CHAPTER–1

INTRODUCTION

1.1 General

Geologists have a keen interest in understanding the processes and conditions that operate at considerable depths in the continental crust. Lower crustal rocks are generally found in two forms: exposed deep crustal metamorphic rocks and xenoliths. Xenoliths are less significant due to their smaller size while exposed deep crustal rocks play a crucial role in understanding the Earth's geological processes, tectonic history, and the composition of the deep continental crust (Rudnick et al. 1995). Granulites are high- grade metamorphic rocks that form at depths of around 20-30 km in the Earth's crust (Harley, 1989). They offer valuable information about the processes and conditions of the continental crust. By studying them, researchers can infer details about past tectonic events and understand the processes driving plate tectonics and mountain-building **(**Harley, 1989, Wang et al., 2019**).** Amphibolites have been a subject of much debate in metamorphic petrology. They are believed to be derived from igneous rocks, representing fragments of older oceanic crust (Turner, 1948). The study of these rocks allows geologists to understand the processes and conditions under which they were formed and provides insights into the metamorphic evolution of a particular region (Eleuza, 1985). These rocks can form in various tectonic settings, such as mid-oceanic ridges, island arcs and subduction zones providing valuable information about past plate tectonics and crustal dynamics (Honkamo, 1987). Throughout Earth's history spanning approximately 3.5 billion years, there have been periodic formations and disintegrations of supercontinents due to tectonic processes (Nance et al., 2014). These events of "making and unmaking" supercontinents had a significant impact on the evolution of the lithosphere, atmosphere and hydrosphere and have provided a suitable environment for the evolution of life on Earth (Hannisdal and Peters, 2011; Hoffman and Schrag, 2002; Santosh, 2010). The study of this "supercontinent cycle" is essential to understanding the dynamic processes of the earth (Condie, 2003, 2015; Evans, 2003). In the Precambrian era, Earth's history records the joining and breakup of three major supercontinents i.e Columbia, Rodinia, and Gondwana (Zhao et al., 2002, 2004, 2011; Meert and Santosh, 2017; Dalziel et al. 2000) (Fig.1.1). The configuration and position of these supercontinents have been the subjects of intense debate among geologists. Palaeomagnetic data have limited utility in reconstructing these early supercontinents due to scattered palaeomagnetic poles and poorly constrained ages (Hou et al., 2008). Evidence for the configuration of these supercontinents primarily comes from the correlation of the collisional orogens within and between the cratonic blocks based on precise geochronological dating and petrological characterization of the orogens (Condie, 2002).

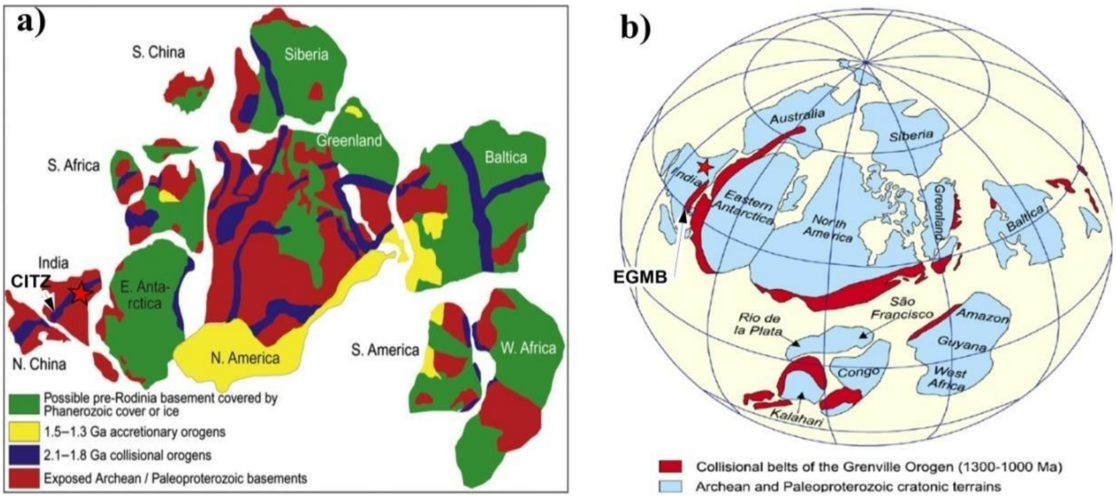

Figure 1.1 (a) the arrangement of the worldwide collisional zones spanning 2.0-1.8 billion years and accretionary belts formed between 1.8-1.3 Ga is shown on a configuration of the Columbia supercontinent (Zhao et al., 2002). (b) Rodinia supercontinent reconstruction around 1000 Ma (modified after Dalziel et al.,2000). The spot of the Chhotanagpur granite gneiss complex within India is shown by a red star. Proterozoic orogenic belts of the Indian subcontinent are marked by a black arrow- Central Indian Tectonic Zone (CITZ) and Eastern Ghats Mobile Belt (EGMB).

The Precambrian history of the Indian subcontinent records nearly three billion years of crustal evolution, with multiple events of amalgamation and extension shaping its current shape and configuration (Meert et al., 2010). The accretion of different crustal fragments (cratons and mobile belts) mostly occurred during the Proterozoic period when the supercontinents: Columbia (~2100-1600Ma), Rodinia (~1100-900Ma), and Gondwanaland (~ 550-530 Ma) formed (Fig. 1.1, Bhowmik et al., 2014, 2012; Brandt et al., 2014). The effects of the first two orogenies are prominent along the central part and eastern margin of the present-day Indian cratonic blocks with the Eastern Ghats Mobile Belt forming through the amalgamation of Indian cratonic blocks with East Antarctica and Australia (Fig. 1.1, Dasgupta et al., 2013). The Central Indian Tectonic Zone (CITZ) acted as a connecting link that brought together the northern and southern Indian cratonic blocks, ultimately leading to the expansive landmass known as the Greater Indian Landmass (Yedekar et al., 1990; Roy and Prasad, 2003; Bhowmik et al., 2012). However,there is ongoing debate and contrasting theories about the configuration of the Rodinia supercontinent, and the involvement of the Indian subcontinent in it. Some researchers suggest that the Indian Shield was attached to the Rodinia supercontinent as a coherent block, sharing its boundary with East Antarctica along the Eastern Ghats belts (Moores, 1991; Hoffman, 1991; Dalziel, 1991). Others propose that India was never a part of Rodinia and evolved as a separate landmass composed of several micro-continents, which amalgamated much later (Powell and Pisarevsky, 2002).

The geological features of the Indian landmass were shaped by tectonic activity during the formation of four supercontinents at different times: Kenorland, Columbia, Rodinia, and Gondwana (Rogers and Santosh, 2002; Dwivedi et al., 2020).

The Archaean, spanning from 3.5 to 2.5 Ga, witnessed significant development, mechanisms, and evolution of continental crust before 2.5 Ga (Guitreau et al., 2014). The Archean cratons, containing diverse igneous and metamorphic rocks with records of crustal evolution, magmatic intrusions, and tectonic indicators, are crucial for understanding the early history of the earth (Pearce, 2014). These cratons consist of superacrustal rocks forming the basis for micro-continental, continental, and super-continental evolution and stabilization (Naqvi, 2005; Condie, 2015). Indian subcontinent comprised two significant Archean Cratons: northern Indian cratons (Bundelkhand and Aravalli) and southern Indian cratons (Bastar, Singhbhum and Dharwar) (Ramakrishnan and Vaidyanadhan, 2010). The collision of these two cratonic blocks occurred during the Paleo-Mesoproterozoic subduction-accretion process, and they were amalgamated along the Central Indian Tectonic Zone (CITZ) (Naganjaneyulu & Santosh, 2010). However, the exact direction of subduction and the timing of collision between the North Indian cratons and the South Indian cratons remain uncertain. Recently, Deshmukh et al. (2020) have presented a series of events in their research. Initially, there was a process of southward subduction of the North Indian cratonic block, followed by the detachment of a slab beneath the South Indian cratons between 1.75 to 1.55 billion years ago. Subsequently, a reversal in subduction polarity occurred during the Meso-Neoproterozoic era, leading to the sousor orogeny and the eventual amalgamation of geological features. The region known as the Central Indian Tectonic Zone (CITZ) is situated between the Son Narmada North Fault to the north and the Central Indian Shear (CIS) zone to the south (Yedekar, 1990). This CITZ is divided into three segments: the northern Mahakoshal Mobile Belt (MMB) spanning 2.4 to 1.7 billion years, the Central Betul Supracrustal Belt occurring around 1.5 billion years ago, and the southern Sausar Mobile Belt (SMB) ranging from 1.4 to 0.9 billion years (Roy et al., 2003). Within these supracrustal rock formations of theCITZ, four prominent granulite belts can be identified. These include the Balaghat– Bhandara and Ramakona–Katangi Granulite Belt situated within the Sausar Series, the Chhatuabhavna Granulites within the Bilaspur–Raigarh Belt and the Makrohar Granulite Belt located in the northwestern portion of the Chhotanagpur Granite Gneiss Complex (CGGC) (Acharya and Roy, 2000) (Figure 2).

To know the Chhotanagpur Granite gneissic complex contribution to worldwide Proterozoic mountain-building processes, a thorough examination of the geological and chronological features is essential that influenced its development (Karmakar et al., 2011). The CGGC is a poly-metamorphic and poly-deformed high-grade terrane, and rocks that occur as enclaves within the host granitic gneiss can provide the early techno- metamorphic history of the region. The research on CGGC can help address the questions about the configuration of supercontinents and their role in the amalgamation with East Antarctica. Therefore, conducting a comprehensive investigation of various lithologies within a polymetamorphic terrane allows for the documentation of different aspects of the intricate metamorphic evolution experienced by that specific terrane, considering factors such as pressure, temperature, and fluid composition. By integrating these distinct sets of metamorphic data and supplementing them with reliable geochronological information, a comprehensive understanding of the terrane evolution can be achieved. In this thesis, the petrological observations obtained from multiple lithologies, including pelitic, mafic, and calc-granulite are compared, and correlated with robust geochronological evidence to reconstruct a coherent petro-tectonic history of the Chhotanagpur Granite gneiss complex. The outcomes of this study are then utilized to gain insights into the crustal evolution of the Indian shield and its involvement in the configuration of Proterozoic supercontinents.

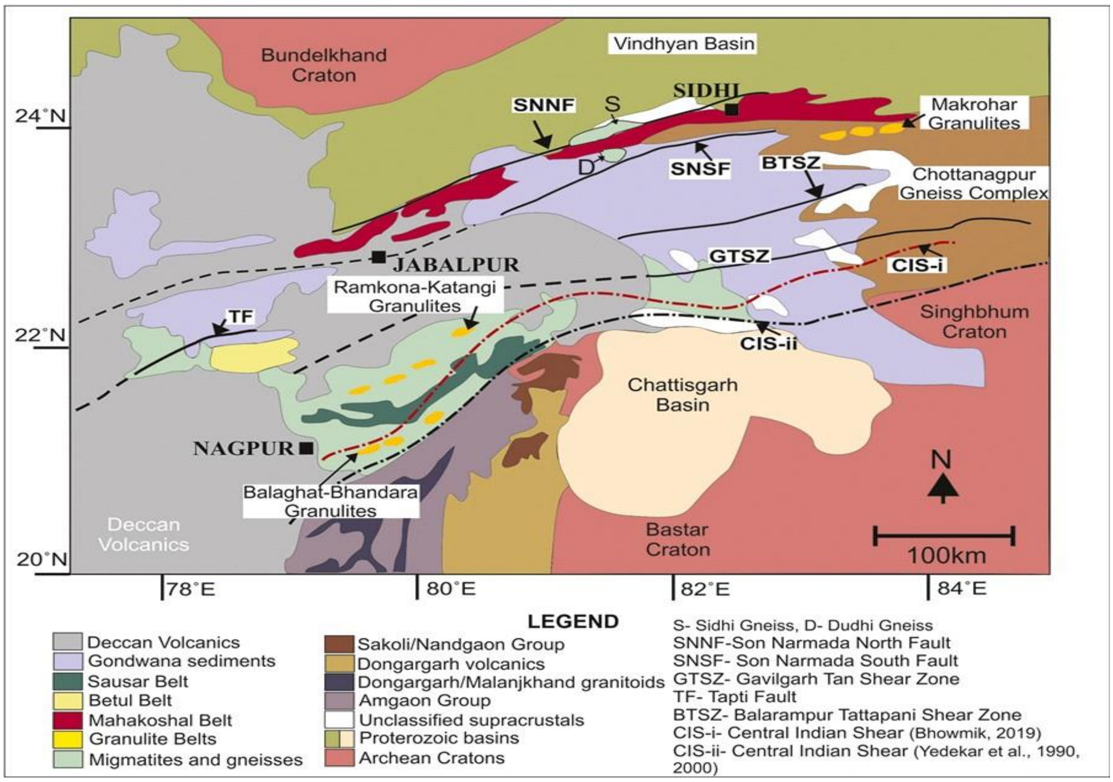

Figure1.2 Geological map of the Central Indian Tectonic Zone (CITZ) (modified after Deshmukh *et al.* 2020) illustrates the arrangement of distinct lithological regions within the folded belt.

1.2 Scope of the Investigation

Granulites have emerged as valuable sources of information about the deeper crust of the earth and contribute significantly to our understanding of deep crustal processes. This study focused on important aspects related to the formation and metamorphic evolution of amphibolite to granulite facies rocks. Detailed investigations were carried out using various techniques such as petrography, mineral chemistry, geothermobarometry, geochemistry, geochronology, and bulk composition modelling for the rock samples from the Makrohar area of the Chhotanagpur granite gneiss complex (CGGC) (Fig. 1.2). The study areas predominantly exhibit amphibolite to granulite facies rocks including amphibolites, garnet-bearing gneisses, mafic granulites, pelitic granulites and calc-silicate granulites. These rocks display a wide range of mineral paragenesis and chemical compositions. The rock types found in the study area include pelitic granulites (comprising garnet, biotite, cordierite, sillimanite, plagioclase, K-feldspar ilmenite), amphibolites (comprising garnet, amphibole, plagioclase, clinopyroxene, biotite, quartz and ilmenite), calc-silicate granulites (comprising clinopyroxene, garnet, plagioclase, sphene, clinozoisite and plagioclase), mafic granulites (comprising orthopyroxene, clinopyroxene, amphibole, biotite, plagioclase and ilmenite) and garnet-bearing gneisses (comprising garnet, amphibole, plagioclase, clinopyroxene, biotite, quartz and ilmenite). To understand the mineral chemistry, element distribution, and phase compatibility relationships coexisting minerals were analyzed using electron microscopy. Geothermobarometric models were then utilized to deduce the metamorphic conditions based on the data from coexisting minerals. The study also investigated element partitioning behaviour to calibrate thermodynamic models for accurate estimation of metamorphic conditions. The partitioning of elements in coexisting phases is influenced by pressure, temperature, and composition. P-T pseudosections were employed to constrain the metamorphic history of mafic granulites, pelitic granulites, garnet-bearing gneisses, garnet-bearing amphibolites and calc-silicate granulites. The Perple_X v.6.8.2 software with an internally consistent dataset (Holland and Powell, 2011) was used to calculate significant pseudo sections representing various mineral equilibria, helping derive the P-T path. The P-T-t paths depict the metamorphic evolution of these rocks in P-T space over time, revealing information about heat sources, tectonic transport rates, local structural settings and tectonic processes. Such paths are crucial in developing geodynamic models for crustal evolution in the study area. Analysing the major, trace, and rare earth elements of metapelites and metabasics offers insights into them depositional and tectonic environments as well as the nature of their protoliths before undergoing metamorphism.The exposed metamorphic terrains provide essential information about magmatic processes in the lower crust. Rare-earth elements play a promising role in determining the origin of metasomatized and metamorphic rocks in the higher amphibolite facies of regional metamorphism, shedding light on the role of anataxis in the evolution of the lower continental crust.

1.3 Methodology

The author has carried out fieldwork in and around the present study area for the collection of rock samples using Survey of India Toposheets No. 64I/9 and 64I/13 at a 1:50,000 scale during August 2018, February 2020, and July 2021. All the gathered field data and information were plotted on the map. The study area around Makrohar was covered by Toposheet No. 64I/9, while the surrounding region around the study area was covered by Toposheet No. 64I/13. During fields, more than 120 representative samples were collected from various rock outcrops using a Global Positioning System (GPS) instrument (Garmin GPS MAP 78s) to record the sample location (latitude and longitude). In addition, a Brunton compass was employed to measure other relevant structural aspects. For petrographic analysis, more than 100 thin sections of different rock types were prepared and examined using the Leica petrological microscope (LEICA DM 2500 P) in the engineering geoscience lab, Department of Civil Engineering. The study focused on investigating mineral textural relationships and the timing of crystallization and deformation. The mineral content and textural analysis of granulite rocks were studied petrographically to know about the nature and environment in which the rock was created. Microphotographs were taken to interpret different forms of texture, coronas, and symplectic intergrowths. These microscopic studies provided valuable information about the composition of rocks such as calc-granulites, pelitic granulites, mafic granulites, amphibolites and garnet-bearing gneiss as well as the signatures of prograde and retrograde metamorphic mineral assemblages. Based on detailed microscopic investigations, representative thin slides were selected for EPMA (electron microprobe analysis). The EPMA analysis was conducted at the Department of Geology, BHU (Varanasi), India, using the CAMECA SX five-electron microprobe. This analysis helped in determining the mineral chemistry of various silicate minerals, as well as providing back-scattered (BSE) images of the selected minerals. The acquired data of the silicates and oxides from EPMA are employed to calculate the end-members activity of some minerals such as garnet, biotite, amphibole, clinopyroxene, orthopyroxene, K-feldspar, plagioclase, sillimanite, cordierite, ilmenite and sphene using Activity-Composition (AX) program of (Holland and Powell, 2003). The elements and structural formulae obtained from the AX program were vital in interpreting mineral chemistry and understanding how it varied within the mineral assemblages due to changes in physical and chemical conditions. For determining the metamorphic conditions of the studied rocks, microprobe studies of several coexisting mineral pairs were employed along with relevant geothermobarometry models. The geothermobarometry models used including garnet- biotite Fe-Mg exchange reaction (Thompson, 1976; Goldman and Albee,1977; Holdaway and Lee, 1977; Lavrent‘eva and Perchuk, 1981; Hodges and Spear, 1982; Ferry & Spear, 1978; Ganguly and

Saxena, 1984; Perchuk and Lavrent'eva, 1983; Perchuk et al., 1985; Dwivedi et al., 2007; Bhattacharya et al., 1988; Williams and Grambling, 1990), garnet- cordierite Fe-Mg exchange reaction (Thompson, 1976; Holdaway and Lee, 1977; Well, 1979; Dwivedi, Mohan and Lal, 1998; Perchuk et al., 1985; Bhattacharya et al., 1988), garnet-clinopyroxene Fe-Mg exchange reaction (Ellis & Green, 1979; Dahl, 1980: Ganguly, 1979; Krogh, 1988; Yang Ai, 1994), amphibole-plagioclase exchange reaction (Holland and Blundv, 1994); orthopyroxene-clinopyroxene equilibria (Wood and Banno,1973; Wells,1977; Powell,1978) and geobarometry models such as garnet-cordierite- sillimanite-quartz-equilibria (Thompson, 1976; Holdaway and Lee, 1977; Wells and Richardson, 1979; Wells, 1979; Perchuk et al., 1985; Dwivedi, Mohan and Lal, 1997), garnet-biotite-plagioclase-quartz-equilibria (Hoisch,1990), orthopyroxene-clinopyroxene- equilibria (Mercier et.al., 1984), garnet-clinopyroxene-plagioclase-quartz-equilibria (Eckert et al., 1991; Holland and Powell, 1985; Holland and Powell, 1990; Berman, 1988; Moecher et al., 1988), amphibole-plagioclase-quartz-equilibria (Schmidt, 1992) provide information on the conditions of minerals that are once considered to have been inequilibrium with each other. These models allowed for the estimation of the physical and chemical conditions that the minerals experienced while in equilibrium with each other during metamorphism. For the U–Th–total Pb chemical dating of monazite, thin sections of garnet-bearing gneiss and pelitic granulite were prepared and examined using an electron probe microanalysis (EPMA) on a CAMECA SX five instrument. Pressure- temperature-composition (P-T-X) pseudosection and pressure-temperature (P–T) pseudosection were calculated for specific bulk compositions of pelitic granulite, amphibolites, mafic granulite, calc-silicate and garnet-bearing gneiss using the Perple_X v.6.8.2 software and the latest published internally consistent thermodynamic dataset by Connolly (2005, 2009). These pseudosections, along with isopleth thermobarometry and geochronological data, provided valuable information about the metamorphic evolution and history of the rocks. The representative rock samples were selected for geochemical analysis, based on petrographic research. Major oxides, trace and rare earth elements of the rocks were analysed using X-ray fluorescence (XRF) and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) at the Birbal Sahni Institute of Palaeosciences Lucknow, India.The geochemical analysis of rocks aimed to determine their protolith composition, tectonic environment and various petrogenesis processes.

1.4 Purpose of the Thesis

This section provides an overview of all of the thesis chapters with the primary aim of determining the metamorphic evolution of the granulite facies rocks in the Makrohar granulite belt. The key objectives and outcomes of the thesis work are as follows:

- Prepare a detailed geological map of the areas around the Makrohar granulite belt on an enlarged scale using field data collected through the Global Positioning System (GPS). Representative rock samples from the study area were collected and analysed to identify the different rock types and their occurrences.

- Extensive petrography was conducted on various rock types that occurred in the study region, focusing on mineral assemblages and reaction textures. This analysis aimed to establish the time relationship between crystallisation and deformation processes.

- Mineral chemistry and structural formula computation were performed using an electron microprobe. The obtained data helped to examine the specific mineralogy of different phases present in the rocks and infer P–T stability and other mineral substitutions.

- A geochemical investigation of major oxide, trace elements and rare earth elements from various metamorphic rocks was carried out to propose the nature of protoliths and their petrogenesis.
- Conventional methods and internally consistent mineral datasets were utilized to discuss the Pressure–temperature conditions of the metamorphic rocks. Various geothermobarometer models were applied to derive information on a change in the condition of the rock from its origin to the formation of peak mineral assemblages and its retrogression.
- Pseudosection modelling was conducted by using the whole rock composition of various rock types in different model systems (NCKFMASH, NCFMAST- HC, NCKFMASHT and NCKFMASHTO) with the Perple_X software. The predicted isopleths in the P–T pseudosection were verified using EPMA data ofdifferent mineral phases. These phase equilibria models along with the monazite dating helped determine the P-T-t trajectory path of the studied rocks.
- The collected data was also used to propose a geodynamic model for the metamorphic evolution of the granulite facies rock.