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

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By

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CHAPTER - 10

SUMMARY AND CONCLUSION

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. Among the many Archean cratons of India, BuC has perhaps the most complex evolutionary history. It has been broadly agreed that many micro-blocks are united to form the basement of the BuC, which is of the Archean age. 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. BuC comprises Bundelkhand gneissic complex (BnGC), Bundelkhand metavolcanic and metasediments (BMM), Madawara igneous complex (MIC), Bundelkhand granitoid (BG) of different episodes, Quartz reef (QR), Mafic dyke swarms (MDS), Banded Iron Formations (BIFs).

The BuC is divided into two large E-W trending greenstone belts, the northern belt and the southern belt, both of which contain supracrustal units that are tectonically imbedded 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. This belt stretches from Babina in the west to Mahoba in the east. This greenstone belt is well exposed in the Babina and Mauranipur areas and contains metamorphosed basic rocks of the Paleo-Mesoarchean age, felsic volcanic rocks of the Mesoarchean age, and metasedimentary rocks (BIFs). The Babina and Bhauti areas in the CBGB contain felsic volcanic rocks of 2.542–2.622 Ga. According to existing geochronological data, ultramafic-mafic magmatism marks the beginning of the CBGB around 2.780 Ga, and felsic volcanism marks the termination of the CBGB around 2.542 Ga.

The CBGB region comprises high-grade metamorphic rocks such as gneisses, pelitic granulites, amphibolites, TTGs and other high-grade rocks. The pelitic granulites are present in the vicinity of TTG rocks and show a mixture of leucocratic and melanocratic domains in outcrop. Pelitic granulites are massive and medium to coarse-grained with a grey to pinkish color due to the abundance of garnet with a greasy appearance and granulitic texture. The garnet-biotite gneisses typically show bands of dark and light-coloured minerals and are medium to coarse-grained. Various structural features have been observed in garnet-biotite gneisses, such as folding, faulting, and augen-tail structure. Amphibolites are present as enclaves within the TTG gneisses and felsic granitoids; however, they have also been reported from the Mauranipur and Babina regions as intrusive dykes in the TTG gneisses. Various rocks such as BIF, calc-silicate rocks, white schists, quartzites, and metapelites have also been exposed to amphibolites. Amphibolites of Mauranipur are found with garnetiferrous gneisses, whereas amphibolites of the Babina are associated with meta-ultramafic rocks. Amphibolites from both sites exhibit a nematogranoblastic texture, in which all the previous textures and structures are wiped out.

Electron microprobe analyses (EPMA) of minerals from the different mineral assemblages are given. Garnet from studied rocks comprises primarily of a solid solution of the end members almandine, pyrope, grossularite, and spessartine. The garnets consist of 2.21 to 74.09 mol% almandine, 6.55 to 49.65 mol% pyrope, 0.36 to 19.07 mol% grossularite, and 1.95 to 50.06 mol% spessartite in the studied rocks. The pyrope content of garnet from the different rock types indicates the following trend: pelitic granulites > garnet-biotite gneisses > amphibolites. The elemental X-ray map of garnet shows that garnet is rich in Fe, Al, and Si elements and has a depletion of Mg and Ca elements. The garnet shows considerable variation in the values of almandine, pyrope, grossular, and spessartine from rim to rim. The orthopyroxenes are mainly a solid solution of enstatite and ferrosilite having En (38.85–47.09) mol%, Fs (51.27–58.32) mol%, Wo (0.24–1.78) mol%, and Ac (0.21–1.41) mol%. The clinopyroxenes from garnet-bearing amphibolites are mainly solid solutions of wollastonite (47.31–48.45 mol%), enstatite (29.30–31.22 mol%), and ferrosilite (20.29–23.39 mol%). The calculated X_{Mg} value of clinopyroxene ranges from 0.59 to 0.65. It has a higher X_{Mg} content and a lower Al content than orthopyroxene. The clinopyroxenes from garnet absent amphibolites are mainly solid solutions of wollastonite (35.89–53.60 mol%), enstatite (23.85–40.53 mol%), and ferrosilite (11.29–39.34 mol%). The calculated X_{Mg} value of clinopyroxene ranges from 0.40 to 0.81. The X_{Mg} ratio of amphibole ranges from 0.69-0.89. The amphibole from the Mauranipur and Babina regions contains (p.f.u) Na = 0.276–0.497, K = 0.022–0.062, and Ti = 0.031–0.054. This indicates that these amphiboles have crystallized near the metamorphism's thermal peak under amphibolite facies. The X_{Mg} values of cordierite vary between 0.61 and 0.69. Insignificant amounts of Na_2O and K_2O are commonly present, ranging from 0.319 to 0.643 wt% and 0.013 to 0.066 wt%, respectively. The biotites' analyses display a wide range of X_{Mg} (0.31 to 0.61). The wide range of variation indicates the following trend of X_{Mg} in biotites; pelitic granulites (0.38 to 0.61) > amphibolites (0.45 to 0.49) >garnet-biotite gneisses (0.31 to 0.44). The Al^{IV} content of biotites from all studied rock samples varies from 2.402 to 2.960 p.f.u. In the Bundelkhand region's analyzed biotites, the amount of TiO_2 in biotite from the amphibolites is higher than in pelitic granulite and high-grade gneisses. The TiO_2 content of biotite from high-grade gneisses ranges from 1.41–1.99 Wt% and in pelitic granulites from 1.00–1.95 Wt%. The plagioclases of all the studied rock samples are solid solutions of Ab (37.41-60.15) mol%, An (40.04-63.39) mol% and Or (0.01-0.75) mol%. The X_{Ca} = [Ca/(Na+Ca+K)] ratio range from 0.40 to 0.59 for pelitic granulites, from 0.45 to 0.63 for high-grade gneisses and from 0.01-

0.75 for amphibolites. Epidote is present as inclusions within the amphibole and clinopyroxene in amphibolites. The values of X_{Al} [X_{Al}=Al/(Al+Fe^{3+})] ranges from 0.84-0.85. The values of X_{Fe} [X_{Fe}=Fe/(Fe+Al)] varies from 0.15–0.16. All epidotes belongs to clinozoisite–epidote–piemontite series dominated by clinzoisite (83.39–84.97 mol%) having epidote (14.71–16.08 mol%) and piemontite (0.24–0.72). Fe_2O_3 varies from 12.85–14.11 wt%. Chlorites are present in pelitic granulites as well as in amphibolites. Chlorites of pelitic granulites are of Brunsvigite composition, whereas chlorites of amphibolites are of Ripidolite composition. Al^{IV} and Al^{VI} found in these rocks lie between 1.97-3.11 and 0.84-1.64 pfu, respectively. BaO is found in a trace amount. The X_{Fe} values for amphibolites are higher (0.67–0.69) than the X_{Fe} values for pelitic granulites. Sillimanites are present in pelitic granulites. The Al-content of sillimanites ranges between 3.897 and 3.960 p.f.u. Sillimanite includes minor amounts of Cr and Fe. Total Fe as Fe^{2+} has been analyzed. The Cr and Fe content vary from 0.001 to 0.002 p.f.u. and 0.018 to 0.03 p.f.u., respectively.

Geochemical analysis of pelitic granulites reveals that the protolith is of diorite, granodiorite, and quartz–monzonite nature. According to the geochemical study, pelitic granulites are formed by the deposition of felsic sediments along a convergent margin and are then metamorphosed. The geochemical data of pelitic granulites show their unusual composition because they do not correspond to any normal igneous or sedimentary rocks. The minerals of the pelitic granulites' total composition suggest that they were derived from argillaceous parent rocks. However, no undesirable sedimentary structures have survived due to the rocks' recrystallization and reconstitution. Low TiO_2 and high Al, K, and Si content reveal that granitic-rich sediments dominated the pelitic provenance. Pelitic granulites contain a good amount of Ba and Rb, as feldspar is an essential mineral for hosting Ba and Rb in terrigenous sedimentary rocks. Moreover, the analyzed geochemical data indicate that pelitic granulites are probably redeposited and metamorphosed products of weathered

Archean crusts. 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 granulites protolith came from volcanic arc granite (VAG) and a syn-collisional tectonic environment, whereas the Y+Nb vs Rb plot verifies that the protolith came from VAG. The enrichment of K, Th, U, Pb, and HREE in the investigated rocks and the depletion of Nb, Sr, and Ti in the protolith are linked to the mid-upper crust or subduction-related formation of their protolith. The Grt-Bt gneisses are compositionally variable in major oxides as; SiO_2 (57.64–77.83 wt%), Al_2O_3 (7.46–16.31 wt%), MgO (0.47–8.02 wt%), FeO (2.61–13.91 wt%), K_2O (0.99–3.13 wt%), and also contains lesser amounts of TiO_2 (0.62–1.66 wt%), CaO (1.80–3.51 wt%), Na_2O (1.03–3.26 wt%) and P_2O_5 (0.14–0.65 wt%). Samples show considerable variation in the K_2O/Na_2O ratios of 0.78–1.55, suggesting its potassium-rich character. The combined alkali (K_2O+Na_2O) wt% is 2.03–6.11. The Al_2O_3/(CaO+ Na_2O + K_2O) ratio ranges between 1.00 and 2.34. The TAS diagram for Grt-Bt gneisses displays a contracting protolithic nature varying from diorite, granodiorite, and granite. The variation of the different major oxides with SiO_2 illustrates a substantial role in the fractionation and crystallization of minerals during the successive evolution of parental magma. The negative anomaly of Nb and Ti for all samples 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 Grt-Bt gneisses have a small negative Eu anomaly, which indicates the removal of calcic plagioclase from the magma, probably at the initial stage. The Th, La, V, Ce, and Sm enrichment is a likely consequence of the growth of biotite. Differences in the trace elements and REE abundances and variation in the $(La/Lu)_N$ ratio from 95.60 to 266.17 indicate heterogeneous sources and large variation in the degree of partial melting and effect of crustal contamination. The Y vs Nb and (Y+Nb) vs Rb tectonic discrimination diagrams show that the protolith of most Grt-Bt gneisses had an affinity toward the volcanic arc granite (VAG). This study proposes that the Bundelkhand Grt-Bt gneisses are derived mainly from a felsic magma source. This felsic magma is produced by the heat generated during the subduction procedure in the area. The garnet-bearing amphibolites are compositionally variable in major oxides such as SiO_2 (57.64–77.83 wt%), Al_2O_3 (7.46–16.31 wt%), MgO (0.47–8.02 wt%), FeO (2.61–13.91 wt%), and also contain lesser amounts of TiO_2 (0.62–1.66 wt%), CaO (1.80–3.51 wt%), and Na_2O (1.03–3.26 wt%). Similarly, garnet-absent amphibolites have also variation in major oxides as; SiO_2 (57.64–77.83 wt%), Al_2O_3 (7.46–16.31 wt%), MgO (0.47–8.02 wt%), FeO (2.61–13.91 wt%), whereas it contains lesser amounts of TiO_2 (0.62–1.66 wt%), CaO (1.80–3.51 wt%), Na_2O (1.03–3.26 wt%). The garnet-bearing amphibolites are projected into the basalt region; three garnet-absent amphibolites are projected into the basaltic field, and three are projected into the basaltic andesitic field. As a consequence, we propose that amphibolites exhibit both spreading and subduction signs, making their tectonic setting difficult to determine. Afterwards, it is critical to look for crustal contamination in amphibolites and determine what role it played in their formation. The studied amphibolites have moderately enriched LREE and LILEs (Ba, Rb, Th, U, and K), but negative anomalies of Nb, Ta, Zr, and Ti. 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. Although the BuC amphibolites can be metamorphosed from mafic rocks up to high-grade metamorphism, their petrogenetic characteristics are accessed by the immobile trace elements such as HFSEs (Ti, Zr, Y and Nb), REEs (La, Sm and Yb) and transition elements (Sc, Y and V). The tectonic environment is distinguished by HFSE and REE and is linked to the formation of amphibolites. The Th/Nb vs Ba/Nb discrimination diagram shows a clear influence of the shallow subduction component on garnet-bearing and garnet-absent amphibolites but no 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. Furthermore, the concentration of LILEs is nearly identical to the southern BuC metabasalt composition and is significantly lower than the Archean Upper Continental Crust. The subduction-influenced source is also supported by high Th/Yb and low Nb/Yb content; these rock data are located beyond the MORB-OIB array, where garnet-bearing and garnet-absent amphibolites are found in the field of continental arc and intra-oceanic arc basalt, respectively. According to our findings, the basaltic protolith was formed during orogenic (compressive) tectonism at active margins of island arcs, and their regime was subduction-related. Both amphibolite samples are close to the island basalt setting in the Th/Nb vs Ce/Nb tectonic discrimination diagram. However, in the Y vs La/Nb diagram, both the amphibolites fall in the field of BABB. This evidence indicates amphibolite generation in a back-arc region during an extensional regime. According to field occurrences of amphibolites and their relationship with host TTGs rocks, geochemical data, and concluded metamorphic records, the protolith of the amphibolites was formed during subduction-related settings in an arc-related setting as enclaves of mafic rocks. These rocks also participated in the Neoarchean collisional tectonism, where amphibolite patches went through pre-peak to peak metamorphism. Meanwhile, these amphibolites interacted with subduction-derived fluids, causing geochemical changes. The amphibolites underwent retrograde metamorphic processes during the exhumation stage.

The various conventional geothermobarometry pairs such as garnet–orthopyroxene and garnet–biotite geothermometers and garnet–orthopyroxene–plagioclase-quartz and garnet-biotite-plagioclase-quartz geobarometers have been used for evaluating the temperature and pressure conditions for pelitic granulites (Grt-Opx-Bt-Sil). For the pelitic granulite, the estimated temperature by Grt-Bt thermometry provides prograde temperatures of 639ºC–697ºC for garnet core and biotite included in garnet and 615ºC–661ºC for garnet and matrix biotite, whereas pressure of 5.8 kbar at 700ºC using the garnet-biotite-plagioclase-quartz geobarometer (GBPQ). Similarly, Grt-Opx thermometry provides peak temperatures of 760ºC–841ºC for core values and 713ºC–829ºC for rim values of garnet and orthopyroxene and peak pressure has been observed as 6.43–7.42 kbar at 800ºC using the garnet–orthopyroxene–plagioclase-quartz (GOPQ) barometer.

For Grt-Opx-Crd-Bt-Sil pelitic granulites, we have used conventional geothermobarometry pairs such as garnet–biotite, garnet–orthopyroxene and garnet–cordierite geothermometers as well as garnet-biotite-plagioclase-quartz, garnet–orthopyroxene–plagioclase-quartz and garnet-cordierite-sillimanite-quartz geobarometers for evaluating the temperature and pressure conditions. For the pelitic granulite, the estimated temperature by 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 6.49–7.49 kbar 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 4.89 kbar. *P-T* conditions are an essential parameter to understanding the metamorphic evolution under which a rock was formed. We have tried to obtain the pressure and temperature conditions through which these granulites form the most suitable minerals to achieve meaningful metamorphic *P-T* conditions. The various conventional geothermobarometry pairs such as, garnet–biotite geothermometers and garnet-biotite-plagioclase-quartz geobarometers have been used for evaluating the temperature and pressure conditions for Grt-Bt gneiss rocks. For the Grt-Bt gneiss, the garnet–biotite exchange geothermometer was applied to inclusion and matrix biotite, and 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. Ferry & Spear (1978) show a relatively low temperature (539ºC), while Thompson (1976) shows a high temperature (597°C). However, the pressure of metamorphism, according to the garnet-biotite-plagioclase-quartz geobarometer, is 5.32 kbar at 600ºC. The Grt–Cpx geothermometer can measure the temperature of the peak metamorphic stage; Ellis & Green (1979) found 834ºC, and Ravna (2000) found 760ºC at 7.0 kbar pressure. At this stage, we have taken probe data from the garnet core portion and clinopyroxene to achieve the peak *P–T* conditions. Simultaneously, GCPQ (Grt-Cpx-Pl-Qz) geobarometry calculated 7.42 and 6.46 kbar pressures at a constant temperature of 800ºC using Newton & Perkins (1982) and Eckert et al. (1991) models, respectively. Afterwards, garnet and clinopyroxene are unstable during post-peak metamorphism, which can be caused by retrograde metamorphism. We used the Holland & Blundv (1994) model to constrain the temperature condition as 556ºC at 4.5 kbar pressure, as measured by an Amp-Pl geobarometer, during the post-peak metamorphism. However, the pressure condition for post-peak metamorphism is estimated to be 5.04 kbar at 550ºC by Bhadra & Bhattacharya (2007) using an Amp-Pl-Qz geobarometer model. The amphibole-plagioclase geothermometer provides two different temperature and pressure conditions based on the chemical compositions of the rim and core portions. The Holland & Blundy (1994) model predicts 517ºC and 685ºC from the rim and core compositions, respectively, whereas the Bhadra & Bhattacharya (2007) model of the Amp-Pl-Qz geobarometer predicts 5.21 and 6.78 kbar pressure from the rim and core portions.

For the pelitic granulite, *P–T* pseudosections were calculated in the chemical system NCKFMASHTO. The *P–T* pseudosection has been constructed for the same sample (M-9) in the range of 3–8 kbar and 400–1000°C. The biotite, sillimanite, plagioclase define the pre-peak metamorphic condition. Quartz crystals that occur as inclusions within garnet and their respective mineral assemblages are found under low temperature and pressure conditions. The *P–T* condition of pre-peak metamorphism is found in the range of 4.00–5.12 kbar and 560–600°C, and the *P–T* condition of this stage is determined from garnet and biotite X_{Mg}isopleth contour lines that are identical to the studied microprobe data. The peak assemblage (grt + opx + bt + plg + sill + k-fs + melt + ilm + qz) has a *P–T* stability field ranging from 6.40–6.62 kbar and 700–730°C. The petrographic examination has revealed the isothermal decompression retrograde reaction, in which the consumption of garnet results in the creation of cordierite under low pressure circumstances, implying the following reaction: Crd + bt + kfs + melt Grt + sill + qz. At higher pressures, garnet, biotite, and sillimanite bearing assemblages are stable, whereas cordierite bearing assemblages dominate in the pseudosection's low-pressure equilibrium field. Cordierite is found in the matrix during the retrograde metamorphic stage, with lower X_{Mg} values. The retrograde metamorphic assemblage in *P–T* pseudosection contains grt + crd + bt + plg + kfs + melt + ilm + qz, which are stable in the range of 4.20–4.40 kbar pressure and 670–692°C temperature according to the textural interpretation.The pseudosection of the garnet-biotite gneisses has been prepared in the NCKFMASHT system. The *P–T* pseudosection is constructed in the range of 3–8 kbar and 400–800℃. The required mineral assemblage (Grt-Bt-Pl-Kfs-melt-Ilm-Qz) represented a peak metamorphic assemblage and occupied a field in the *P–T* range of 6.35–6.75 kbar and 755–780ºC. Instead, we have also observed similar mineral assemblages under lower pressure and temperature conditions. The melt phase does not exist here, whereas H_2O is available as a component. Therefore, we would like to say that this stable phase may evolve during the retrograde metamorphic condition. Their *P–T* condition is comparatively low, which is between 4.80–5.28 kbar and 718–735℃. *P–T* pseudosections were calculated in the chemical system NCKFMASHTO for the garnet-bearing amphibolites and in the NCFMASHTO system for the garnet-absent amphibolite. The *P–T* pseudosection for sample B-6 was built in the *P–T* range 3–9 kbar and 400–900°C in the NCKFMASHTO system. Chlorite exists under medium pressure (4.0–6.6 kbar) and lower temperatures (400–550°C) condition as meta-stable phase with amphibole and biotite. Pseudosection has validated three metamorphic stages for garnet-bearing assemblages, with the isopleth lines of garnet, amphibole, clinopyroxene, and biotites defining the appropriate *P–T* conditions of these metamorphic stages. The Amp-Chl-Bt-Pl-Qz-Ilm is a meta-stable mineral assemblage that may have formed prior to pre-peak metamorphism and is dominated by chlorite. This acquired phase is stable in the *P–T* range 3.2–6.2 kbar/420–550°C, and amphibole and chlorite isopleths further narrow the *P–T* range to 4.35–4.1 kbar/515–475°C. 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. Amphibole and garnet isopleths defined the *P–T* conditions as 6.5–6.25 kbar and 590–580ºC. The peak metamorphic assemblage is known as Grt-Amp-Cpx-Bt-Pl-Qz-Ilm-H_2O, and it occurs at higher *P–T* conditions. The *P–T* conditions for garnet-bearing amphibolite's peak metamorphic stage are defined as 7.4–6.8 kbar/805–760°C using isopleth lines of amphibole, garnet, clinopyroxene, and biotite. The post-peak metamorphic assemblage has fewer mineral characteristics such as Amp-Bt-Pl-Qz- Ilm and is stable at a *P–*

T range of 6.15–4.0 kbar and 750–580°C. Amphibole and biotite isopleths reveal the *P–T* conditions of the post-peak metamorphism at 4.75–4.45 kbar/615–585ºC. The *P–T* pseudosection was plotted for the garnet-absent amphibolites (sample K-1) under *P–T* ranges of 3–9 kbar and 400–900°C in the NCFMASHTO system. The mineral paragenesis Amp-Cpx-Ep-Pl-Qz-Ab-Ilm characterizes the pre-peak metamorphism, acquiring the field in the *P–T* range 4.0–6.4 kbar/400–450°C. Amphibole, clinopyroxene, and plagioclase isopleths narrow the *P–T* conditions of the pre-peak metamorphic stage to 5.8–5.0 kbar/400–450°C. The peak metamorphic stage paragenesis is characterized by Cpx-Amp-Pl-Qz-Ilm-H_2O. In this case, epidote becomes unstable as the temperature rises and does not appear in the peak assemblage. Peak metamorphic assemblage is stable at 7.4–7.0 kbar/810–785°C, which is demarcated by the isopleths of amphibole, clinopyroxene and plagioclase. Afterwards, clinopyroxene becomes unstable and consumed to form amphibole. 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.

Three types of thermodynamics methods were used to compute *P–T* conditions, i.e., conventional (mono-equilibrium) geothermobarometry, multi-equilibrium geothermometry, and forward modelling. These methods yielded more or less the same results for granulites, Garnet-biotite gneisses and amphibolites of the BuC. *P-T-t* paths represent a rock or a terrain through *P–T* space with time. The clockwise *P-T-t* path has been obtained from orthopyroxene-bearing pelitic granulites by thermodynamic calculation and pseudosection modeling. The pre-peak metamorphic stage was recorded between the range of 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 metamorphic assemblages and textural relationship have been described with special emphasis for garnetiferous Mauranipur garnet-biotite gneisses. 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. *P–T* estimation and pseudosection modelling in the NCKFMASHT system was shown the garnet-biotite gneisses experienced metamorphism of pentavariant stability field (Grt, plg, k-fs, bt, ilm, qz, melt) stable at the *P–T* range of 6.35–6.75 kbar and 755–780ºC. We have also observed similar mineral assemblages under lower pressure and temperature conditions. Here, the melt phase does not exist, whereas H_2O is available as a component. Therefore, we would like to say that this stable phase may evolve during the retrograde metamorphic condition. Their *P–T* condition is comparatively low, between 4.80–5.28 kbar and 718–735ºC. The geochemical interpretation provides significant evidence that the garnet-biotite gneisses were generated in a subduction zone tectonic setting, and the protoliths of garnet-biotite gneisses were further metamorphosed by the continent-continent collision. The clockwise *P–T* path is constrained by the *P–T* pseudosection of garnet-bearing amphibolite (B-6) from the Babina region. This *P–T* path generates three prominent metamorphic assemblages and 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 rose, 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 burial tectonism, characterized by a continuous increase in pressure and temperature. 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 amphibolites have significant similarities in petrographic reaction texture, mineral chemistry, geochemical composition, geothermobarometry, and bulk composition modelling and can be interpreted as being generated by the same magma but solidifying at different depths. The pseudosection has provided *P*–*T* condition between meta-stable and pre-peak metamorphism in the transition from greenschist to amphibolite facies. However, the appearance of garnet with clinopyroxene and associated mineral paragenesis indicates sufficient pressure and temperature to equilibrate the granulite facies. 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 rock classification diagram indicates that the rocks are basaltic to basaltic-andesite in composition and that they descended from the same protolith. The diverse mineralogical characteristics are due to distinct metamorphic grades; the Zr/TiO_2 vs Nb/Y diagram shows that there was only minor contamination during metamorphism. The petrographical reaction texture, phase equilibria modelling, and geochemical signatures of garnet-bearing and garnet-absent amphibolites from the Mauranipur and Babina regions have supported the geodynamics model for BuC evolution. The central part of the BuC includes enclaves of mafic-ultramafic, amphibolites, schists, BIF and metasedimentary rocks within the basement of TTGs and granitoids. 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 3000 million years ago by joining the Indian subcontinent's Dharwar and Singbhum cratons, South Africa's Kaapvaal craton, and Western Australia's Pilbara cratons. The Yilgarn and Zimbabwe cratons accreted with the original Ur~2.5 Ga to form the extended Ur. The structure of crustal blocks in expanded Ur is thought to exist until the Mesozoic supercontinent Pangea stabilizes. Zircons of 3.4–3.5 Ga were found in the BuC and linked to crust formation events in the Dharwar and Singbhum cratons, once part of the Ur supercontinent. The 3.6–3.2 Ga TTGs and the 3.43 Ga mafic-ultramafic complexes were reported in the central BuC. Similarly, 3.3–3.2 Ga TTG gneisses from Aravalli Craton and 3.36–3.2 Ga TTGs from the Western Dharwar Craton were also reported. Crustal development in the BuC is comparable to that of the Eastern Dharwar Craton in terms of time and geodynamic pattern, but several vital distinctions exist. Subduction occurred in an island-arc regime in the Eastern Dharwar Craton and an active continent margin regime in the BuC. The Western and Eastern Dharwar Cratons were involved as one structure in an accretion-collision event in the late Neoarchean (ca. 2.5 Ga), giving rise to southern Dharwar Craton granulites. Thus, comparing the crustal history of the Bundelkhand, Aravalli, Western, and Eastern Dharwar Cratons demonstrates that geodynamic mechanisms similar to present platetectonic and mantle-plume mechanisms were operating during that time. 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. The Kenorland Supercontinent is crescentic form according to the paleotectonic reconstruction based on geological and paleomagnetic data. 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.

Scope for future Work

After a quick look at the existing literature survey, one will decipher that there is no active research on the pelitic granulites within the BuC. Based on the previous literature study described above, it is clear that within the BuC, many high-grade metamorphic rocks have been discovered in the Mauranipur and Babina regions. Afterwards, investigation of the study area revealed that the Mauranipur area contains granulite facies rocks, like; pelitic granulites, high-grade gneisses, and amphibolites. Though various rock types have been identified and mapped in the Mauranipur and Babina regions, there is no systematic study on developingdiverse metamorphic mineral assemblages based on micro-textural studies. A detailed petrographic and microtextural investigation is essential to unravel specific mineral reactions and document any prograde or retrograde metamorphism in high-grade terrane. Such systematic studies have not been conducted in the Mauranipur and Babina regions.

If we review the literature, we find that most of the age-dating work has been done on TTGs, BIFs, and felsic granitoids in the BC, but no age-dating has been done on pelitic granulites and amphibolites.

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