# CHAPTER – 1

# INTRODUCTION

*"Although we view the rocks as our friends, they can in some places tell lies to us. To get to the truth behind these lies require perpetual training of the eye of the petrographer and the mind of the petrologist."*

P. Robinson, 1991

## 1.1 General

Granulites are known to represent the lower crust to upper mantle part of the lithosphere and provide important information regarding heat transfer between the lithosphere and asthenosphere during the process of orogenesis; thus granulites are attracting a lot of attention in recent time [5-8]. 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]. 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 Indian peninsular shield has attained its present geological feature after facing different tectonic activity which occurred during the formation of three supercontinents in different periods; Columbia, Rodinia and Gondwana [1, 11-19]. The

Chhotanagpur Granite Gneiss Complex (CGGC) was a part of the Columbia supercontinent in Paleoproterozoic (~1800–1600 Ma), and again it assembled with the Rodinia supercontinents during Neoproterozoic (~1100–900 Ma) age. The Central India Tectonic zone (CITZ) has sutured the Northern Indian Block (NIB) and Southern India Block (SIB) of the Indian peninsular shield. The CITZ aligned between the two primary tectonic settings, namely; the Central Indian Shear Zone (CIS) present along the southern boundary and the Son Narmada North Fault (SNNF) on the 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 CGGC lies at the eastern portion of the east-west trending CITZ. The oldest recorded age of CGGC is ~1600 Ma, which represents the emplacement of felsic gneisses and first metamorphism of pelitic granulites [21]. The detrital zircon of pelitic rock deciphers ~1900–1700 Ma age, which indicates the protoliths of pelitic granulites derived from the other adjacent sedimentary provenance [22, 23]. The MMB situated at the northern boundary with the Vindhyan Supergroup (~1640 Ma; [24]) of the CGGC, and it aligned as a narrow linear belt. The MMB experienced the granite intrusion in Barambaba (~2050 Ma), Jhirgadandi (1750 Ma) and Bori (1800 Ma) area and granitoid intruded in the Rihand-Renusagar area at ~1730 Ma [25, 26], so there is high chance to sediment arrived from this area and deposited in the CGGC basin as protolith of pelitic rocks. The Singhbhum craton present at the southern boundary of the CGGC, it consists of >1800 Ma age rocks [27], might be also a prominent source for the pelitic rocks of the CGGC. The SMB and CGGC have not established any contact relationship, due to thick sediments of Gondwana rocks. However, [28] suggests that the SMB was the western extension of CGGC with evidence of geophysical data.

The Geochronological data (~1629 Ma) of pelitic granulites established a relationship with the $M_1$ metamorphic events from the Daltonganj area of northwest CGGC. High-grade pelitic granulites have extensively occurred at the global scale and act as an essential constituent of orogenic belts [9, 29-31], whereas clockwise P–T–t paths of pelitic granulites are indeed a representative feature of an orogenic setting. Pelitic granulites were formed by the sedimentary protoliths when it metamorphosed up to the granulite facies at middle-lower crustal depth with subduction tectonics [9, 29, 31-33].

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 are a typical lithological variety of lower crust rocks within high-grade metamorphic terrains worldwide [40-43] and their occurrence provides relevant information on crustal-scale processes. In particular, the detailed study of their mineral assemblages can return constraints on the thermal structure that was assumed by orogens during their collapse stage [44]. Moreover, mafic granulites may sometimes record a former high- and/or ultra-high pressure metamorphic evolutionary history [41, 42, 45-50], or a former magma emplacement in the lower crust before successive granulite-facies imprint [51]. Whilst magmatic signatures of mafic rock bodies are more likely to be erased during granulite facies metamorphism, but some petrological and geochemical characters may sometimes be preserved [44]. Accordingly, mineral exsolution is a particular type of texture that is formed in minerals either by rapid dissociation of fluids from two associated thermodynamic phases or by asymmetric nucleation and development of crystals [52-54]. In metamorphic rocks, development of exsolution texture is primarily due to reduction in pressure [55-57] and variations in the oxidation state [58], while temperature and oxygen fugacity act as important factor in the development of exsolution texture in igneous rocks [59, 60]. Therefore, mineral exsolution textures provide essential information about the variation in pressure, temperature, oxygen fugacity, and fluid availability during the exhumation history of mafic granulites.

In metamorphosed mafic rocks, the presence of both clinopyroxene and orthopyroxene is the natural evidence that granulite facies conditions were attained during regional metamorphism [61]. In India, two-pyroxene mafic granulites have been reported from different Precambrian terrains: (i) The Shillong Meghalaya Gneissic Complex [62-64]; (ii) The Southern Granulite Belt ([65] and references therein); (iii) The Eastern Ghats Granulite Belt [44, 66, 67]; (iv) The Central Indian Tectonic Zone (CITZ) [68]. However, the Chhotanagpur Granite Gneiss Complex (CGGC) is a part of the CITZ and is situated in the eastern part; it is characterized by medium to high-grade metamorphic rocks with enclaves of mafic granulites in the granitic-gneissic country rocks. The Purulia region of the eastern part of the CGGC consists of lower crustal high-grade metamorphic rocks such as mafic granulite, Mg-Al granulite and enderbite rocks, which occur as enclaves within the amphibolite and quartzofeldspathic gneisses [69-71] .They recognized the prograde metamorphism of mafic granulites due to the breakdown of amphiboles from Saltora region of the eastern CGGC. The NE of

CGGC, Dumka and Deoghar represent Meso-Neoproterozoic mafic granulite and khondalite that exist as an enclave in the felsic orthogneiss [3, 72-74]. The mafic granulites of the Purulia and Dumka region show HP metamorphism and the age of metamorphism lies around ~1000 Ma [70, 73].

## 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, geochronology and phase equilibria modelling with appropriate bulk composition of the rocks from Daltonganj area.

The study area is located toward 14 km southwest of Daltonganj in the north-western margin of the Chhotanagpur Granite Gneiss Complex (CGGC) within Hazaribagh-Giridih belt. The areas around Sokra, Datam, Dokra, Kui, Bheda, Khatauni, Nawa and Mahawat-Muria are a part of granulite terrain of the CGGC and show a wide range in mineral paragenesis and chemical composition. The mafic granulites (Orthopyroxene–clinopyroxene–hornblende–plagioclase($An_{40-45}$)–quartz, Garnet–clinopyroxene–hornblende–plagioclase–quartz), Pelitic granulites (Garnet–cordierite–biotite–sillimanite–biotite–plagioclase($An_{15-23}$)–potash-feldspar), and High-grade gneiss (Garnet–cordierite–gedrite–biotite–chlorite–quartz, Garnet–cordierite–hypersthene–gedrite–biotite–quartz) are the primary rock type found in the study area.

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 used to constraining the metamorphic evolution of the 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 pattern of *P-T-t* trajectory would help to postulate the geodynamic model for crustal evolution in the Chhotanagpur belt during the Proterozoic.

The major, trace and rare earth element analyses of the mafic granulites, pelitic granulites and high-grade gneisses may reflect the nature of depositional and tectonic environments and the nature of their protoliths prior to their metamorphism. Main insights on the magmatic process occurring in the lower crust are provided by careful study of the exposed granulite terrains.

Transmission Electron Microscopy (TEM) has used for identification of minerals and characterization of their unit cell parameters. In our study, TEM images and selected area electron diffraction (SAED) patterns are used to distinguish different forms of gedrite and also the identification of clinopyroxene–orthopyroxene exsolution texture and study their mutual intergrowths. The exsoluton textures under TEM analysis suggest few of the clinopyroxene grains contain lamellae of orthopyroxene as sub-solidus exsolution features.

The geochronological investigation is an essential proxy in the field of metamorphic petrology. Magmatic emplacement and poly-metamorphic events have distinguished by zircon and monazite dating.

### 1.3 Methodology

The study area was mapped using Survey of India Toposheet no. 73A/1 on 1:50,000 scale, during three different field seasons (May – 2017, January – 2018, and February & March – 2020), all the information and data collected from the field were plotted on the map. During these fieldwork sessions, more than two hundred fifty representative samples were collected from the available rock outcrops of study area. The mapping was carried out by Global Positioning System instrument (Garmin GPSMAP 78s) for recording the location (latitude/longitude) of the collected samples and Brunton compass for measuring other structural features of interest.

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, pelitic granulites and high-grade gneiss 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.

This study employed U-Pb zircon and U-$Th_{total}$-Pb monazite dating methods to obtain absolute ages and poly-metamorphic events. The U-Pb zircon ages for pelitic and mafic granulites rocks were obtained using LA-ICP-MS instrument at the Department of Earth and Planetary Systems Science, Hiroshima University, Japan. Besides, two high-grade gneiss samples were analyzed for EPMA monazite dating method at the Department of Geology, Banaras Hindu University.

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 pressure and temperature (*P-T*) conditions of metamorphic rock can be determined by the conventional method on assorted models of geothermobarometry. 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.

The chemical compositions of minerals were plotted in ACF and AFM diagrams to predict the variation in the mineral paragenesis of mafic granulites and high-grade gneisses. Phase petrology along with the *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, pelitic granulite and high-grade gneiss 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 major oxides, trace and rare earth element (REE) were analyzed using X-ray fluorescence (XRF) and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) instrument at Birbal Sahni Institute of Palaeosciences (BSIP) Lucknow, India. Geochemistry of the rocks is studied to assess the nature of the protolith and their possible tectonic environment. 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 Purpose of the Thesis

This part is a summary of all the chapters of the research thesis. It aims to unravel the metamorphic evolution of the basement rocks from CGGC of eastern India. These are the objectives discussed for the thesis and the research outcome:-

(a) A detailed geological map on the enlarged scale (4 inches to a mile) of the areas around Sokra, Datam, Khatauni, Kui, Dokra and Mahawat- Muria 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.

(b) 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.

(c) 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 of the 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.

(d) Based on the bulk rock composition of different rocks, modelling will be carried out using Perple_X software in various model systems such as NCKFMASH and NCKFMASHTO. The calculated isopleths in said *P-T* pseudosection were corroborated with the obtained EPMA data of different mineral phases. Calculated mineral equilibria in the form of pseudosection provide essential constraints on determining the *P-T* conditions of the rock in relation with different mineral equilibria and the reaction textures, therefore, these phase equilibria modelling together with the geochronological age of the rock will be applied to derive its *P-T-t* path and the metamorphic evolution of the rock.

(e) 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.

(f) 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.

(g) U-Pb zircon dating and U-$Th_{total}$-Pb monazite dating of the granulite rocks are used to derive the age of the magmatic emplacement and the various metamorphic events which are preserved in the study area.

(h) The above information is jointly presented to propose a geodynamic model for the tectono-metamorphic evolution of Daltonganj Granulite Belt (DGB) of CGGC and also provide evidence of attachment to eastern India with Australia and Antarctica during Columbia and Rodinia supercontinent assembly.