CHAPTER - 2

LITERATURE REVIEW

"Literature is news that stays news."
Ezra Pound

2.1 General

This chapter covers previous research works related to granulite formation and compilation of literature studies according to various methodology and rocks from the study area. Review of literature is an indispensable part of any research work. It provides a solution to the problem raised by various scientists and researchers' previous work. Rocks are the most important natural resources of nature, and preserve the evolutionary and geodynamic history of the Earth. The literature related to the study of the research area is presented in the following sections.

2.2 Introduction

The type locality of granulite is Granulitgebirge in Saxony, East Germany. The term "granulite" first appears in the literature [105]. Granulite facies were first observed by [106], which developed during regional metamorphism. The formation of amphibolite for granulite facies was regarded as a paired metamorphic belt, resulting in an island arc or continental margin overriding upon the oceanic plate [107, 108], where the heat source was derived from sub-crustal magmatism and are thought to have formed *insitu*. Granulites are high-grade metamorphic rocks in which the silicates are free from a hydroxyl group, and these are dominated by garnet, pyroxene and plagioclase, whereas micas are absent, but cordierite may be present. Granulites are characterized by hypersthene + diopside instead of hornblende and other amphiboles or by kyanite and sillimanite + garnet instead of muscovite and biotite. Granulites are coarse granular rocks formed at high *P-T* condition, which exhibits gneissic structure due to parallel arrangement of grains, and it is known as granoblastic texture. More than 30% of mafic minerals (predominantly pyroxene) in granulites can be identified as mafic granulites, while less than 30% of mafic minerals (mainly pyroxene) can be referred to as felsic granulites.

The granulite facies rocks represent the exhumed portion of the lower section of the Earth's crust; however, their study is necessary to carry out crust-mantle interaction. Younger terrains represent sporadically exposure of the granulites, which may be developed along fault zones during tectonic upliftment, whereas lower continental crust composes abundance of granulite in the Precambrian shield.

2.3 Previous work in the Chhotanagpur Granite Gneiss Complex

The area is composed almost entirely of Precambrian granitic rocks and gneisses. The gneisses contain sub-parallel lenticular enclaves of metasediments and metamorphosed mafic [109] and ultramafic rocks, mostly following the foliation direction of the country rocks. The ultramafics act as a host for magnetite deposits [110, 111] and base metal mineralization. The intrusive granites cut across the entire sequence and appear to be post-tectonic [112]. The mafic minerals, viz, biotite and hornblende, are more abundant in the tonalitic gneiss than in the other variety of gneisses [113]. The first anorthosite massif discovered in India near Saltora at the eastern edge of the Peninsular shield [114] is an enormous anorthosite massif within Chhotanagpur Granite Gneiss Complex (CGGC). Subsequently, it was referred to as 'Bengal Anorthosite' [115]. The granitic rocks of western CGGC have been studied in great detail across the Palamau district of Jharkhand between McCluskieganj and Daltonganj [116-119] and have been considered to be of anatectic origin. Several charnockite, granulite, khondalite and leptynite have been identified from various locations of CGGC [120]. The cordierite-anthophyllite-spinel rock and cordierite-hypersthene granulite near Daltonganj [121], phyllite-mica schist with porphyroblasts of andalusite near Nagar Untari [122] and also of the cordierite-bearing assemblages in other localities in Palamau have been observed [120, 123]. The country rocks were folded and metamorphosed during the development of the Central India Tectonic Zone (900±200 Ma; [124-126]). The metasediments and the gneisses have been profusely intruded by syntectonic mafic rocks now represented by amphibolites, meta-dolerite, meta-norite, meta-gabbro and pyroxene granulite [127].

The CGGC consists of a wide variety of rocks and is exhibiting four stages of metamorphism (M_1 to M_4) and deformation that recorded in the: the M_1 occurred at about 1870–1660 Ma, the M_2 is considered to happen between 1550–1450 Ma, the M_3 varies from 1200–930 Ma, and the last M_4 event lies between 870–780 Ma [70, 72, 128-130].

2.4 Monazite and Zircon Geochronology

Electron microprobe dating (EPMA) of monazite is one of the best applications for *insitu* geochronology in recent decades and is a rapid as well as cost-effective technique. Monazite is the common accessory minerals in supracrustal rocks; monazite has been used extensively to acquire information about tectono-metamorphic evidence and depositional history of sediments ([131, 132] and references therein). Monazite has several essential features that indicate an appropriate mineral for U-Th-Pb dating. These comprise: (a) high content of U [133]; (b) Pb is not incorporated at the time of crystallization [134]; (c) the U-Th-Pb component reveals high closure temperature (>900 °C; [135]; (d) monazite found from the various lithology [136]; (e) amphibolite-granulite facies is suitable for the formation of monazite [137-140]. The electron microprobe technique allows geochronology in recreating the *P-T-t* path history for metamorphic rocks. Chemical zoning in monazite has correlated with distinct age domains, whereas Y and Th act as characteristic elements [141, 142].

Monazite (Ce, La, Y, Th) [PO_4] is a phosphate of rare earth element that contains substantial amounts of U and Th but contains negligible amounts of Pb. The radiogenic Pb has reorganized the monazite ages by diffusion through the monazite lattice and is unaffected over geological timescales, both experimentally and empirically [135, 143, 144]. Monazite can also be developed during partial melting, where P and REE are saturated in the melt phase [145, 146]. The monazite grains tend to preserve prograde and retrograde metamorphic events, not necessarily to preserve the peak metamorphic condition [147]. The combined characteristics of monazite such as reactivity and isotopic robustness with silicate minerals make it an ideal contender for recreation of poly-metamorphic events and deformation within metamorphic rocks. Monazite is a widespread phosphate mineral that occurs as an accessory mineral in diverse crystalline rocks. It commonly preserves discrete age-composition domains within a single thin section, individual grains, and specific micro-textural environments in poly-deformed rocks. As such, polygenetic monazite occurrences are utilized increasingly for deciphering complex histories of grain growth, recrystallization, dissolution and regrowth [139, 148-151]. The record of such grain-scale processes in monazite can be linked to regional thermotectonic histories when integrated with a full complement of petrofabric, petrologic, and geochronologic data [141, 142, 152-155].

U–Pb zircon dating is the oldest dating method that can be used to analyze the age of rocks that range from 1 million years to 4.5 billion years ago [156, 157]. Zircon ($ZrSiO_4$) has various characteristics that make it very valuable for petrologists and geochronologists. LA-ICP-MS (Laser Ablation Inductively Coupled Plasma Mass Spectrometry) is used for geochronological analysis on zircon grains that is particularly suitable for providing rapid and accurate U-Pb ages [158-160] and is also capable of analyzing the zoning patterns of zircon and other minerals. Zircon is usually used for U–Pb geochronology, due to their mechanical and chemical stability, and ubiquity in all types of rocks. Both monazite and zircon reveal enormous closure temperature for the U-Th-Pb system and low Pb diffusivity [135, 161], thus are essential for dating the high-grade metamorphic events. Zircon can either grow during partial melting of prograde metamorphism, or crystallize during the solidification of melt [162-164], or develop from the breakdown of Zr-bearing mineral phases like garnet and ilmenite [165, 166]. Single monazite has preserved various zoning patterns due to coupled dissolution and recrystallization processes, and therefore record various apparent ages. Both of these minerals have shown complex behaviour in high-grade metamorphism and can record the past geological events to improve the timing of tectono-magmatic events [163].

2.5 Geothermobarometry and phase equilibria modelling

Metamorphic rocks can be formed under a wide *P-T* range; the mineral recrystallization occurs due to change in existing *P-T* condition resulting in the creation of new mineral phases that are stable within the new metamorphic conditions. The development of new mineral phase also depends upon the bulk rock composition. So, the interpretation of micro-textures combined with mineral assemblages and compositions in metamorphic rocks form the fundamental and most crucial step to determine *P-T-t* paths in any area. Its mineral assemblage can broadly suggest the determination of *P-T* conditions attained by any metamorphic rock. The other way to estimate *P-T* condition is by analyzing the chemical composition of minerals that are solutions of various minerals such that their equilibrium relationships among solid solutions serve as geothermometers and geobarometers. It is noted that during the transformation of a particular rock either non-metamorphic or even metamorphic to a newly formed metamorphic rock, various thermodynamic variables occur. These thermodynamic variables such as entropy, enthalpy and free energy form mafic formulation of any geothermometers/geobarometers. The advancement in petrology by use of geothermobarometers developed by the involvement of thermodynamic dataset and improved activity models of minerals has contributed significantly for the better understanding of the evolution of metamorphic rocks.

The geothermobarometric studies have been found to have critical applications in understanding granulites' genesis. Different techniques have been the most significant improvements in metamorphic petrology to quantify the *P-T* condition of metamorphism and evaluate the processes, which caused granulite metamorphism. Geothermometry of metamorphic rocks is typically based on Fe and Mg exchange of mineral pairs; therefore due to difference in mineral assemblage temperature estimations were done using garnet-biotite, garnet-cordierite, garnet-orthopyroxene, garnet-clinopyroxene, and orthopyroxene-clinopyroxene. However, the use of solvus thermometry began in the 1950s, i.e. before solid solution geothermometry based on Fe-Mg exchange. Since Ti content in biotite is always temperature-dependent, thermometry based on the Ti content of biotite was also used. It is well known that solid-solid reactions are susceptible to pressure and temperature conditions, and it acts as good geobarometers if the temperature can be derived from some other methods (e.g. exchange thermometry). The work on geobarometers began in 1970’s and successively done by [167], using plagioclase-garnet-Al_2SiO_5-quartz assemblage [168]. In the present study garnet-cordierite-sillimanite-quartz geobarometry has been used for pressure estimation. The *P-T* conditions may also be estimated using the P_{av}, T_{av} and PT_{av} methods, using probe data of the minerals and the THERMOCALC software ver.

3.47 [99], with an internally consistent dataset (tcds62) of [80] updated to comply with activity models of [169]. The THERMOCALC has overcome the two problems, including inverse modelling, to calculate the geothermobarometry using PT_{av} and forward modelling to calculate phase diagrams for different model systems.

With the advancement in science, pseudosections modelling have evolved as the most robust and accurate techniques in metamorphic petrology that are used to evaluate the *P-T* condition thereby suggesting the evolution of metamorphic rocks [78-80, 170-172]. A pseudosection is used to interpret mineral paragenesis that can be further represented on the *P-T* diagram. In present work instead of making petrogenetic grids, pseudosections were made because it displays only those set of fields and reactions that are possibly experienced by the particular bulk composition used. The pseudosection is challenging to calculate by hand since many phases are involved which change composition with a change in *P-T*. Therefore many phase equilibria modelling programs such as PERPLE_X, THERMOCALC, THERIACDOMINO etc., are being used. It constructs phase diagram using fixed bulk composition concerning varying parameters like pressure, temperature, composition etc.

The dataset has since been refined and developed [99, 173, 174]; the concept of geothermobarometry is well highlighted by [102]. The quality of an internally consistent dataset (tcds62) of [80] updated to comply with activity models of [169], the a–x relationships for silicate minerals and fluid has been drastically changed and improved, particularly in terms of handling multi-component phases that also involve order-disorder models [81, 102, 174, 175]. The PT pseudosection was constructed by using Perple_X 6.9.0 software [78, 79] and end-member thermodynamic data from [80] (filename: hp62ver.dat). They can deliver significant constraints on calculating *P-T* conditions and observing reaction textures, although care should be taken to investigate whether modelling has been performed in a suitable chemical system because it may misinterpret [104]. Petrography suggests that the reaction textures has a diverse spatial arrangement of mineral phases, usually consisting of layers (corona) and micro-scale mineral intergrowths (symplectites) that partially replace coarse-grained minerals [176].

The granulites were reported near Saltora area of Bankura district, *P-T* condition range from 950 to 750°C at 8 kbar in mafic granulites [177]. The garnet-sillimanite-biotite–plagioclase coexisting mineral phase has an intersecting equilibrium [178, 179] and has 11 kbar/870°C *P-T* condition. The garnet–aluminosilicate–plagioclase–quartz (GAPQ) geobarometary produced a maximum pressure of 10.5 kbar. The low-pressure condition (5.4 kbar) was calculated by orthopyroxene–cordierite geobarometary [180] which was due to decompression retrograde metamorphism and was demarcated by symplectitic of orthopyroxene and cordierite [70]. The garnet–orthopyroxene–plagioclase–quartz geothermobarometry was applied for mafic granulite, suggesting a *P-T* range of 6.7–7 kbar and 760–780°C.

The *P-T-t* paths for the granulites of CGGC were constructed on the reaction textures, whereas petrogenetic grids based on phase relations. A petrogenetic grid of the garnet-cordierite-gedrite gneisses in FMASH system was constructed, and a prograde clockwise *P-T-t* path was deduced with peak granulitic metamorphic condition at 710±50°C/6.2±0.5 kbar based on internally consistent garnet-cordierite-sillimanite-quartz geothermobarometers [97, 181]. The pseudosection of granulite represents a maximum pressure condition was attained at 11 kbar with 870°C, and it further went to healthy retrograde decompressive clockwise *P-T* path with pressure achieved at 5 kbar [70].

2.6 Geochemistry

Geochemical parameters such as Si, Al, Mg, Ca, Na, K, Ti, P and Mn are considered major elements. Oxides of these elements show a well-defined variation and act as the major constituent of bulk rock chemistry. Hence, they are used to classify the different rock types. The total alkali vs silica (TAS) diagram [182] was considered nomenclature and volcanic rocks classification. The TAS diagram was intended for common fresh volcanic rocks. Major oxides have a mobile nature during metamorphism [183]; therefore, the classification of diagrams is plotted using immobile trace elements. [184] proposed a diagram based on immobile trace elements such as Th, Zr, Y and La to represent magmatic affinity to rock samples.

The trace elements cannot be rigorously defined, but those elements are usually taken to mean concentrations of less than a few thousand parts per million (ppm) present in rocks. The trace elements are used to comprehend the magmatic emplacement of igneous rocks and provide information about the partial melting, crystal fractionation and source composition. The concentration of trace elements will never change; however, the melting process's extent depends on the various factors such as melting process, the remaining solid phases after elimination of the melts, any differentiation before final crystallization, and potential interactions with foreign country rocks or melts [185]. The change in rare earth elements (REEs) patterns can be used to derive information related to the rocks protolith's genesis. Progressive variations of the REE plots suggest that the protolith may be obtained by crystallization from parent magma [186]. The enrichment of elements can also provide important information on mineral fractionation at variable depth. Enrichment in HREE suggests garnet fractionation as HREE makes high partition co-efficient and is highly compatible in garnet [187]. [188] also suggested clinopyroxene act as a sink of LREE and garnet for HREE. Thus, garnet plays a crucial role in the partitioning of trace element during crystal fractionation of V and Cr [189, 190]. The abundances of LILE (Rb, Ba, U, Pb) and LREE are deduced due to enrichments by a fluid-rich component [191]. There is no observable variation recorded in REE abundance between metamorphosed rocks and unmetamorphosed rocks [192]. The REEs contents have not changed during the prograde regional metamorphism of metapelites that ranged from greenschist facies to amphibolite facies [193]. The oceanic tholeiites and related amphibolites have shown similar REEs distribution and suggest the metamorphic process was isochemical [194].

Terrigenous sediments contain the information about the composition, geodynamic setting and evolution of the early continental crust. Their geochemical composition is a function of the complex interaction of various variables, such as sedimentary provenance, weathering, transportation and diagenesis ([195] and references therein). Many studies have traditionally shown that geochemistry plays a crucial role as a sensitive indicator in determining the provenance of sedimentary and metasedimentary rocks and also to investigate the geodynamic setting in which they were deposited [196-205]. Numerous studies have emphasized the immobile trace elements and REEs in particular as reliable in studying the provenance and depositional setting of the metasedimentary rocks, particularly in pelitic and semi-pelitic rocks [196, 206, 207].

2.7 Why to need of this study

After having a quick look at the existing literature survey, one will decipher that there is no active research done in a recent decade within the Daltonganj region. Based on the previous literature study described above, it is clear that within the CGGC, two regions preserve granulite grade rocks, i.e., Dumka-Deoghar region and Baro-Saltora (Purulia) region. However, the literature survey provided the signature of presence the high-grade metamorphic rocks within the Daltonganj region. Afterwards, investigation of the study area revealed that the Daltonganj area contains granulite facies rocks, like; mafic granulites, pelitic granulites and high-grade gneisses. Though various rock types have been identified and mapped in Daltonganj region, there is no systematic study on the development of various metamorphic mineral assemblages based on micro-textural studies. The detailed petrographic and microtextural investigation is essential to unravel specific mineral reactions to document any prograde or retrograde metamorphism in any high-grade terrane. Such systematic studies have not been carried out in the Daltonganj region.

There is only a reconnaissance type of *P-T* estimate available for the Daltonganj by few early workers. Many thermodynamic models have been formulated to estimate the *P-T* conditions and software to calculate the pseudosection for investigating the stable phase with appropriate *P-T* condition. For any meaningful interpretation of *P-T* data, specific mineral-reactions have to be used based on the petrographic study. A combination of specific mineral reactions and mineral *P-T* estimate will help to unravel the exhumation history of high-grade metamorphic rocks, whether they have undergone Isobaric Cooling (IBC), and Isothermal Decompression (ITD) *P-T-t* path, which has a significant bearing on the tectonic process in the lower continental crust.

Compared to the vast extent and enormous area of CGGC, the reported U-Pb ages are limited in number. The majority of them are whole-rock age of samples drawn mostly from the western part of the CGGC. Based on Rb–Sr whole-rock isochron age dating, monazite dating and U-Pb zircon dating, the CGGC has four phases of metamorphism [72]. The only emplacement of granitic rock was recorded in Daltonganj region; 1741 Ma [208], 1119 Ma [209], 975 Ma [210]. However, there is no study done on the Daltonganj regarding the metamorphism. In this study, the first time applies the monazite and U-Pb dating for emphasizes the age of emplacement and various metamorphic events.

Another major problem that needs to be investigated is the geochemical analysis of mafic granulites, pelitic granulite and high-grade gneisses. The purpose of this study is to identify the genetic evolution of these rocks, and geochemical characterization of metamorphic rocks is an essential feature to know the nature of protolith, the character of magma or tectonic environment for magma generation and Petrogenesis of these studied rocks.

A critical evaluation of the above problems needs a careful study of the metamorphic process and evolution of mafic granulites, pelitic granulites and high-grade gneisses. The present research aims to study the lithological and metamorphic mineral assemblages and study *P-T-t* paths of all three metamorphic rocks to unravel the relative metamorphic processes.