Koraput sector of the Eastern Ghats belt. Indian Minerals, v.43, pp.247-264.

Nanda, J., Gupta, S. and Dobmeier, C.J. (2008) Metamorphism of the Koraput Alkaline Complex, Eastern Ghats Province, India,, Evidence for reworking of a granulite terrane. Precambrian Res. (In Press), doi:10.1016/j.precamres.2008.06.012

Narayanaswami, S. (1975) Proposal for charnockite-khondalite system in the Archaean shield of Peninsular India. Geol. Surv. India, Misc. Publ., v.23, pp.1-16.

Nash, C.R., Rankin, L.R., Leeming, P.M. and Harris, L.B. (1996) Delineation of lithostructural domains in northern Orissa (India) from Landsat Thematic Mapper imagery. Tectonophysics, v.260, pp.245-257.

Neogi, S. and Das, N. (2000) Lithotectonic domains and metamorphic history of the boundary zone of the Eastern Ghats mobile belt and the Bastar craton, Deobhog area, Central India. Geol. Surv. India, Spec. Publ., v.57, pp.180-204.

Owada, M., Osanai, Y., Toyoshima, T., Tsunogae, T., Hokada, T., Crowe, W.A. and Kagami, H. (2003) Early Proterozoic tectonothermal events in the Napier Complex, East Antarctica: implications for the formation of East Gondwana. Gondwana Res., v.6, pp.231-240.

Pal, S. and Bose, S. (1997) Mineral reactions and geothermo-barometry in a suite of granulite facies rocks from Paderu, Eastern Ghats granulite belt: a reappraisal of the P–T trajectory. Proc. Indian Acad. Sci. (Earth Planet. Sci.), v.106, pp.77-89.

PAUL, D.K., RAY BARMAN, T., MCNAUGHTON, N.J., FLETCHER, I.R., POTTS, F.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. Jour. Geol., v.98, pp.253-263.

PISAREVSKY, S.A., WINGATE, M.T.D., POWELL, C.M., JOHNSON, S. and EVANS, D.A.D. (2003a) Models of Rodinia assembly and fragmentation. *In*: M. Yoshida, B.F. Windley, and S. Dasgupta (Eds.), Proterozoic East Gondwana: Supercontinent Assembly and Breakup. Geol. Soc. London, Spec. Publ., v.206, pp.35-55.

PISAREVSKY, S.A., WINGATE, M.T.D. and HARRIS, L.B. (2003b) Late Mesoproterozoic (*ca* 1.2 Ga) palaeomagnetism of the Albany–Fraser orogen: no pre-Rodinia Australia–Laurentia connection. Geophysical Jour. Internat., v.155, pp.F6-F11.

PRASAD, S., BHATTACHARYA, A., RAITH, M. and BHADRA, S. (2005) The origin of orthopyroxene/biotite + plagioclase coronas from the Bolangir anorthosite complex (India), and implications for reconstructing P-T paths. Am. Mineral., v.90, pp.291-303.

RAITH, M.M., DOBMEIER, C. and MOURI, H., (2007) Origin and evolution of Fe-Al granulite in the thermal aureole of the Chilka Lake anorthosite, Eastern Ghats Province, India. Proc. Geol. Assoc., v.118, pp.87-100.

RAMAKRISHNAN, M., NANDA, J.K. and AUGUSTINE, P.F. (1998) Geological evolution of the Proterozoic Eastern Ghats Mobile Belt. Geol. Surv. India Spec. Publ., v.44, pp.1-21.

RICKERS, K., MEZGER, K. and RAITH, M.M. (2001a) 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., v.112, pp.183-210.

RICKERS, K., RAITH, M.M. and DASGUPTA, S. (2001b) Multistage reaction textures in xenolithic high-MgAl granulites at Anakapalle, Eastern Ghats Belt, India: examples of contact polymetamorphism and infiltration-driven metasomatism. Jour. Meta. Geol., v.19, pp.561-580.

ROGERS, J.J.W. and SANTOSH, M. (2002) Configuration of Columbia, a Mesoproterozoic Supercontinent. Gondwana Res., v.5, pp.5-22.

Sanyal, S. and Fukuoka, M. (1995) P–T–D history of granulites from Anakapalle, Eastern Ghats; evidence for polyphase(?) granulite metamorphism. *In*: M. Yoshida and M. Santosh (Eds.), India and Antarctica during the Precambrian. Mem. Geol. Soc India, no.34, pp.125-141.

SARKAR, M., GUPTA, S. and PANIGRAHI, M.K. (2007) Disentangling tectonic cycles along a multiply deformed terrane margin: Structural and metamorphic evidence for mid-crustal reworking of the Angul granulite complex, Eastern Ghats Belt, India. Jour. Struct. Geol., v.29, pp.802-818.

SARKAR, A. and PAUL, D.K. (1998) Geochronology of the Eastern Ghats Precambrian mobile belt-a review. Geol. Surv. India, Spec. Publ., v.44, pp.51-86.

SARKAR, A., BHANUMATI, L. and BALASUBRAMANYAN, M. N. (1981) Petrology, geochemistry and geochronology of the Chilka Lake igneous complex, Orissa state, India. Lithos, v.14, pp.93-110.

SARKAR, A., PATI, U.C., PANDA, P.K., KUNDU, H.K. and GHOSH, S. (2000) Late-Archaean charnockitic rocks from the northern marginal zones of the Eastern Ghats Belt: A geochronological study. Geol. Surv. India Spec. Publ., v.57, pp.171-179.

SEN, S. K. (1987) Origin of leptynites, an orthopyroxene-free granite gneiss in two granulite terranes of India. *In*: A.K. Saha (Ed.), Geological Evolution of Peninsular India, Petrological and Structural Aspects, Recent Researches in Geology, Hindusthan Publ. Corpn., New Delhi, v.13, pp.117-124.

SEN, S.K. and BHATTACHARYA, S. (1997) Dehydration melting of micas in the Chilka Lake Khondalites: The link between the metapelites and granitoids. Proc. Indian Acad. Sci. (Earth Planet. Sci.), v.106, pp.277-297.

SEN, S.K., BHATTACHARYA, S. and ACHARYA, A. (1995) A multi-stage pressure–temperature record in the Chilka Lake granulites: the epitome of the metamorphic evolution of Eastern Ghats, India. Jour. Meta. Geol., v.14, pp.287-298.

SENGUPTA, P., DASGUPTA, S., BHATTACHARYA, P.K., FUKUOKA, M., CHAKRABORTI, S. and BHOWMICK, S. (1990) Petrotectonic imprints in the sapphirine granulites from Anantagiri, Eastern Ghats Mobile Belt. India. Jour. Petrol., v.31, pp.971-996.

SENGUPTA, P., KARMAKAR, S., DASGUPTA, S. and FUKUOKA, M. (1991) Petrology of spinel granulites from Araku, Eastern Ghats, India, and a petrogenetic grid for sapphirine-free rocks in the system FMAS. Jour. Met. Geol., v.9, pp.451-459.

SENGUPTA, P., DASGUPTA, S., BHUI, U.K., EHL, J. and FUKOAKA, M. (1996) Magmatic evolution of mafic granulites from Anakapalle, Eastern Ghats, India: implications for tectonic setting of a Precambrian high-grade terrain. Jour. Southeast Asian Earth Sci., v.14, pp.185-198.

SENGUPTA, P., SANYAL, S., DASGUPTA, S., FUKUOKA, M., EHL, J. and PAL, S. (1997a) Controls of mineral reactions in high-grade garnet–wollastonite–scapolite bearing calc-silicate rocks: an example from Anakapalle, Eastern Ghats, India. Jour. Meta. Geol., v.15, pp.551-564.

SENGUPTA, P., DASGUPTA, S., EHL, J. and RAITH, M.M. (1997b) Thermobaric evolution of a suite of Mg-Al granulites from Paderu: further evidence for a ACW P-T path in the Eastern Ghats Belt, India. Beih. z. Eur. Jour. Mineral., v.9(1), p.331.

SENGUPTA, P., SEN, J., DASGUPTA, S., RAITH, M., BHUI, U.K. and EHL, J. (1999) Ultrahigh temperature metamorphism of metapelitic granulites from Kondapalle, Eastern Ghats Belt: implications for the Indo-Antarctic correlation. Jour. Petrol., v.40, pp.1065-1087.

SENGUPTA, P., RAITH, M.M. and DASGUPTA, S. (2004) Comment on: •High-temperature dehydration melting and decompressive P–T path in a granulite complex from the Eastern Ghats India• by S. Bhattacharya and R. Kar. Contrib. Mineral. Petrol., v.147, pp.123-125.

SENGUPTA, P., DASGUPTA, S., DUTTA, N. and RAITH, M.M. (2008) Petrology across a calcsilicate-anorthosite interface from the Chilka Lake Complex, Orissa: implications for Neo-

Proterozoic crustal evolution of the Eastern Ghats Belt. Precambrian Res., v.162, pp.40-58.

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. Jour. Geol., v.105, pp.645-656.

SHAW, R.K. and ARIMA, M. (1996a) High-temperature metamorphic imprint on calc-silicate granulites of Rayagada, Eastern Ghats, India: implication for the isobaric cooling path. Contrib. Mineral. Petrol., v.126, pp.169-180.

SHAW, R.K. and ARIMA, M. (1996b) Mineral chemistry, reaction textures, thermobarometry and P–T path from orthopyroxene granulites of Rayagada, Eastern Ghats, India. Jour. Southeast Asian Earth Sci., v.14, pp.175-184.

SHAW, R.K. and ARIMA, M. (1998) A corundum-quartz assemblage from the Eastern Ghats Granulite Belt, India: evidence of high P–T metamorphism? Jour. Met. Geol., v.16, pp.189-196.

SIMMAT, R. and RAITH, M.M. (2008) U–Th–Pb monazite geochronometry of the Eastern Ghats Belt, India: Timing and spatial disposition of poly-metamorphism. Precambrian Res., v.162, pp.16-39.

SUBBA RAO, M.V. and DIVAKARA RAO, V. (!999) Geochemistry and petrogenesis of the basic granulites in the Eastern Ghats Mobile Belt: Implications for the emplacement of the protoliths in an extensional environment. *In*: A.T. Rao, V. Divakara Rao and M. Yoshida (Eds.), Eastern Ghats Granulites, Gondwana Res. Group Mem., v.5, pp.51-63.

SUBBA RAO, M.V., BHASKAR RAO, Y.J., SIVA RAMAN, T.V. and GOPALAN, K. (1989) Rb-Sr age and petrology of the Elchuru alkaline complex: implications to alkaline magmatism in the Eastern Ghats mobile belt. Mem. Geol. Soc. India, no.15, pp.207-223.

SUBRAMANYAM, C. and VERMA, R. K. (1986) Gravity field, structure and tectonics of Eastern Ghats. Tectonophysics, v.126, pp.195-212.

TAKAMURA, T., DIVI, R.S., RAO, A.T., YASUTAKA, T. and YOSHIDA, M. (2000) Sheath folds in the northeastern part of Visakhapatnam, Eastern Ghats mobile belt, India. Geol. Surv. India, Spec. Publ., v.57, pp.279-289.

UPADHYAY, D. (2008) Mesoproterozoic alkaline magmatism at the southeastern cratonic margin: constraints on craton-Eastern Ghats Belt suturing and implications for crustal evolution in Peninsular India. Precambrian Res., v.162, pp.59-69.

UPADHYAY, D. and RAITH, M.M. (2006a) Intrusion age, geochemistry and metamorphic conditions of a quartz-monzonite intrusion at the craton-Eastern Ghats Belt contact near Jojuru, India. Gondwana Res., v.10, pp.267-276.

UPADHYAY, D. and RAITH, M.M. (2006b) Petrogenesis of the Kunavaram alkaline complex and the tectonothermal evolution of the neighboring Eastern Ghats Belt granulites, SE India. Precambrian Res., v.150, pp.73-94.

UPADHYAY, D., RAITH, M.M., MEZGER, K. and HAMMERSCHMIDT, K. (2006a) Mesoproterozoic rift-related alkaline magmatism at Elchuru, Prakasam Alkaline Province, SE India. Lithos, v.89, pp.447-477.

UPADHYAY, D., RAITH, M.M., MEZGER, K., BHATTACHARYA, A. and KINNY, P.D. (2006b) Mesoproterozoic rifting and Pan-African continental collision in South-Eastern India: evidence from the Khariar alkaline complex. Contrib. Mineral. Petrol., v.151, pp.434-456.

VIJAYA KUMAR, K., FROST, C.D., FROST, B.R. and CHAMBERLAIN, K.R. (2007) The Chimakurti, Errakonda, and Uppalapadu plutons, Eastern Ghats Belt, India: An unusual association of tholeiitic and alkaline magmatism. Lithos, v.97, pp.30-57.

WINGATE, M.T.D., PISAREVSKY, S.A. and EVANS, D.A.D. (2002) Rodinia connections between Australia and Laurentia: no SWEAT, no AUSWUS? Terra Nova, v.14, pp.121-128.

ZHAO, G.C., CAWOOD, P.A., WILDE, S.A. and SUN, M. (2002) Review of global 2.1–1.8 Ga orogens: implications for a pre-Rodinia supercontinent. Earth Sci. Rev., v.59, pp.125-162.

ZHAO, G., SUN, M., WILDE, S.A. and LI, S. (2004) A Paleo-Mesoproterozoic supercontinent: assembly, growth and breakup. Earth Sci. Rev., v.67, pp.91-123.

ZHAO, G., SUN, M., WILDE, S.A., LI, S. and ZHANG, J. (2006) Some key issues in reconstructions of Proterozoic supercontinents. Jour. Asian Earth Sci., v.28, pp.3-19.

(Received: 8 May 2008; Revised form accepted: 1 September 2008)