Metamorphic evolution of granulite facies rocks of areas around Makrohar (Singrauli), Madhya Pradesh, India

Thesis submitted in partial fulfillment for the
Award of Degree

Doctor of Philosophy

By

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Dedicated to my beloved family and respected supervisor

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November, 2023

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DECLARATION BY THE CANDIDATE

I, **Vikas Pandey**, certify that the work embodied in this thesis is my own bonafide work and was carried out by me under the supervision of Prof. S.B Dwivedi from July 2017 to November 2023, 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.

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It is certified that the above statement made by the student is correct to the best of my/our knowledge.

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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
SEM	**:**	Scanning electron microscope
SIB	**:**	Southern India Block
SMB	**:**	Sausar Mobile Belt

SNNF	**:**	Son Narmada North Fault
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
Grs	**:**	Grossular
Grt	**:**	Garnet
Gr	**:**	Graphite
Hbl	**:**	Hornblende
Ilm	**:**	Ilmenite
Kfs	**:**	K-feldspar
Ky	**:**	Kyanite
Liq	**:**	Liquid
Mag	**:**	Magnetite
Ml	**:**	Melt
Mnz	**:**	Monazite
Opx	**:**	Orthopyroxene
Pl	**:**	Plagioclase
Py	**:**	Pyrope
Qz	**:**	Quartz
Sil	**:**	Sillimanite

Sps	**:**	Spessartine
Ts	**:**	Tschermakite
Zrn	**:**	Zircon

PREFACE

The Chhotanagpur Granite Gneiss Complex (CGGC) is a region of high-grade metamorphic basement with metasedimentary enclaves and mafic to ultramafic rocks. It covers about 100,000 km^2 and is located at the eastern extension of the Central India Tectonic Zone (CITZ). The CGGC terrain is bounded in the north by the Mahakoshal Mobile Belt and in the south by the North Singhbhum Mobile Belt (NSMB). The most prominent rock types within the CGGC are granitic gneisses, migmatites, and amphibolites. The Monghyr-Saharsa Ridge and the South Purulia Shear Zone are bounded at the northern and southern periphery of the CGGC, respectively. Chhotanagpur Granite Gneiss Complex CGGC consists of granite gneisses and migmatites with enclaves of metasedimentary and metaigneous rocks. The study area around Makrohar lies in the northwestern extremity of Chhotanagpur Granite Gneiss Complex (CGGC) and occurs as a tongue parallel to the Son Narmada South Lineament. The Makrohar granulite belt comprises high-grade metamorphic rocks including pelitic granulites, mafic granulites, calc-silicate granulite, amphibolites, garnet-bearing gneisses, dolerite, andmetabasalt are exposed as major rock types.

Microscopic investigations of the studied rock samples have revealed distinct types of mineral assemblages in five rock types such as**:** Garnet-cordierite-biotite-sillimanite- plagioclase-illmenite-quartz in pelitic granulites; garnet-biotite-plagioclase-illmenite -quartz- k-feldspar in garnet-bearing gneisses; orthopyroxene-clinopyroxene-amphibole-plagioclase- biotite-quartz-ilmenite in mafic granulites; garnet- clinopyroxene-plagioclase-sphene-quartz- clinozoisite in calc-silicate granulites and garnet- clinopyroxene-amphibole-plagioclase- biotite-quartz-ilmenite in amphibolites. Electron microprobe analyses (EPMA) of minerals from the different mineral assemblages are used to observe the characteristics of mineral phases. Garnet compositions range between 24.35 and 84.86 mol% almandine, 0.34 to 17.93

mol% pyrope, 3.17 to 73.25 mol% grossularite, and 1.97 to 3.98 mol% spessartite. Garnet X_{Mg} in different rock types varies from 0.01 to 0.28, exhibiting trends: garnetiferous amphibolite > garnet-bearing gneisses > pelitic granulites > calc-silicate granulites. Cordierite shows X_{Mg} ranging from 0.63 to 0.66, with traces of Na_2O (0.46–0.89 wt%) and K_2O (0.04–

0.16 wt%). Biotite X_{Mg} varies widely (0.30–0.69) influenced by Ti and Al^{VI} occupancy in the octahedron, with a notable decrease in X_{Mg} as Ti increases. X_{Mg} of amphiboles vary from

0.38 to 0.71, while amphibole's Al^{IV} and Al^{VI} content vary (0.32–1.45 and 0.13–0.60 p.f.u., respectively). Analyzed pyroxenes plot on a $CaSiO_3$-$MgSiO_3$-$FeSiO_3$ diagram, with orthopyroxene close to hypersthene and coexisting clinopyroxene within the diopside and augite field in mafic granulites, and the hedenbergite field in calc-silicate granulites. Orthopyroxene and clinopyroxene X_{Mg} range between 0.44–0.49 and 0.29–0.70, respectively, with relatively lower Al_2O_3 content (0.32–0.69 wt%) in the investigated areas compared to other terrains.

EPMA monazite dating has delineated two distinct age ranges for monazite: 1529 to 1743 Ma and 874 to 1111 Ma from pelitic granulites, while garnet-bearing gneiss preserves ages from 822 to 1014 Ma. Weighted mean age distributions obtained using the ISOPLOT program (Figure 5.8a–d) depict a metamorphic peak at an estimated 1655 ± 30 Ma (n = 14, MSWD = 4.3) and a retrograde metamorphism at 910 ± 31 Ma (n = 19, MSWD = 9.3). Geochemical examination of metabasics show significant variation in major oxide composition. The Zr/Ti vs Nb/Y diagram places garnetiferousamphibolites in the sub-alkaline basalt category and mafic granulites in the basaltic-andesite field, signifying characteristics of both spreading and subduction tectonics. Analysis of immobile trace elements suggests minimal contamination from the Earth's crust in the formation of these rocks. Discrimination diagrams (Th/Nb vs Ba/Nb, Nb/Th vs Zr/Nb) suggest metabasics associated with arc-like settings,

aligning with subduction influences. These samples resemble intra-oceanic arc basalt and arc basalt fields, indicating their formation in active island arc margins related to subduction during orogenic events. Evidence suggests their formation during subduction and arc-related settings, contributing toNeoarchean collisional tectonism. These metabasic patches underwent metamorphism before and during peak conditions and interacted with fluids derived from subduction, resulting in geochemical alterations. Retrograde metamorphic processes occurred during their exhumation.

Multiple classic geothermobarometry techniques, like garnet–biotite and garnet– cordierite thermometers, were used to gauge temperature and pressure in pelitic granulites (Grt-Crd-Bt-Sil-Pl-Qz). For instance, in pelitic granulites, Gt-Bt thermometry suggested prograde temperatures around 690 ± 62 ºC at a consistent pressure of 6 kbar. Meanwhile, the garnet-biotite-plagioclase-quartz geobarometer (GBPQ) indicated pressures of 6.2 kbar at 600ºC. In garnet-bearing gneisses, Gt-Bt thermometry indicated temperatures of 566 ± 33 °C at 6 kbar, while GBPQ suggested 5.11 kbar at 600°C. Similarly, Grt-Crd thermometrydisplayed post-peak temperatures of 575 ± 28 ºC at 5 kbar, whereas garnet-cordierite- sillimanite-quartz geobarometry showed pressures of 5.55 ± 0.73 kbar at 600ºC. Overall, the average conditions involving garnet, biotite, plagioclase, cordierite, and sillimanite werearound 679 ± 63 °C/5.3 ± 0.9 kbar considering (H_2O) = 1. For calc-silicate granulites, conventional garnet–clinopyroxene exchange geothermometers and garnet–clinopyroxene–plagioclase–quartz geobarometers determined temperature and pressure conditions. Garnet- clinopyroxene exchange thermometry indicated temperatures of 675 ± 89 ºC at 7 kbar pressure. The average conditions with garnet, clinopyroxene, plagioclase, epidote, and quartz were approximately 624 ± 97 °C/5.6 ± 0.8 kbar assuming (H_2O) = 1. Mafic granulite pressure-temperature conditions were evaluated using orthopyroxene–clinopyroxene conventional exchange geothermobarometers. Peak temperatures were around 887° ± 62°C at6 kbar, and peak stage pressures

were estimated at 6.15± 0.3 kbar. Post-peak metamorphic stage pressures, derived from the aluminium-in-amphibole barometer, were estimated at 2.28 ± 0.15 kbar. For garnetiferous amphibolites, garnet–clinopyroxene conventional geothermobarometers determined peak temperatures at approximately 643 ± 51 ºC at 5.0 kbarpressure. Post-peak metamorphic stage pressures were estimated at 4.30 ± 0.28 kbar for garnetiferous amphibolites and 5.26 ± 0.21 kbar for garnet-absent amphibolites. In the study, P–T pseudosections were computed for various granulite types using different chemical systems. The pelitic granulite displayed equilibrium, peak, and retrograde mineral assemblages at distinct temperature and pressure ranges. Similarly, the mafic granulite exhibited mineral assemblages across varying P–T conditions. Isobaric T–X (CO_2) pseudosections for calc-silicate granulites constrained CO_2 mole fractions and temperature conditions for specific mineral assemblages. Garnetiferous amphibolites were also analyzed, showing distinct metamorphic stages marked by specific mineral compositions at different P– T conditions. The peak metamorphic stage was characterized by higher P–T settings, while the post-peak stage had different mineral compositions at lower P–T conditions, as delineated by amphibole and biotite isopleths. Overall, various traditional geothermobarometry methods were employed to estimate temperature and pressure conditions for different rock types, providing insights into their metamorphic histories and mineral assemblage stability ranges at different stages. Three thermodynamic approaches were employed to establish temperature and pressure (P–T) conditions: traditional geothermobarometry, multi-equilibrium geothermometry, and forward modeling. Across garnet-bearing gneisses, granulites, and amphibolites in the study area, these methods produced similar results. The P-T-t paths delineate a rocks journey through P–

T space over time. In the case of pelitic granulites, thermodynamic calculations and pseudosection modeling revealed a clockwise P-T-t path. At the peak stage, the rock underwent burial, evident in temperature shifts indicating increased pressure. This phase witnessed high-pressure conditions, ranging from 7.40 to 6.70 kbar, and temperatures between 760 to 740°C. Subsequently, the rock followed an almost isothermal decompression path (ITD) into the post-peak stage, characterized by garnet and cordierite, at pressures of 4.80 to 4.60 kbar and temperatures from 730 to 725°C. Similar clockwise P-T-t paths were identified in garnetiferous amphibolites. At the peak stage, the rock exhibited a mineral assemblage stable at 7.3–7.1 kbar/810–790ºC. Post-peak conditions showcased different minerals at 4.5–4.1 kbar/610–590ºC due to decompression, indicating exhumation. Mafic granulites in the Makrohar area also displayed a clockwise P-T path. Peak temperatures were recorded at 887° ± 62°C at 6 kbar, while post-peak conditions were estimated at 2.28 ± 0.15 kbar/593 ± 50°C. Two distinct metamorphic events were identified from the Paleoproterozoic to Neoproterozoic periods, delineating the complex evolution of the CGGC terrain. Monazite dating revealed two ages for the pelitic protolith at ~1655 Ma and ~910 Ma, with only pelitic granulites preserving the peak metamorphic event (M1) during Late Paleoproterozoic (~1655 Ma) and exhumation resulted into retrograde metamorphism during Neoproterozoic (~910 Ma) era. Several magmatic intrusions documented in the CGGC indicated a diverse geological history involving subduction and collision-related tectonic processes. The geodynamic interpretation of the study area suggests interactions between Archean cratons, rift development, sedimentation, and subduction-related tectonics. The CGGC metamorphic events offer insights into crustal thickening, and subduction processes, shaping

the region geological history during the Paleoproterozoic era and exhumation during Neoproterozoic era. These findings align with the formation of supercontinents and various orogenic events, contributing to a broader understanding of continental movements and geological changes across different geological eras.