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REVIEW ARTICLE

Eastern Ghats Belt, Grenvillian-Age Tectonics and the Evolution of the Greater Indian Landmass: A Critical Perspective

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Abstract | The configuration of the Greater Indian Landmass was achieved during the late Proterozoic era (Grenvillian-age) through tectonic cycles involving cratonic blocks of India and East Antarctica in the broad framework of the assembly of the supercontinent Rodinia. Geological evidences are recorded from orogenic belts separating southern, northern and western cratonic blocks of India and its transcontinental neighbor East Antarctica. Eastern Ghats Belt of India played a pivotal role in the continental amalgamation process and it evolved in tandem with the Central Indian Tectonic Zone and the Aravalli Delhi Mobile Belt. We have collated geological and geochronological evidences from the cratonic blocks and the bounding orogenic belts to trace back the Grenvillian-age tectonics surrounding India and its eventual manifestation as the configuration of the Greater Indian Landmass. The status of the Greater Indian Landmass as a part of Rodinia is debated and unresolved issues are highlighted.

1 Introduction

The ca. 1.70–0.75 Ga time frame of the Earth witnessed remarkable similarity in terms of lithospheric, atmospheric, hydrospheric and atmospheric characters which has been attributed to the stability of two ancient supercontinents Columbia (or Nuna) and Rodinia.[25] The supercontinent Rodinia is believed to have assembled through a series of subduction–accretion–collision processes during ca. 1200–850 Ma combining most of the continental fragments.[26, 80, 85, 88] These continental fragments were joined by large-scale orogenic belts encircling the assembled continents, of which the Grenville Belt is an archetypal example.[26, 113] How and when these continental fragments were joined in the growing supercontinent Rodinia is an intriguing question and many competing hypotheses exist[80, 85, 88] and references therein). The all-inclusive Rodinia fit model by Li et al.[80] is now contested by many[27, 81, 88] as some of the continental blocks interpreted to have constituted a part of Rodinia in the former model are now considered "lone wanderers".[88] It is now apparent that the assembly of Rodinia occurred over a prolonged period which started with the joining of Laurentia with Baltica and Siberia through the Grenville orogen during ca. 1200–1000 Ma.[80] The Rayner-Eastern Ghats (R-EG) orogen evolved during ca. 1000–900 Ma and is believed to have joined the cratonic blocks of India and East Antarctica as a part of Rodinia assembly[19, 43–45, 64, 67, 89, 96] and references therein). This time lag of orogenic development is possibly linked with the position of the assorted continental blocks in terms of interior and exterior parts of the supercontinent.[102]

The R-EG orogen has long been considered as a Meso-Neoproterozoic belt within the broad framework of Rodinia until recent reconstruction of the supercontinent.[88] Prominent tectonothermal activities occurred at the Eastern Ghats Belt and the Rayner Complex during ca. 1000–900 Ma. Moreover, similar structural, metamorphic and isotopic signatures (Pb, Sr) of the source materials [54] imply that the R-EG orogen evolved as a single belt through accretionary orogenesis (reviewed in[44, 45]). A detailed tectonic development of the Eastern Ghats Belt is presented in

Supercontinent—Amalgam of several continental blocks as a single extensive continent, mainly driven by the plate tectonic process in which continental plates get fused and oceanic plates get consumed.

Craton—The tectonically most stable part of a continent.

Orogenic belt—Mountain belts produced by tectonic process that stitch cratonic blocks.

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Dasgupta et al. [44, 45] and we are not repeating the same here. A peep into the recent literature prompts us to review the tectonic processes that were operating around the Indian continent in the broad time frame of Rodinia assembly.

As far as the Archean nuclei are concerned, the Indian continent consisted of three southern (in the present geographical coordinate) cratonic blocks, namely the Dharwar, Bastar and the Singhbhum, which are believed to have attached together since inception, possibly as a supercraton. Commonly termed as the South Indian Block or SIB, this supercraton was joined with the Aravalli-Bundelkhand and Marwar cratons (comprising the Northern Indian Block or NIB) during the ca. 1000 Ma orogenic processes though the Central Indian Tectonic Zone or CITZ[11, 13] and references therein). This amalgam is commonly perceived as the Greater Indian Landmass (GIL) and it is argued that the present configuration of India (Fig. 1) was achieved at ca. 900 Ma;[13, 15, 19, 34] Saha et al.[119] Here, we present the tectonic scenarios surrounding the GIL to correlate with the ongoing assembly of Rodinia. There is a possibility that a proto-GIL was achieved during ca. 1600–1540 Ma[5, 7, 12, 14] during the assembly of Columbia. Since this configuration does not include the larger part of the Eastern Ghats Belt, we are not exploring it further in the present context.

Greater Indian Landmass—The coherent landmass of present day India that was formed at ca. 1.0 Ga by large-scale tectonics and continental amalgamation.

2 Geological Setting

Peninsular India is constituted of dispersed Archean cratonic nuclei tied together by orogenic belts of broadly Proterozoic age. Five known cratonic blocks, namely Singhbhum, Bastar, Dharwar, Bundelkhand and Aravalli contain nuclei that are largely tectonically unaffected since ca. 2500 Ma, while the Proterozoic orogenic belts record episodic growth (mostly reworking of older crust with minor juvenile addition) during ca. 1700–500 Ma. With the exception of the Himalayas and the Southern Granulite Terrane, the rest of India (including the vast terrane now covered by the Deccan basalt) represents the GIL (Fig. 1), which remained remarkably stable until the Phanerozoic era. The moot question that intrigues one is how and when the configuration of the GIL was achieved. The answer to this question can be sought from the E–W trending Central Indian Tectonic Zone (CITZ) which separates the NIB from the SIB. With the publication of new and improved geological, paleomagnetic and geochronological data from the CITZ and the bounding cratons, new models for the configuration of the GIL have been proposed recently.[11, 13, 14, 119] Based on these data, it is more or less accepted that the GIL configuration was achieved during the ca. 1060–1000 Ma when the SIB was underthrusted below the NIB as a result of continental collision, although an earlier phase of amalgamation at ca. 1600–1540 Ma has been considered for the assembly of the proto-GIL.[13, 14, 119] The present review will address this issue in a later section, but before that, let us have a brief overview of the different components of the GIL.

3 Archean Cratonic Nuclei

The NIB is constituted of the Bundelkhand and Aravalli cratons, often considered as a combined proto-continent with unmistakable Archean ancestries.[120] A separate cratonic unit, named the Marwar block, is postulated to have existed at the western part of the Aravalli craton. For the Aravalli craton, the Banded Gneissic Complex (BGC) represents the basement for the overlying Proterozoic metasedimentary rocks of Aravalli and Delhi Supergroups.[48, 69, 114, 115, 131] The BGC has a checkered history with complex interplay of magmatism, metamorphism and deformation since ca. 3.3 Ga.[58] The cratonization of the BGC (Aravalli craton) and the adjoining Bundelkhand craton occurred at 2.5 Ga with emplacement of granite.[142, 143] The Bundelkhand craton is composed of granitic basement (massif) over which lie the Proterozoic sedimentary successions and Deccan Trap volcanics of Cretaceous age. It is argued that the massif component of the craton is composed of TTG gneisses of ca. 3.59–3.30 Ga age[77, 94, 119] and reworked by subduction–accretion–collision setting at the end Neoarchean-Early Paleoproterozoic era[109] and references therein). A close look at the history of the two adjoining cratonic blocks of NIB finds no major difference except the fact that these are separated by a lineament which is considered as northern extension of the CITZ.[119] The information about the Marwar block is cryptic without much information about the nature of basement over which lies the sedimentary successions.[46, 47] The western (Marwar block) and the eastern (Aravalli-Bundelkhand) cratonic blocks are separated by the Phulad lineament, a major terrane boundary shear zone with characteristics of a suture.[33]

Three cratonic blocks, namely the Singhbhum, Bastar and Dharwar, constitute the SIB; each having distinct Archean ancestries. The Singhbhum craton constitutes ca. 3.50 Ga Iron Ore Group of rocks [101] which is an enclave suite containing metavolcanics and banded iron

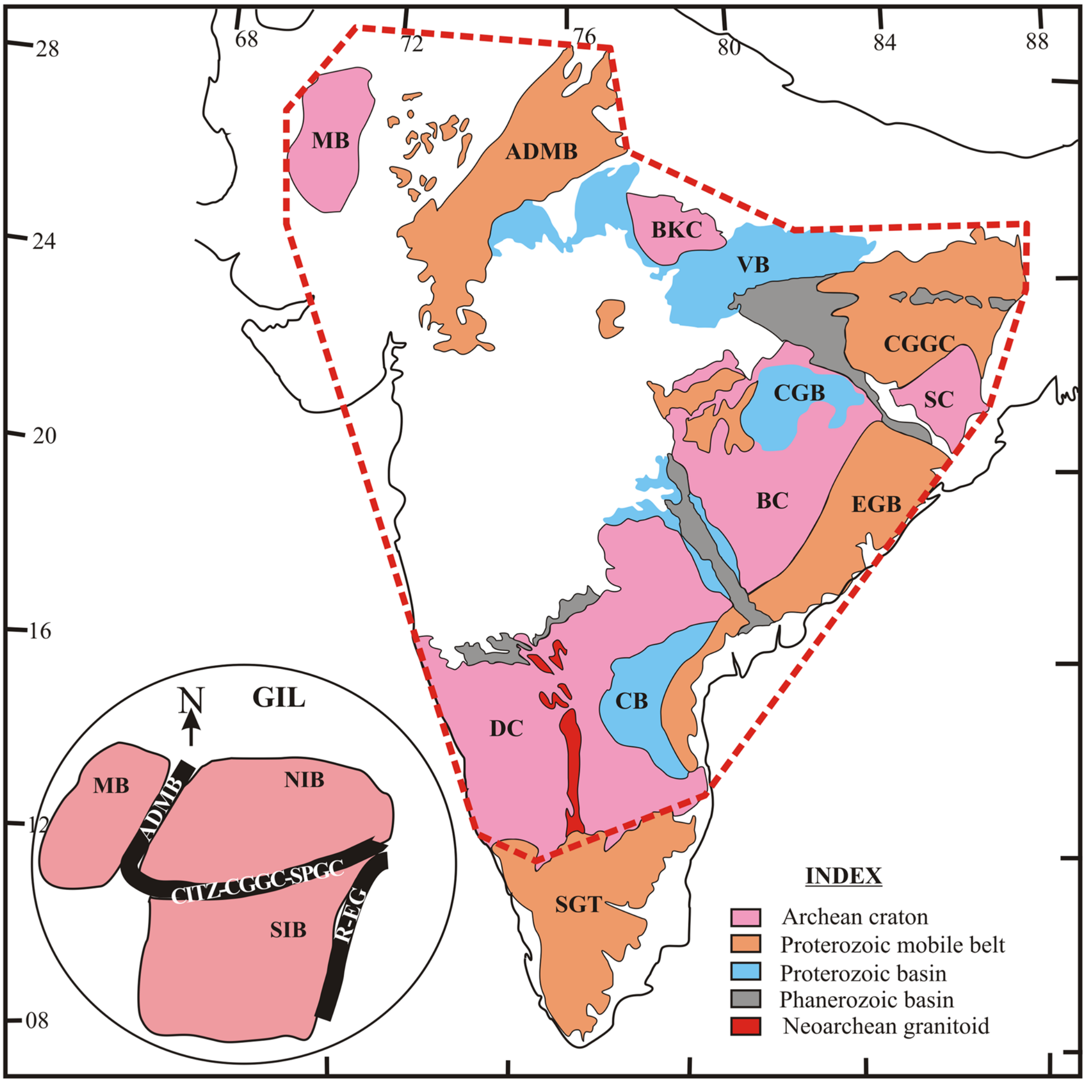

Figure 1: Broad geological map of India showing the approximate boundaries (in red stippled line) of the GIL (modified after.[119] A cartoon diagram of the GIL (modified after[13] is shown in the inset which is stitched by the orogenic belts. *MB* Marwar block, *ADMB* Aravalli-Delhi Mobile Belt, *BKC* Bundelkhand craton, *VB* Vindhyan Basin, *CGB* Chattisgarh basin, *CGGC* Chhotanagpur Granite Gneiss Complex, *SC* Singhbhum craton, *BC* Bastar craton, *EGB* Eastern Ghats Belt, *CB* Cuddapah Basin, *DC* Dharwar craton, *SGT* Southern Granulite Terrain, *CITZ* Central Indian Tectonic Zone, *SPGC* Shillong Plateau Gneissic Complex.

formation (BIF)-bearing greenstones within ca. 3.45–3.10 Ga granitoids of TTG affinity.[1, 93, 100, 116, 134, 138] The Singhbhum craton at its south is flanked by the Rengali Province which records the southward growth of the craton through complex tectonothermal evolution during ca. 3.0–2.50 Ga [21, 34, 82] and development of successive sedimentary basins down to the Paleoproterozoic era.[41] The Y-shaped Rengali Province also separates the Singhbhum craton from the southwesterly placed Bastar craton and southerly placed Eastern Ghats Belt (Fig. 2). The Bastar craton consists of ca. 3.56–3.51 Ga TTG gneiss-granite[57, 108, 124] which formed the basement of the Proterozoic sedimentary successions. The Dharwar craton is separated from the Bastar craton by the Karimnagar belt-Pranhita–Godavari basin (Fig. 1) and exposes a large section of Archean continental crust having a complex evolutionary history. The western part of the craton is consisted of ca. 3.40–3.00 Ga TTG gneiss, intruded into and overlain by greenstone.[73, 75, 97, 105] The late Archean (ca. 2.74–2.55 Ga) granite-greenstone succession bears important evidence of crust-mantle coupling in an accretionary setting[49, 74] and references therein). The eastern part of the craton is composed of younger (ca. 2.7–2.53 Ga) granite-greenstone succession.[74, 106] Voluminous granite of ca. 2.52–2.50 Ga emplacement age occurs between the two cratonic blocks, but their abundance is higher in the eastern side.[98]

4 Proterozoic Eastern Ghats Belt

The Proterozoic Eastern Ghats Belt (EGB) occur along the east coast of India flanking the SIB (Fig. 3) and played crucial role in connecting the cratonic blocks of India with East Antarctica[44, 45] and references therein). This regionally extensive geologically complex orogenic belt exposes ultra-high temperature (UHT) lower crustal section that recorded growth histories of the supercontinent Columbia and Rodinia. While the entire belt is a collage of several crustal provinces and isotopic domains, the southern part of the EGB (Ongole domain) evolved during the assembly of Columbia during ca. 1.80–1.54 Ga.[19, 45, 126] The regionally extensive northern part of EGB (Eastern Ghats Province after[52] and domains 2 and 3 after[112] records the assembly of Rodinia joining the cratonic India with East Antarctica ([45] for a review). Despite much disagreement regarding the evolution of EGB, it is now established beyond doubt that the northern part of the EGB (Eastern Ghats Province) evolved together with the Rayner Complex as a single orogenic belt (the R-EG belt by [96] through subduction-accretion processes during the time frame ca. 1.13–0.90 Ga.[19, 40, 79, 89, 137] In a recent review, Dasgupta et al.[45] presented in detail how the different domains/provinces of EGB evolved, which is not repeated here. We are more interested in evaluating the consanguinity of EGB in the light of recent supercontinent reconstruction models where India is considered an outsider in the Rodinia framework,[27, 81, 88, 107] which is quite different from the earlier models.[80] At the same time, we will make a tour surrounding the SIB to check whether the sequence of events has any correlation between EGB and the formation of the GIL. To begin with, let us draw our attention to the contacts of EGB with the bounding cratons of the SIB.

5 The EGB-SIB Contacts

5.1 EGB-Bastar Craton

The boundary between the EGB and the Bastar craton has long been recognized as a tectonic discontinuity and is variably referred to as the 'Eastern Ghats Frontal Thrust',[103] the 'Eastern Ghats Boundary Shear Zone'[52] and the 'Terrain Boundary Shear Zone'.[16] Marked by a steep gravity anomaly,[133] this boundary is also structurally characterized by a wide mylonitic zone.[4, 61, 103] Structural and petrological studies suggest that the hot granulitic lower crust was thrusted on the craton, which caused heating of the craton

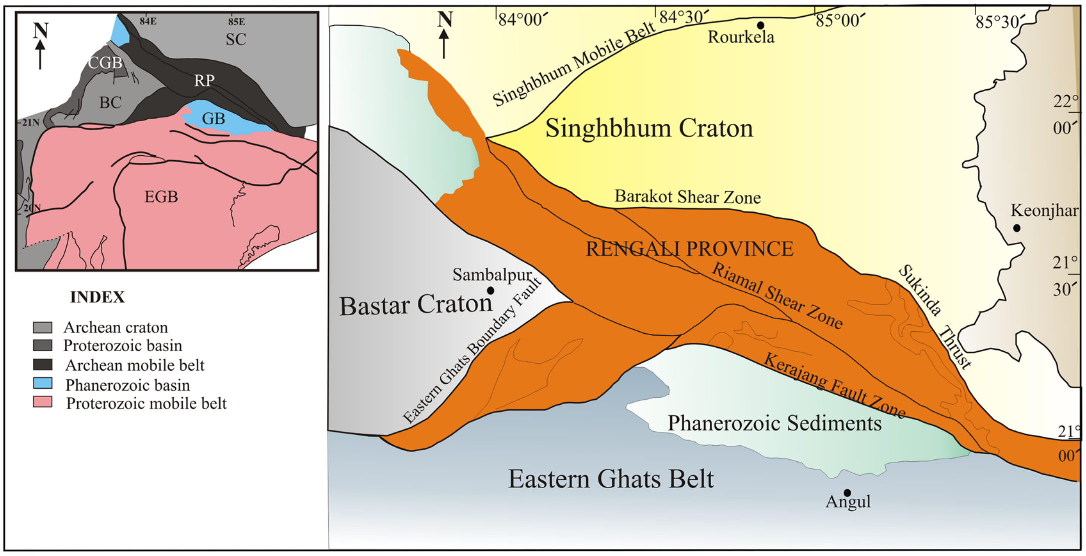

Figure 2: Geological map of the Rengali Province (modified after[21] which is bound by major fault/shear zones. The inset shows the location of the terrane in the geological map of eastern India (modified after.[52] *CGB* Chattisgarh basin, *RP* Rengali Province, *SC* Singhbhum craton, *GB* Gondwana Basin, *EGB* Eastern Ghats Belt, *BC* Bastar craton.

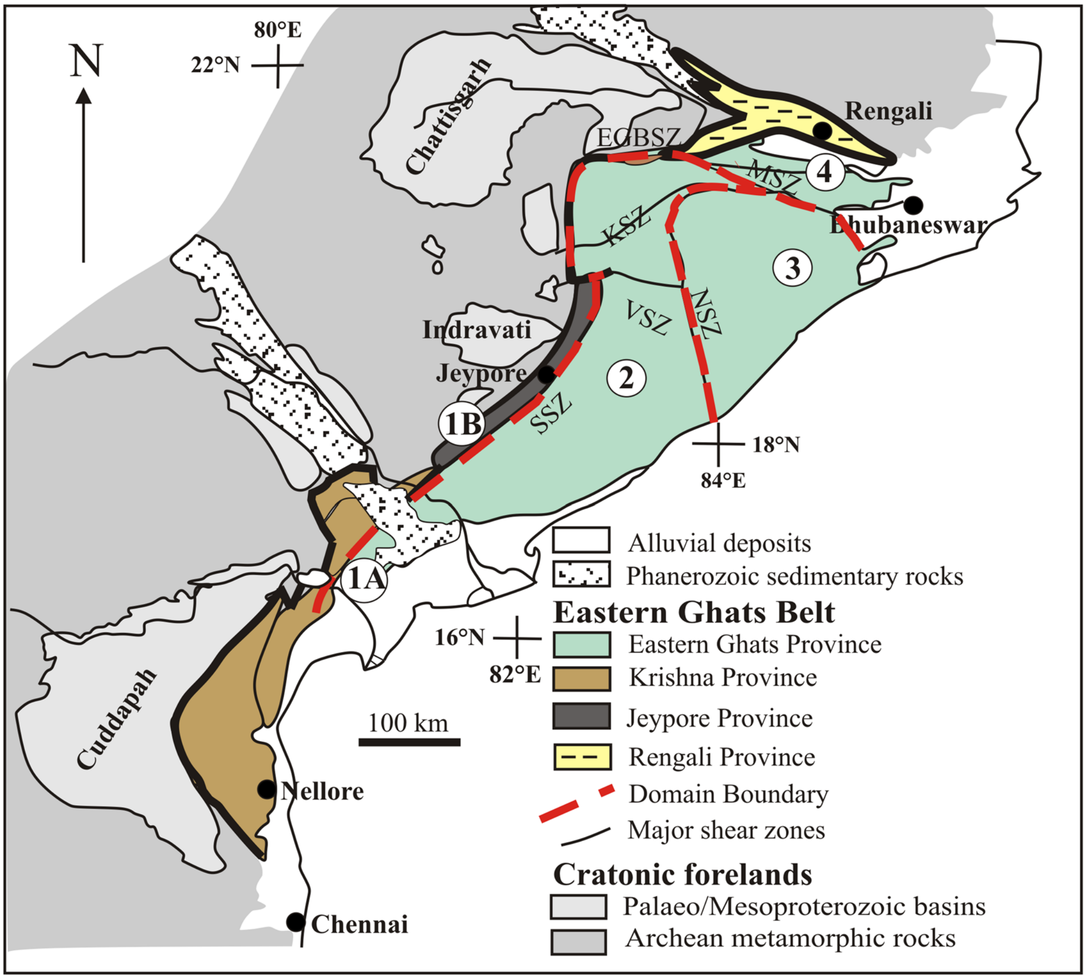

Figure 3: Geological map of the Eastern Ghats Belt with crustal provinces (after[52] and domains (after[112]. Major shear zones and domain boundaries are also shown. Crustal domains are marked by numbers in circle. *EGBSZ* Eastern Ghats Boundary Shear Zone, *MSZ* Mahanadi Shear Zone, *KSZ* Koraput Shear Zone, *SSZ* Sileru Shear Zone, *VSZ* Vamshadhara Shear Zone, *NSZ* Nagavalli Shear Zone.

vis-à-vis cooling and decompression of the granulitic thrust sheets.[4, 31, 39, 62] Structural modeling shows that the boundary thrust actually represents either the listric frontal thrust or the basal décollement of the EGB,[16] which implies the formation of a fold-and-thrust sequence with a number of stacked thrust sheets. While the kinematics of the event is characterized, the timing of the thrusting event remains a bone of contention. Two distinct age groups of ca. 1000–900 Ma and ca. 550–500 Ma are reported from the northern part of the contact zone,[130] but it was not clear until very recently what these ages imply with respect to the thrusting event. In a recent work, Chatterjee et al.[31, 32] demonstrated the nature of age zonation across the contact. The ca. 1000–900 Ma EG-R event largely cratonized the northern EGB (Eastern Ghats Province) against SIB and the SIB+EG-R Ma crust was reworked later during the ca. 550–500 Ma due to thrusting.[31] It is important to note that the adjacent cratonic block (footwall) was affected only by the later event. There is no record of magmatism and other crucial evidences for ocean closure along the contact, defying its status as a true suture. Therefore, the ca. 550–500 Ma event most likely represents an intracratonic orogenic front in response to far-field stresses imparted by the Pan-African orogeny occurring in East Gondwana. If this was the scenario, the cratonization of northern EGB was mostly completed during ca. 900 Ma.

5.2 EGB-Singhbhum Craton

The situation in the northern boundary is complicated due to the presence of a separate crustal province (cf. Rengali Province of [52]) between the EGB and the Singhbhum craton. Almost unclassified, the Rengali Province received much attention in recent times presumably due to preservation of Meso-Neoarchean high-temperature (HT) granulite metamorphism and its possible role in EGB-craton assembly.[20, 82] Apart from some Ar–Ar dates in the range ca. 700–400 Ma from amphibolite-facies rocks [38], nothing was certain about the timing of magmatism and high-grade metamorphism of the Rengali Province till recently. New petrological, structural, geochemical and geochronological data, however, clearly show that felsic magmatism and granulite–amphibolite facies metamorphism occurred in the time span of ca. 3050–2500 Ma [6, 21, 34, 42, 82]. Structural and geochronological data further indicate that the Rengali Province evolved as a southern margin of the Singhbhum craton;[55, 56, 82] which witnessed successive cycles of basin development during ca. 2500–1800 Ma.[41] As we consider the Rengali Province an extension of the craton, the northern boundary of the EGB must lie somewhere in-between, possibly along the Kerajung Fault (Fig. 2). Although a major part of the fault zone is concealed under the Phanerozoic Gondwana basin, the exposed parts of southern Rengali do not show any evidence of ca. 1000–900 Ma metamorphism or magmatism. Of course, there are very few data to confirm this, but nothing has been reported so far. On the contrary, there is a report of ca. 500 Ma thermal/shearing event close to the Kerajung Fault which may be related to reactivation of the fault zone.[56] Sporadic records of ca. 900 Ma event are identified from monazite from the rocks near the eastern fringe of Rengali Province that marks the northernmost extension of the EGB.[130] There is no record of ca. 1000–900 Ma granulite facies metamorphic imprint on the high-grade gneisses or low-grade supracrustals of southern part of the Rengali Province. This absence of evidence may be explained by the resilience of the granulite-amphibolite grade Rengali basement by the ca. 900 Ma EGB front. Strangely, the low-grade supracrustals developed over the gneissic basement recorded multiple cycles of basin opening,[41] but no effect of the ca. 900 Ma event. The basins must have been developed prior to ca. 900 Ma (no detrital zircon < 1800 Ma), but escaped the strong EGB imprint. The most interesting results come from a supracrustal sequence occurring north of the Rengali Province. The Malaygiri supracrustal sequence records ca. 950 Ma Barrovian metamorphism imprinted on garnet–staurolite schist.[34] It is argued that the ca. 950 Ma event is the response of EGB orogeny by Singhbhum craton.[34] This could be considered as a clinching evidence for EGB-Singhbhum craton collision, but there are problems. The major problem is the critical position of Rengali Province which debarred the direct contact of EGB with the craton sensu stricto. Moreover, if the cratonic block witnessed Barrovian metamorphism along a clockwise P–T path, the continental block must have underthrusted below the EGB front. There is no evidence of high-grade EGB rocks in the vicinity. Probably, the ca. 950 Ma event is related to tectonism of broadly similar age of EG-R orogeny, somewhere in the Prydz Bay, Vestfold Hills of East Antarctica. Like the western margin, there is no report of magmatism and no possibility of getting a suture here.

5.3 EGB-Dharwar Craton

A major part of the EGB-Dharwar craton boundary is masked by the overlying sedimentary successions of Cuddapah basin (Fig. 1). A number of fold-thrust belts showing low- to medium-grade metamorphic characters occur along the contact zone. The southern part of EGB (Ongole domain) is flanked by the Nellore schist belt consisting of geologically and geochemically distinct multiply deformed volcano-sedimentary successions of the Vinjamuru Group, the Kandra ophiolite complex, the Kanigiri ophiolitic mélange and the Udaigiri Group.[118] The Vinjamuru Group shows Archean protolith signatures,[110] but its timing of metamorphism (amphibolite facies) and juxtaposition to Kandra ophiolite complex occurred after ca. 1.9 Ga.[117, 139, 140] The deformation and emplacement of syntectonic granite (Vinukonda granite) within the Vinjamuru Group occurred along the eastern boundary of the Nallamalai Fold belt at ca. 1589 Ma.[53] The Kandra ophiolite belt consists of imbricate thrust slices of dismembered ocean plate and interpreted to have originated under a supra-subduction zone setting at ca. 1.9 Ga.[117, 139, 140] A second exotic unit, represented by the Kanigiri ophiolitic mélange, bears a somewhat similar supra-subduction setting signature and interpreted to have been emplaced at ca. 1334 Ma.[51] These ophiolitic sequences are argued to preserve relics of subduction–accretion process over an extended period (ca. 1800–1300 Ma) at the eastern margin of the Dharwar craton and are broadly correlated with the assembly and breakup of Columbia.[44, 45, 118] Late granites, apparently clubbed with the Prakasam Alkaline Province plutons, were emplaced in the northern part of the Nellore schist belt and are interpreted to represent a Mesoproterozoic rifting episode along the contact, but their status is not clear (e.g.,[127]. Zircon Hf signatures suggest that the provenance of the Paleoproterozoic as well as Neoproterozoic sedimentary successions of the western Cuddapah basin is the Eastern Dharwar craton, but the signatures of the Ongole domain have strong resemblance with those of the Nallamalai fold belt.[35, 68] The last major tectonothermal event in the Ongole domain occurred at ca. 1540 Ma when it was cratonized with the Dharwar craton.[125]

Recently, Sheppard et al.[128] deduced Pan-African age (531 ± 7 Ma) from in situ monazite dating of metamorphosed shale and siltstone from the Nallamalai Fold belt of the Cuddapah basin. These authors argue that this Pan-African event was responsible for folding, nappe stacking and very low-grade metamorphism. Although it is not clear how monazite grew in such low temperature conditions, this new age constraints imply Pan-African tectonism in the sedimentary basin close to the Ongole domain during the assembly of Gondwana.

6 Where is the India-Antarctica Suture?

Early Rodinia reconstruction models assumed collision of India and East Antarctica[95] which would imply closure of an ocean in-between with a possibility of a suture occurring between the two blocks. Metamorphic history of the EGB suggests no evidence of a collisional orogeny; rather a more appropriate evolutionary model is accretionary tectonics. [44, 45] With the accumulation of geological data from the Indian side (EGB) and the Antarctic side (Rayner Complex), it is now clear that the EGB-Rayner combine or R-EG evolved as a single accretionary orogen without any ocean closure in-between.[54, 65, 67, 96] Accretion was presumably initiated at the continental margin of the Indian side (SIB, to be precise) with development of subduction zone (Fig. 4) and associated accretionary wedge and magmatic/continental arc. Let us now reconstruct the scenario to figure out what exactly happened during the ca. 1000–900 Ma time frame. We must discuss R-EG as a single orogenic belt in this time frame. The ca. 1000 Ma UHT metamorphism is conspicuous in EGB and this was possibly related to the high asthenospheric heat flow in back-arc setting.[44] Although there are records of granulite metamorphism and magmatism in the Prydz Bay region of the Rayner Complex during ca. 1000–960 Ma,[81] metamorphic condition in the latter never reached UHT, which is exclusive to the EGB. Therefore, a westward subduction (in the present geographic setting) is indicated and EGB was positioned at the back-arc side during the ongoing subduction. In addition to that, prolonged felsic magmatism occurred in the Rayner Complex during ca. 1290–1060 Ma and these magmatic rocks show arc signatures.[63, 129, 132] Geochemical signatures of felsic magmatic rocks from EGB are scarce and their emplacement ages are mostly unknown (ca. 1190 Ma granite emplacement in Phulbani domain, EGB: Ganguly et al. under revision). Therefore, a comparison of EGB and Rayner Complex before ca. 1000 Ma is fraught with uncertainties. However, preponderance of the arc magma is notable in the Antarctic side which constituted the fore-arc region of the accretionary system. If the EGB and the Rayner Complex represent back-arc and arc–fore-arc settings, respectively, then a collision between arc–fore-arc and back-arc systems can be conceived prior to ca. 1.0 Ga. Since the boundary passes between two litho-tectonic domains of contrasting tectono-magmatic and tectono-thermal history, it may be appropriate to consider the boundary a suture that existed at an uncertain time prior to ca. 1.0 Ga. However, the unified R-EG orogen came into existence thereafter and the Rayner Complex (including the Prydz Bay) is considered as the Indian component of East Antarctica.[27] Pb-isotopic signatures of the gneissic rocks of the Rayner Complex along the Prydz Bay region show characteristics identical to the Dharwar craton of SIB,[54] which also supports the fact that the R-EG belt evolved from the Indian side. The R-EG, therefore, evolved as a circum-cratonic accretionary orogenic belt (Fig. 5) like the present-day Pacific. The accretion–collision during ca. 1000–960 Ma most possibly took place between the SIB and the continental blocks of central Antarctica like the Lambert Microcontinent[81] or more probably the Ruker Province.[92] Once accepted, the actual suture between SIB and the Ruker Province and rest of the central Antarctic craton (Crohn Craton of[18] must be lying south of McRobertson Land;[81, 92] Fig. 6). In this context, the geology of the Fisher Terrane can be of special interest. The latter is composed of mafic volcanics and plutonic rock complex[78] which is interpreted to represent a calc-alkaline arc.[90] It is argued that three arcs collided and fused together between the Napier Complex and Lambert Terrane during the ongoing accretion and collision.[81] The terrane underwent amphibolite facies metamorphism and granite emplacement during ca. 1200–950 Ma.[92] Although no conclusive reports are available, we suspect that some of the mafic rocks could be part of dismembered ophiolite which may be considered as a direct proof of the missing suture between India and East Antarctica. There are reports of

Accretionary tectonics—Tectonic process which is dominated by plate subduction, accretion and eventual collision.

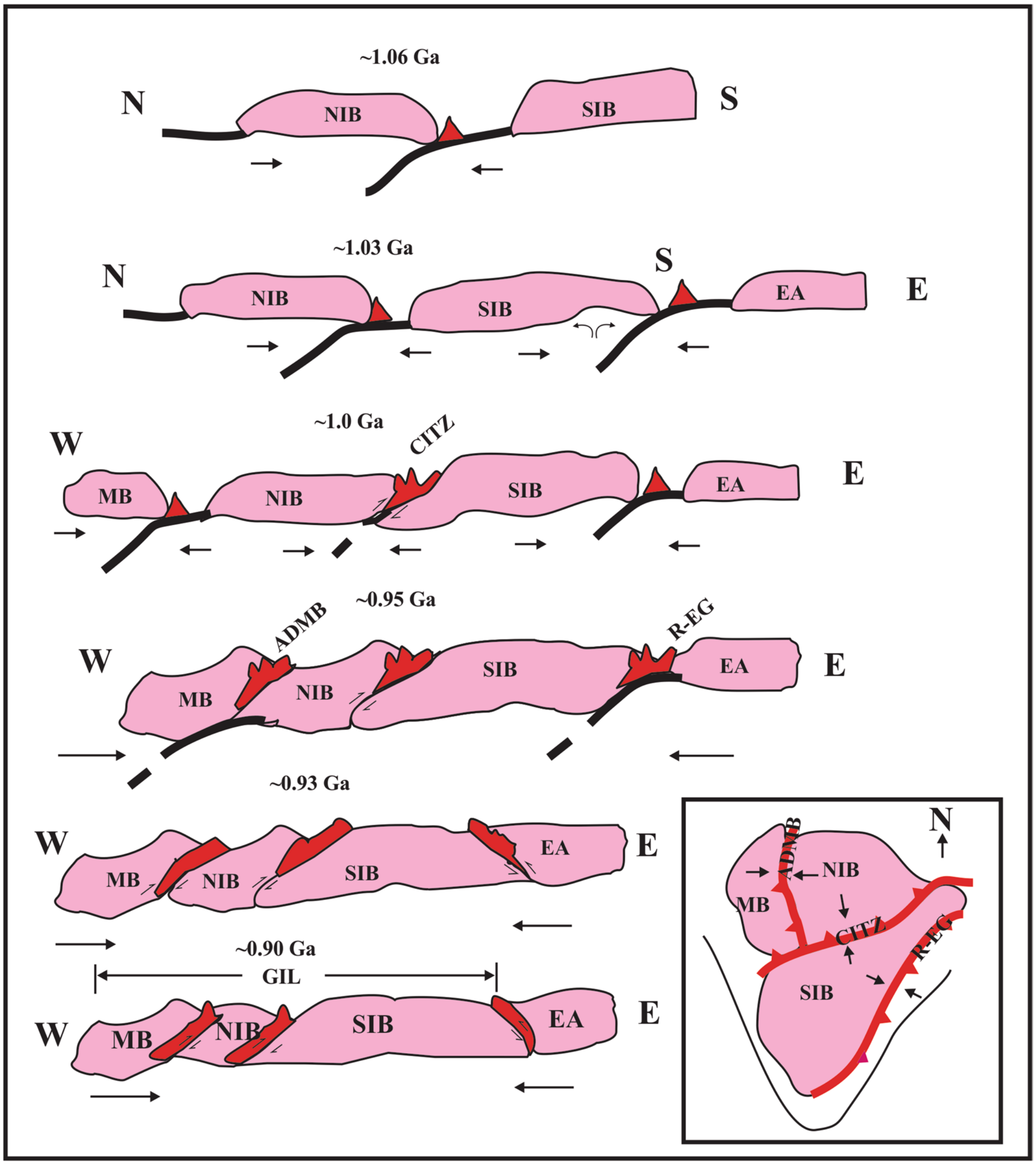

Figure 4: Cartoon diagram illustrating the accretionary growth of the GIL during the time frame 0f ca. 1.06–0.90 Ga as a part of Rodinia. Sequential development of accretionary orogens along E–W (present day) and N–S (present day) directions during this span eventually juxtaposed cratonic fragments of India and East Antarctica. The approximate time frames have been considered from the published geochronological data as described in the text. The inset is a simplistic cartoon of the GIL at approximately 0.9 Ga. *GIL* Greater Indian Landmass, *NIB* Northern Indian Block, *SIB* Southern Indian Block, *MB* Marwar Block, *EA* East Antarctic Block, *R-EG* Rayner-Eastern Ghats belt, *CITZ* Central Indian Tectonic Zone.

collisional tectonics (clockwise P–T path) from the granulites near McRobertson Land.[81]

The R-EG orogen was wide in extent (100–200 km) and formed by closure of an ocean developed between SIB and Ruker Terrane through at least two-phase orogenic events (subduction-accretion and final collision) during ca. 1000–960 Ma and ca. 930–900 Ma which is well documented from the Prydz Bay region of the Rayner Complex.[81] The ca. 930–900 Ma metamorphic imprints are also reported from the Lambert Terrane and Clemens Massif.[36, 37, 91] For the EGB, a similar two-stage orogenic event has been conceived recently ([45] where the ca. 1030–970 Ma event witnessed UHT metamorphism and emplacement of charnockite and

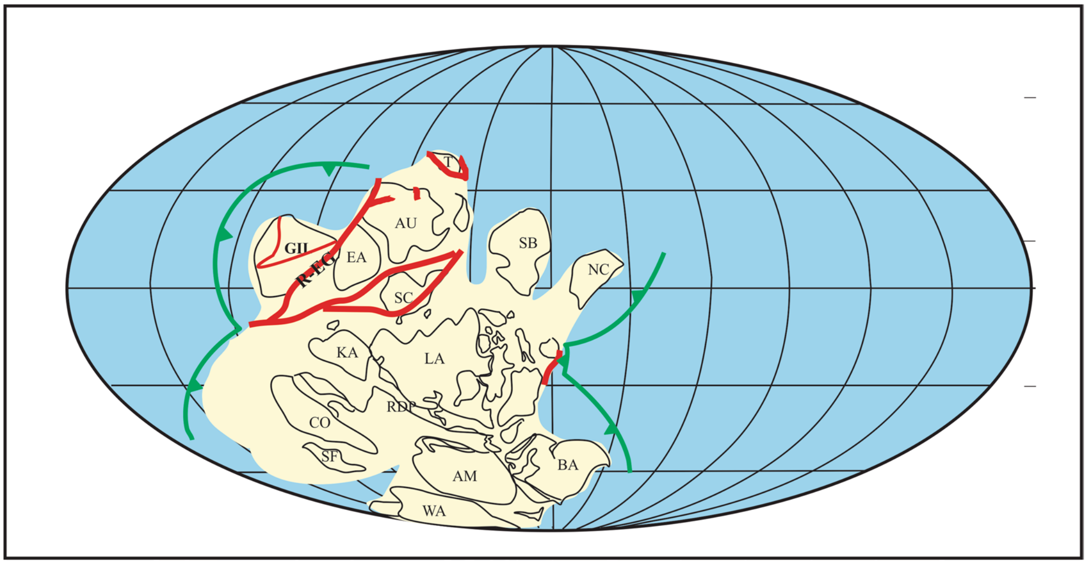

Figure 5: Reconstructed configuration of the supercontinent Rodinia at ca. 0.90 Ga (modified after [80] where the Rayner-Eastern Ghats belt (R-EG) have developed as a circum-cratonic orogen. Abbreviations used for cratonic blocks: *GIL* Greater Indian Landmass, *T-Tarim* EA-East Antarctica, *SB* Siberia, *Au* Australia, *SC* South China, *LA* Laurentia, *KA* Kalahari, *RDP* Rio de la Plata, *CO* Congo, *SF* Sao Francisco, *AM* Amazonia, *BA* Baltica, *WA* West Africa, *NC* North China.

granite while the ca. 950–900 Ma event is a granulite facies reworking which exhumed the deep crust to shallower level (see[45] for detail). This is not consistent with single stage prolonged evolutionary model of Korhonen et al.[79] Interestingly, a similar controversy exists in case of Prydz Bay, where both single continuous evolution[17, 63] and two separate stages of evolution[24] have been postulated.

7 The Other Side of Indian Continental Margin

From the foregoing discussion, we have developed a picture of the sequence of events that occurred at the eastern margin of the SIB (in the present coordinate) involving R-EG during ca. 1000–900 Ma. Now we shift our focus to the other side of the SIB. We look at the geological evolution of the CITZ to find out clues. It appears that the northern and north-western margin of the SIB (in the present co-ordinates) underthrusted below the NIB through CITZ during ca. 1060–960 Ma.[9–11, 13] The Sausar belt of the CITZ exposes a Barrovian metamorphic sequence that recorded a clockwise P–T evolution, which is considered as a cratonic response of the underthrusted continental block.[11, 13] The consequent crustal thickening and upper amphibolites to granulite facies metamorphism in the structurally lower plate and crustal anatexis, locally producing post-peak dry charnockitic magma, at ca. 0.98 Ga are evidenced by zircon Hf isotopic compositions [13]. It is already known that the CITZ is a suture and the ca. 1060–960 Ma event eventually closed an ocean basin (Sausar basin) that existed between the NIB and the SIB (Fig. 4). Looking further east, the Chhotanagpur Granite Gneiss complex (CGGC) also preserves a fair share of Grenvillian-age evolution. Mafic granulites and felsic orthogneisses of the CGGC evolved through clockwise P–T path implying the onset of collisional tectonics during ca. 950 Ma.[99] Apart from that, many places of CGGC record granulite facies metamorphism during ca. 1000–950 Ma.[28–30, 50, 76, 83, 99, 111] Combining all these information, it can be argued that the continental crust of the SIB was underthrusted below the NIB along the CGGC in a similar style as that of the CITZ during the ca. 1060–950 Ma. The eastward extension of the NIB must be buried under the thick sediments of the Indo-Gangetic alluvium. It is thus apparent that the CITZ-CGGC combine represents a suture that was extended northwards between the NIB and the Marwar block along the western margin of the ADMB.[8, 11, 15] For the latter terrane, Bhowmik et al.[15] recently proposed a Grenvillian-age paired metamorphic belt, which is a consequence of west-directed continental subduction and collision of continent and arc–back-arc systems.[8, 11, 15] Seen in that context, it is probable that the ocean closure during the

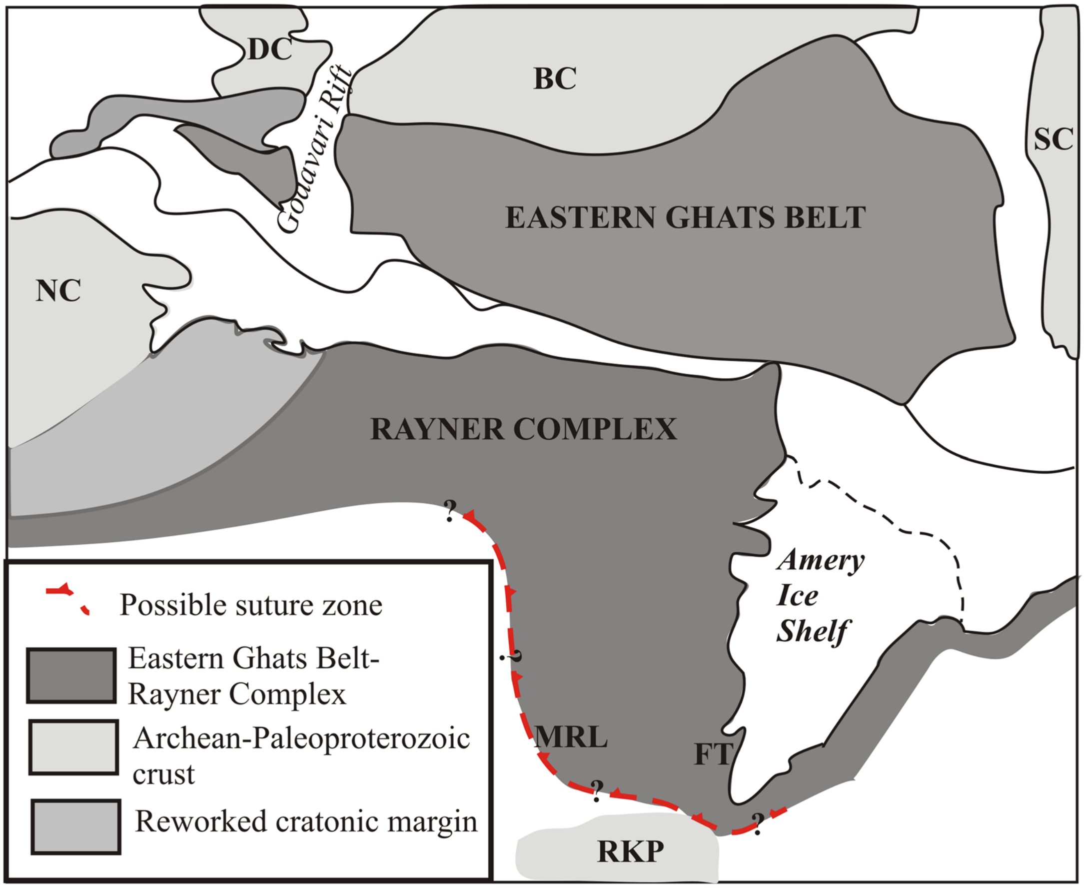

Figure 6: A possible correlation map of India and East Antarctica at ca. 900 Ma showing the positions of the Eastern Ghats Belt and the Rayner Province (modified afte [81, 92, 96]. Positions of possible suture zones are shown in the diagram (see text for details). *BC* Bastar craton, *DC* Dharwar craton, *SC* Singhbhum craton, *NC* Napier Complex, *RKP* Ruker Province, *MRL* McRobertson Land, *FT* Fisher Terrane.

Grenvillian-age orogeny occurred from all sides (introversion?) causing widespread magmatism, metamorphism, thrusting, shearing and fold development along the suture. If we see the features in a holistic way, the ca. 1060–900 Ma time witnessed flurry of activities surrounding the continental landmass (SIB) which was evolving as a supercraton.

8 Cratonization of the EGB: Significance of Pan-African Signatures

There is a controversy regarding the timing of cratonization of the EGB as both Grenville-age (ca. 900 Ma) and Pan-African-age (ca. 500 Ma) imprints are present at the boundaries. As discussed earlier, the imprints of the Grenvillian-age event are pervasive in the EGB which lies on the eastern and northern parts of the SIB (Fig. 3). Pan-African (ca. 550–500 Ma) metamorphic signatures are highly localized in EGB, mostly along shear zones.[52] This observation led Dobmeier and Raith[52] to conclude that the Grenvillian-age crust of the EGB had long-lasting stability like its Antarctic counterpart (Rayner Complex). Let us focus on two boundaries of EGB where Pan-African age events have been reported. Along the northern boundary of EGB with the Rengali Province, ca. 530–500 Ma metamorphic event is recorded from the mica schist of the Rengali Province adjacent to the Kerajung Fault Zone.[56] Muscovite grains in the schistose rock produced sillimanite and K-feldspar by dehydration reaction driven by heating, arguably resulted from shearing, thrusting and unroofing of the deeper crust in a crustal-scale flower structure.[56] The grade of metamorphism reached up to upper amphibolite facies (K-feldspar-sillimanite zone) only along the shear/thrust zone. This can be considered as a direct response of the extended Singhbhum craton, which also preserves some evidence of Grenvillian-age imprint.[34] Along the western margin, the EGB rock suite is argued to have thrusted over the Bastar craton along a major shear zone.[4, 16, 39, 136] Recently, Chatterjee et al.[31, 32] documented age zonation across an EGB-Bastar transect where the ca. 950 Ma metamorphic event is located at the interior part of the orogenic belt and the ca. 500 Ma metamorphism is imprinted on the EGB thrust sheet as well as on the basement gneisses of the Bastar craton. The grade of metamorphism was amphibolite-lower granulite facies which locally transformed hornblende into clinopyroxene.[32] Both these examples show that moderate to high temperature metamorphism occurred only along the shear zones due to thrusting of the EGB on to the bounding SIB. There is no record of magmatism, ocean closure and suturing during this time along the margins of EGB, unlike the case of the Southern Granulite Terrane[119] and references therein). The ca. 550–500 Ma event in the EGB-SIB sector is thus intracratonic in nature, as conceived by Dobmeier and Raith,[52] albeit without precise age data along the terrane boundaries. We also consider a similar possibility while the actual Pan-African suture is located farther east of the R-EG along the Trans-Antarctic Mountain[67, 81] and the ca. 550–500 Ma events are the cratonic response to far-field stresses of the Pan-African orogeny.[52]

9 India in Rodinia: Constraints from Paleomagnetic Data

Meert[85] made an interesting observation on the distribution of continental blocks within a supercontinent. Accordingly, the continental blocks which remained joined together in several supercontinent cycles are termed as “strange attractors”. The India–Antarctica–Australia–Madagascar combination, commonly known as the East Gondwana, is considered as a strange attractor. On the other hand, distinctly located continental blocks, like the South China, are termed as “lonely wanderers”. In the configuration of Rodinia, the position of India is controversial. Some models propose that India became part of Rodinia during ca. 900 Ma[80] and others), while others consider India as a lonely wanderer in the broad framework of Rodinia.[26, 81, 88, 107] In the latter model, India and part of the East Antarctica (Napier Complex + Rayner Complex + Ruker Terrane) never became part of Rodinia, which is based on paleomagnetic constraints from the ca. 1070 Ma Vindhyan and ca. 750 Ma Malani rocks.[59, 84]

Continental reconstruction is based on apparent polar wander paths which provide quantitative and robust evidence about relative positions (latitude and orientation) of continental blocks in the erstwhile supercontinents. However, many workers highlighted the ambiguities in paleomagnetic data that may lead to critical errors in reconstructions.[22, 86] Meert[85] discussed the issue of hemispheric ambiguity for high paleolatitude positions and described how it can be cross-checked from the established temporal sequence of paleomagnetic poles from two (or more) different continents. In case of the Precambrian continental blocks, the temporal resolution is poor and one has to rely often on paleomagnetic poles from rocks that differ in age by more than 100 Ma. Alternatively, spatially and temporally separated poles from separate cratonic nuclei can be analyzed to find coeval poles conforming to a fixed reconstruction.[121] Moreover, factors like secondary magnetizations in Precambrian rocks complicate the matter.[87, 135]

The ca. 1070 Ma (Vindhyan) and ca. 750 Ma (Malani) ages for paleopole reconstructions have, however, problems. The ca. 1070 Ma age for Vindhyan is slightly older than the ca. 1000 Ma closure of NIB-Marwar block. Therefore, its ancestry before amalgamation should not be treated as convincing evidence. Similarly, ca. 750 Ma is another crucial time for supercontinent cycle. It was the time when Rodinia began to disintegrate and the ca. 900 Ma configuration of India could have been disturbed. It is possible that the NIB was fragmented from the India towards North China and the pole positions are masking the position of India during ca. 900 Ma. In a recent work, Wang et al.[141] suggested that NW India was spatially linked to the South China and Madagascar blocks during the time frame of 800–780 Ma as a continuous geodynamic system. These workers further argue that this continuous system evolved either along the periphery of Rodinia or as outboards of the supercontinent with the age of convergent plate margin magmatism coinciding with breakup of the supercontinent. It can be argued that the ca. 1060–900 Ma events occurred surrounding the Indian land masses, united them as the GIL. This cannot be possible without ocean closure and does not justify the role of India as a lone wanderer. The surrounding cratonic blocks must have closed in and the possibility that India remained a part of Rodinia can still be possible.

10 Discussion and Unresolved Questions

The GIL assembly was distinctly related to the tectonic scenario developed surrounding the SIB. While the CITZ marks the northern tectonic margin, the EGB preserves a fragment of the eastern tectonic margin of the SIB. The counterpart of the EGB is the Rayner Complex which is now displaced to East Antarctica. We have argued that the Grenvillian-age orogeny is by and large responsible for development of GIL. A relatively recent development regarding this orogeny in the Indian context is a possible identification of a paired metamorphic belt in the Aravalli Delhi Mobile Belt or ADMB.[15] Identification of high heat flow along the western boundary of the South Delhi Fold Belt raises the possibility of arc-related metamorphism at ca. 1.0 Ga, which might be paired with collision-related metamorphism at the same age in adjoining parts of the ADMB.

We now intend to focus on three important related aspects that highlight some unresolved issues.

10.1 Amalgamation of Domain 2 (Part of Eastern Ghats Province) and Ongole Domain

Mezger and Cosca[89] envisioned, on the basis of geochronological data, that part of EGB occurring south of the Godavari rift has a contrasting geological history with respect to the northern part. This implies that the Godavari rift could be taken as the boundary between the southern and northern EGB. Subsequently, ca. 1.0–0.90 Ga metamorphic event was reported from pelitic granulites occurring south of the Godavari rift[137] which suggest that the suspected boundary between the ca. 1.6 Ga Ongole domain and the ca. 1.0–0.9 Ga domain 2 of the Eastern Ghats Province should lie at high angle to the Godavari rift. To find the exact location of the boundary between these two contrasting age crustal domains, one needs high-resolution age data from closely spaced localities along an E–W transect. Upadhyay et al. [137] deduced zircon U–Pb ages from felsic gneisses of Vijaywada area (their sample KR 8) which lies close to the Ongole domain. The obtained age information is very complex spanning 1.20–0.5 Ga. Using Hf isotopic signatures, these workers argued that zircon grains were produced by an early anatectic process (ca. 1.20–1.0 Ga) while the later events (< 1.0 Ga) possibly reworked zircon grains by coupled dissolution-reprecipitation process. This conclusion implies that although the cratonization of the Ongole domain occurred at ca. 1.54 Ga;[125] the ca. 1.2–1.0 Ga event finally joined it with the Domain 2. Interestingly, Mezger and Cosca[89] reported Ar–Ar age from hornblende of the Ongole domain, which can be considered as a possible response of the cratonized Ongole domain of the impending ca. 1.2–1.0 Ga orogeny. This needs to be checked with more robust geochronological data. The suspected boundary should have N–S orientation whose structural character would provide significant information about the nature of juxtaposition. Given the disposition of the rocks, we speculate a major shear zone between the two that needs to be verified.

10.2 UHT Metamorphism in the EGB and its Absence in the Rayner Complex

It is important to mention that although the R-EG evolved as a single orogen, UHT metamorphism is exclusive to EGB as there is no report of it in the Rayner Complex. This implies that the cause of UHT metamorphism during the evolution of R-EG was spatially restricted to the Indian side. In a recent review on time scales of UHT metamorphism, Harley[66] made an elaborate discussion on possible tectonic setting for both long-lived and short-lived UHT metamorphism. He argued that the back-arc basin can be considered as an ideal setting for UHT metamorphism, where short-lived UHT metamorphism will be facilitated by enhanced heat flow by magmatic under-accretion and mantle heat advection under extensional accretionary setting. This setting is quite different from the long-lived collisional orogenic settings.[3, 70–72] In a recent study, Bhowmik and Chakraborty [7] used sequential kinetic modeling to demonstrate how an apparently long-lived accretionary process can be resolved into several short-lived tectonic pulses which may have direct implication in Proterozoic tectonics. A strong temporal link among magmatism, crustal growth and granulite metamorphism is a characteristic feature of UHT metamorphism in back-arc basin. In this context, emplacement of voluminous granitic and charnockitic magma during ca. 1.0–0.95 Ga in the EGB [2, 19, 60, 104] can be considered as the magmatic component of the EGB back-arc basin. The mentioned spatial restriction warrants that the back-arc basin was positioned at the Indian side with a westerly dipping subduction polarity, which needs to be checked with geophysical data.

10.3 Significance of ~ 1.7–1.5 Ga Events in the Indian Scenario

The widespread occurrence of tectonothermal activities at ~ 1.7–1.5 Ga in different Proterozoic mobile belts of India implies that the “boring billion” was eventful here. Such events were recorded in the Ongole Domain,[19, 125] ADMB, [11, 23, 123]

CITZ [13] and Chhotanagpur Granite Gneiss Complex.[99, 122] The exact significance of such activities is speculative and it is not clear whether a continuous orogen existed, which will be obviously related to the Columbia supercontinent.

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