CHAPTER 2
GEOLOGICAL BACKGROUND

The NE-SW trending Meso-Neoproterozoic Eastern Ghats Belt (EGB) is situated along the easternmost part of Peninsular India (Fig. 2.1). This belt is surrounded in the north by the Singhbhum Craton and Bastar Craton and Dharwar cratons at the behavior west. This belt is almost entirely composed of granulite facies rocks. Ramakrishnan et al. (1998) subdivided this belt into four longitudinal lithological zones (Fig. 2.2a) based solely on the lithological disposition of rocks without considering the geochronologic or metamorphic history of the belt. The lithological zones are described below.

1. Western Charnockite Zone (WCZ): This is primarily composed of charnockite suite of rocks (including enderbite), with sporadic occurrences of mafic-ultramafic rocks and a negligible quantity of metapelites.
2. Central Migmatite Zone (CMZ): Migmatitic supracrustal rocks including garnet-bearing diatexite, leptynite, aluminous granulite, and calc-silicate rocks, make up the majority of this zone. Charnockites, porphyritic granitoids, and massif-type anorthosites are intrusives in these rocks.
3. Western Khondalite Zone (WKZ): Metapelites (also known as khondalite) make up the majority of the zone, with intercalated quartzite, calc-silicate rocks, marble, and aluminous granulites. Charnockites occur as intrusive in the supracrustal sequence. Furthermore, this zone has been reported to contain several massif-type anorthosite occurrences.
4. Eastern Khondalite Zone (EKZ): Although this zone shares similarities with the WKZ lithologically, the zone is truncated at the coast of the Bay of Bengal. Anorthosite is not known to exist there.

Ramakrishnan et al. (1998) further identified a Transition Zone in the west separating the EGB from the adjacent Bastar craton but its lithological characters and actual position are debatable. Subsequent investigations revealed various contradictions within this longitudinal categorization, including the Transition Zone (Dasgupta and Sengupta, 2003). Rickers et al. (2001) made a comprehensive study based on Sm-Nd, Rb-Sr, and ^{207}Pb-^{206}Pb isotopic signatures of different rock types throughout the EGB. Based on their data, they argued that EGB is a collage of four separate isotopic domains with differing protolith dates and metamorphism styles and these domains are separated by large-scale lineaments (Fig. 2.2b). These isotopic domains were named as Domain 1 (including 1A and 1B), 2, 3 and 4. Metamorphic histories were not integrated in this classification. In a later study, Dobmeier and Raith (2003) integrated metamorphic, structural and geochronological data with the isotopic data of Rickers et al. (2001) and offered a classification of EGB. Accordingly, EGB is constituted of four separate crustal provinces, some of the latter are further constituted of crustal domains (Fig. 2.2c). These crustal provinces, which are located from south to north, are designated as the Krishna Province, the Jeypore Province, the Eastern Ghats Province, and the Rengali Province. The low- to medium-grade Paleo-Neoproterozoic Udaygiri and Vinjamuru domains, as well as the high-grade Ongole domain, make up the Krishna Province, which is located in the southern part of EGB (south of the Godavari Rift). This province overalps with isotopic domain 1A of Rickers et al. (2001). The rest of the provinces occur on the north of the Godavari Rift. The high-grade mafic granulites and charnockites are the constituent rocks of the Jeypore Province, which is interpreted to have developed during the Neoarchean time, but robust geochronological data are missing (Dobmeier and Raith, 2003). This province overlaps with the isotopic domain 1B of Rickers et al. (2001). The centrally located Eastern Ghats Province is constituted of seven different crustal domains, namely Visakhapatnam, Phulbani, Rampur, Khariar, Tikarpara, Angul and Chilka Lake. This province overlaps with the isotopic domains 2, 3 and 4 of Rickers et al. (2001). The northerly situated Meso-Neoarchean Rengali Province is distinguished by its medium- to high-grade rocks (Bose et al., 2016). This province overlaps with a part of the isotopic domain 4 of Rickers et al. (2001). These four crustal provinces exhibit diverse metamorphic characters and ages (Dasgupta et al., 2013, 2017; Bose and Dasgupta, 2018; Bose, 2020). A brief overview of the tectonometamorphic histories of the crustal provinces and their constituent domains are described below.

Krishna Province

Udayagiri, Vinjamuru, and Ongole are the three separate domains that make up the Krishna Province (Dobmeier and Raith, 2003). Only the Ongole domain among these shows signs of ultra-high temperature (UHT) metamorphism; the other two domains underwent lower grades of metamorphism.

Ongole domain: The prominent features within this domain include mafic-ultramafic-anorthosite complexes, notably exemplified by the Kondapalle Complex, along with suspected ophiolite complexes such as the Kandra and Kanigiri ophiolite complexes (Vijayakumar et al., 2010, 2011; Dharma Rao et al., 2011; Sain et al., 2017; Sain and Saha, 2018). Additionally, voluminous calc-alkaline magmatic rocks in the form of enderbite and charnockite are accompanied by lesser amounts of metapelitic migmatites and alkaline rocks. Analysis of detrital zircon ages reveals Palaeoproterozoic sources predominate in the sediments, with an estimated maximum age of ca.2.40–1.75 Ga and a modest contribution from Archaean sources ca. 3.40 Ga (Upadhyay et al. 2009; Henderson et al. 2014; Sarkar et al. 2014). The beginning of metamorphism in the Ongole Domain, which is thought to be the earliest, began between 1.65 and 1.60 Ga concomitantly with a large incidence of arc-type magmatic activity (Upadhyay et al. 2009; Bose et al. 2011; Henderson et al. 2014; Sarkar et al. 2014). The emplacement age of Kondapalle mafic-ultramafic complex is at ca. 1.69 Ga (Dharma Rao et al. 2012) possibly associated with intense charnockite magmatism at ca. 1.72 Ga (Kovach et al., 2001) and 1.75 Ga (Sarkar et al., 2014). The rocks in the Ongole domain underwent a phase of ultra-high temperature (UHT) metamorphism, which followed an anticlockwise pressure-temperature (P-T) pattern, around 1.68-1.60 Ga (Sengupta et al., 1999; Sarkar et al., 2014). This UHT metamorphism is argued to have taken place at a condition higher than 950°C and 6-7 kbar (Sarkar and Schenk, 2014 and references therein). This metamorphic cycle was overprinted by a separate metamorphic event that occurred at ca. 1.54 Ga (monazite chemical age) and is characterized by high peak pressure (9.5 kbar) and low peak temperature (780°C) followed by an isothermal decompressive retrogression in an overall clockwise P-T path (Sarkar and Schenk, 2014; Sarkar et al., 2014). In the Ongole Domain, there is evidence of an earlier UHT metamorphism in the metapelitic granulite enclave within a mafic granulite at ca. 1.76 Ga (Bose et al., 2011). According to Dasgupta et al. (2017), this earlier UHT metamorphism phase might be associated with the emplacement of mafic-ultramafic complexes within a broader tectonic setting characterized by subduction and accretion related to Columbia Supercontinent cycle. The Kandra Ophiolite Complex is a prime example of how this tectonic setting was essential in generating magmatic activity through the creation of an ocean basin (Vijayakumar et al., 2010, 2011). The ca 1.68-1.60 Ga UHT metamorphism in the Ongole domain occurred along an anticlockwise P-T path caused by magmatic heat advection while the ca.1.54 Ga clockwise metamorphic cycle was caused by continental collision during the final phase terrane collision between the Kondapalle magmatic arc and the East Antarctica within the Columbia supercontinent (Sarkar and Schenk, 2016). At ca. 1.45 Ga, rifting in the cratonized block paved the way for the emplacement of alkaline magma during the opening up of a potential ocean basin. Geological activities were finally completed at a time of localized deformation and relatively modest thermal activity at around 1.30-1.10 Ga (Mezger and Cosca, 1999). It is important to mention that the Ongole Domain was largely unaffected by the Grenvillian-age orogeny.

Vinjamuru and Udaygiri domain: Both Vinjamuru and Udaygiri domains contain rocks of lower metamorphic grade. The Vinjamuru domain, located along the western side of the Ongole domain, is made up of mafic schist containing garnet and pelitic schists containing staurolite-kyanite. These geological formations are closely linked to thin granite gneiss, with minor ferruginous quartzite and calc-silicate rocks (Ramam and Murty, 1997; Dobmeier and Raith, 2003; Saha et al., 2015). Two metamorphic pulses have been reported here at ca.1.63-1.59 Ga and ca. 1.55 Ga (Chatterjee et al., 2016), both pulses indicating amphibolite facies metamorphic condition (Chatterjee et al., 2016). The age of the first metamorphic pulse broadly coincides with the emplacement of the Vinukonda granite at ca. 1.59 Ma (Dobmeier et al., 2006). According to Dobmeier et al. (2006), phengitic mica has developed in the rocks due to a low-grade metamorphic event that took place between 501-474 Ma. As noted by Saha et al. (2015), the steep contact zone between the Ongole and Vinjamuru domains is characterized by a series of east-vergent thrusts accompanied by a sinistral strike-slip movement.

The Udayagiri domain, which is further west of the Vinjamuru domain, is composed primarily of phyllites and quartzites, intercalated with modest amounts of metatuff and mafic metavolcanics. Limited published research is available on this domain which indicates lower grade greenschist facies metamorphic condition (Babu 1998). These rocks form a stack of west-vergent thrusts that were deposited over the Cuddapah basin, located to the west of the Udayagiri domain.

Eastern Ghats Province (EGP)

The isotopic domains within the EGP were described by Dobmeier and Raith (2003) based on Nd isotopic data from Rickers et al. (2001) and distinct metamorphic ages across ductile shear zones. However, the boundaries of these domains are mostly undefined, except for a few studies (Chetty et al., 2003; Saha and Karmakar, 2015). The significance of distinct age populations across shear zones which separates the Domains (Chetty, 2010) and the details of metamorphic events and timing of shearing remain mostly unknown. The different domains of the EGP are described below.

Vishakapatnam Domain: Visakhapatnam domain constitutes the isotopic domain 2 of Rickers et al. (2001) and it occupies the heartland of the EGP. The western boundary of this domain is marked by the Sileru Shear Zone and its northern boundary is demarcated by the Nagavalli-Vamshadhara Shear Zone (Fig. 2.3). The southern tip of this domain is cut across by the Gadavari Rift while the eastern margin of the domain is obscured under the Bay of Bengal. This domain has received the maximum attention as a large number of petrological studied were carried out. In this domain, the predominant lithologies are pelitic migmatites and quartzo-feldspathic gneisses (referred to as leptynite locally), accompanied by calc-alkaline rocks such as charnockite and granite. Numerous occurrences of spinel and sapphirine-bearing aluminous granulite have been reported from this domain and these rocks have experienced UHT metamorphism during ca. 1.3-0.99 Ga (Bose et al., 2011, 2022; Das et al., 2011, 2021; Korhonen et al., 2013). Although mafic granulites and calc-silicate granulites are present in smaller quantities, they have provided significant petrological insights too (Dasgupta et al., 1991, Dasgupta 1993, Bhowmik et al., 1995, Sengupta et al., 1997, Sengupta and Raith, 2002; Dasgupta and Pal, 2005). Upadhyay et al. (2009) reported the presence of juvenile source material with ages ranging from 2.7 to 1.9 Ga, which broadly aligns with the Nd isotopic data presented by Rickers et al. (2001). Although the age of the basement formation is yet unknown, Bose et al. (2011) found evidence of a thermal pulse there at 1.76-1.70 Ga in the form of inherited oscillatory-zoned zircon grains. The authors speculate that the Palaeoproterozoic zircon dates could represent either magmatic or metamorphic processes in the sedimentary source regions. Interestingly, this time period coincides with a period of global magmatic activity (Condie et al., 2009), as well as the accretion of the Columbia supercontinent (Rogers & Santosh 2002; Zhao et al., 2002). According to Upadhyay et al. (2009), detrital zircon populations indicate that sedimentation in the region likely occurred between 1.40 and 1.20 Ga, associated with the opening of an ocean basin through rifting. However, Kelsey et al. (2017) determined an emplacement age of 1.58 Ga for mafic magma in the same area, which contradicts the detrital zircon evidence. It remains to be confirmed whether the mafic rock studied by Kelsey et al. (2017) constitutes the basement of the EGB or not.

It is generally agreed upon that the rocks from this domain have experienced UHT metamorphism (> 1000 ˚C) at lower crustal depths (corresponding to pressure about 7-8 kbar) in an anticlockwise P-T path (reviewed in Dasgupta et al., 2017). The timing of this UHT metamorphism has been estimated within an acceptable range of uncertainty by different studies, ranging from 1.03-0.99 Ga (Bose et al., 2011) to 1.13 Ga (Korhonen et al., 2013), considering the limitations of the dating techniques used. In contrast, Mitchell et al. (2018) observed different results in their study, as they did not find evidence of an anticlockwise pressure-temperature (P-T) path within the same domain. However, the workers also documented UHT metamorphism at ca. 1.0 Ga. It is petrologically established that the retrograde P-T path of the UHT metamorphism involves near-isobaric cooling (references in Dasgupta et al., 2017; Korhonen et al., 2013; Mitchell et al., 2018), but there is disagreement on the duration and nature of this cooling. While one group argued for a single long-lived (Δt ~170 Ma) single cycle orogeny (Korhonen et al., 2013; Mitchell et al., 2018) suggesting cooling up to ~ 0.9 Ga, the other group put forward textural evidence to establish two shorter period orogenic phases (Bose et al., 2011; Das et al., 2011). The latter model has recently been further quantified by geospeedometric data (Bose et al., 2022). This latter study demonstrated that two separate cycles of metamorphism (M_1 and M_2) occurred in shorter pulses ((Δt ~40 Ma) where the M_1 metamorphism (ca. 1030-990) was shortly overprinted by the M_2 metamorphism (ca. 940-900). These workers further argued that the evolution of these two cycles is connected to multiple alternating periods of extension (pull) and compression (push) within an accretionary tectonic environment, occurring approximately at 1030-900 Ma. Apart from this, thermal activity in this domain is manifested by the emplacement of S-type granitoids at ca. 0.98 Ga (Bose et al., 2011), i.e., the waning stage of the M_1 metamorphism. The granulitic rocks of this domain further suffered reworking during Pan-African orogeny at ~500 Ma, under amphibolite facies condition (reviewed in Dasgupta et al., 2017; Kelsey et al., 2017) or sporadically at higher temperature (~ 800°C, Das et al., 2021; Mitchell et al., 2018). However, the Pan-African event in this domain is best manifested by fluid-induced metamorphic changes (Das et al., 2021).

Chilka Lake domain: The rocks found within this domain possess the youngest protolith ages (1.80-2.20 Ga) in the EGB. The boundaries of this area align with the Mahanadi and Nagavalli-Vamasdhara shear zones (Rickers et al., 2001). Despite being grouped as the Eastern Ghats

Province by Dobmeier and Raith (2003), Domain 3's lithological makeup differs significantly from that of Domain 2's. While metapelitic migmatites, quartzofeldspathic gneisses (including charnockite), and minor calc-silicate and mafic granulites are prevalent in both domains, Domain 3 exhibits a significantly higher frequency of massif-type anorthosite occurrences. These anorthosites have been dated at approximately 0.79 Ga (Krause et al., 2001), 0.85 Ga (Chakrabarti et al., 2011), and 0.98 Ga (Chatterjee et al., 2008). The vast majority of geochronological data suggests that the anorthosite magmatism took place between 0.93 -0.98 Ga. Sen et al. (1995) claimed that the Chilka Lake granulites underwent a multistage tectonometamorphic evolution and achieved a maximum P-T of approximately 12 kbar and 1000°C, but Dasgupta and Sengupta (2003) disputed this on the ground that the petrological and tectonic interpretations are problematic. Evidence of UHT metamorphism (>1000°C, 7.5 kbar) was observed by Raith et al. (2007) and Sengupta et al. (2008) in pelitic and calcsilicate rocks that are in contact with anorthosite massifs. Simmat and Raith (2008) determined an approximate age of 1.0 Ga and classified it as a significant tectonothermal event in this area. Subsequently, younger events were identified through monazite spot dates ranging from approximately 0.8-0.5 Ga. Bose et al. (2016a) carried out a comprehensive study of the granulites in the Chilka Lake area, utilizing petrological, geochronological, and fluid inclusion data. Their findings revealed a multi-stage evolutionary history for domain 3. In accordance with this, the domain 3 underwent peak UHT metamorphism (900–950°C, 8.5–9 kbar) at roughly ca. 0.98 Ga with a potential clockwise P–T path, followed by three tectonometamorphic events at roughly ca. 0.78 Ga (800°C, 7 kbar), ca. 0.75 Ga (700°C, 6 kbar), and ca. 0.52 Ga (800°C, 6 kbar). The later events are similar to those identified by Mitchell et al. (2018) from the Visakhapatnam domain. Notably, the event occurring at 0.8 Ga aligns with the documented timeframe of the breakup of the supercontinent Rodinia. Furthermore, Mitchell et al. (2018) and Bose et al. (2016a) both found evidence of high-grade metamorphic overprinting (granulite facies) at about 0.5 Ga in both the domain, which has important implications for the formation of East Gondwana and the correlation of sections of the Eastern Ghats Belt with the East Antarctica.

Phulbani domain: Dobmeier and Raith (2003) recognized a distinct domain called the Phulbani Domain which is interpreted to have separated from the Visakhapatnam domain by the Nagavalli-Vamshadhara Shear Zone (Fig. 2.3). This domain is separated from the westerly placed Rampur domain by the Koraput-Sonepur shear zone (Fig. 2.3). The petrological history of the domain is characterized by a prominent 0.98 Ga UHT metamorphism followed by a near-isobaric cooling-dominated retrograde P-T path which has been determined from aluminous granulites (Ganguly et al., 2017). The P-T conditions and time frame of this UHT metamorphism coincides with those of the Visakhapatnam domain. The emplacement of porphyritic charnockite at ca. 0-98-0.97 Ga is broadly synchronous with the time of UHT metamorphism (Paul et al., 1990; Crowe, 2003; Dobmeier and Raith, 2003; Ganguly et al., 2018). According to Ganguly et al. (2018), the rocks of Phulbani area record three distinct events (ca. 1173 Ma, ca. 1000-900 Ma and ca. 781 Ma) where the ca. 1173 Ma age is interpreted as the crystallization age of granite magma (possibly formed the basement of EGP), and the younger ca. 781 Ma event indicates the timing of a localized shear-induced thermal event.

Rampur and Tikarpara domains: These domains occur in the northern and north-western parts of EGP (Fig. 2.2c). Petrological, structural and geochronological data are lacking from Rampur and Tikarpara domains.

Khariar domain: The Khariar Domain, located in the westernmost margin of the northern EGP, shares a boundary with Bastar Craton in the west and Rampur-Phulbani domains in the south. This domain is consisting of deformed alkaline rocks, mostly represented by nepheline syenite. The interpreted crystallization age of the alkaline magma is ca.1480-1471 Ma (Upadhyay et al., 2006; Ranjan et al., 2018). Apart from that anorthosite magma was emplaced in this domain at ca. 933 Ma (Krause et al., 2001 from Bolangir area) and ca. 980 (Raith et al., 2014 from the Turkel area). The absence of evidence for metamorphism in the Khariar domain during the ca. 1.0-0.90 Ga time is apparent from the published U-Pb zircon ages data (Upadhyay et al., 2006; Raith et al., 2014; Ranjan et al., 2018). On the contrary, Simmat and Raith (2008) obtained ca. 1159 Ma age from monazite inclusion within garnet in the aluminous granulite and mylonitized khondalite which they interpreted as the age of high-temperature metamorphism. Additionally, they reported a younger age of UHT metamorphism at ca 1065 Ma from monazite from the aluminous granulite. However, these monazite ages are not texturally constrained and thus the timing of metamorphism in Khariar domain is still not established. Recent geochronological findings from the southwestern region of the Khariar domain indicate the occurrence of two distinct thrusting events, accompanied by metamorphism. These events involved the initial thrusting of EGP rocks onto the Bastar Craton at ca. 0.9 Ga, followed by another thrusting event at ca. 0.5 Ga (Chatterjee et al., 2017a, b; Padmaja et al., 2021). During the late Neoproterozoic to early Paleozoic Pan-African tectonothermal event, the Khariar domain experienced moderate effects, including westward thrusting onto the Bastar Craton. The western margin juxpositioned of EGP against Bastar Craton along the Terrane Boundary Shear Zone (TBSZ), that shows thrust slip character along the west and southwestern side and strike-slip character in the northern side (Biswal et al., 2007). The northwest front of the EGP exhibits a fold-thrust belt structure characterized by a series of granulitic thrust sheets, with the TBSZ serving as the underlying detachment zone. The age of the syn-kinematic nepheline syenite plutons emplaced along the TBSZ, as determined by SHRIMP dating, suggests a Pan-African time when the EGP was juxtaposed with the Bastar Craton (Biswal et al. (2007).

Angul domain: The Angul domain is separated from the Phulbani domain by the Mahanadi Shar Zone (MSZ). Detailed petrological and geochronological data are not available from the Angul Domain. Sarkar et al. (2007) carried out a structural study along with broad metamorphic characterization. These workers have documented an early granulite-facies metamorphism at ~ 800°C, 8 kbar which was followed by a near-isothermal decompression-dominated clockwise (?) P-T path. The age of the granulite-facies metamorphism is estimated to be ca. 960 Ma (Mezger and Cosca 1999). Additionally, a subsequent amphibolite facies metamorphism affected the pre-existing granulite-facies assemblages, occurring at ~650°C, 6 kbar at ca. 700-650 Ma (Mezger and Cosca 1999; Dobmeier and Simmat 2002). It is significant to note that Aftalion et al. (1988) reported an upper intercept age at ca. 1159 Ma from the zircon grain of augen gneiss of the Angul domain, which they attributed as the crystallization age of a portion of the basement. Conversely, Simmat and Raith (2008) documented ages of approximately 1260-1200 Ma and 995-975 Ma based on monazite from metapelitic rocks. They interpreted these ages as corresponding to the early granulite facies metamorphism and the latest high-temperature tectonometamorphic event that defined the fabric, respectively. In a recent work in this domain two distinct metamorphism events ca. 1200 Ma and ca. 1000 Ma have been characterized from aluminous granulite at (Banerjee et al., 2022). This older event is a new finding in the EGP and thus the metamorphic history of the Angul Domain looks different from the rest. Additionally, there is no evidence of UHT metamorphism in the rocks of this domain. They also proposed juxtaposition of Angul-

Tikarpada area to the Prydz Bay area of East Antarctica and later become joined with EGP at ~550-500 Ma. Bose and Gupta (2018, 2020) suggested that the MSZ experienced dextral strike-slip movement based on structural data. Earlier studies (Lisker and Fachman, 2001; Crowe et al., 2001) estimated this movement to have occurred around 0.5 Ga.

Jeypore Province

Jeypore Province is located along the westernmost part of the EGP sharing contact with the Bastar craton through a shear zone called the Terrain Boundary Shear Zone (TBSZ). Except for a few scattered geochronological data, geological history of this province is very sketchy. The province comprises granulite facies meta-igneous rocks, dominated by charnockite and enderbite that contain bands, lenses and xenoliths of basic granulites. According to Subba Rao et al. (1998), protoliths of such rocks originated from poorly fractionated tholeiitic and intermediate magmas which evolved in a rift setting. These workers further argued that the charnockite-enderbite rocks are of calc-alkaline affinity possibly a product of arc-related magmatism. Archaean Nd model ages (3.9-3.0 Ga) and Pb isotopic signatures of the charnockite-enderbite rocks suggest their crystallization from a magma before ca. 3.0 Ga (Rickers et al., 2001). Preliminary U-Pb data from zircons indicate a high-grade metamorphic event at ca. 2.8 Ga, without later thermal effects (Kovach et al. 2001), but such metamorphism has not been well-constrained from textural data. The Koraput alkaline complex is the product of alkaline magmatism that occurred in the Jeypore Province around ca. 1.39 Ga (Ranjan et al., 2018). On the contrary, Nanda et al. (2018) argued that the alkaline complex intruded the EGP at ca. 850 Ma. According to Ranjan et al. (2018), these alkaline rocks suffered large Neoproterozoic overprinting events at roughly ca. 0.95 Ga, ca. 0.81 Ga and ca. 0.66 Ga. Saikia et al. (2018) suggested that the monazite chemical age data from the Koraput anorthosite fall into three groups: 0.94 Ga, 0.88–0.75 Ga, and 0.57 Ga. Accordingly, the oldest, intermediate and youngest ages correspond to the crystallization of anorthosite magma, breakup of Rodinia, and the assembly of Gondwana.

Rengali Province

Rengali province is located in the north of the Angul domain and having protolith age from 2.90-2.50 Ga (Rickers et al., 2001). The Rengali Province is composed of both granulite-facies gneisses/ charnockites and amphibolite-facies metavolcanic and metasedimentary rocks

(Mahapatro et al. 2012; Bose et al. 2015; Chattopadhyay et al. 2015; Ghosh et al. 2016) that represent the exhumed deeper section of the Singbhum Craton along its southern margin during ca. 3.0-2.5 Ga (Mahapatro et al., 2012; Bose et al., 2016a). The major granulite-facies metamorphism is broadly synchronous with the emplacement of charnockite magma followed by granitoid magmatism at ca. 2.8 Ga (Bose et al., 2016b). As the Rengali Province represents the southern extension of the Singbhum craton, the geochemical fingerprints of the charnockite and the granitoids point to a post-collisional setting inside a plate (Dasgupta et al., 2017). According to Bose et al. (2015), the orogeny at ca. 2.8 Ga brought together the deeper crustal mafic granulite and the shallower-level pelitic granulites, creating a juxtaposition. On the other hand, Misra and Gupta (2014) and Bhattacharya et al. (2016) hypothesized that the high-grade rocks of the Rengali Province may have formed as a septum or crustal component of the nearby Bastar Craton. Over an extended period of time, the low-grade supracrustal strata of the province underwent several cycles of sedimentation associated with the basin tectonics (Das et al., 2017a). The supracrustals underwent an amphibolite facies metamorphism at ca. 0.98 Ga, which was followed by additional tectonothermal episodes at roughly 0.85-0.80 Ga and 0.62-0.50 Ga (Chattopadhyay et al. 2015). According to Ghosh et al. (2016), the final stage of tectonothermal activity involved regional transpression, which caused the middle crust to be extruded over the upper crust. Chattopadhyay et al. (2015) concluded that the supracrustals in the Rengali Province share a remarkably similar tectonic history with the adjacent domains 3 and 4 of the EGP. This similarity, although occurring under different P-T conditions and possibly representing different crustal sections, suggests a connection between the adjoining parts of the EGP and the northern cratonic mass (Singhbhum) during the Grenvillian Orogeny around 0.95-0.98 Ga.

Cratonic contact of EGB

EGB-Bastar Craton

The tectonic discontinuity contacts between the Bastar Craton and EGB is variously named as 'Eastern Ghats Frontal Thrust' (Neogi and Das, 2000), 'Eastern Ghats Boundary Shear Zone' (Dobmeier and Raith, 2003), 'Terrane Boundary Shear Zone' (Biswal et al., 2007), and is characterized by a wide mylonite zone (Bhadra et al., 2004; Gupta and Bhattacharya, 2000; Neogi and Das, 2000). The craton experienced thrusting, resulting in the hot granulitic lower crust being pushed onto it. This thrusting led to the heating of the craton while the granulitic thrust sheets experienced simultaneous cooling and decompression (Gupta et al., 2000; Bhadra et al., 2004; Das et al., 2008; Chatterjee et al., 2017a, b; Padmaja et al., 2021). Biswal et al. (2007) conducted structural modelling, which reveals that the boundary thrust corresponds to either the listric frontal thrust or the basal décollement of the EGB. This suggests the development of a fold-and-thrust sequence involving multiple stacked thrust sheets. While the kinematics of this thrusting has been well-defined, the timing of the event has remained unknown until now. In the northern section of the contact zone, two distinct age groups are reported: approximately 1000-900 Ma and 550-500 Ma (Simmat and Raith, 2008). However, the connection between these ages and the thrusting event remains unclear. Chatterjee et al. (2017a, b) documented the existence of an age zonation across the contact in a recent study. Therefore, the ca. 1000–900 Ma age event significantly cratonized the northern EGB (EGP) with the cratonic South Indian Block and was subsequently reworked during the ca. 550–500 Ma. It is significant to note that only the later event had an impact on the nearby cratonic block (footwall). Its position as a real suture is contested by the absence of magmatism and other critical indicators of ocean closure along the contact. Hence, it is highly probable that the event around 550-500 Ma corresponds to an intracratonic orogenic front, resulting from the far-field stresses exerted by the Pan-African orogeny taking place in East Gondwana. On the contrary Padmaja et al., (2021) interpreted additional burial of the rocks in the Bastar as a consequence of the rocks being thrust beneath the EGP, which aligns with the seismic data currently available (Singh and Singh 2019). The ca. 500 Ma event was further correlated with the amalgamation of Bastar and EGP forming the Greater India Landmass.

EGB-Singhbhum Craton

Due to the presence of a separate crustal province (Rengali Province), the direct contact between EGB and Singhbhum Craton is absent. The boundary between the Rengali Province and the EG is demarcated by the Kerajang Fault Zone while the boundary separating the Rengali Province and the Singbhum Craton is defined by the Sukinda Thrust. Dobmeier and Raith (2003) considered Rengali Province as a separate unit because it has preserved an evolutionary history different than EGB. Recently, Rengali Province get much attention from the geologic fraternity due to the presence of Meso-Neoarchean granulite-amphibolite facies metamorphism (ca. 3.0-2.8 Ga; Bose et al., 2016b). This high-temperature metamorphism was followed by felsic magmatism at ca. 2800-2750 Ma (Bhattacharya et al., 2016; Bose et al., 2016; Chattopadhyay et al., 2015;

Mahapatro et al., 2012). The structural and geochronological evidence suggests that the Rengali Province developed as the southern boundary extension of the Singhbhum Craton (Ghosh et al., 2010, 2016; Mahapatro et al., 2012; Das et al., 2017a) which indicates that the northern boundary of the EGB must lie somewhere in-between, possibly along Kerajaung Fault zone. While a significant portion of this fault is covered by the Phanerozoic sediments of the Gondwana basin, the visible sections do not exhibit any signs of metamorphism or magmatism of ca. 1000-900 Ma age. It is important to note that a ca. 500 Ma thermal/shearing event that occurred along the Kerajung Fault (Fig. 2.3) has been reported and may have been responsible for the reactivation of the fault zone (Ghosh et al., 2016). Occasional evidence of a ca. 900 Ma event is detected in monazite samples obtained from rocks near the eastern boundary of the Rengali Province, which represents the furthest northern extension of the EGB (Bose et al., 2021). However, the high-grade gneisses and low-grade supracrustals in the southern half of the Rengali Province show no signs of the ca. 1000-900 Ma granulite facies metamorphic signature. Intriguingly, the Malaygiri supracrustal sequence, situated north of the Rengali Province, reveals a Barrovian metamorphism in garnet-staurolite schist at ca. 950 Ma (Chattopadhyay et al., 2015). Accordingly, Chattopadhyay et al. (2015) proposed that the ca. 950 Ma event resulted from the collision of EGB with the Singhbhum Craton. This was found problematic later (Bose and Dasgupta, 2018) since no petrological evidence is present which can prove underthrusting of the cratonic rock beneath the EGB front.

EGB-Dharwar Craton

The boundary between the EGB and Dharwar Craton is predominantly concealed beneath the sedimentary layers of the Cuddapah basin. Along the contact zone, there are several fold-thrust belts with low- to medium-grade metamorphic characteristics. According to Saha et al. (2015), the Nellore schist belt, which is a member of the Vinjamuru Group, the Kandra ophiolite complex, the Kanigiri ophiolitic mélange, and the Udayagiri Group flank the southern portion of the EGB (Ongole domain). The Vinjamuru Group, which has Archean protolith characteristics, underwent amphibolite facies metamorphosis and was juxtaposed to the Kandra ophiolite complex after roughly 1.9 Ga (Saha, 2011; Vijaya Kumar et al., 2010, 2011). Accordingly, imbricate thrust slices of broken oceanic lithosphere make up the Kandra ophiolite belt, which is thought to have formed in a supra-subduction zone environment. At ca. 1589 Ma, the Vinjamuru Group observed syntectonic granite emplacement (Vinukonda granite) along the eastern edge of the Nallamalai Fold belt. Another distinct unit, known as the Kanigiri ophiolitic mélange, exhibits similar characteristics of a supra-subduction setting and is believed to have been emplaced around ca.1334 Ma (Dharma Rao et al., 2011). These ophiolitic sequences are interpreted as remnants of a subduction-accretion process that occurred between approximately 1800-1300 Ma along the eastern margin of the Dharwar craton. They are broadly associated with the formation and breakup of the supercontinent Columbia (Dasgupta et al., 2013; Dasgupta et al., 2017; Saha et al., 2015). In the northern region of the Nellore schist belt, late granites associated with alkaline magmatism (Prakasam Alkaline complex) were intruded. These granites are interpreted as indicative of a Mesoproterozoic rifting event along the contact (Sai, 2013; Upadhyay et al., 2006). At ca. 1540 Ma, the Ongole Domain underwent significant tectonothermal event when it cratonized with the Dharwar Craton (Sarkar and Schenk, 2014). In situ, monazite dating of metamorphosed shale and siltstone from the Nallamalai Fold belt of the Cuddapah Basin recently yielded a Pan-African age of ca. 531 Ma (Sheppard et al., 2017) which is interpreted to be responsible for folding, nappe stacking, and low-grade metamorphism. Although the growth of monazite under such low-temperature conditions remains somewhat ambiguous, this new age constraint indicates Pan-African tectonic activity in the sedimentary basin near the Ongole domain during the final assembly of Gondwana.

EGB and East Antarctica

In recent times, extensive geological research conducted by both the Indian sector (EGB) and East Antarctica has revealed fascinating evidence pointing towards a similar geological evolutionary history. The Oygarden-Stilwell area, which is a portion of the modified Napier Complex in Kemp land, along with the adjacent Scorseby charnockite (Kelly et al., 2002; Halpin et al., 2007, 2013), serves as a precise correlation point between the edge of the Napier Complex in Kemp land and the Eastern Dharwar craton/southern Eastern Ghat Belt (Ongole domain) at the terminal stage of Columbia assembly (Bose et al., 2011; Sarkar et al., 2016; Dasgupta et al., 2017; Giri et al., 2023). In the context of Rodinia, EGP's domains 2 and 3 were connected with the cratonic region of south India, encompassing the Ongole domain, along with the Rayner Complex of East Antarctica approximately 0.95-0.90 billion years ago (Dasgupta et al., 2017; Bose et al., 2022; Ganguly et al., 2018). The northern part of the EGP including the Angul domain and Rengali Province were attached to the Prydz Bay region of East Antactica as part of Rodinia supercontinent (Dasgupta et al., 2017; Banerjee et al., 2022). This interpretation is rooted in the examination of petrological clues found within the rock records, such as the characteristics of rocks and the timing of metamorphism (Kelly et al., 2002; Dasgupta et al., 2017; Halpin et al., 2012). Additionally, the analysis of the pressure-temperature-time (P-T-t) history further reinforces this idea (Bose et al., 2022; Bose and Dasgupta, 2018; Harley, 2003). Furthermore, a significant contribution to this understanding comes from the planisplastic reconstruction of the pre-drift rift extension between Antarctica and India, as explored by Veevers et al. (2009). Notably, their study highlights prominent cross structures, such as the Mahanadi and Labert Rifts, the Pranhita-Godavari Rift, and the Robert Glacier, which align in a collinear fashion, providing valuable insights into the shared geological history between India's sector and East Antarctica.

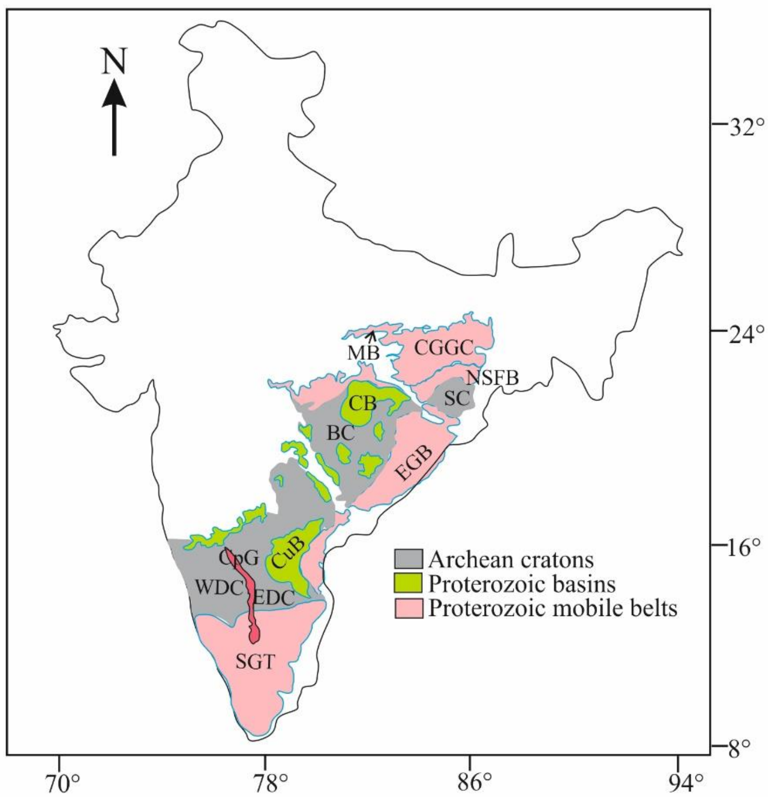

Fig. 2.1 Geological map of India showing the distribution of cratons , mobile belts and Proterozoic basins (modified after Ramakrishnan and Vaidyanadhan, 2008) WDC- Western Dharwar Craton; EDC- Eastern Dharwar Craton; BC- Bastar Craton; SC- Singhbhum Craton; BnC- Bundelkhand Craton; EGB- Eastern Ghats Belt; MB- Mahakoshal Belt; SGT- Southern Granulite Terrain, CGGC- Chotnagpur Granite Gneiss; NSFB- North Singhbhum Fold Belt; CB- Chattisgarh Basin, CuB- Cuddapah Basin, CpG- Cosepect Granite.

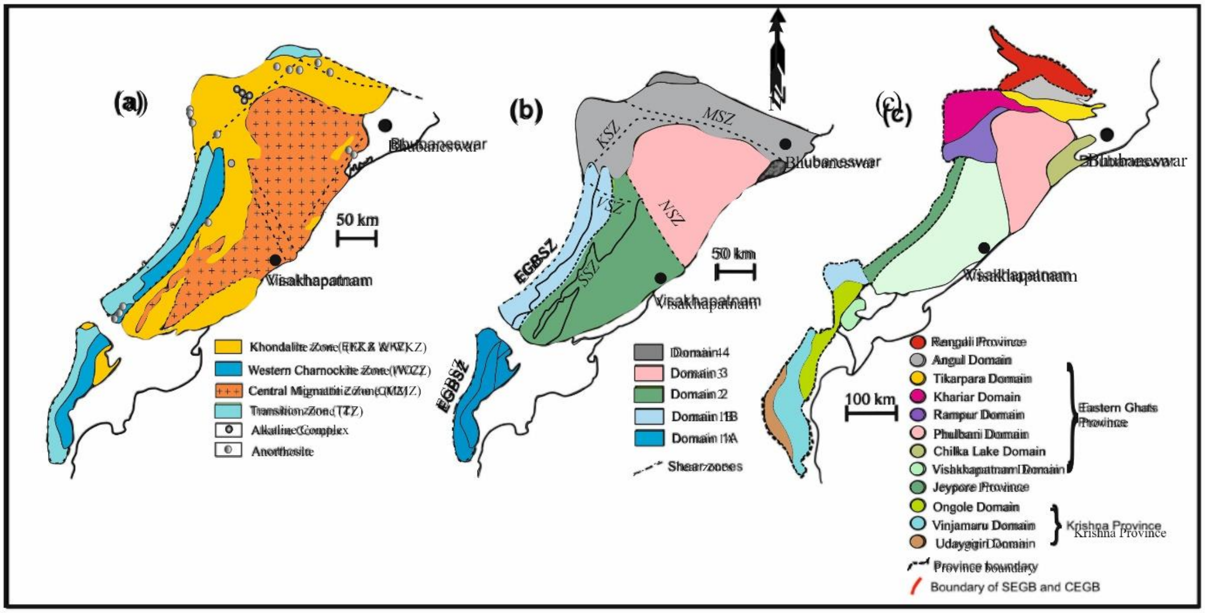

Fig. 2.2 Geological map of EGB. (a) after Ramakrishnan *et al*., (1998); (b) after Rickers *et al*., (2001); (c) after Dobmeier and Raith (2003)

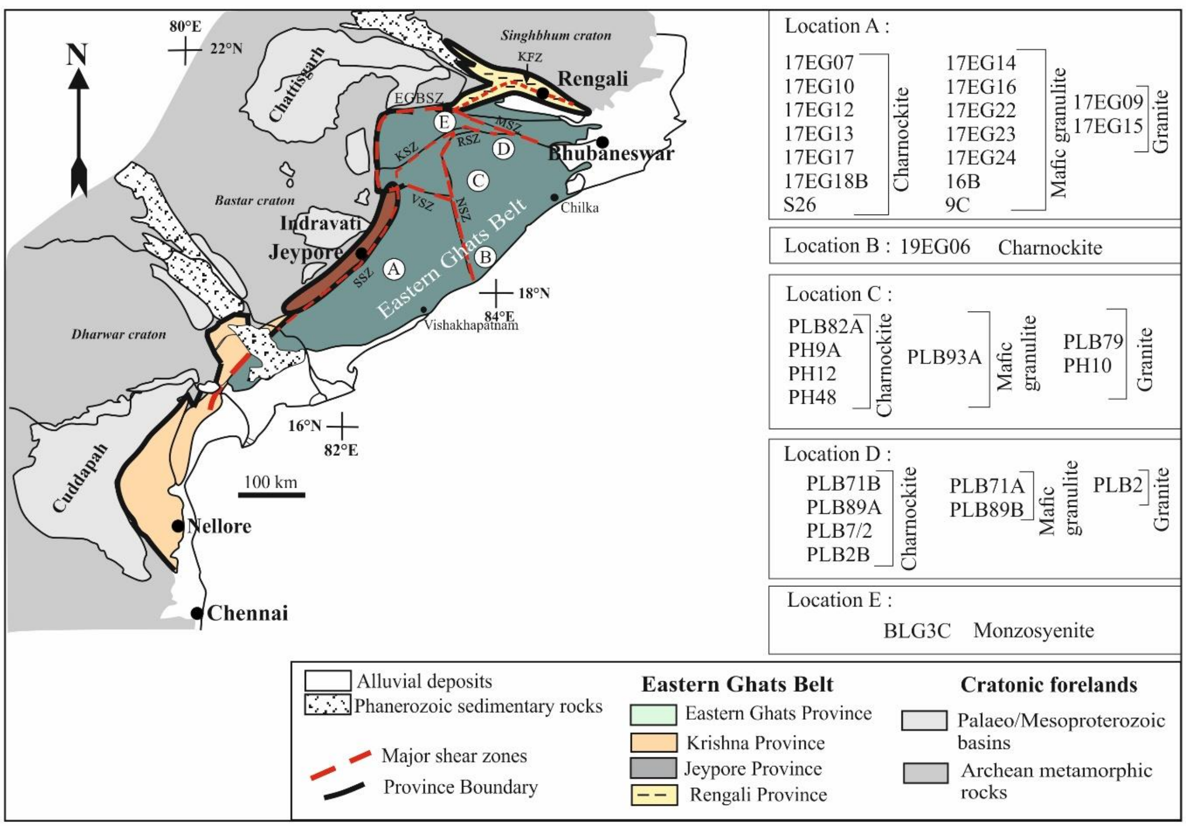

Fig. 2.3 General map of EGB showing sample locations of the study area and the major shear zones are shown as MSZ- Mahanadi Shear Zone, VSZ- Vamsadhara Shear Zone, NSZ- Nagavalli Shear Zone, SSZ- Sileru Shear Zone, KSZ- Koraput-Sonepur Shear Zone, EBSZ- Eastern Ghats Boundary Shear Zone, KFZ- Kerajung Fault Zone.