CHAPTER 1

INTRODUCTION

The continental crust of the juvenile Earth started to form at the Hadean-Paleoarchean era with the onset of tectonic regime (Harrison 2009; Turner et al., 2014; Burnham and Berry, 2017; Hastie et al., 2023) which has changed dramatically afterwards in a secular fashion (Foley, 2018; Cawood et al., 2018; Hawkesworth and Brown, 2018). Studies have indicated that owing to the higher mantle temperature of the early Earth, subducted slabs would exhibit reduced strength to make them prone to detachment and sinking into the mantle (Moyen and Van Hunen, 2012). As a consequence to this, sporadic episodes of subduction would be expected in a stagnant lid type tectonic regime. The reduced viscosity of the Hadean mantle would yield reduced stress within the lithosphere, inhibiting the commencement of subduction. This, in turn, would facilitate intermittent periods of subduction as the mantle gradually cooled (O'Neill et al., 2007; O'Neill and Debaille, 2014). Stability of the continental crust was achieved during the Mesoarchean-Neoarchean era and the state remained relatively undisturbed with fewer seismic discontinuities since then. It is also expected that the Archean continental crust was thinner than the post-Archean counterpart (see however, Hastie et al., 2023). Subsequently, the continental crust was recycled multiple times as evident from rock record and geochemical data. The earliest continents, commonly known as cratons (<3 Ga) were primarily composed of mafic rock types (Kamber et al., 2005; Dhumie et al., 2015; Tang et al., 2016; Greber et al.,2017) although they did contain some felsic components like tonalite-trondhjemite-granodiorite (TTG; Martin and Moyen 2002; Laurent et al., 2019). The mid- to late Archean era appears to represent a distinct temporal interval during which the Earth experienced substantial and enduring transformations (Condie et al., 2016). The transition from Earth's early mafic crust to the stabilization of felsic continents around 3.0-2.0 Ga, suggests a significant chemical differentiation possibly triggered by the onset of some form of mobile lid tectonics (Chowdhury et al., 2017 and reference therein). Additionally, the eclogitic inclusion rather than peridotitic ones within diamonds (Shirey and Richardson, 2011), the occurrence of granulite metamorphism under high-pressure conditions (Brown, 2014), growing percentage of basalts with "arc-like" mantle sources, onset of substantial horizontal plate movements, are also considered as the consequence of modern style plate tectonics (Brown and Johnson, 2018). Almost 60-70 % of the present volume of the bulk continental crust generated by ca. 3.0 Ga confirmed from detrital zircon analysis and the growth was continuous rather than episodic (Cawood et al., 2013). An essential component of the growing continental crust remains the felsic igneous rocks that evolved from a TTG type characters to a strongly peraluminous granite (SPG) type during the Neoarchean era (Spencer et al., 2019). Magmatic charnockite is a component of such felsic magmatic suite which occupies large geographical areas in regional granulite terranes (Frost and Frost, 2008; Rajesh, 2012).

During Proterozoic era a paradigm shift of plate tectonics style took place (Cawood et al., 2009; Brown and Johnson, 2018) which led to rapid crustal growth after ca. 2.0 Ga (Hurley and Rand, 1969). As the mantle had cooled sufficiently, a stable convection cell starts operating which led to formation of island and continental arcs. Magmatic underplating, generally basaltic in composition, produced high -velocity basal layer and thickened crust. Thus, Proterozoic crust has achieved significantly greater thickness (~45 km) as compared to that of the Archean province (~35 km) (Durrheim and Mooney, 1991). Many workers suggest that crust formation was not continuous rather episodic in nature (Condie, 2005; Rino et al., 2004). The repeated collisions of different crustal fragments, magma accumulation beneath the crust, and the terrane-joining process were responsible for the episodic growth patterns which were likely presumably influenced by the cycles of orogeny (Rudnick, 1995; Condie, 1997, 2005; Johnson and Harley, 2012), namely collisional and accretionary. Collisional orogens were either produced by continent-continent collision and closing of open ocean basin (Sui, 2013; Li and Zhao, 2007; Zhao and Zhai, 2013), or by arc-continent collision due to closing of back-arc basin (Bai, 1993; Faure et al, 2004; Brown et al., 2011). Such collisional orogens show asymmetry thermal structure due to one sided subduction producing low T/P metamorphism in the subduction zone and a high T/P metamorphism in the back-arc/orogenic hinterland (Brown, 2006, 2007a, b). Paired metamorphic belts are distinctive features associated with the processes of subduction and plate tectonics (Brown, 2009; 2010b). On the other hand, accretionary mountain belts encompass the amalgamation and joining of juvenile smaller crustal fragments such as ophiolites, island arcs, oceanic plateaus, microcontinents, etc., resulting in the creation of composite sedimentary-magmatic accretionary structures (Condie et al., 2009). While the evidence for collisional orogeny is relatively scarce before ca. 2.0 Ga, it is suggested that accretionary mountain belts might have already been present during the early Archean eon (Condie, 2007). Through repeated occurrences of accretion into supercontinents, these cycles helped cratonic nuclei expand over time, gradually becoming continents (Rogers and

Santosh, 2003). However, the extent to which these processes alter the relative lengths of various types of plate boundaries and the rates of spreading and subduction remains uncertain (Korenaga, 2008; Silver and Behn, 2008). It has been reported that subduction followed by plate amalgamation and dispersal are characterized by metamorphic rocks of the Proterozoic age. Apparently, there are data gaps within the time intervals 2.4-2.0 Ga, 1.5-1.1 Ga and 0.9-0.6 Ga, matching with the periods of supercontinent breakup spanning from Nuna or Columbia (Zhao et al., 2004) to Rodinia (Li et al., 2008), and to Gondwana/Pangea (Ernst et al., 2013). This implies that in the Proterozoic era, collision-related metamorphic rocks with observed thermal gradients ranging from 350-750°C/GPa were conserved due to orogenic processes linked to the formation of supercontinents (Brown, 2008, 2009).

Orogenic belts are characterized by their mobility, high heat flow, metamorphism, magmatism, and deformation, that connect the cratonic blocks (Cawood et al., 2009; Johnson and Harley, 2012 and references therein). Such belts have generally exposed the lower crustal rocks in the form of regional granulite terrane. Rocks of such a granulite terrane provide important information regarding field relations, mineralogy, reaction microstructure, P-T-t paths, compositional variations and patterns of metamorphic style associated with orogenesis which are combined to decipher the tectonic style operated during orogenic events (Brown 2009; 2007a). Especially, the discovery of ultrahigh temperature (UHT) metamorphic rocks and the associated magmatic rocks in granulite terrane from these orogenic belts provide key information in understanding the lower crustal processes and thermal anomaly of the deep crust. Thermomechanical models offer compelling evidence that the UHT metamorphism is indeed feasible within a subduction-accretion system (Sizova et al., 2014; Chowdhury et al., 2017) where the backarc is the prime location for this high thermal anomaly at low to moderate pressure (<10 kbar, Currie and Hyndman, 2006; Hyndman, 2015). Another significant concern in such orogenic cycle is the length of time during which high-temperature conditions persisted. It has been observed in geologic record that both long-lived and short-lived orogenesis were operative (Harley, 2016). Granulite terranes that cooled gradually after undergoing the UHT metamorphism are typically classified within the category of long-lived orogenic belts, with durations > ca. 100 Ma (Clark et al., 2018; Korhonen and Johnson, 2015; Harley, 2016). On the other hand, kinematic modelling demonstrates short-lived orogeny in Proterozoic era where tectono-metamorphic processes within an orogenic cycle responded to polycyclic, pulsed nature with individual cycles typically lasting < ca. 10 Ma (Anczkiewicz et al., 2014; Viete and Lister, 2017; Bhowmik and Chakraborty, 2017). In such cases, textural imprints, petrochronology, P-T data and fluid evolutionary histories are important factor in order to understand how the cooled post granulitic lower crust behave during later metamorphic pulses (Bosse and Villa, 2019).

The Indian continental fragment has preserved several high-temperature metamorphic terranes, namely the Aravalli-Delhi Mobile Belt (ADMB), Central Indian Tectonic Zone (CITZ), Southern Granulite Terrane (SGT), and the Eastern Ghats Belt (EGB). These terranes encircle the ancient continental nuclei, namely the Dharwar, Bastar, and Singhbhum cratons (Fig. 1.1). Among these mobile belts, the SGT, CITZ, and EGB have received significant geological attention due to their excursion to UHT metamorphism in the Proterozoic era. The occurrence of UHT metamorphism in the EGB was documented a few decades back (Lal et al., 1987; Sengupta et al., 1990, 1991, 1999; Dasgupta et al., 1991, 1995, 1997; Bhowmik et al., 1995; Mohan et al., 1997; Bose et al., 2000). The extensively visible terrane of the EGB has a complex history and is understood to signify amalgamation of various distinct crustal provinces and domains (Mezger and Cosca, 1999; Rickers et al., 2001; Dobmeier and Raith, 2003). The evolution of EGB is believed to be linked with parts of the East Antarctica during the assembly of the two Proterozoic supercontinents, namely Columbia and Rodinia (Dasgupta and Sengupta, 2003; Bose et al., 2011; Upadhyay et al., 2009; Dasgupta et al., 2013, 2017; Sarkar et al., 2015; Bose and Dasgupta, 2018). The southern part of EGB suffered UHT metamorphism at ca. 1.6 Ga as part of Mesoproterozoic supercontinent Columbia due to amalgamation of the Dharwar craton of India with the Napier complex of East Antarctica. The central part of EGB is relatively younger in the context of UHT metamorphism and evolved through the amalgamation of Bastar and Singhbhum carton with the continental blocks of East Antarctica through the vastly spread-out accretionary belt, known as the Rayner-Eastern Ghats (R-EG) belt (Morrissey et al., 2015). The latter played a pivotal role in joining the continental blocks in the Indo-Antarctic region within the broader context of the Neoproterozoic supercontinent Rodinia (Dasgupta et al., 2013, 2017; Bose and Dasgupta, 2018). The striking resemblances observed between the Grenvillian age region in the EGB and the Rayner Complex (RC) in Antarctica have led scientists to propose that India and the Antarctic block were part of a unified landmass that evolved together within the supercontinent Rodinia during the Grenville period (Dalziel, 1991; Li et al., 1996; Mezger and Cosca, 1999).

While a substantial amount of geological data has been collected from this region, there are still some unresolved issues, which are outlined below.

1. The principal focus on the geological evolution of the central and the northern parts of the EGB in the last few decades was centered on the characterization of UHT metamorphism and its geographical extent. It is now well-established fact that both central and northern-northwestern part of EGB has suffered UHT metamorphism at ca. 1030-990 Ma (Upadhyay et al., 2009; Bose et al., 2011, 2022; Das et al., 2011, 2021; Dasgupta et al., 2013, 2017; Korhonen et al., 2013; Ganguly et al., 2018). The information about UHT metamorphism is significant indeed, but the evidence of UHT metamorphism is mostly provided by the aluminous granulites which is very sporadic in occurrence in otherwise vastly exposed felsic gneisses of the EGB. The prevalent felsic rocks represented by charnockite and felsic gneiss have not been explored in any detail from this part of the EGB. In granulite terranes, these felsic rocks hold special significance as they play important role in the process of metamorphism. In certain cases, such rocks are considered as potential heat sources for heat that would cause UHT metamorphism (Schorn et al., 2020). On the other hand, charnockite and felsic magmas are reported as result of UHT metamorphism (Rajesh et al., 2014; Klaver et al., 2015). Charnockite magmatism in the EGB occurred in two episodes, viz. ca. 1700-1600 Ma (as noted by Bose et al., 2011, and Sarkar et al., 2015), and ca. 1000-950 Ma (Grew and Manton, 1986, Aftalion et al., 1988; Paul et al., 1990; Shaw et al., 1997; Krause et al., 2001). Apart from their emplacement ages, no detailed information about the petrological and geochemical evolution of such rocks is known, particularly the younger (ca. 1000-950 Ma) charnockite. This is a serious gap in information given that charnockite forms a large geographic area of the central and northern EGB. The question still lingers about whether these rocks have undergone metamorphism. If they have, what is the highest pressure-temperature (P-T) condition recorded in these rocks, and whether they have experienced UHT metamorphism, remains uncertain.

2. Magmatic charnockites are commonly present in many regional granulite terranes, with notable examples being the Mawson charnockite of Rayner Province in East Antarctica (Young et al., 1997; Halpin et al., 2012) and unclassified charnockites in Peninsular India (Tomson et al., 2006, 2013; Rajesh, 2012; Gao et al., 2021). Rajesh (2012) carried out a

study on magmatic charnockites from two Proterozoic terranes of Peninsular India, specifically the Southern Granulite Terrain and the EGB. He attributed the formation of charnockite to arc accretion processes occurring during significant orogenic events. It is worth noting that charnockite of a similar kind, as reported in the Mawson area of the Rayner Province, exhibit three separate instances of magmatic crystallization: ca. 1145−1140 Ma, ca. 1080−1050 Ma and 985−960 Ma (Halpin et al., 2012). If the origin of the charnockite magma is identical, it raises the question of why the EGB exhibits a singular history of emplacement concerning Grenvillian age tectonics. A more detailed sampling and robust geochronological study is required to resolve this issue.

3. While numerous geochemical investigations have been conducted in the Mawson area (Zhao et al., 1997; Young et al., 1997), there is a notable absence of corresponding data from the EGB. To gain a comprehensive understanding of the tectonic history of the terrane during the time when India and East Antarctica shared geological events, it is essential to carry out thorough and systematic geochemical studies along with meaningful correlation. The intimate association of granite and charnockite raises question about whether they are product of different suite of magma or are the product of same felsic magma under contrasting fluid regimes (Harlov et al., 2013). Therefore, a detailed investigation of these rocks, including their precise field relationships, texture, and fluid characteristics, is essential to gain a clear understanding of the process operating in an orogenic lower crust.

4. An ongoing debate regarding the EGB revolves around whether it underwent an extended cooling phase of ca.180 Ma post UHT metamorphism (Korhonen et al., 2013b) which supports the concept of a long-lasting orogenic cycle. This idea has recently been challenged, with arguments favoring two distinct cooling events occurring around ca. 1030−970 Ma and ca. 950−900 Ma (Bose et al., 2022). In such a scenario, the geochronological history (both magmatic and metamorphic) of the felsic magmatic rocks, including both charnockite and granites, become significant since they evolved in a close temporal proximity to UHT metamorphism of the EGB.

5. While extensive research has been conducted on the indications and features of fluid-rock interactions in regional-scale granulite terranes like the Bamble Sector in Norway, Shevaroy Hills Massif, South India, the fluid evolution history of the EGB remains less comprehensively documented, with only a few isolated areas having been studied in this context (as noted in Mohan et al., 1997; Sarkar et al., 2003a; Bose et al., 2009, 2016, Ganguly et al 2017; Das et al., 2021). All of these investigations indicate that a dense CO_2 fluid with a high density exceeding 1.0 gm/cm^3 played a key role in dehydrating the lower crust and sustaining elevated temperature conditions. Additionally, the significant fluorine content in fluor-biotite (>3 wt.%; Bose et al., 2005; Ganguly et al., 2017) and fluor-wagnerite (> 6 wt.% F, Das et al., 2017) within mineral assemblages suggests a potential presence of halogen-rich fluids during both the peak and retrograde metamorphic phases. However, none of the fluid inclusion reports presence of brine, possibly due to their wetting behaviour with mineral phases (Touret, 1985; Watson and Brenan, 1987; Manning and Aranovich, 2014). In such instances, the presence of oxide-sulphide-silicate mineral associations along with metamorphic history can aid in clarifying how fluids contributed to oxidizing and/or reducing extensive portions of the lower crust during granulite facies metamorphism. Mafic granulite possesses a composite composition that enables the coexistence of oxide, sulphide, and silicate minerals for a significant portion of its evolutionary timeline. Such mafic granulites are sporadically present in charnockite, felsic gneiss and pelitic gneiss and these rocks can offer a better explanation of fluid-rock interaction at deep crustal level. Furthermore, minor components such as sulphates can offer further insights into solid-fluid interactions, particularly in the latter stages of its evolution.

6. Existing scientific literature suggests a robust association between the EGB and the Rayner Province in East Antarctica, primarily relying on metamorphic and geochronological data from a segment of the EGB. Although data from the Rayner Complex is abundant, it is crucial to assess this proposed correlation with fresh geological insights derived from the broader EGB area.

Objective of the present study

Taking into account all the issues described above, a large area has been selected for the present study including the central to northern-northwestern part known as Eastern Ghats Province (EGP; after Dobmeier and Raith, 2003). Except some sporadic age and geochemical data of felsic and mafic granulites (Grew and Manton, 1986; Aftalion et al., 1988; Paul et al., 1990; Shaw et al., 1997; Sengupta et al., 1996; Krause et al., 2001; Ganguly, 2018) no detailed geological investigation has been carried out on these rocks. A comprehensive study of such rocks is expected to furnish crucial insights into the metamorphic and tectonic history of the EGP, particularly during the period when the combined India and East Antarctica shared a common geological history.

The main objective are as follows:

1. To unravel the tectonometamorphic and geochronological history of the orthogneissic rocks of the EGP. This will help to identify the crustal growth history of the EGP.
2. To understand the juxtaposition of the EGP with the cratonic parts of India along the NW margin and the effect of hot orogeny on the colder cratonic lithosphere.
3. To understand the behavior of deep crustal fluid during metamorphism on a regional and local scale. This will help in evaluating the effect of fluid on the stability of datable minerals (monazite, zircon).
4. To understand the geochemical evolution and paleotectonic settings of the orthogneisses (especially charnockite and mafic granulite), so that a model could be proposed and a proper correlation with its Antarctic counterpart could be made.