CHAPTER–9

SUMMARY AND CONCLUSION

The Chhotanagpur Granite Gneiss Complex (CGGC) is characterized by the Proterozoic high-grade metamorphic basement with supracrustal metasedimentary enclavesby younger mafic to ultramafic rocks. It is situated at the eastern extension of the Central India Tectonic Zone (CITZ) covering about 100,000 km^2. The eastern part of CITZ is sandwiched between the Mahakoshal Belt and the Sausar Belt toward the northern andsouthern portions. The southernmost portion of the Sausar Belt preserves evidence of UHT granulite facies metamorphism, and the northward extension of the Sausar Belt represents multi-phase metamorphism. The CGGC terrain is bounded in the north by Mahakoshal Mobile Belt, with the Vindhyan Basin and the southern part is bounded by the North Singhbhum Mobile Belt (NSMB). Mafic granulites are mainly exposed in the Murguma- Purulia-Raghunathpur area, Bero-Saltora area, Dumka, Daltonganj, Mor Valley and Makrohar area of CGGC in this study. The most prominent rock types within the CGGC are granitic gneisses and migmatites with innumerable enclaves of metasedimentary rocks and amphibolites and are intruded by granitic and mafic rocks. Over large parts study area of metamorphism reached up to upper amphibolites facies and locally granulite facies.

The Makrohar granulite belt comprises high-grade metamorphic rocks including pelitic granulites, mafic granulites, calc-silicate granulite, amphibolite, garnet bearing gniesses, dolerite and metabasalt are exposed as major rock types. The mafic granulites occur as discontinuous and scattered enclaves within the migmatites gneisses throughout the areas. In the mafic granulites and amphibolites, hornblende is oriented to define the foliation. Retrogression of orthopyroxene and clinopyroxene to hornblende in the mafic granulites has been attributed to late hydration and retrogression.

Electron microprobe analyses (EPMA) of minerals from the different mineral assemblages are given. Garnet consists of 24.35 to 84.86 almandine, 0.34 to 17.93 pyrope, 3.17 to 73.25 grossularite, 1.97 to 3.98 spessartite end-member (in mol%). The X_{Mg} of garnet in the different rock types varies from 0.01–0.28 and shows the following trends: garnetiferous amphibolite > garnet-bearing gneisses> pelitic granulites > calc-silicate granulites. Cordierite has X_{Mg}, which ranges from 0.63 to 0.66 and insignificant amounts of Na_2O and K_2O ranging from 0.46 to 0.89 wt% and 0.04 to 0.16 wt% are commonly present. The X_{Mg} of biotite displays a wide range from 0.30 to 0.69 and is affected by octahedron occupancy of Ti and Al^{VI}, and shows a significant decrease in X_{Mg} with an increase in Ti. Higher content of TiO_2 in biotite from garnet absent amphibolites (More than 4 wt%) although the low content of TiO_2 in pelitic granulite and garnet-bearing gneisses may be due to their formation, was observed during retrogression. The X_{Mg} in amphiboles ranges from 0.38 to 0.71 and the Al^{IV} and Al^{VI} content of amphibole varies from 0.32 to 1.45 and 0.13 to 0.60 per formula unit (p.f.u.), respectively. The analysed pyroxenes are plotted in a triangular end-member diagram $CaSiO_3$-$MgSiO_3$-$FeSiO_3$ orthopyroxene lies close to hypersthene and coexisting clinopyroxene plots within the diopside and augite field in mafic granulite and hedenbergite field in calc-silicate granulites. The X_{Mg} of orthopyroxene and clinopyroxene ranges between 0.44 to 0.49 and 0.29 to 0.70. The orthopyroxene from the investigated areas has relatively poor Al_2O_3 content (0.32 to .69 wt%) compared to other terrains. Feldspar compositions from garnet-bearing gneisses and garnet-absent amphibolites are andesine, while those from mafic granulites and garnetiferous amphibolites are labradorite and pelitic granulites are Oligoclase in composition. EPMA dating has generated two age domains, and the calculated monazite age range is from 1529 to 1743 Ma and 874 to 1111 Ma from K-1, while 822 to 1014 Ma ages are preserved in M-1. The weighted average age distribution and probability density plot were obtained using the ISOPLOT program as depicted in Figure 5.8a–d. The estimated Weighted mean age 1655 ± 30 Ma (n = 14, MSWD = 4.3) represents a peak metamorphic event and the weighted mean age 910 ± 31 Ma (n = 19, MSWD = 9.3) indicates the retrograde metamorphism.

Geochemical analysis of metabasics exhibit significant variability in major oxide composition, encompassing SiO_2 (48.30–50.92 wt%), Al_2O_3 (11.04–15.52 wt%), MgO (4.14–5.85 wt%), FeO (13.17–17.54 wt%) as well as lesser quantities of TiO_2 (0.51–1.85 wt%), CaO (8.53–11.49 wt%), and Na_2O (2.08–2.66 wt%). The Zr/Ti versus Nb/Y diagram reveals that all garnetiferous amphibolites fall in the sub-alkaline basalt field while mafic granulites are found in the basaltic-andesite field. As a consequence, we propose that metabasics 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 its role in their formation. The studied metabasics have moderately enriched LREE and LILEs (Ba, Rb, Th, U, and K), but negative anomalies of Nb, Sr and Ti. The metabasics show lower Th concentrations ranging from 1.45 to 2.19 ppm. This low Th content indicates minimal to no contribution from crustal contamination. The petrogenetic characteristics of metabasic 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 Th/Nb vs Ba/Nb discrimination diagram shows a clear influence of the deeper subduction component on mafic granulites and garnetiferous amphibolites show no influence deeper subduction component. The Nb/Th vs Zr/Nb tectonic discrimination diagram suggests an arc-like setting for the meta basics from the study area, whereas the Zr vs Zr/Y plot suggests an island arc setting. 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 garnetiferous amphibolites and mafic granulites are found in the field of intra-oceanic arc basalt and 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.

Metabasic 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, metabasics fall in the field of BABB. This evidence indicates metabasics generation in a back-arc region during an extensional regime. According to field occurrences of these rocks, geochemical data and concluded metamorphic records, the protolith of the metabasics was formed during subduction-related and arc-related settings. These rocks also participated in the Neoarchean collisional tectonism, where metabasic patches went through pre-peak to peak metamorphism. Meanwhile, these metabasics interacted with subduction-derived fluids, causing geochemical changes. The metabasics underwent retrograde metamorphic processes during the exhumation stage.

The various conventional geothermobarometry pairs such as garnet–biotite and garnet– cordierite geothermometers and garnet–biotite–plagioclase-quartz and garnet-cordierite- sillimanite-quartz geobarometers have been used for evaluating the temperature and pressure conditions for pelitic granulites (Grt-Crd-Bt-Sil-Pl-Qz). For the pelitic granulite, the estimated temperature by Gt-Bt thermometry provides prograde temperatures of 690 ± 62 ºC at a fixed pressure of 6 kbar whereas pressure of 6.2 kbar at 600ºC using the garnet-biotite- plagioclase-quartz geobarometer (GBPQ). For the garnet-bearing gneiss, the estimated temperature by Gt-Bt thermometry provides prograde temperatures of 566 ± 33 °C at a fixed pressure of 6 kbar whereas pressure of 5.11 kbar at 600°C using the garnet-biotite- plagioclase-quartz geobarometer (GBPQ). Similarly, Grt-Crd thermometry provides post- peak temperatures of 575 ± 28 ºC at a fixed pressure of 5 kbar, whereas garnet-cordierite-sillimanite-quartz geobarometer was used to estimate the pressure of 5.55 ± 0.73 kbar at 600ºC. The average PT condition was estimated with coexisting phases involving garnet, biotite, plagioclase, cordierite and sillimanite is 679 ± 63 °C/5.3 ± 0.9 kbar for an (H_2O) = 1. The temperature and pressure conditions of their formation have been estimated with the help of conventional garnet–clinopyroxene exchange geothermometers and garnet–clinopyroxene– plagioclase–quartz geobarometers. The temperature estimate through the garnet- clinopyroxene exchange thermometer of the calc-silicate granulites of the study area is 675 ± 89 °C at a fixed pressure of 7 kbar and pressure is 5.55 ± 0.74 kbar at 600°C. The average PT condition was estimated with coexisting phases involving garnet, clinopyroxene, plagioclase, epidote and quartz is 624 ± 97 °C/5.6 ± 0.8 kbar for an (H_2O) = 1.

The pressure-temperature conditions of the mafic granulites were determined using orthopyroxene–clinopyroxene conventional exchange geothermobarometers. The peak temperature estimates of coexisting orthopyroxene–clinopyroxene of the study area was 887° ± 62°C at a fixed pressure of 6 kbar. The pressure condition of the peak stage was obtained using the two-pyroxene barometer of Mercier et al. (1984), which provided an estimate of 6.15± 0.3 kbar. The pressure condition of the post-peak metamorphic stage was obtained using the aluminium-in-amphibole barometer of Schmidt (1992), which provided an estimate of 2.28 ± 0.15 kbar. The temperature estimates of the Hbl–Pl–Qz thermometer of Holland and Blundy (1994), at pressure obtained using the aluminium-in-amphibole barometer of Schmidt (1992) suggests an estimate of 593 ± 50°C. The pressure-temperature conditions of the garnetiferous amphibolites were determined using garnet–clinopyroxene conventional geothermobarometers. The peak temperature estimates of coexisting garnet–clinopyroxene of the study area were 643 ± 51 ºC at a pressure of 5.0 kbar. The pressure condition of the peak stage was obtained using the garnet–clinopyroxene– plagioclase–quartz geobarometers, which provided an estimate of 5.62 ± 0.62 kbar. Afterwards, garnet and clinopyroxene are unstable during post-peak metamorphism, which can be caused by retrograde metamorphism.The pressure condition of the post-peak metamorphic stage was obtained using the aluminium-in-amphibole barometer of Schmidt (1992), which provided an estimate of 4.30 ± 0.28 kbar for garnetiferous amphibolite and garnet absent amphibolites provided an estimate of 5.26 ± 0.21 kbar. The temperature estimates of the Hbl–Pl–Qz thermometer of Holland and Blundy (1994), at pressure obtained using the aluminium-in-amphibole barometer of Schmidt (1992) suggest an estimate of 612 ±

28°C for garnetiferous amphibolite and garnet absent amphibolites provided an estimate of 620 ± 42°C. The average PT condition ofgarnetiferous amphibolite was estimated at 706 ± 63 °C/5.5 ± 0.9 kbar for an (H_2O) = 1 and garnet absent amphibolite 616 ± 81°C/5.2 ± 0.7 kbar for an (H_2O) = 1. For the pelitic granulite, *P–T* pseudo sections were calculated in the chemical system NCKFMASH model system. The *P–T* pseudosection has been constructed in the range of 650-900 °C and 4.5-7.5 kbar. The equilibrium mineral assemblage (Gt-Bt-Crd-sil-Pl-Qz-melt) estimated for the pelitic granulite lies in the P–T range of 730 -765°C to 5.1- 6.3 kbar. The peak mineral assemblage (Grt-Bt- Sil-Pl-Qz-melt) was stable in the P-T range of 740–750 °C and 6.7–7.4 kbar. The retrograde mineral assemblage (Gt-Crd-Bt -Pl-Qz-melt) formed during Post-peak (M2) metamorphism, lies in the P–T range from 725 -730 °C and 4.5 - 4.7 kbar are derived by contouring X_{Mg} isopleths of garnet and cordierite. For the mafic granulite, *P–T* pseudosection was constructed in the NCKFMASHTO modal system and the P-T range of 3–8 kbar and 750–900 °C. The equilibrium mineral assemblage (Opx-Cpx-Bt-Amp-Pl-Ilm) estimated for the mafic granulite lies in the P–T range of 730 -5.2 to 6.4 kbar and 810 to 850°C. The peak mineral assemblage (Opx-Cpx-Amp-Pl-Ilm-melt) was stable in the P-T range of835 and 870°C at 5.0 – 6.9 kbar. The Isobaric T–X (CO_2) pseudosection of calc-silicate granulites was estimated based on bulk composition to constrain the mole fraction of CO_2 and temperature condition of equilibrium mineral assemblage (GrtCpx-Sph-Cz-Pl). The Isobaric T–X (CO_2) pseudo section was constructed in the NCFMAST-HC model system and is constructed in the range of 300-800 °C and at a fixed pressure of 7 kbar. The mole fraction of CO_2 (XCO_2 > 0.4) is a suitable constituent for the formation of stable mineral assemblage such as (Grt-Cpx-Sph-

Cz-Pl) along with a temperature range from 620 -635°C. *P–T* pseudosections were calculated in the chemical system NCKFMASHTO for the garnetiferous amphibolites and were built in the *P–T* range of 3–9 kbar and 400–900°C. Pseudosection has validated two metamorphic stages for garnetiferous assemblages, with the isopleth lines of garnet, amphibole, clinopyroxene, and biotites defining the appropriate *P–T* conditions of these metamorphic stages. 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 the peak metamorphic stage of garnetiferous amphibolites are defined as 7.1–7.3 kbar/790–810 ºC. 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 6.10–4.10 kbar and 760–590ºC. Amphibole and biotite isopleths delineate the conditions for post-peak metamorphism more specifically at 4.10–4.50 kbar/590–610ºC.

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 garnet- bearing gneisses, granulites and amphibolites of the study area. *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 pelitic granulites by thermodynamic calculation and pseudosection modelling. In the peak stage, the rock undergoes burial, marked by significant changes in temperature conditions, indicating an increase in pressure. During this phase, the P-T conditions reached high-pressure conditions, ranging from 7.40 to 6.70 kbar and temperatures between 760 and 740°C. After the peak stage, the rock followed a nearly isothermal decompression path (ITD) as it transitioned into the post-peak stage. The post-peak stage is characterized by the presence of garnet and cordierite and with P-T conditions falling within the range of 4.80 to 4.60 kbar and 730 to 725°C. The geodynamic interpretation of the peak stage metamorphism in the study area suggests a single-cycle process involving subduction and exhumation, as evidenced by the complete clockwise P-T-t path. The clockwise *P-T-t* path has been obtained from garnetiferous amphibolites by thermodynamic calculation and pseudosection modelling. In the peak stage, the rock is characterized by the mineral paragenesis Grt-Amp-Cpx-Bt-Pl- Qz-H_2O and this field is stable at a *P–T* range of 7.3–7.1 kbar/810–790ºC. The mineral assemblage of the post-peak metamorphic stage Amp-Bt-Pl-Qz-Ilm is stable at a *P–T* range of 4.5 – 4.1 kbar/610–590ºC, which acquires a Grt and Cpx 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. We have established evidence for two metamorphic stages and a clockwise P-T path from mafic granulites of the Makrohar area using mineral assemblages, textural relations and conventional geothermobarometry. This *P–T* path generates two prominent metamorphicassemblages. The peak temperature (M1) estimates of coexisting orthopyroxene– clinopyroxene was 887° ± 62°C at a fixed pressure of 6 kbar and peak pressure condition of 6.15± 0.3 kbar. For the post-peak metamorphic stage (M2), The P-T condition estimated was 2.28 ± 0.15 kbar/ 593 ± 50°C. Four distinct metamorphic events have been recognized between the Paleoproterozoic and Neoproterozoic periods and make the complex evolutionary history of CGGC terrain. The M1 metamorphic event took place at ~1650 Ma and successively M2 event was recorded during ~1450 Ma, consecutively the M3 stage occurred at ~1000 Ma, followed by the last metamorphic event (M4) lies between 870–780 Ma. The CGGC preserved the oldest crustal component of the Paleoproterozoic age at ~1750- 1660 Ma in this period mainly granite emplacement has been recorded from the north-easternportion. This same age has been recorded from the Mahakoshal Supracrustal Belt (MB) and agroup of workers represented as CGGC granites resulted from the extension of MB. In the present study, the U-Th-Pb^T monazite dating represents two geochronological ages of pelitic protolith at ~1655 Ma and ~910 Ma. In the study area, only pelitic granulites have preserved the M1 metamorphic event. In contrast with these metamorphic events, a few magmatic intrusions also occurred in the CGGC, where the anorthositic magmatic activity was recorded in older metasedimentary granulites during ~1550 Ma. The pseudosection of pelitic granulite has been plotted in the NCKFMASH system, the pelitic granulite reached peak metamorphism (M1) and later underwent to isothermal decompression (ITD) path (M2). Out of four metamorphic events, only two of them have been found in the pelitic granulites. Due to the complex metamorphic history of CGGC, the M1 metamorphic event is challenging to identify, but the monazite occur as the inclusion in garnet have paleoproterozoic age thus M1 event is understood as the age of peak metamorphism (~1655 Ma) of pelitic granulites. Monazite grain occurs occur as the inclusion in cordierite gives Neoproterozoic age domains. The M2 event is interpreted as the retrograde metamorphism with 725 -730 °C and- 4.7 kbar and shows P-T conditions related to the Isothermal decompression (~910 Ma).

The geotectonic setting model suggests two Archean cratons; Bundelkhand craton and Singhbhum craton with adjacent Baster craton rifted during the late Archean Paleoproterozoic period, which led to the separation of these two cratons and consequentlyled to the development of the sedimentary basin. The rift portion developed as a sink basin for sedimentation which arrived from different sources such as older craton and mobile belt. It is inferred that the NW CGGC area pelitic granulite underwent a progressive phase of tectonothermal processes where the initial occurrence of crustal thickening (M1) was followed by quick exhumation of the crustal lithosphere (M2), these processes indicate that collision or subduction-related tectonic processes. The subduction process reported by the emplacement of felsic magmatism along the northern part of the CGGC (1.76–1.66 Ga), also from the adjoining area on the northern extent of CGGC (1.69 Ga), and substantial magmatic emplacement recorded in Mahakoshal Belt (~1.8–1.7 Ga), which indicated that tectonothermal evolution of adjacent terrain of CGGC basin during the late Paleoproterozoic time. Before the ~1.65 Ga age, there was a development of the oceanic environment and deposition of the sediments from the adjacent terrain which contains the Paleoproterozoic volcano-sedimentary rocks. Moreover, it was a great chance to develop a rift basin or oceanic basin among the Singhbhum Mobile Belt and Mahakoshal Mobile Belt during the period of 1.86–1.65 Ga. Different types of sediments were deposited in this oceanic basin and accompanied by the formation of HP/MT pelitic granulites at ~1.65 Ga; it was due to the subduction of the oceanic lithosphere. The 1.65 Ga age is considered the oldest metamorphic (M1) age from the NW CGGC and pelitic granulite is the only rock type that consists of the first stage of metamorphism. Mafic granulites are calc-alkaline and their generation is related to island arc as well as subduction-related settings. Our study results emplacement of the basaltic protolith was during the orogenic (compressive) tectonism at active margins of islandarcs, and their regime was subduction-related. The basaltic magma was formed at the orogenic tectonic environment; it was a result of a convergence of the CGGC and the Mahakoshal Belt, where the Mahakoshal micro-plate subducted beneath the north-western CGGC crustal domain and may be breakdown into the lower lithosphere. Late Paleoproterozoic orogenic belts have been recognized from different parts of India, i.e., the Eastern Ghats Mobile Belt, and Aravalli Delhi Fold Belt, and this age recorded from the Antarctica (Kemp Land) of Napier Complex, these collectively led to the formation ofColumbia Supercontinent. However, finally, it concluded that Greater India and Antarctica plates amalgamated during the Paleoproterozoic age as the Columbia supercontinent. During this rifting period, many magmatic processes were obtained, viz., like emplacement of anorthosite and khondalite around 1550 Ma and 1510 Ma respectively. The development of Rodinia started from the Grenvillian orogenic age ~1100–900 Ma. The CGGC of eastern India shows a shred of evidence of the Grenvillian orogeny age at 1100–900 Ma which is strongly preserved, and it postulates that the Grenvillian orogeny suture was very near the CGGC of India. The Indian and Australian continental plate ‘s transpressional movement mayexplain the 1100–1000 Ma metamorphic events investigated from the Pinjarra orogen. It was assumed that the pelitic granulites would be affected by the retrograde metamorphism during the Neoproterozoic era in the Makrohar granulite belt. The high-pressure peak metamorphism, followed by a rapid decrease in pressure, is believed to be linked to a subsequent exhumation event during the Neoproterozoic era.