CHAPTER-1

INTRODUCTION

1.1 General

Granulites are regarded as a significant geological entity that offers valuable insights into the composition and characteristics of the lower crust. They serve as a crucial constraint in enhancing our understanding of the probable nature and composition of the lower crust. Granulites are recognised as geological formations that correspond to the lower crust and upper mantle regions of the lithosphere. They serve as valuable indicators for understanding the heat exchange mechanisms through interface that separates the lithosphere and asthenosphere throughout the orogenesis process. Consequently, granulites have garnered significant interest in contemporary research. The given range is from 5 to 8. Additionally, these indications offer insights into the significant processes of tectonic and chemical evolution, which play a crucial role in the accumulation of Earth's crust, the stabilisation of crustal structures, and the formation of continents. [9]. Granulites are formed at a depth of 25– 30 km, where crustal metamorphisms are known to occur within pressure limits of 7–13 kbar and temperature ranges of more than 800ºC [9]. These entities are widely regarded as the primary contemporary counterparts for investigating the geodynamic evolution and tectonic history of the Earth. Several modes of granulite occurrence in varieties of terrains are recognized worldwide, and forms significant components of most continental Precambrian shield areas and are widely, though variably, distributed in space and time within the Proterozoic. [9, 10] summarised the various modes of occurrences of granulites worldwide:

(a) Prograde metamorphism from the greenschist to granulite facies

(b) Uniform granulite facies metamorphism and lack of transition to lower grade

(c) Reworking of the older basement complex within or between the cratonic blocks

(d) Isolated uplifted blocks separated by lower grade rocks or different age domain by younger average fault/shear

(e) As slices, slab or fragments in the younger mountain belt.

(f) As xenoliths in basalts and kimberlites.

The geological characteristics of the Indian peninsular shield have been shaped by numerous tectonic events that occurred during the formation of three distinct supercontinents: Columbia, Rodinia, and Gondwana. [1, 11-19]. The Central India Tectonic Zone (CITZ) is responsible for the amalgamation of the Northern Indian Block (NIB) and Southern India Block (SIB) within the Indian peninsular shield and is situated between two main tectonic settings: the Central Indian Shear Zone (CIS) along its southern boundary and the Son Narmada North Fault (SNNF) on its northern side. The CITZ consists of three prominent components along north-south; the northern Mahakoshal Mobile Belt (MMB) (2400–1700 Ma), the Central Betul Supracrustal Belt (~1500 Ma) and the southern Sausar Mobile Belt (SMB) (1400–900 Ma) [20]. The Proterozoic Betul Belt holds significant importance as a supracrustal unit under consideration which provides evidence of long-lasting crustal accretion and expansion within the Central Indian Tectonic Zone (CITZ). The Betul belt is composed of granite gneisses with an estimated age of approximately 2167 ±11 Ma, mafic volcanics (pillowed lava) with an age of approximately 2051±80 Ma, rhyolite with an age of 1715±10 Ma, and earlier granitoids (1671±29 Ma). These rocks have seen many stages of deformation and have undergone regional metamorphism at amphibolite-facies conditions. The primary geochemical composition of gneisses, pillow lava, and mafic intrusions is characterised by arc-like signatures, whereas rhyolite and granites are commonly found in anorogenic and back-arc environments. The origin of pillow lavas and mafic intrusions seems to involve the incorporation of previously formed crustal material, which may include associated sediments. This is evidenced by the examination of their overall chemical composition and the isotopic ratios of Sr and Nd. The Betul granite gneisses were intruded into the Earth's crust approximately 2167 million years ago in a tectonic environment characterised by collision. These gneisses formed from the partial melting of pre-existing rocks in the Earth's crust that share similarities with the Bundelkhand craton. It is possible that these granite gneisses serve as the underlying foundation for the supracrustal series. The supracrustal units, comprising mafic volcanics and rhyolites, exhibit a bimodal suite that originated within the arc and back-arc setting, concomitant with contemporaneous sedimentation. The findings from the examination of data on bulk rock geochemistry and age suggest the presence of two different episodes of A-type granite magmatism, which took place approximately 1674 Ma and 1079 Ma, respectively. The aforementioned phases exhibited distinct geochemical properties, whereby the initial phase emerged inside an anorogenic framework, while the subsequent phase occurred in a back-arc environment. Notably, both phases transpired subsequent to a collisional incident. The deposition of more recent post-orogenic granites, notably the Navegaon granites, took place in a back arc environment within the time frame of around 1079-954 Ma. The occurrence of this emplacement event coincided with a collisional event that transpired within the Sausar belt. The age determination of monazite in Hbl gabbro yields a weighted mean of 1026 ± 97 Ma (MSWD=0.15), suggesting the presence of regional metamorphism of Grenville age in the Central Interior Terrane Zone (CITZ). The rock formations found in the Betul belt, which range from approximately 2167 Ga to 954 Ma, display significant associations with geological events that affected Laurentia, Baltica, Australia, and East Antarctica during the time intervals corresponding to the Columbia (around 2.1-1.7 Ga) and Rodinia (around 1.2-0.9 Ga) supercontinents [2]. The MMB is located at the northern limit adjacent to the Vindhyan Supergroup, which has an estimated age of around 1640 million years [24]. The MMB is oriented as a narrow linear strip. The Betul Group is composed of supracrustal rocks that exhibit low-to-medium grade metamorphism, which occurred within the amphibolite facies [3]. The presence of Betul supracrustals in the Central Indian Tectonic Zone (CITZ) serves as a significant indicator that the protoliths may have undergone metamorphism up to the granulite facies.

Ultra-high temperature (UHT) metamorphic phase occurs at the temperatures range of 900–1050ºC, with a broad pressure range of 7–13 kbar [9]. High-temperature gneisses are characterized by the presence of corona texture with garnets that are assumed to have formed during isobaric cooling [9]. A coronal texture is developed around orthopyroxene of garnet in of mafic to intermediate composition rocks [34-36]. Mafic magmatic enclaves occur in many granitoid plutons, and felsic melts developed these enclaves through crustal anatexis of mantle-derived mafic magmas [37-39]. The intrusive mafic magmas are incorporated into the pre-existing felsic rich composition of gneissic rocks; later, the newly formed rocks will be enriched in mafic composition.

Mafic granulites represent a frequently encountered lithological subtype of lower crustal rocks that are widely distributed in high-grade metamorphic terrains worldwide [40-43]. The presence of these rocks offers valuable insights into crustal-scale geological processes. The examination of the mineral compositions in particular can provide valuable insights into the temperature conditions that orogens experienced during their collapse phase [44]. Furthermore, it is worth noting that mafic granulites have the potential to preserve evidence of previous high- and/or ultra-high pressure metamorphic processes [41, 42, 45-50], as well as indications of prior magma intrusion in the lower crust prior to subsequent granulite-facies alteration [51]. Although the magmatic characteristics of mafic rock formations are often obliterated during granulite facies metamorphism, certain petrological and geochemical features may occasionally remain intact (44). Mineral exsolution is a distinct texture that arises in minerals from either the fast separation of fluids from two interconnected thermodynamic phases or through the uneven initiation and growth of crystals [52-54]. The primary cause for the development of exsolution texture in metamorphic rocks is the reduction in pressure [55-57] and variations in the oxidation state [58]. On the other hand, in igneous rocks, the development of exsolution texture is influenced by temperature and oxygen fugacity as significant factors [59, 60]. Hence, mineral exsolution textures offer crucial insights on the fluctuations in pressure, temperature, oxygen fugacity, and fluid availability throughout the exhumation process of granulites.

The coexistence of clinopyroxene and orthopyroxene in metamorphosed mafic rocks serves as empirical proof that granulite facies conditions were achieved throughout the process of regional metamorphism [61]. Granulites have been documented in many Precambrian terrains in India. These include the Shillong Meghalaya Gneissic Complex [62-64], the Southern Granulite Belt [65] and related sources, the Eastern Ghats Granulite Belt [44, 66, 67], and the Central Indian Tectonic Zone (CITZ) [68]. The Proterozoic Betul Belt holds significant importance as a supracrustal unit, serving as a record of the prolonged process of crustal accretion and expansion within the Central Indian Tectonic Zone (CITZ). Throughout the Proterozoic period, the tectonic zone's numerous crustal units have experienced multiple instances of subduction, collision, and accretionary orogenesis, resulting in noteworthy constraints. The unresolved issue of the metamorphic grades leading to the granulite facies alteration of protoliths has persisted for several decades.

1.2 Scope of the Investigation

Granulites are seen today as new eyes into the Earth's deeper crust and have marked a significant leap forward in decoding deep crustal processes. In this study, key issues of current interest on the formation and evolution of granulites were considered based on detailed petrography, mineral chemistry, geochemistry, geothermobarometry, and phase equilibria modelling with appropriate bulk composition of the rocks in and around Betul.

The studied area is situated within the Betul supracrustal belt, which exhibits a regional trend oriented in the ENE–WSW direction. The rock formations located in the Betul Group region are widely acknowledged as a notable division of the Central Indian Tectonic Zone (CITZ). The Betul Group is composed of supracrustal rocks that exhibit low-to-medium grade metamorphism, metamorphosed under amphibolite facies. The areas around Chicholi, Bargaon, Biskhan, Sonaghati and Nimpani form part of granultic terrains which expose rocks in the form of patches in outcrops show a wide range in mineral paragenesis and chemical composition.

Electron microscope analyses of the coexisting minerals would throw light on mineral chemistry, distribution of element in coexisting phases and a phase compatibility relationship. The metamorphic conditions can be inferred from the coexisting minerals through the pertinent models of geothermobarometry. The study of partitioning behaviour of elements provides an excellent opportunity to calibrate the thermodynamic equations for estimating the metamorphic condition. The partitioning of elements in coexisting phases is a function of the pressure, temperature and composition [75-77].

The P–T pseudosections are utilised to constrain the metamorphic development of gneissic and granulitic rocks. Here, Perple_X v.6.8.2 software [78, 79] is used with the internally consistent data set [80] for facilitated many phase diagrams to calculate important pseudosection of different mineral equilibria and deduce P-T path. The phase equilibria modelling in the various systems, viz., Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O (NCKFMASH), 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 history of metamorphic evolution of granulites concerning P-T space in regard to time represents the P-T-t paths, which can elucidate many parameters such as a source of heat to achieve the thermal peak, local structural setting, tectonic process and the rate of tectonic transport.

The analysis of major, trace, and rare earth elements in mafic granulites and pelitic granulites can provide insights on the depositional and tectonic environments, as well as the characteristics of their protoliths prior to undergoing metamorphism. Main insights on the magmatic process occurring in the lower crust are provided by careful study of the exposed granulite terrains.

1.3 Methodology

The study area was mapped using Survey of India Toposheet no. 55F/15 and 55J/15 on 1:50,000 scale, during the different field seasons (January – 2017, January – 2018), all the information and data collected from the field were plotted on the map. During these fieldwork sessions, collection of more than one hundred representative samples was undertaken from the available rock outcrops of study area. The mapping process involved the utilisation of a Global Positioning System instrument (Garmin GPSMAP 78) to accurately document the geographical coordinates (latitude and longitude) of the gathered samples. Additionally, a Brunton compass was employed to measure several structural characteristics of significance. More than one hundred fifty thin sections were prepared of the different rock samples for petrography study under the Leica petrological microscope (LEICA DM 2500 P). The textural relations of minerals were studied with respect to time relations between crystallization and deformation. Petrographical study was used for the selection of different important rock slides for electron microprobe analysis (EPMA). The microprobe analyses of the minerals of representative samples have been used for the detailed study of minerals Chemistry, distribution of different elements in coexisting phases and estimation of P-T conditions of metamorphism through the pertinent models of geothermobarometry. Rockslides of suspected minerals were also separated for the microprobe analysis. Petrographic study of the mineral content and the textural relationship of granulite rocks reveal essential information about nature and environment under which the rock was likely to be formed. The study of photomicrographs is vital in the interpretation of different types of reaction texture as well as coronas, exsolution and symplectite intergrowth. The microscopic studies reveal the nature of the rock composition like; pelitic, mafic and high-grade gneiss, and it also provides ideas about the preservation of prograde or retrograde metamorphic mineral assemblages.

After the detailed microscopic studies, few representative thin slides of mafic granulites and pelitic granulites were selected for EPMA (electron microprobe analysis). The analysis was carried out at Department of Geology, Institute of Science (Banaras Hindu University), Varanasi. Mineral Chemistry of different silicate minerals, Back Scattered Electron (BSE) image and X-ray mapping of selected minerals were analyzed by CAMECA SXFive electron microprobe. The minerals identified through the petrographic study are analyzed by EPMA to get the value of their chemical composition based on their silicates, oxides and halides. The acquired data of the silicates and oxides from EPMA are employed to calculate the endmembers activity of some minerals such as biotite, amphibole, feldspar, garnet, clinopyroxene, orthopyroxene, cordierite, sillimanite, ilmenite and hematite using Activity-Composition (AX) program of [81]. The elements of these mineral and their calculated structural formulae obtained from AX program provide valuable data for interpretation of mineral chemistry and their compositional variation within the mineral assemblages to changes in both physical and chemical conditions.

The microprobe analyses of the different coexisting minerals pairs were applied to the pertinent models of geothermobarometry to estimate the P-T conditions of metamorphism of the rocks of the investigated areas. Two methods are mainly employed to determine P-T conditions of rocks, viz. conventional or directly calibrated method, which is based on the direct application of chemical equilibrium of specific mineral reaction during metamorphism and internally consistent geothermobarometry method which is based on the application equilibrium thermodynamic datasets expressed as activity-composition (a-x) of minerals, melt and fluids. The determination of pressure and temperature (P-T) conditions in metamorphic rock can be achieved through the application of conventional geothermobarometry methods on various models. Application of various geothermometry models such as garnet-orthopyroxene Fe-Mg exchange reaction [82-85], biotite-garnet Fe-Mg exchange reaction [86-89], cordierite-garnet Fe- Mg exchange reaction [84, 86, 90-95] and geobarometry models such as garnet cordierite- sillimanite-quartz-equilibria [86, 91, 92, 96, 97] provide information on the conditions of minerals that are once considered to have been in equilibrium with each other. The progress and availability of a vast internally consistent dataset of equilibrium thermodynamic have significantly improved the methods of calculating the phase equilibria through which different P-T and composition of equilibrium mineral assemblages can be calculated [98-103]. Therefore, in recent years with the development of software for calculation of mineral phase equilibria in P-T Pseudosection and the availability of thermodynamic dataset on activity-composition of minerals, much focus has been given to internally consistent geothermobarometry method for petrological calculation rather than the conventional method.

P-T Petrogenetic grid, Pressure-temperature composition (P-T-X) pseudosection and pressure-temperature (P-T) Pseudosection are calculated for the specific bulk composition of the mafic granulite and pelitic granulite using the latest published internally consistent thermodynamic

dataset [78, 79] by Perple_X v.6.8.2 software. Pseudosections of equilibrium mineral assemblages can be calculated in different appropriate model systems such as NCKFMASH and NCKFMASHTO systems. Pseudosections can be used as a powerful tool to constrain the P-T evolution of metamorphic rocks and metamorphic reaction texture [104]. 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 Pressure-Temperature-Time (P-T-t) path and evolutionary history of the metamorphic rock.

Based on the petrographic studies, rock samples were selected for whole rock analysis for studying the geochemistry of granulites and gneisses. The analysis of the major oxides, trace elements, and rare earth elements (REE) was conducted at the Birbal Sahni Institute of Palaeosciences (BSIP) in Lucknow, India, using the X-ray fluorescence (XRF) and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) instrumentation. The examination of the geochemistry of rocks is conducted in order to evaluate the characteristics of the protolith and the potential tectonic setting in which they formed. On account of the analogous chemical and physical properties of Rare Earth Elements (REE), small differences in size and behaviour are exploited by many petrological processes causing the REE series to become fractionated relative to each other; as a result, this phenomenon is employed to determine the protolith of the rock and discuss various petrogenesis.

1.4 Research Gap

This part is a summary of all the chapters of the research thesis. It aims to unravel the existence of granulite facies of metamorphic history of the Betul supracrustal belt. These are the objectives discussed for the thesis and the research outcome:-

A detailed geological map on the enlarged scale (4 inches to a mile) of the areas around Chicholi, Bargaon, Biskhan, Sonaghat and Nimpani has been prepared based on collected data from the field using Global Positioning System (GPS), representative rock samples collected from the area will give us the idea on different types of rocks and its occurrence in the area.

Detailed petrography of the various rock types present in the study area has been undertaken with particular emphasis on the mineral assemblages, reaction textures, coronas and symplectites intergrowth of minerals. The petrography has been aimed to decipher the time relationship between crystallization and deformation concerning their different textures and fabrics observed in the rock.

Electron microprobe analyses of phases are used to discuss the mineral chemistry and calculation of their structural formula. The mineral chemistry data will be plotted on relevant diagrams to discuss the detailed mineralogy ofthe various phases present in the rocks and also provide important information about the other mineral substitutions, the grade of metamorphism and infer P-T stability.

Based on the bulk rock composition of different rocks, modelling will be carried out using Perplex software in various model systems such as NCKFMASH and NCKFMASHTO. The isopleths calculated in the P-T pseudosection were validated by comparing them with the EPMA data obtained for various mineral phases. The determination of the pressure-temperature (P-T) conditions of a rock is facilitated by the analysis of mineral equilibria through the use of pseudosections. These calculated mineral equilibria, along with the examination of reaction textures, offer crucial limitations in understanding the P-T conditions of the rock.

To discuss the P-T condition of the rocks based on the conventional method and by using an internally consistent dataset of the minerals. The various models of geothermobarometry have been used to compute the P-T conditions of metamorphic rocks. Appropriate interpretation of the P-T condition will be made to derive the information on a change in the condition of the rock from its origin till the peak mineral assemblages were formed and its retrogression

Geochemical analysis of various metamorphic rocks to the major, trace and rare earth elements has been carried out to postulate the nature of protoliths of the rocks and their petrogenesis.

The above information is jointly presented to propose the concept of the occurrence of granulite facies of metamorphic condition within the rocks of Betul Supracrustal belt highlighting the P-T condition and characteristics of the protoliths during the assembly of the Indian subcontinent during the suturing along the Central Indian Tectonic Zone (CITZ).