# CHAPTER 1

# INTRODUCTION

It is generally agreed upon that the Earth's continental crust started evolving since the later part of the Hadean time (Burnham and Berry, 2017 and references therein). This crust formation process was slow in the early Earth, but became more rapid after ca. 2 Ga (Hurley and Rand, 1969). There are contrasting hypotheses regarding the rapidity of crustal growth in the Precambrian time (Reymer and Schubert, 1984). According to the most accepted model, continental growth was episodic in nature rather than being continuous (Taylor and McLennan, 1985; Condie, 2005). These episodic growth processes are manifestations of repeated collision of discrete crustal fragments, magma underplating and terrane accretion presumably triggered by orogenic cycles (Nelson, 1991; Rudnick, 1995; Condie, 1997, 2005; Johnson and Harley, 2012). These cycles eventually grew cratonic nuclei into continents through multiple episodes of accretion into supercontinents (Rogers and Santosh, 2003). In geological records, the cratonic blocks are found to be welded together by orogenic belts that are the areas of high heat flow, metamorphism, magmatism and deformation (Cawood et al., 2009; Johnson and Harley, 2012 and references therein). Physical and chemical processes in such orogenic belts are complex and varied yet challenging in order to trace back the evolution of continental crust. The high-grade rocks of these belts are particularly important as they provide direct evidences of orogenic processes.

It is now accepted that in majority of the cases, orogenic processes were controlled by plate tectonics (Condie, 2015 and references therein). This opened up an important debate regarding the timing of initiation of plate tectonics on Earth. While some workers believe that plate tectonics was initiated at the Archean-Proterozoic boundary (Stern, 2005), new evidences suggest that the process could have initiated as early as ca. 3.5 Ga (Greber et al., 2017). This has got significant bearing on the crustal evolution process and the nature of Archean-age orogenic belts (Bose et al., 2016a and references therein). Unfortunately, much of the Archean orogenies still remain unknown due to fragmentary rock records. The records are much clearer in the orogenic belts formed during the Proterozoic time when a paradigm shift of plate tectonic style took place (Cawood et al., 2009; Brown and Johnson, 2018). Some of the well-known orogenic belts now spread across the different continents grew and evolved during this protracted time (ca. 2000-500 Ma) and their unique styles, pressure (P) – temperature (T) – time (t) histories lead to the hypothesis of supercontinent cycles (Murphy and Nance, 1989; Moores, 1991; Dalziel, 1991; Rogers and Santosh, 2003). The configurations of the supercontinents Gondwana, Rodinia and Columbia found major supports from numerous evidences from the orogenic belts which are thought to have connected different continents in specific time frames of the Proterozoic era.

Orogenic belts expose lower crustal rocks which are presently disposed as regional granulite terranes. These rocks provide suitable clues in terms of reaction textures, *P*-*T*-*t* paths and its geometries which are integrated to unravel the tectonic pulses operative in different orogenic events (Harley, 1989). The understanding of lower crustal processes received a major impetus in recent time with the discovery of ultrahigh temperature (UHT) metamorphic rocks from different orogenic belts (Harley, 2008; Kelsey and Hand, 2015). Once considered as an exclusive class of rocks, UHT metamorphic rocks are now reported worldwide implying widespread thermal anomaly in the deep crust. Two specific tectonic settings are invoked to explain this thermal anomaly. The most acceptable tectonic scenario for low- to moderate pressure (<10 kbar) UHT rock is the heat flow in the backarc basin in a subduction-accretion setting (Currie and Hyndman, 2006; Hyndman, 2015). On the other hand, abundance of high heat producing elements in continental plateau region characterized by thickened crust can also produce UHT metamorphism in deep crust (Clark et al, 2015). Recent thermomechanical models provide crucial evidence that UHT metamorphism can actually take place in a subduction-accretion system (Chowdhury et al., 2017). These evidences lent credence to the tectonic models envisaged for UHT metamorphism. Another important issue for high-temperature granulites (including the UHT rocks) is the duration of high thermal condition at the lower crust. In a review, Harley (2016) demonstrated how time-temperatures histories can vary for granulite-UHT terranes (Fig. 1.1). There are reports of UHT metamorphism where thermal anomaly is interpreted to have persisted over 100 m.y. (Clark et al., 2018) while kinematic modeling shows very short-lived orogeny in the tune of 10 m.y. is also possible in Proterozoic time (Bhowmik and Chakraborty, 2017). In either case, the tectonic significance of the time-temperature evolution is profound considering the thermal and rheological behavior of the lower crust. The significance of time with respect to metamorphism in any orogenic belt is thus of prime importance. It also provides the most crucial tool to correlate orogenic events in erstwhile members of any supercontinent. Interestingly, it is suggested that the initiation of major supercontinent cycles coincides with high-T (including UHT) metamorphism (Fig. 1.2).

Zircon U-Pb geochronology is considered as the most robust tool to decipher the timing of key thermal events in granulite facies terranes, particularly those underwent UHT conditions. Zircon, being a versatile mineral, can grow in different stages of an orogenic system and thus provides timing of pre-, syn- and even post-metamorphic events (Fig. 1.3). High-resolution ion microprobe analysis can retrieve age information from different internal domains of single zircon crystal that undergoes multiple cycles of growth (Krogh, 1993; Bowring and Williams, 1999; Kelly et al., 2002; Hokada et al., 2004). Such cycles have been deciphered from zircon age domains in many ancient orogenic belts (Black et al., 1986; Möller et al., 2003; Hokada et al., 2004). Monazite electron microprobe chemical dating is a complementary tool for characterizing rocks with complex thermal histories as it gives better textural controls for in-situ analysis (Kelsey et al., 2007; Simmat and Raith, 2008, Bhowmik et al., 2014 and references therein). Slow diffusion rate of Pb (Cherniak at al., 2004) and negligible amount of common Pb in monazite (Parrish, 1990) make monazite chemical age quite reliable. If used in tandem with zircon U-Pb dating, monazite chronology may also constrain the timing of UHT metamorphism (e.g. Bose et al., 2011, 2016b). However, the growth processes of zircon and monazite in metamorphic systems are varied depending on several key factors (Kelsey et al., 2008; Taylor et al., 2016 and references therein). Monazite and zircon can exhibit similar metamorphic ages (Hermann and Rubatto, 2003), but there are reports where monazite ages both predated (Johnson et al., 2015) and postdated (Clark et al., 2014; Harley and Nandakumar, 2014) the peak metamorphism recorded by zircon ages. Taylor et al. (2016) discussed the issue of complex growth histories of these two important accessory minerals in the same metamorphic system and offered some solutions to interpret ages from such rocks. Given the uncertainties of the different isotopic and chemical systems, Precambrian orogenic belts are now better understood in geologic time frames. In-situ analysis of REE chemistry of zircon equilibrating with garnet (Taylor et al., 2016), Ti concentration of different age domains of zircon (Ewing et al., 2013) are some of the modern approaches to relate textures with ages in complex metamorphic rocks.

Apart from P and T, fluid is the other important variable to bring about significant changes in the lower crust. Granulite facies metamorphism is generally considered to be fluid-deficient (Harley, 1989), but, if present, fluid is either internally buffered by mineral equilibria or externally fluxed (cf. Newton et al., 1980). The compositions of the fluids are generally constrained to the C–O–H system, but recent natural and experimental data indicate the presence of halogen-rich brine (Markl and Piazolo, 1998; Tsunogae et al., 2003; Tropper et al., 2013). Fluid can be responsible for large-scale mass movement, partial melting and differentiation of crust (Harlov and Austrheim, 2013). It can partially or completely reset the isotopic signatures in very robust minerals like zircon (Geisler et al., 2007). Oxidizing fluids can play a significant role in imposing mineralogical and textural variations which can be monitored by Fe–Ti–Al-bearing oxide minerals like magnetite, hematite, ilmenite, spinel, corundum, and rutile (Frost et al., 1988; Lindsley et al., 1990; Ghiorso and Sack, 1991; Andersen et al., 1993; Harlov, 1992; Bose et al., 2009).

The Indian continental fragment preserves some of the high-T metamorphic terranes including the Aravalli Fold Belt (AFB), Central Indian Tectonic Zone (CITZ), Southern Granulite Terrane (SGT) and the Eastern Ghats Belt (EGB) which flank the oldest continental nuclei namely the Dharwar, Bastar and Singbhum cratons. Of these mobile belts, the SGT, CITZ and the EGB have gained much attention because these were affected by UHT metamorphism during the Proterozoic era. Although the UHT metamorphism in SGT (Sajeev et al., 2001; Tateishi et al., 2004; Tsunogae and Santosh, 2006, 2010, 2011; Braun et al., 2007; Prakash et al., 2007; Sato and Santosh, 2007; Tadokoro et al., 2007; Kondou et al., 2009; Santosh et al., 2009; Shimizu et al., 2009; Brandt et al., 2011; Shazia et al., 2012) and CITZ (Bhowmik et al., 2005; Bhowmik, 2006; Bhandari et al., 2011; Bhowmik et al., 2014) are relatively recent discoveries, the UHT metamorphism in EGB was reported long back (Lal et al., 1987, Kamineni and Rao, 1988; 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 vastly exposed terrane of the EGB has a complex history and interpreted to represent an amalgam of several discrete crustal provinces and domains (Dobmeier and Raith, 2003). Formation and evolution of this latter terrane is interpreted to be linked to the portions of the East Antarctica during the formation of the two Proterozoic supercontinents namely the Columbia and the Rodinia (Dasgupta and Sengupta, 2003; Bose et al., 2011; Upadhyay et al., 2009; Dasgupta et al., 2013; S. Dasgupta et al., 2017; Sarkar et al., 2015; Bose and Dasgupta, 2018). The southern part of this thousand kilometer long belt witnessed UHT metamorphism at ca. 1.6 Ga during amalgamation of the Dharwar craton of India with the Napier complex of east Antarctica to be a part of the Mesoproterozoic supercontinent Columbia. However, the UHT metamorphism at the central part of this belt is relatively younger in age and evolved due to accretion of the Bastar craton of India and the cratonic blocks of east Antarctica (Ruker Province) at ca. 1000–900 Ma. This accretionary mobile belt, recently named as the Rayner-Eastern Ghats (R-EG) belt (Morrissey et al., 2015) holds the key to the proposed Indo-Antarctic correlation in the larger framework of the Neoproterozoic supercontinent Rodinia (Dasgupta et al., 2013; S. Dasgupta et al., 2017; Bose and Dasgupta, 2018).

Although considerable amount of geological information is available from this belt, there are some issues which remain unresolved. These are elucidated below.

(1) Considering the vast expanse of the terrane, UHT metamorphism has been documented from few localities of the EGB. These include Araku-Panirangini (Sengupta et al., 1991; Das et al., 2011), Anantagiri (Sengupta et al., 1990; Korhonen et al., 2013a, b), Raygada (Shaw and Arima, 1998), Paderu (lal et al., 1987; Pal and Bose, 1997), Vizianagram (Sarkar et al., 2003a, b), Sunkarametta-Loteru (Bose et al., 2000, 2006), Chilka lake (Sen et al., 1995; Raith et al., 2007; Sengupta et al., 2008; Bose et al., 2016b) and Kondapalle (Sengupta et al., 1999; Sarkar and Schenk, 2014). It remains to be tested whether the

UHT metamorphism in EGB is highly localized, or there are more such occurrences in hitherto uncharacterized localities in EGB. The tectonic implications for these two extreme cases are highly contrasting.

(2) The already established metamorphic history of the EGB have been correlated with geochronological data (Bose et al., 2011; Das et al., 2011; Korhonen et al., 2013b), but the deformation history of the terrane have rarely been correlated with metamorphic vis-à-vis age data (see however, Dobmeier and Simmat, 2002; Das et al., 2011; Saha and Karmakar, 2015). The structural architecture of the megascopic shear zones in EGB has not been checked in many instances by field data (see however, Gupta et al., 2000; Biswal et al., 2007) although some of these are interpreted as terrane boundaries (Chetty et al., 2003). It remains to be checked whether these shear zones are locales of fluid and mass transfer.

(3) While the imprints and characters of fluid rock interaction in regional-scale have been rigorously studied from other granulite terranes (e.g the Bamble Sector, Norway), the fluid evolution history of EGB is not well-documented excepting some isolated areas (Mohan et al., 1997; Sarkar et al., 2003a; Bose et al., 2009, 2016b). Recent literature shows that different fluid species have significant control over high temperature metamorphism of lower crust (Touret and Huizenga, 2011). To address this issue, a comprehensive pressure-temperature-time-deformation-fluid (*P-T-t-D-f*) history of a part of the EGB is required and the northern part of this belt appears to be the most suitable for such type of investigation.

(4) Granulite facies rocks of the EGB are associated with magmatic rocks of mafic, ultramafic, anorthositic, alkaline, charnockitic and granitic compositions in different

localities. Except very few work on mafic-ultramafic, alkaline and anorthositic rocks (reviewed in Dobmeier and Raith, 2003) there is practically no petrological and geochemical data on the origin and evolution of the charnockite and granitic rocks. These latter rocks can provide important information regarding the coupling of lower crust and mantle during orogenic events. Apart from meagre amount of geochronological data (Paul et al., 1990; Aftalion et al., 1988), little is known about these rocks from the EGB.

(5) The domain-based subdivision of the EGB necessitates discrete evolutionary histories for each domain. As metamorphic and geochronological data are available from some of the domains, it is important to check whether these domains are really discrete in character. At the same time, the interpreted domain boundaries which are presently identified as megascopic shear zones need to be looked at.

(6) Published literature envisages that the EGB has a strong correlation with the Rayner Complex of East Antarctica which is based on metamorphic and geochronological records from a part of the EGB. While the records from the Rayner Complex are abundant, the proposed correlation needs to be evaluated from new geological information from the larger part of the EGB.

## Objectives of the present study

Considering all these aspects mentioned above, an area within the Phulbani domain of the EGB was selected for the present study. The Phulbani domain is flanked by two crustal-scale shear zones namely the Nagavalli-Vamsadhara shear zone (NVSZ) at the west and the Ranipathar shear zone (RSZ) at the north. Dobmeier and Raith (2003) suggested that this domain acted as an indentor-like protrusion of internal portions of the Eastern Ghats orogeny. Except from some sporadic geochronological data from charnockite and khondalite (Paul et al., 1990; Simmat and Raith, 2008; Upadhyay et al., 2009) and some unpublished geological reports of the Geological Survey of India, detailed metamorphic, structural and fluid data are absent from this domain. This created difficulties to correlate its tectonometamorphic evolution with the neighboring domains.

The main objectives of the present study are:

1. To understand the metamorphic history of the rocks of the Phulbani domain on the basis of petrological investigation.
2. To unravel the structural evolution in order to characterize the deformation phases that affected the Phulbani domain.
3. To build a geochronological evolutionary history of the Phulbani domain for constraining the timing of the metamorphic events.
4. To reveal the fluid evolution of the rocks belong to the Phulbani domain and correlate it with the metamorphism.
5. To propose a possible tectonic model for the evolution of the Phulbani domain.
6. To correlate the tectonometamorphic evolution of the Phulbani domain with the evolutionary histories of the neighboring domains.
7. To understand the role of the Phulbani domain during the Precambrian supercontinent cycle.