CHAPTER – 1

INTRODUCTION

1.1 General

Geologists are usually curious about the compositional characteristics of the deep continental crust as well as the processes that govern its operation. Deep crustal rocks are generally found in two forms: xenoliths and exposed high-grade rocks. Xenoliths are essential but less valued than crust since they are smaller; therefore, high-grade metamorphic terrains are an important source of knowledge about the lower crust (Rudnick et al. 1995). Gneisses, migmatites, and granulites are unearthed in vast amounts in the Archean cratons and orogenic belts. As a result, they are well-equipped to respond to inquiries about the tectonic formation and development of the continental crust.

Granulites exhumed to the surface in metamorphic belts reveal lower mantle processes.The crustal rocks and granulites help us understand tectonic evolution, the metamorphic history of deep continental crust development, the nature of the lower crust, crust building processes, and the magmatic processes that drive lower crust evolution (Carter & Tsenn, 1987; Harley, 1989, Wang et al., 2019). Granulites are generated at depths of 25–30 km on a regional scale when crustal metamorphism is known to occur at pressures of 7–13 kbar and temperatures of more than 800ºC (Harley, 1989). Granulite is found in various terrains around the world. It is a significant component of most continental Precambrian shield areas and is extensively spread in space and time throughout the Proterozoic. Harley (1989, 1992) summarised the various modes of occurrence of granulites worldwide:

- Greenschist to granulite facies prograde metamorphism
- Metamorphism of the uniform granulite facies with no transition to lower grade
- Reworking of the older basement complex within or between the cratonic blocks

- Isolated uplifted blocks separated by lower grade rocks or different age domains by younger average fault/shear
- As slices, slabs, or fragments in the younger mountain belt.
- As xenoliths in basalts and kimberlites

The ultrahigh-temperature (UHT) metamorphic phase occurs between 900 and 1050ºC, with a pressure range of 7 to 13 kbar (Harley 1989, 1992). In mafic to intermediate composition rocks, a coronal pattern develops around orthopyroxene of garnet (St-Onge & Ijewliw, 1996; Dziggel et al., 2012; Faryad et al., 2015). Many granitoid plutons have mafic magmatic enclaves formed by crustal anatexis of mantle-derived mafic magmas in felsic melts (Wyllie, 1984; Barbarin & Didier, 1992; Gogoi et al., 2018). The intrusive mafic magmas are integrated into the gneissic rocks' pre-existing felsic rich composition, and the newly produced rocks will be enriched in mafic composition subsequently. In granulites representing diverse pressure-temperature (*P–T)* conditions, a vast range of mineral assemblages is found. The granulites also have distinct reaction textures, indicating that mineral reaction successions have occurred. These reactions are mainly utilized to figure out *P–T* pathways, metamorphic histories, and rock evolution. Ultrahigh-temperature (UHT) metamorphism (temperatures of 900 to 1100ºC and pressures of 7–13 kbar) produces Mg–Al granulites, whereas some granulites are formed at lower *P–T* (900ºC and 6 kbar).

Similarly, the origin of amphibolites has always been a contentious and fascinating issue in metamorphic petrology (Satynarayan 1984). Amphibolites are thought to be derived from igneous rocks of basic and tholeiitic magma that represent fragments of older oceanic crust, but metasomatism of calcareous sediments can also result in the formation of amphibolites (Turner, 1948). Amphibolites were formed from pre-existing rocks that have undergone a series of mineral and chemical changes as a result of metamorphism. These rocks have a variety of origins and have been identified as the most problematic; additionally, they play a significant role in elucidating the history of Archean crustal evolution (Elueze, 1985; Honkamo, 1987). Most researchers believe that three processes, namely meta-igneous, meta-sedimentary, and metasomatic, are the most valid processes for the formation of amphibolites (Orville, 1969). Garnet-bearing amphibolites represent a variety of metamorphic conditions, including high to ultrahigh-pressure metamorphism, which can be prograde or retrograde (Miyashiro, 1994; Lou et al., 2013). These amphibolites can be formed from various magmas, including basalts, mantle-derived magmas, volcano-sediments, and even pelagic sediments (Wu et al., 2013). These magmas can develop in multiple tectonic settings, including mid-oceanic ridges (MORs), island arcs, and ocean islands. Therefore, garnet-bearing amphibolites are also helpful in understanding the metamorphic history of a terrain. Field, petrological, and geochemical investigations, along with conventional geothermobarometers and *P–T–t* paths, can all be used to better understand tectonism and metamorphic evolution in any terrain (Harley, 1989; Brown, 1993; Vernon, 1996). Most metamorphic processes decipher two *P–T* paths, clockwise and anticlockwise. The clockwise path represents isothermal decompression during subduction, whereas the anticlockwise path represents isobaric cooling caused by intrusion and underplating of intrusive mantle-derived magma (Thompson & England, 1984; Maruyama et al., 2010). This mantle-derived magma may have evolved from an intra-continental magmatic arc (Wells, 1980), an incipient rift environment (Sandiford & Powell, 1986), and mantle plumes (hotspots) (Bohlen, 1991).

The Hadean era (4.4–4.0 Ga), Acasta Gneisses found in northwestern Canada show that continental crust formation began early in Earth's history (Zeh et al. 2014). The Indian landmass developed its current geological features as a result of tectonic activity during the formation of four supercontinents at different times: Kenorland, Columbia, Rodinia, and Gondwana (Rogers & Santosh, 2002; Meert, 2003; Li et al., 2008; Dwivedi et al., 2020; Kumar et al., 2021). The Archaean eon ranges between 3.5 and 2.5 Ga, and the time before

2.5 Ga records most continental crust development, mechanisms, and evolution (Armstrong, 1981; Guitreau et al., 2014). Because the Archean Cratons contained various igneous and metamorphic rocks that recorded different levels of magmatic and metamorphic crustal evolution, several stages of magmatic intrusion, and tectonic indicators, the Archean Cratons became the primary subject of study for understanding the Earth's early history (Pearce, 2014). The Archean Craton is made up of superacrustal rocks that serve as the foundation for micro-continental, continental, and super-continental evolution and stabilization (Naqvi, 2005; Condie, 2015). The entire Indian subcontinent was made up of two vital Archean Cratons: a northern Indian block (Aravalli and Bundelkhand) and a southern Indian block (Singhbhum, Dharwar, and Bastar) (Ramakrishnan & Vaidyanadhan, 2010). During the Paleo-Mesoproterozoic subduction-accretion collision, these two crustal blocks were stitched along the E–W trending Central Indian Tectonic Zone (CITZ: Naganjaneyulu & Santosh, 2010). The CITZ is divided into three sections running north to south: the northern Mahakoshal Mobile Belt (MMB) (2.4–1.7 Ga), the Central Betul Supracrustal Belt (1.5 Ga), and the southern Sausar Mobile Belt (SMB) (1.4–0.9 Ga) (Roy et al., 2003). The Son-Narmada faults bind the Bundelkhand Craton (BuC) to the south, and the Yamuna Fault in the north separates it from the Himalayas (Singh et al., 2009). The Vindhyan and Bijawar basins mark the eastern and western margins of BuC, respectively, and are separated from the Deccan province by CITZ (Roy et al., 2000). Tonalite–trondhjemite–granodiorite (TTG) gneisses and granitoids dominate the cores of all cratons, with meta-sedimentary, meta-volcanic, and ultramafic–mafic volcanic rocks also present (Naqvi, 2005; Jayananda et al., 2015). The metamorphic evolution of these Archean cratons' rock complexes is also essential to understanding the geodynamics and tectonic nature of the geological complexes. The BuC is an important unit of the northern Indian shield because it records crustal evolution from the Archean (3.55–2.7 Ga) in the TTG around the Mauranipur and Babina regions, along with several magmatic episodes of gabbros, granites, komatiites, and basaltic pillow lavas from the Paleoproterozoic (2.5–1.8 Ga) (Malviya et al., 2006; Joshi et al., 2013). Most of the 2.55–2.52 Ga granitic rocks are found in the central part of the BuC, but basaltic rocks of 3.4 Ga are found concurrently with the TTG rocks (Kumar et al., 2013; Singh et al., 2018, 2019). However, the metamorphic processes of various rock assemblages within the BuC are still insufficiently studied. Metapelites and metabasalts have shown high-grade metamorphism with *P*–*T* values of 6.2 kbar/730°C and 5.44 kbar/720°C, respectively (Singh & Dwivedi, 2009, 2015). Similarly, Nasipuri et al. (2019) reported high-grade metamorphism of 6.5–8.5 kbar/630–720°C in the TTGs of the Sukwan area. Instead, ultrahigh-pressure amphibolite facies metamorphism has also been preserved in white schists from the Babina region, with *P*–*T* conditions represented as 18 kbar/630°C (Saha et al. 2011). The garnet-bearing BIF from the Mauranipur region has a peak temperature of ~500°C at 0.1–0.2 GPa, indicating lower amphibolite facies (Raza et al., 2021). In the BuC, many medium to high-grade rocks, including amphibolites, have been reported (Singh et al., 2015). Based on textural and mineralogical analyses, several authors have concluded that greenschist to amphibolite facies metamorphism occurred in meta-mafic and meta-ultramafic rocks of the BuC (Saha et al., 2011; Singh & Dwivedi, 2015). These examples have drawn attention to the new opportunities for determining the high-grade metamorphic conditions in the Archean BuC.

1.2 Scope of the Investigation

Granulites are now regarded as new eyes into the Earth's deeper crust, as they have aided in the understanding of deep crustal processes.Major issues of current interest in the formation and evolution of amphibolites, high-grade gneisses, and pelitic granulites were considered using detailed petrography, mineral chemistry, geochemistry, geothermobarometry, geochronology, and phase equilibria modelling with the appropriate bulk composition of rocks from the Mauranipur and Babina region of the BuC.

The study areas are Mauranipur and Babina, which are in the Central Bundelkhand Greenstone Belt (CBGB) near the Saprar River and the Sukwan Dam, respectively. The areas around Mauranipur, Babina, Roni, and Kuraicha have generally medium to high-grade facies rocks, including TTGs, amphibolites, high-grade gneisses, pelitic granulites, and Banded Iron Formations (BIFs), and show a wide range in mineral paragenesis and chemical composition. The Amphibolites (garnet–amphibole–clinopyroxene–plagioclase–biotite–chlorite–ilmenite–quartz, amphibole–clinopyroxene–plagioclase–epidote–ilmenite–quartz), Pelitic granulites (garnet–orthopyroxene–sillimanite–cordierite–plagioclase–biotite–K-feldspar, garnet–Orthopyroxene–sillimanite–plagioclase–biotite–K-feldspar, garnet–sillimanite–cordierite–plagioclase–biotite–K-feldspar, Garnet–sillimanite–plagioclase–biotite–K-feldspar), and High-grade gneiss (garnet–biotite–plagioclase–K-feldspar–ilmenite–quartz) are the primary rock type found in the study area.

An electron microscope analysis of coexisting minerals would provide mineral chemistry, element distribution in coexisting phases, and a phase compatibility relationship. The metamorphic conditions can be deduced from the coexisting minerals using geothermobarometric models.

The study of element partitioning behaviour is an effective way to calibrate thermodynamic models for calculating the metamorphic condition. The partitioning of elements in coexisting phases is a function of pressure, temperature, and composition (Ramberg & Devore, 1951; Perchuck, 1967).

The *P*–*T* pseudosections are employed to constrain the metamorphic history of the amphibolites, high-grade gneisses, and pelitic granulites. Here, Perple_X v.6.8.2 software (Connolly, 2005, 2009) is used with an internally consistent data set (Holland & Powell, 2011) to calculate significant pseudosections of various mineral equilibria and derive the *P*–*T* path. The phase equilibria modelling in the multiple systems, viz., Na_2O-CaO-K_2O-FeO-

$MgO-Al_2O_3-SiO_2-H_2O-TiO_2$ (NCKFMASHT), $Na_2O-CaO-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2-O_2$ (NCFMASHTO), $Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2-O_2$ (NCKFMASHTO) and mineral assemblages concluded from the textural relationships and phase compatibility relations. The *P-T-t* paths show the history of metamorphic evolution of amphibolites, pelitic granulites, and high-grade gneisses in *P–T* space through time, which can reveal numerous characteristics such as the source of heat used to reach the thermal peak, local structural setting, tectonic process, and tectonic transport rate. The P-T-t trajectory path may be useful in developing a geodynamic model for crustal evolution in the BuC.

The major, trace, and rare earth element analyses of amphibolites, pelitic granulites, and high-grade gneisses may reflect the nature of depositional and tectonic environments as well as the character of their protoliths prior to metamorphism. The exposed metamorphic terrains provide important insights into the magmatic processes occurring in the lower crust. Rare-earth elements are a promising new technique for determining the parentage of metasomatized andmetamorphic rocks in the higher amphibolite facies of regional metamorphism, and they may help us understand the role of anataxes in the evolution of the lower continental crust.

Geochronology is a powerful tool for determining the age and evolutionary history of rocks and the Earth. Geochronology is used for recreating orogenic belt geodynamic history, dating plutonic or volcanic rock emplacement, metamorphic processes, sediment deposition, and determining the age of the parent rocks from which sedimentary detritus is formed. Geochronological investigations are an essential proxy in the field of metamorphic petrology.

1.3 Methodology

During three distinct field seasons (February–2018, September- 2019, and July 2021), the author mapped the study region using Survey of India Toposheet no. 54K/6 and 54O/4 on a 1:50,000 scale and plotted all of the information and data received from the field on the map. The study area surrounding the Babina region is covered by Toposheet no. 54K/6, while the area surrounding the Mauranipur region is covered by Toposheet no. 54O/4. More than 250 representative samples were obtained from the area's various rock outcrops throughout these fieldwork periods. A Global Positioning System instrument (Garmin GPS MAP 78s) was used for recording the location (latitude and longitude) of the obtained samples. A Brunton compass was also used for measuring other structural aspects of relevance.

More than 150 thin sections of various rock types were prepared for petrography analysis using the Leica petrological microscope (LEICA DM 2500 P). Mineral textural relationships were investigated in terms of time relationships between crystallization and deformation. The selection of distinct key rock slides for electron microprobe (EPMA) investigation was based on a petrographical study. Microprobe examinations of representative mineral samples were utilized to investigate the chemistry of minerals, the distribution of different elements in coexisting phases, and the calculation of P–T metamorphism conditions using relevant geothermobarometry models. For the microprobe investigation, rockslides of probable minerals were also separated. The mineral content and textural connection of granulite rocks can be studied petrographically to learn more about the nature and environment in which the rock was created. The interpretation of distinct forms of response texture, coronas, and symplectite intergrowth requires the use of photomicrographs. Microscopic studies disclose the nature of rock compositions such as pelitic, amphibolites, and high-grade gneiss, as well as show the signature of prograde and retrograde metamorphic mineral assemblages.

After detailed microscopic investigations, we chose a few thin slides of amphibolites, pelitic granulites, and high-grade gneiss for EPMA (electron microprobe analysis). The analysis was conducted at the Department of Geology, Banaras Hindu University (Varanasi), India. The CAMECA SX five electron microprobe was used to examine the mineral chemistry of various silicate minerals, as well as the Back Scattered (BSE) picture and X-ray mapping of chosen minerals. EPMA analyses the minerals identified through a petrographic investigation to determine their chemical composition based on silicates, oxides, and halides. The acquired data of the silicates and oxides from EPMA are employed to calculate the end-members activity of some minerals such as biotite, amphibole, feldspar, garnet, clinopyroxene, orthopyroxene, cordierite, sillimanite, ilmenite and hematite using Activity-Composition (AX) program of Holland and Powell (2003).The elements of these minerals and their calculated structural formulae obtained from the *AX* programme provide valuable data for the interpretation of mineral chemistry and their compositional variation within the mineral assemblages to changes in physical and chemical conditions.

Microprobe studies of several coexisting mineral pairs were used with relevant geothermobarometry models to determine the *P–T* metamorphism conditions of the studied rocks. The conventional or directly calibrated method is based on the direct application of chemical equilibrium of specific mineral reactions during metamorphism, and the internally consistent geothermobarometry method, which is based on the application of equilibrium thermodynamic datasets expressed as activity-composition (a-x) of minerals, melt, and fluids. The traditional approach of several models of geothermobarometry can be used to determine the *P–T* conditions of metamorphic rock. Application of various geothermometry models such as garnet-orthopyroxene Fe-Mg exchange reaction (Sen & Bhattacharya, 1984; Harley, 1985; Lee & Ganguly, 1988; Aranovich & Podlesskii, 1989 and Bhattacharya et al., 1991), biotite-garnet Fe-Mg exchange reaction (Thompson, 1976; Holdaway and Lee, 1977; Ferry & Spear, 1978; Perchuk et al., 1985; Dwivedi et al., 2007), cordierite-garnet Fe-Mg exchange reaction (Thompson, 1976; Holdaway& Lee, 1977; Well, 1979; Perchuk et al., 1985; Bhattacharya et al., 1988; Aranovich & Podlesskii, 1989; Perchuk, 1991; Dwivedi et al., 1998), garnet-clinopyroxene Fe-Mg exchange reaction (Ellis & Green,1979; Ravna, 2000), amphibole-plagioclase exchange reaction (Holland & Blundv,1994); and geobarometry models such as garnet-cordierite-sillimanite-quartz-equilibria (Thompson, 1976; Wells, 1979; Perchuk et al., 1985; Nichols et al., 1992), garnet-biotite-plagioclase-quartz -equilibria (Wu et al., 2004), garnet-orthopyroxene-plagioclase-quartz-equilibria (Perkin & Chipera, 1985; Bhattacharya et al., 1991; Lal, 1993), garnet-clinopyroxene-plagioclase-quartz-equilibria (Newton & Perkins, 1982; Eckert et al.,1991), amphibole-plagioclase-quartz-equilibria (Bhadra & Bhattacharya, 2007) provide information on the conditions of minerals that are once considered to have been in equilibrium with each other. The development and availability of a large, internally consistent dataset of equilibrium thermodynamics has greatly enhanced the methods for computing phase equilibria, allowing for the calculation of varied *P–T* and composition of equilibrium mineral assemblages (Berman, 1988; Powell & Holland, 1988, 1994; Holland & Powell, 1990, 1996, 1998). As a result, with the development of software for calculating mineral phase equilibria in *P–T* pseudosection and the availability of thermodynamic datasets on the activity-composition of minerals in recent years, the internally consistent geothermobarometry method for petrological calculation has received a lot of attention rather than the traditional thermobarometry method.

The chemical compositions of minerals were plotted in ACF and AFM diagrams to predict the variation in the mineral paragenesis of amphibolites and high-grade gneisses. Phase petrology, along with the Pressure-temperature-composition (P-T-X) pseudosection and pressure-temperature (*P–T*) Pseudosection are calculated for the specific bulk composition of the amphibolites, pelitic granulite and high-grade gneiss using the latest published internally consistent thermodynamic dataset (Connolly, 2005, 2009) by Perple_X v.6.8.2 software. Pseudosections of equilibrium mineral assemblages can be calculated in different appropriate model systems, such as NCKFMASHT, NCFMASHTO, and

NCKFMASHTO systems. Pseudosections can be used as a powerful tool to constrain the *P–T* evolution of metamorphic rocks and metamorphic reaction texture (White et al., 2007). Since the modelled rocks can be a simplification of natural rock composition, apparently fewer degrees of uncertainties are involved in the model system is closer to the modelled rock; therefore more extensive model system is preferred to determine the *P–T* condition experienced by the rock and to derive a *P–T* path. Pseudosection combined with isopleth thermobarometry and geochronological data can yield convincing information on the *P-T-t* path and evolutionary history of the metamorphic rock.

Rock samples were chosen for whole rock analysis based on petrographic research in order to explore the geochemistry of amphibolites, granulites, and gneisses. At the BirbalSahni Institute of Palaeosciences (BSIP) in Lucknow, India, the major oxides, trace elements, and rare earth elements (REE) were studied using X-ray fluorescence (XRF) and an Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) system. The rocks' geochemistry is investigated to determine the protolith's composition and likely tectonic environment. Because of the analogous chemical and physical properties of rare earth elements (REE), many petrological processes exploit slight differences in size and behaviour, causing the REE series to become fractionated relative to each other. As a result, this phenomenon is used to determine the protolith of the rock and discuss various petrogenesis.

1.4 Purpose of the Thesis

This section contains a synopsis of all of the research thesis chapters. Its goal is to determine the metamorphic evolution of the basement rocks from the BuC in the northern Indian shield. These are the main objectives of the thesis work and the research outcome: -

- A detailed geological map of the areas surrounding Mauranipur, Babina, Kuraicha, and Roni has been prepared on an enlarged scale (1 cm to 1 km and 1 inch to a km). Based on field data collected using the Global Positioning System (GPS), representative rock samples collected from the area will give us an idea of the different types of rocks and their occurrence in the area.

- Detailed petrography was performed on the numerous rock types found in the study region, with a focus on mineral assemblages, reaction textures, and mineral intergrowth. The goal of petrography was to use the various textures and fabrics found in rock to determine the time link between crystallization and deformation.
- Mineral chemistry analysis and structural formula computation using an electron microprobe. The mineral chemistry data will be displayed on relevant diagrams to examine the specific mineralogy of the numerous phases found in the rocks, as well as to infer *P–T* stabilityand other mineral substitutions.
- The whole rock composition of different rock types is used to calculate the pseudosection modelling in various model systems such as NCKFMASHT, NCFMASHTO, and NCKFMASHTOusing Perple_X software. The predicted isopleths in the *P–T* pseudosection were verified using EPMA data from various mineral phases. The calculated stable mineral equilibria phases in the pseudosection provide important constraints for determining the *P–T* conditions of the rock in relation to different mineral equilibria and reaction textures. Thus, these phase equilibria models will be used in conjunction with the rock's geochronological age to derive the *P-T-t* trajectory path and metamorphic evolution of the studied rocks.
- To discuss the *P–T* condition of the rocks using the conventional method and an internally consistent mineral dataset. The *P–T* conditions of metamorphic rocks have been computed using various geothermobarometer models. Appropriate interpretation of the P–T condition will be made 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.

- A geochemical investigation of major, trace, and rare earth elements from various metamorphic rocks has been carried out to propose the nature of protoliths and their petrogenesis.
- To establish a relationship between metasedimentary (pelitic granulites) rocks and adjacent rocks that occur as xenoliths or are intruded by TTGs, the minimum age of pelitic granulites is the TTGs, implying that studied rocks are older than the TTGs. If the metamorphic age of pelitic granulites is older than that of the TTGs, it will have the age of a metamorphic event that occurred prior to the TTG's emplacement. We were approached to perform Lu-Hf dating of garnet grains by Laser ablation multi-collector inductively coupled plasma (LA-ICP-MC-MS) due to a lack of zircon and monazite grains in the studied rocks.
- The above data is combined to propose a geodynamic model for the tectono-metamorphic evolution of the BuC's Central Bundelkhand Greenstone Belt, as well as an accretion relation of the northern Indian shield to the Ur and Kenorland supercontinent during the Archean.