# THESIS CERTIFICATE

This is certified that the work contained in this thesis titled **"Petrological, geochronological and tectono-metamorphic evolution of granulite facies rocks of the Daltonganj (Palamau) Jharkhand, India"** submitted by "**Ravi Ranjan Kumar**" to the Indian Institute of Technology (BHU), Varanasi has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of Ph.D. Degree.

Varanasi – 221005

Date: 05/04/2021

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# DECLARATION BY THE STUDENT

I, **“Ravi Ranjan Kumar”**, certify that the work embodied in this thesis is my own bona fide work and carried out by me under the supervision of **“Prof. S. B. Dwivedi”** from July 26, 2016 to April 5, 2021, at the **“Department of Civil Engineering”**, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other’s work, paragraph, text, data, results, etc., reported in journals, books, magazines, reports dissertations, theses, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

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Ravi Ranjan Kumar

*Dedicated to my beloved family and respected supervisor*

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# List of Abbreviations

**AX** Activity-Composition

**BMB** Bihar Mica Belt

**BSE** Back Scattered image

**CGGC** Chhotanagpur Granite Gneiss Complex

**CHIME** CHemical Isochron MEthod

**CIS** Central Indian Shear Zone

**CITZ** Central India Tectonic zone

**DOB** Dalma Ophiolite Belt

**EDS** Energy-dispersive X-ray spectrometry

**EPMA** Electron microprobe analysis

**HFSE** High field strength element

**HREE** Heavy rare earth elements

**IBC** Isobaric Cooling

**ICP-MS** Inductively Coupled Plasma-Mass Spectrometry

**ITD** Isothermal Decompression

**LA-ICP-MS** Laser Ablation Inductively Coupled Plasma Mass Spectrometry

**LILE** large-ion lithophile element

**LREE** Light rare earth element

**MMB** Mahakoshal Mobile Belt

**NIB** Northern Indian Block

**NSMB** North Singhbhum Mobile Belt

**P-T** Pressure and temperature

**P-T-t** Pressure-Temperature-Time

**REE** Rare earth element

**SAED** Selected area electron diffraction

**SEM** Scanning electron microscope

**SIB** Southern India Block

**SMB** Sausar Mobile Belt

**SNNF** Son Narmada North Fault

**TEM** Transmission Electron Microscopy

**UHT** Ultra high-temperature

**XRF** X-ray fluorescence

# List of Mineral Abbreviations

**Ab** Albite

**Alm** Almandine

**Amp** Amphibole

**Ann** Annite

**An** Anorthite

**Ap** Apatite

**Aug** Augite

**Bt** Biotite

**Chl** Chlorite

**Cpx** Clinopyroxene

**Crd** Cordierite

**Di** Diopside

**Ged** Gedrite

**Grs** Grossular

**Grt** Garnet

**Gr** Graphite

**Hbl** Hornblende

**Ilm** Ilmenite

**Kfs** K-feldspar

**Ky** Kyanite

**Liq** Liquid

**Mag** Magnetite

**Mc** Microcline

**Mnz** Monazite

**Opx** Orthopyroxene

**Plg** Plagioclase

**Prp** Pyrope

**Qz** Quartz

**Sill** Sillimanite

**Sps** Spessartine

**Ts** Tschermakite

**Zrn** Zircon

# Preface

The east-west trending Central India Tectonic Zone (CITZ) is located in the middle of peninsular India, which is about 1500 km long and is considered as Proterozoic mobile belt. The CITZ is the suture zone of the Southern Indian Block (SIB) and the Northern Indian Block (NIB), which develops the Great Indian landmass during the Proterozoic period. The CITZ has three parts from west to east; the central mainland region is located among the Mahakoshal Mobile Belt (MMB) in the north and the Sausar Mobile Belt (SMB) in the south, the Chhotanagpur Granite Gneiss Complex (CGGC) situated at the east of the central region and the eastern most part is Shillong-Meghalaya Gneissic Complex (SMGC). The Monghyr-Saharsa Ridge and the South Purulia Shear Zone are bounded at the northern and southern periphery of the CGGC, respectively.

The Daltonganj area falls under the western edge of the CGGC, which covers a vast area (100,000 sq km) of eastern India. The CGGC is situated among the two mobile belts, the North Singhbhum mobile belt in the southern part and the MMB and Vindhyan sediments in the northwestern part of the CGGC. However, the western part is surrounded by the Gondwana fluviatile deposits. The Ganges alluvial covers the northern region, and the Rajmahal basalt bounds the northeastern part. The CGGC consists mainly of high-grade metamorphic terrain, with rocks ranging from amphibolite to granulite grade. The CGGC consists of mafic granulites, pelitic granulites, high-grade gneiss, khondalite, migmatites, leptynite, migmatites and meta-igneous rocks, which are intruded by a variety of mafic to ultramafic rocks like; tholeiitic basalts (Rajmahal Traps), gabbro-anorthosite, dolerite, syenite, along with felsic rocks granite, rapakivi granite, pegmatite, and aplite during the various geological time.

The study area around Daltonganj lies in the NW extremity of the CGGC within the Daltonganj (Palamau)-Hazaribagh-Dumka belt. The investigated area falls between latitude 23ºº54'50''N to 23º58'30''N and longitude 84º02'E to 84º06'30''E in the Survey of India Toposheet number 73A/1. The study area extends in the east up to Renukoot and in the NNW direction to Japala of Garhawa district. A thrust separates it to Vindhyan Supergroup, which lies in Sasaram. The study area is located 14 km away from Daltonganj in the southwestern part. The study area consists of mafic granulite, pelitic granulite, high-grade gneiss (garnet-cordierite-gedrite gneiss, garnet-cordierite-orthopyroxene gneiss), migmatitic granite gneiss, massive granite, khondalite (garnet-cordierite-sillimanite-graphite gneiss), amphibolite, dolomitic marble and dyke in the localities around Datam, Sokra, Dokra, Nawa, Mahawat-Muria, Kui, Rakh Pahar and Khatauni.

Textural associations of mineral phases, mineral composition and transmission electron microscopy (TEM) analyses of the rock samples are suggested that the three stages of gedrite. The bundles, prismatic and fibrous are three different forms of gedrites, which have been observed under the TEM images. TEM nanophotographs and selected area electron diffraction patterns show the distribution of metallic element position at the different lattice site. TEM analyses revealed that some of the clinopyroxenes have exsolution texture, where orthopyroxene occurs as thin lamellae within the porphyroblast of clinopyroxene. The measured lattice parameters of Opx and Cpx were; a = 18.4, b = 8.8, c = 5.3 Å and a = 9.4, b = 8.9, c = 5.4 Å respectively determined by electron diffraction pattern.

Electron microprobe analyses (EPMA) of minerals from the different mineral assemblages are used to observe the characteristics of mineral phases. The $X_{Mg}$ of garnet in the different rocks show the following trends: high-grade gneisses (0.21–0.30)

> mafic granulites (0.24–25) > pelitic granulites (0.17–0.23). The higher content of $TiO_2$ in biotite from mafic granulites (More than 4 wt%) is similar to other granulite facies terrains. Cordierite has a variable range of $X_{Mg}$, ranging from 0.604 to 0.795; higher values correspond to the high-grade gneiss, whereas in pelitic granulites included cordierite within garnet shows 0.78 and matrix cordierite shows 0.68. The $X_{Mg}$ ratio of hornblende ranges from 0.38 to 0.52, and $Al^{IV}$ and $Al^{VI}$ content varies from 1.453 to 1.875 and 0.0 to 0.478 p.f.u. respectively. Although in gedrite, the $X_{Mg}$ varies from 0.46 to 0.53 and it contains a significant amount of $Na_2O$, up to 1.95 wt%. In mafic granulites, orthopyroxene lies close to hypersthene and coexisting clinopyroxene plots within the diopside and augite field. The $X_{Ca}$ = (Ca/Ca+Na+K) ratio of plagioclase from mafic granulites range from 0.52 to 0.93.

The high-grade gneisses are classified on the basis of total alkali versus silica (TAS) plot; in this classification scheme, all of the garnet-cordierite-amphibole gneisses lie in the basalt field, and the remaining two garnet-orthopyroxene-amphibole gneisses fall in the basaltic andesite field. However, mafic granulite samples show basaltic nature, and pelitic granulites display diorite and monzonite, whereas few samples are gabbroic in nature. High-grade gneiss shows excellent availability of the compatible element (Cr, Ni, Co, V) and low $TiO_2$ suggests a mafic source rock or may be more possibility of mantle origin. The substantial depletion of K and Na is most pronounced if their protoliths are considered the mafic metavolcanic. Negative Nb and Sr anomalies suggest the involvement of subduction orogeny. Y–La–Nb triangular plot and Yb–Th discrimination diagram indicate the calc-alkaline basaltic nature of these gneisses developed at the island arc domain during subduction-related processes. The enhanced abundance of LREE and LILE (Th, Ta, U, Pb) is better interpreted due to enrichment by fluid-related metasomatism. High-grade gneiss shows calc-alkaline rich mafic fluids intruded in the pre-existing rocks and then emit its mafic components (Fe, Mg). In the process, the modal availability of the felsic component of pre-existing rocks decreases, and it signifies a 'restitic' origin of the studied gneisses. The mafic granulite shows high elemental concentrations of Mg, V, Cr, and Co suggest that they be derived from primary magmatic sources. The amount of HFSE (Y, U, Pb, Hf, Nb, Ta) is small, indicating that the rock is derived from the mafic source. Nb has negative anomalies that showed crustal contamination. The Zr vs Nb/Zr diagram confined that protolith of pelitic granulite encountered a subduction-related tectonic setting. The Y vs Nb and Rb vs (Y+Nb) tectonic discrimination diagram reveals that the protolith has an affinity towards the within plate granite (WPG). After establishing the relationship between the $(Y/Nb)_N$ vs $(Th/Nb)_N$ diagram, it is used to establish the discrimination between oceanic islands, continental crust and convergent margin rocks, and all samples are located in the convergent margin rocks field. In pelitic granulite, some sedimentary features have also been observed as overall enrichment of ∑REE may be due to immobile REE accumulation during the sedimentation; also, low content of Sr attribute to the leaching effect. Sr is depleted because they are highly mobile and are easily transported during sediment dehydration. Pelitic granulites have a high Rb and Ba content, as the feldspar is a significant host of Rb and Ba in terrigenous sedimentary rocks.

The *P-T* conditions of high-grade gneiss have been calculated by various conventional geothermobarometry. The garnet-orthopyroxene geothermometry suggests temperature lies between 735 and 809ºC, whereas garnet-cordierite and garnet-biotite exchange geothermometers reveal temperature ranges from 610 to 654ºC and 522 to 581ºC, respectively. However, garnet–cordierite–sillimanite–quartz geobarometer shows pressure lies between 6.9-7.43 kbar. Pseudosection modelling of high-grade gneiss in the NCKFMASH system using the software Perple_X shows the The pre-peak metamorphic stage was recorded between the range of 5.78–6.15 kbar and 600–622°C, and the first stage $Grt_1$ developed under pressure conditions of 6.70 kbar. The *P-T* condition of the peak metamorphism is at 8.65–9.42 kbar and 772–788°C. For the post-peak metamorphic stage, the mineral assemblage $Grt_3$-$Amp_3$-Crd-Bt-melt-Plg-Qz remains as orthopyroxene-free phase. This post-peak stage is confined at 5.71–6.18 kbar and 745–762°C, which is constrained by the isopleth lines of garnet ($X_{Mg}$) and cordierite ($X_{Mg}$). Various methods to constrain the *P-T* conditions of mafic granulites have been used, such as conventional and multi-equilibrium thermobarometry as well as forward thermodynamic modelling. Results from multi-equilibrium thermobarometry, using the software THERMOCALC, suggest that the mafic granulite's peak conditions at average pressure-temperature ($PT_{av}$) conditions of 6.7±1.19 kbar/ 814±60°C. In contrast, exsolution bearing opx-cpx minerals crystallised at a relatively lower temperature (772±14°C), determined by the conventional geothermometers. The peak to retrograde evolution of these mafic granulites is constrained through phase equilibrium modelling in the NCKFMASHTO model system. Phase equilibria results of peak conditions (i.e. 6.0-6.78 kbar and 775-808°C) are consistent for those obtained through multi-equilibrium and conventional thermobarometry, while the retrograde path is defined down to ~4.5 kbar and ~540°C. The same model system as mafic granulite is chosen for the pelitic granulites. The pseudosection is characterized by large high variance (F = 3-6) garnet-bearing fields. Garnet-biotite geothermometer is used to calculate temperature condition and the estimated temperature varies from 716 to 806°C, and garnet-biotite-plagioclase-quartz geobarometer inferred that the pressure lies at 8.47. However, garnet-cordierite geothermometer provides the temperature condition ranges from 661 to 717°C, whereas garnet-cordierite-sillimanite-quartz geobarometer was used to estimate the pressure and it ranges from 5.35 to 6.24 kbar.

The *P-T* condition of pre-peak metamorphism is found at ~3.2 kbar and ~620ºC, and the *P-T* condition of this stage is derived by the $X_{Mg}$ isopleth contour lines of garnet and cordierite which are similar to the analyzed microprobe data. The *P-T* stability field for the peak assemblage (grt + bt + plg + sill + kfs + melt + ilm + qz) ranges from 7.40 to 9.10 kbar and 815 to 835°C. Tetravariant fields dominate the pseudosection. The textural interpretation reveals that the retrograde metamorphic assemblage in *P-T* pseudosection contains grt + crd + bt + plg + kfs + melt + ilm + qz + mag, which are stable at pressure ~4.0 kbar and temperature ~790°C. Our results have two fold implications: (i) they show how the integrating of different geothermobarometric methods is the best proxy to constrain the evolution of high-grade metamorphic rocks, and (ii) they pavement to new constraints on the Paleoproterozoic to Neoproterozoic evolution of the CGGC.

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 1.87–1.66 Ga, the $M_2$ is considered to happen between 1.55–1.45 Ga, the $M_3$ varies from 1.2–0.93 Ga, and the last $M_4$ event lies between 0.87–0.78 Ga. The first metamorphic event has been recorded from the pelitic granulites at ~1680–1580 Ma; previously, their protolith must have derived from the different sources which contain the variable age domains ~2400 Ma, ~2000 Ma ~ 1800–1700 Ma. The geochronological age of detrital zircon demarcates the protolith of pelitic granulites and their origin source. It has inferred that the NW CGGC area's pelitic granulite underwent a progressive phase of tectonothermal processes where initially occurrence of crustal thickening ($M_1$) followed by quick exhumation of the crustal lithosphere ($M_2$), these both processes indicate that collision or subduction-related tectonic processes. Mafic granulites show all the age data gathered near the 1600 Ma, with two ages lying over the Concordia line. However, the weighted average age plot shows 1629±6 Ma (MSWD=1.4), validly constraining the magmatic emplacement event. The EPMA analysis of high-grade gneisses produced three age population at 1424 ± 64 Ma, 972 ± 28 Ma and 855 ± 31 Ma with 95% confidence, it indicates that these ages are in the vicinity of the Mesoproterozoic and Neoproterozoic ages.

It has been observed the Earth's evolutionary history must have been a cycle of multiple stages for the accretion and breakup of a supercontinent. The Columbia supercontinent's amalgamation took place between ~2000 Ma to ~1800 Ma, and further breakdown process began after ~1500 Ma. The Indian peninsular shield has preserved a strong signature of the Columbia assembly. The formation of Rodinia supercontinent was started from the Grenvillian orogeny (~1100–900 Ma). The CGGC preserves the age of 1100–900 Ma, showing evidence of a Grenvillian orogeny, and suggesting that the Grenvillian orogeny suture was possessed by the CGGC of India.