Petrology and tectono-metamorphic evolution of amphibolite to granulite facies rocks of the Bundelkhand Craton, Jhansi, India

Thesis Submitted in partial fulfilment

for the Award of Degree

Doctor of Philosophy

By

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This is certified that the work contained in this thesis titled **"Petrology and tectono-metamorphic evolution of amphibolites to granulite facies rocks of the Bundelkhand craton Jhansi, India"** submitted by "**Pratigya Pathak**" 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.

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I, **"Pratigya Pathak"**, 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, 2017 to July 26, 2022, 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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Pratigya Pathak

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List of Abbreviations

AX Activity-Composition

BSE Back scattered image

BuC Bundelkhand craton

BTZ Bundelkhand Tectonic Zone

CBGB Central Bundelkhand Greenstone Belt

CIS Central Indian Shear Zone

CITZ Central India Tectonic zone

E-MORB Enriched mid-ocean ridge basalt

EPMA Electron microprobe analysis

GPS Global Positioning System

GBF Great Boundary Fault

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-MC Laser ablation multi-collector inductively coupled plasma

LILE Large-ion lithophile element

LREE Light rare earth element

MMB Mahakoshal Mobile Belt (MMB)

N-MORB Normal mid-ocean ridge basalt,

OIB Ocean island basalt.

P-T Pressure and temperature

P-T-t Pressure-Temperature-Time

REE Rare earth element

SMB Southern Sausar Mobile Belt

SBGB Southern Bundelkhand Greenstone Belt

SEM Scanning electron microscope

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

Mc Microcline

Mnz Monazite

Opx Orthopyroxene

Plg Plagioclase

Prp Pyrope

Qz Quartz

Sill Sillimanite

Sps Spessartine

Ts Tschermakite

Zrn Zircon

Preface

The Indian subcontinent is divided into two Archean cratonic blocks by the Central Indian Tectonic Zone (CITZ), which runs in the ENE–WSW direction; the northern and southern cratonic blocks. The southern Indian block includes Bastar, Dharwar, and Singhbhum cratons, while the northern Indian block includes the cratons of Bundelkhand and Aravalli. The Great Boundary Fault is the main boundary that divides the northern Indian block into two blocks. The eastern block is known as the Aravalli cratonic block, and the western block is known as the Bundelkhand cratonic block.

The Bundelkhand Craton (BuC) is of semi-circular shape, having an area of about 45,000 km^2 of which only 26,000 km^2 is exposed as an outcrop between 24°11' to 26°27'N and 78°10' to 81°24'E and the rest is covered by alluvium of the Ganga basin. In the west, the BuC is fringed by the Great Boundary Fault (GBF), trending NE–SW, in the north-west by the Gwalior Basin, in the south by the Sonarai Basin, and by the Bijawar marginal basins in the south-east. The Vindhyan Supergroup overlies the marginal basins and surrounds the BuC on three sides. The Gangetic alluvial plains cover the craton on the northern side but the southwestern part is hidden beneath the Deccan basalts. The BuC is divided into two large E-W trending greenstone belts, the northern belt and the southern belt, which contain supracrustal units tectonically embedded with TTGs. The northern belt, also known as the Central Bundelkhand Greenstone belt (CBGB), runs through Mauranipur, Kuraicha, and is exposed in the middle of BuC. Metamorphosed basic rocks, felsic volcanic rocks, metasedimentary rocks (BIFs), pink granites and granodiorites are exposed here. The southern belt stretches from Madaura to Girar and contains a sequence of ultramafic-mafic volcanic rocks, quartzite, BIF, chlorite schist, and marble.

The study area around Mauranipur and Babina lies within the Central Bundelkhand Greenstone Belt. The investigated area falls between latitude 25º09'45" N to 25º15' N, and longitude 78º25' S to 78º35’S in Babina, as well as latitude 25º11'54" N to 25º14'48" N, and longitude 79º05' S to 79º09'35" S in Mauranipur of the BuC. The study area mainly covers the village of Kuraicha, the Saprar river section, and the Sukwa Dam area. The study area consist of TTGs, banded magnetite quartzite (BMQ), quartz reefs ultramafic rocks, amphibolites, granitoids, pelitic granulites, garnet-biotite gneiss, garnetiferous amphibolite, quartzite, granitic gneiss, and migmatite.

Microscopic investigations of the studied rock samples have revealed distinct types of mineral assemblages in three rock types such as**:** Garnet-orthopyroxene-cordierite-biotite-sillimanite-plagioclase-illmenite-quartz, Garnet-orthopyroxene-biotite-sillimanite-plagioclase-illmenite-quartz, Garnet-biotite-sillimanite-plaioclase-illmenite-quartz, Garnet-cordierite-biotite-sillimanite-plagioclase-illmenite-quartz, in pelitic granulites; garnet-biotite-plagioclase-quartz-k-feldspar in garnet-biotite gneisses and garnet-amphibole-plagioclase-biotite-quartz-ilmenite, clinopyroxene-amphibole-plagioclase-epidote-rutile-ilmenite-quartz in amphibolites.

Electron microprobe analyses (EPMA) of minerals from the different mineral assemblages are used to observe the characteristics of mineral phases. The pyrope content of garnet from the different rock types indicates the following trend: pelitic granulites>garnet-biotite gneisses > amphibolites. The X_{Mg} values range between 0.40 and 0.47 and correspond to hypersthenes in pelitic granulites. The X_{Mg} value of cordierite varies between 0.61 and 0.69 in pelitic granulites. The X_{Mg} in biotites shows the following trend: pelitic granulites (0.38 to 0.61) > amphibolites (0.45 to 0.49) >garnet-biotite gneisses (0.31 to 0.44) >. The clinopyroxenes of amphibolites are plotted in the diopside field. The X_{Mg} value of clinopyroxene ranges from 0.59 to 0.65. The amphiboles from amphibolites seize a place in the Tschermakite domain. They have X_{Mg} values from 0.69-0.89. The amphibole contains (p.f.u) Na = 0.276–0.497, K = 0.022–0.062, and Ti = 0.031–0.054.

Geochemical analysis of pelitic granulites reveals much about the protoliths and their geodynamic settings. The total alkali-silica diagrams of pelitic granulites show diorite, granodiorite, and quartz–monzonite fields, showing that the protolith of pelitic granulites came from a variety of sedimentary provenances. In the primitive-mantle-normalized trace-element spider diagram, positive anomalies are detected for Ba, K, Pb, Nd, Sm, Gd, and Y, but significant negative anomalies are detected for high field strength elements (HFSEs) such as Nb, Ta, and Ti, indicating a characteristic feature of subduction orogeny. A decrease in Nb and Ti concentrations confirmed an island arc setting. All samples have positive Eu anomalies in the chondrite-normalized REE patterns. The pelitic granulites acquire the domain of felsic igneous provenance when plotted in the discrimination function diagram. The TiO_2 versus Zr plot confirms this as all the pelitic granulite samples are again plotted in the felsic igneous rocks field. The Zr against Nb/Zr curve suggests that the protolith of pelitic granulites was exposed to a subduction-related tectonic setting. The Y vs Nb plot suggests that the pelitic granulite protolith came from volcanic arc granite (VAG) and a syn-collisional tectonic environment. The TAS diagram for Grt-Bt gneisses displays a contracting protolithic nature varying from diorite, granodiorite, and granite. The primitive mantle normalized spider diagram of Grt-Bt gneisses reveals depletion of Mo, Ho, Tm, Ba, K, Nb, Sr, Hf, Ti, and an abundance of Rb, Th, U, La, Ce, Nd, and Gd. The REE chondrite normalized patterns show enriched LREE and depletion in HREE with high to moderate $(La/Yb)_N$. The negative anomaly of Nb and Ti indicates that a subduction tectonic setting has occurred in the BuC. The Grt-Bt gneisses have high SiO_2 and low Cr and Ni concentrations, interpreted as protoliths derived from the hydrous thickened lower crust or may be due to crustal contamination with ascending partial melt. The Y vs Nb and (Y+Nb) vs Rb tectonic discrimination diagrams show that the protolith of most Grt-Bt gneisses had an affinity towards the volcanic arc granite (VAG), whereas the M-1C sample shows within plate granite (WPG) affinity. Total alkali versus silica (TAS) plot used to classify the amphibolites reveals that all of the garnet-bearing amphibolites are plotted in the basalt region; three garnet-absent amphibolites are projected into the basaltic field, and three are projected into the basaltic andesitic field. The Zr/Ti vs Nb/Y diagram reveals that all garnet-bearing amphibolites plot in the basaltic andesite field, and garnet-absent amphibolites plot in the sub-alkaline basalt field. A decrease in Nb and Ti concentrations has validated an island arc setting. Light rare earth element (LREE) enrichment is higher in garnet-bearing amphibolites than heavy rare earth element (HREE) enrichment (La_N/Lu_N = 2.85–7.21), with a little negative Eu anomaly (Eu_N/Eu_{N*} = 0.76–0.86). However, garnet-absent amphibolites have a slight enrichment of LREE relative to HREE (La_N/Lu_N = 1.20–2.13) with a slight positive Eu anomaly (Eu_N/Eu_N* = 1.00–1.13). The sub-parallel REE patterns show that a phase of compositional variation dominated crystal fractionation. The studied amphibolites have moderately enriched LREE and LILEs (Ba, Rb, Th, U, and K) but negative Nb, Ta, Zr, and Ti anomalies. Garnet-bearing amphibolites show 4.45–5.04 ppm, and garnet-absent amphibolites have low Th (0.65–1.25 ppm), indicating little crustal contamination or no Th addition in amphibolites. The Th/Nb vs Ba/Nb discrimination diagram shows a clear influence of the shallow subduction component on garnet-bearing and garnet-absence amphibolites, but no sign of deeper subduction component influence. The Nb/Th vs Zr/Nb tectonic discrimination diagram suggests an arc-like setting for the amphibolites from the Babina and Mauranipur regions; whereas the Zr vs Zr/Y plot suggests an island arc setting.

The various conventional geothermobarometry pairs have been used for evaluating the temperature and pressure conditions for pelitic granulites. the Grt-Bt thermometry provides prograde temperatures of 640ºC–692ºC for garnet core and biotite included in garnet and 605ºC–660ºC for garnet and matrix biotite, whereas pressure of 5.79 kbar at 650ºC using the garnet-biotite-plagioclase-quartz geobarometer (GBPQ). Similarly, Grt-Opx thermometry provides peak temperatures of 762ºC–845ºC for core values and 712ºC–825ºC for rim values of garnet and orthopyroxene and peak pressure has been observed as 6.49–7.49kbar at 800ºC using the garnet–orthopyroxene–plagioclase-quartz (GOPQ) barometer. However, the garnet-cordierite geothermometer provides the retrograde temperature of 508ºC–604ºC for garnet core and cordierite included in garnet and 489ºC–588ºC for garnet and matrix cordierite, whereas garnet-cordierite-sillimanite-quartz geobarometer was used to estimate the pressure and it ranges from 4.24 to 4.89kbar. For the Grt-Bt gneiss, the garnet–biotite exchange geothermometer was applied to inclusion and matrix biotite. It provides 595ºC–656ºC from biotite present as inclusion in garnet and 578ºC–618ºC from matrix biotite and pressure of 5.0 kbar at 600ºC using the garnet-biotite-plagioclase-quartz geobarometer (GBPQ). In the garnet-bearing amphibolites, the garnet-biotite pair was used to define a temperature of the pre-peak stage from garnet and biotite rim compositions, where biotite exists as inclusion within the garnet; it shows 539 to 597°C at 5.5 kbar. The Grt–Cpx geothermometer can measure the temperature of the peak metamorphic stage as 834ºC and 760ºC at 7.0 kbar pressure. Simultaneously, GCPQ (Grt-Cpx-Pl-Qz) geobarometry calculated 7.42 and 6.46 kbar pressures at a constant temperature of 800ºC. The post-peak temperature condition is 556ºC at 4.5 kbar pressure, as measured by an Amp-Pl geobarometer. The pressure condition for post-peak metamorphism is estimated to be 5.04 kbar at 550ºC using an Amp-Pl-Qzgeobarometer model. *P–T* conditions in garnet-absent amphibolites are 517ºC and 685ºC from the rim and core compositions, respectively, and model of the Amp-Pl-Qzgeobarometer predicts 5.21 and 6.78 kbar pressure from the rim and core portions.

Pseudosection modeling of the pelitic granulites in the NCKFMASHTO system with the help of Perple_X ver.6.9.0 software shows that the *P–T* condition of pre-peak metamorphism is found in the range of 4.00–5.12 kbar and 560–600°C. The peak assemblage has a *P–T* stability field ranging from 6.40–6.62 kbar and 700–730°C. The retrograde metamorphic assemblage is stable in the range of 4.20–4.40 kbar pressure and 670–692°C temperature. The *P–T* pseudosection for the garnet-biotite gneisses represented a peak metamorphic assemblage and occupied a field in the *P–T* range of 6.35–6.75 kbar and 755–780ºC. Similar mineral assemblage has been observed under lower pressure and temperature conditions. The melt phase does not exist here, whereas H_2O is available as a component. Their *P–T* condition is comparatively low, between 4.80–5.28 kbar and 718–735ºC. The assumed value of H_2O and O_2 has been defined by the constructed T-X(H_2O) and T-X(O_2) pseudosection at a fixed pressure of 5.0 kbar for sample B-6. The value of H_2O was determined based on the variation of H_2O in the bulk rock composition ranging from 0.0 to 6.0 mol%, whereas O_2 was calculated based on the variation of O_2 in the bulk rock composition ranging from 0.0 to 1.0 mol%. The meta-stable, pre-peak, and post-peak mineral assemblages are depicted in the T-X(H_2O) diagram with the appropriate amount of X(H_2O) = 4.89 mol%. Similarly, the T-X(O_2) diagram reveals that a 0.50 mol% amount is appropriate, denoted by a large black dashed line. Therefore, 4.89 mol% of H_2O and 0.50 mol% of O_2 are reliable amounts for further *P–T* pseudosection calculation. The *P–T* pseudosection for garnet-bearing amphibolites in the NCKFMASHTO system shows a meta-stable mineral assemblage that may have formed before pre-peak metamorphism and is dominated by chlorite. This acquired phase is stable in the *P–T* range 3.2–6.2 kbar/420–550ºC, and amphibole and chlorite isopleths further narrow the *P–T* range to 4.35–4.1 kbar/515–475ºC. The pre-peak metamorphic assemblages are defined as Grt-Amp-Chl-Bt-Pl-Qz-Ilm-H_2O and are stable in the *P–T* conditions of 6.2–7.5 kbar and 570–595ºC. The *P–T* conditions for garnet-bearing amphibolite's peak metamorphic stage are 7.4–6.8 kbar/805–760ºC. The post-peak metamorphic assemblage is stable at a *P–T* range of 6.15–4.0 kbar and 750–580ºC. The

P–*T* pseudosection plotted for the garnet-absent amphibolites in the NCFMASHTO system shows that the pre-peak metamorphism occurs in the *P*–*T* range of 4.0–6.4 kbar/400–450ºC. Peak metamorphic assemblage is stable at 7.4–7.0 kbar/810–785ºC. The post-peak assemblage is denoted as Amp-Pl-Qz-Ilm-H_2O, and amphibole and plagioclase isopleths are used to define the *P*–*T* conditions of 4.0–3.1 kbar/710–620ºC.

The clockwise *P-T-t* path has been obtained from orthopyroxene-bearing pelitic granulites by thermodynamic calculation and pseudosection modelling. The pre-peak metamorphic stage was recorded between 4.00–5.12 kbar and 560–600°C. This rock undergoes further burial depth, and with a significant change in temperature conditions, this situation indicates an increase in pressure; hence it demarcated the peak metamorphic stage. The *P*–*T* conditions of this stage reached a high-pressure condition with a range of 6.40–6.62 kbar and 700–730°C, following a nearly isothermal decompression (ISD) path to achieve the post-peak stage. The post-peak stage was documented by the appearance of Crd, and Grt, and *P*–*T* conditions were reached at 4.20–4.40 kbar and 670–692°C. The geodynamic significance of the peak (high-pressure) metamorphism from the Mauranipur region of the CBGB suggests subduction and exhumation in a single cycle as a complete clockwise *P-T-t* path. The garnet-biotite gneisses are characterized by the mineral assemblage garnet + biotite + plagioclase + k-feldspar + ilmenite + quartz + melt. *P*–*T* pseudosection modelling shows mineral assemblage Grt-Bt-Pl-Kfs-melt-Ilm-Qz to be stable at the *P*–*T* range of 6.35–6.75 kbar and 755–780ºC. The clockwise *P*–*T* path is constrained by the *P*–*T* pseudosection of garnet-bearing amphibolite. This *P*–*T* path generates three prominent metamorphic assemblages, as well as a previously developed meta-stable mineral assemblage. The meta-stable mineral assemblage Amp-Chl-Bt-Pl-Qz-Ilm appears at the 4.35–4.1 kbar/515–475ºC *P*–*T* condition, suggesting a primitive mineral assemblage. Garnet was not visible at this temperature, but as it rises, it formed a unique mineral assemblage Grt-Amp-Chl-Bt-Pl-Qz-Ilm, which is stable in a narrow region with a *P*–*T* range of 6.5–6.25 kbar/590–580ºC. This assemblage forms under amphibolite facies conditions during the pre-peak metamorphic stage. Later, the Babina region experienced the burial tectonism, which was characterized by a continuous increase in pressure and temperature, and the amphibolites underwent peak metamorphism until the granulite facies metamorphism, characterized by the mineral paragenesis Grt-Amp-Cpx-Bt-Pl-Qz-Ilm-H_2O, and this field is stable at 7.4–6.8 kbar/805–760ºC. The mineral assemblage of the post-peak metamorphic stage Amp-Bt-Pl-Qz-Ilm, is stable at a *P*–*T* range of 4.75–4.45 kbar/615–585ºC, which acquires a Cpx and Grt free field. This post-peak stage occurred after the peak stage as a result of a decompression process that resulted in a decrease in pressure conditions, also known as isothermal cooling, implying that this stage may have developed as a result of decompression and subsequent exhumation of amphibolites on the surface.

The present study proposes a geodynamic model of the BuC based on the *P*–*T* conditions, geochemical analysis and geochronology of the pelitic granulites, garnet-biotite gneisses and amphibolites from the BuC. Both amphibolites register a clockwise path with peak metamorphism, followed by prograde and then retrograde metamorphism, showing three distinct compositions in the three stages of amphiboles. The protoliths of both amphibolites from the Mauranipur and Babina regions were formed by subduction-related tectonic settings and further affected by various thermal and collisional events. The studied amphibolites exist as enclaves and intrusive bodies and have undergone various metamorphic events, which are schematically represented as a plausible geodynamic model for three different stages. Ur is the oldest known Archean supercontinent, having formed 3.0 Ga ago by joining the Indian subcontinent's Dharwar and Singbhum cratons, South Africa's Kaapvaal craton, and Western Australia's Pilbara. Based on the age data and geodynamic settings of the Archean rocks reported from these cratons, it seems that the Bundelkhand, the Aravalli, and the Western and Eastern Dharwar Cratons appear to have been portions of the Kenorland Supercontinent in Archean times. In the Meso-Neoarchean period (2.9–2.7 Ga), subduction-accretion processes gave birth to the active expansion of the continental crust in the northern portion of the Kenorland supercontinent, whilst plume processes and subduction processes prevailed in the southern section. This evidence supported that the Mesoarchean subduction-accretion processes in the BuC were similar to those of the Karelian Craton and the Superior Province in the northern half of the Kenorland supercontinent. In the Neoarchean (ca. 2.6 Ga), the core of the supercontinent was formed, and until then, the crust of the southern part of the supercontinent continued to grow during subduction and accretion processes in the Bundelkhand, Aravalli and Western and Eastern Dharwar Cratons.