CHAPTER - 10

SUMMARY AND CONCLUSION

"It is a sign of intellectual maturity to always crawl to conclusions."
Mokokoma Mokhonoana

The Chhotanagpur Granite Gneiss Complex (CGGC) is characterized by the Proterozoic high-grade metamorphic basement with supracrustal metasedimentary enclaves by 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 and southern 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 Bero-Saltora area, Murguma-Purulia-Raghunathpur area, Mor Valley, Dumka, and Daltonganj CGGC in this study. The most abundant rock types within the CGGC are granitic gneisses and migmatites with innumerable enclaves of metasedimentary rocks and amphibolites and are intruded by various types granitic and mafic rocks.

Within the gneisses enclaves of various sizes, compositions and metamorphic grades occur. Over large parts of metamorphism reached up to upper amphibolites facies and locally granulite facies. The Daltonganj region comprises high-grade metamorphic rocks including high-grade gneisses, mafic granulites, pelitic granulites, sillimanite-graphite-schist, charnockite, amphibolite, and dolerite are exposed as major rock types. The high-grade gneisses are not extensively developed throughout the investigated areas. They occur as lenticular bodies within the granite gneiss. On the weathered surface of these gneisses, the nodules of garnet are generally seen. 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 to hornblende and gedrite in the mafic granulites and high-grade gneisses has been attributed to late hydration and retrogression during the M_4 stage.

Electron microprobe analyses (EPMA) of minerals from the different mineral assemblages are given. Garnet consists of 42.15 to 79.73 almandine, 13.27 to 30.72 pyrope, 0.69 to 18.65 grossularite, 0.45 to 25.77 spessartite end-member (in mol%). The X_{Mg} of garnet in the different rock types varies from 0.17–0.31, and show the following trends: high-grade gneisses > pelitic granulites > mafic granulites. Cordierite has a variable range of X_{Mg}, which ranges from 0.63 to 0.79, higher values correspond to the high-grade gneiss, whereas in pelitic granulites included cordierite within garnet shows 0.79 and matrix cordierite shows 0.68. The X_{Mg} of biotite displays a wide range from 0.46 to 0.74 and is affected by octahedron occupancy of Ti and Al^{VI}, and show a significant decrease in X_{Mg} with an increase in Ti. Higher content of TiO_2 in biotite from mafic granulites (More than 4 wt%) is similar to other granulite facies terrains. The X_{Mg} in hornblende ranges from 0.38 to 0.52 and show a decrease of X_{Mg} with an increase of its Al^{VI} contents. In gedrite the X_{Mg} varies from 0.54 to 0.60 and it contains significant amount of Na_2O, up to 1.82 wt%. The analyzed pyroxenes from mafic granulites 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. The X_{Mg} of orthopyroxene and clinopyroxene ranges between 0.39 to 0.58 and 0.45 to 0.63. The orthopyroxene from the investigated areas has relatively poor Al content (0.28 to 3.80 wt%) compared to other terrains. The X_{Ca} = (Ca/Ca+Na+K) ratio of plagioclase from mafic granulites range from 0.37 to 0.67.

TEM images and selected area electron diffraction (SAED) patterns are analyzed for observation of microstructure of the gedrite. Here three types, i.e., bundles, prismatic and fibrous forms of gedrite have been observed in the TEM images. TEM image shows the different position occupied by gedrite and arrangement of double-chain silicate structure with all the three axial directions. Unit cell parameter of the gedrite detected by TEM are a-axis=18.6 Å, b-axis = 17.8 Å and c-axis = 5.58 Å. TEM investigation has also highlighted a contrast chemical behaviour of opx and cpx at the opx-cpx interface area, with the interface area showing the admixing of the silicate structure of two different minerals i.e., opx and cpx. The measured lattice parameters of Opx and Cpx were; a = 18.4, b = 8.8, c = 5.3 Å and a = 9.4, b = 8.9, c = 5.4 Å respectively determined by electron diffraction pattern. The SAED pattern reflects the ring-like structure, suggesting a crystalline nature for minerals. However, the arrangement of metallic elements is located at different lattice positions.

The high-grade gneisses (HGG) are classified based on total alkali versus silica (TAS) plot, on this classification scheme, all of the garnet-cordierite-amphibole gneisses lie in the basalt field, and the remaining two garnet-orthopyroxene-amphibole gneisses fall in the basaltic andesite field. However, mafic granulite (MG) samples show basaltic nature, and pelitic granulites (PG) display diorite and monzonite, whereas few samples are gabbroic means that the protolith of pelitic granulite was formed from various sedimentary provenances. Bivariate plots of HGG indicate that the post-crystallization secondary process is not affecting the major oxides of the studied gneisses. If the felsic melt is removed from the parent rock undergoing anatexis process, a relative enrichment of Al, Fe and Mg and depletion of Na, Ca, and Si may occur in 'restite'. It corresponds to relative enrichment due to the removal of melt of the granite composition. The removal of granitic melt during anatexis process does not significantly affect the X_{Mg} of the 'restites' compared to the parent host rock. Major oxides of MG are plotted against the MgO wt% to reveal magmatic evolution through elemental partitioning. All pelitic granulite samples have a ferroan character, and most samples are peraluminous with one sample is metaluminous. However, these are calc-alkalic to alkali-calcic variable composition, but a sample has calcic composition. Na_2O vs K_2O diagram represents shoshonitic and ultra-potassic composition, but the SiO_2 vs K_2O diagram clarifies that all the samples are of shoshonitic nature. HGG has less compatible trace elements that suggest an essential process as fractional differentiation in its evolution. Here it has observed that the excellent availability of the compatible element (Cr, Ni, Co, V) and low TiO_2 suggests a mafic source rock or maybe more possibility of mantle origin. The substantial depletion of K and Na is most pronounced if their protoliths are considered the mafic metavolcanic. Negative Nb and Sr anomalies suggest the involvement of subduction orogeny. Y-La-Nb triangular plot and Yb-Th discrimination diagram indicate the calc-alkaline basaltic nature of these gneisses developed at the island arc domain during subduction-related processes. The enhanced abundance of LREE and LILE (Th, Ta, U, Pb) is better interpreted due to enrichment by fluid-related metasomatism. This study conclude that calc-alkaline rich mafic fluids intruded in the pre-existing rocks, and then emit its mafic components (Fe, Mg). In the process, the modal availability of felsic component of pre-existing rocks decreases, and it signifies a ‘restitic’ origin of the studied gneisses. The primitive mantle-normalized trace element patterns of the Daltonganj mafic granulites show a negative peak for Ti, K, Nb, Sr and positive peak for U, Ta, and Hf, which reveals a rich LILE pattern. High elemental concentrations of Mg, V, Cr, and Co suggest that they be derived from primary magmatic sources. The amount of HFSE (Y, U, Pb, Hf, Nb, Ta) is small, indicating that the rock is derived from the mafic source. Nb has negative anomalies that showed crustal contamination. The Zr vs Nb/Zr diagram confined that protolith of pelitic granulite encountered a subduction-related tectonic setting. The Y vs Nb and Rb vs (Y+Nb) tectonic discrimination diagram reveals that the protolith has an affinity towards the within plate granite (WPG). After establishing the relationship between the $(Y/Nb)_N$ vs $(Th/Nb)_N$ diagram, it has used to establish the discrimination between oceanic islands, continental crust and convergent margin rocks, and all samples are located in the convergent margin rocks field. HGG has low HREE content and positive Eu anomaly and negative Sr anomaly and has also been reported against the crustal assimilation. The garnet-orthopyroxene-amphibole gneiss represents a more enriched value of LREE than HREE, which means that orthopyroxene's availability behaves as a sink mineral of LREEs. The sub-parallel REE patterns of mafic granulites suggest that compositional variation resulted from crystal fractionation. The degree of fractionation expressed by the $(La/Yb)_N$ ratios varies from 0.40 to 2.18, relatively low for these rocks. Mantle-derived magma is also identified by the HFSE/LREE proxy and Nb/La (< 0.37) ratio, lower for the Daltonganj basaltic protolith, and represents the provenance of lithospheric mantle. The Nb/U versus Nb discrimination diagram for the mafic granulites is lower than the MORB and OIB (Nb/U ~ 25), which refers to the melt phase originating from the subducted slab and being metasomatized from the mantle source. The subduction influenced source is also sustained by high Th/Yb and low Nb/Yb content; these rock data are beyond the MORB-OIB array in field of intra-oceanic arc basalt. Oceanic tholeiites (MORB) have high K/Rb ratios (often >1000), the high ratios and wide variation in the granulites cannot be primary igneous feature. It is generally agreed that this is related to granulite facies metamorphism. In pelitic granulites, some sedimentary features signify such as overall enrichment of ∑REE possibly due to accumulation of immobile REE during the transportation and sedimentation; also low content of Sr attributable to the leaching effect, low TiO_2 and high content of Al, K, Si bear the pelitic provenance of the protolith. Sr is depleted because they are highly mobile and are easily transported during sediment dehydration. Metapelites have a high Rb and Ba content, as the feldspar is a major host of Rb and Ba in terrigenous sedimentary rocks.

EPMA dating has generated two age domains, and the calculated monazite age range is from 1348 ± 47 to 1482 ± 49 Ma and 896 ± 49 to 1050 ± 63 Ma from R-91-97, while 1322 ± 64 to 1494 ± 65 Ma and 926 ± 58 to 1019 ± 59 Ma ages are preserved in R-91-96. The weighted average age distribution and probability density plot were obtained using the ISOPLOT program as depicted in figure 8a–h. The analysis of sample R-91-97 produced an age population at 1424 ± 64 Ma (figure 8a and b) and 972 ± 28 Ma, with 95% confidence. The sample R-91-96 has an age population of 1390 ± 56Ma and 962±159 Ma, with 95% confidence. The electron microprobe dating of monazite grains has generated a two-age domain from both rocks, which lies around the Mesoproterozoic and Grenville orogeny ages. U-Pb zircon dating of pelitic granulites shown the older age data lie between 1700-1800 Ma with one data is of 1860.6 ±31.2 Ma. On relative probability, density diagram shows 1707.1±8.8 Ma age as the younger detrital age domain. This age group has a high Th/U ratio (>0.2), indicating that detrital zircons formed by the magmatic origin. The sub-rounded and elongated zircon grains recrystallized at different metamorphic events with low Th/U ratio (<0.2), signifying that metamorphic origin of zircon. Twenty-six spot analyses of metamorphically formed zircons decipher late Paleoproterozoic age (1629.8±10 Ma). Mafic granulites show all the age data gathered near the 1600 Ma, with two ages lying over the Concordia line. However, the weighted average age plot shows 1629±6 Ma (MSWD=1.4) validly constraining the magmatic emplacement event.

The NCKFMASH system has been selected for the high-grade gneisses. The pre-peak metamorphic stage was recorded between the range of 5.78–6.15 kbar and 600–622°C, and the first stage Grt_1 developed under pressure conditions of 6.70 kbar. The *P-T* condition of the peak metamorphism is at 8.65–9.42 kbar and 772–788°C. For the post-peak metamorphic stage, the mineral assemblage Grt_3-Amp_3-Crd-Bt-melt-Plg-Qz remains as orthopyroxene–free phase. This post-peak stage is confined at 5.71–6.18 kbar and 745–762°C, which is constrained by the isopleth lines of garnet (X_{Mg}) and cordierite (X_{Mg}). PT pseudosection of mafic granulite was constructed in the NCKFMASHTO system. Garnet absent assemblages was stable at low pressure, whereas orthopyroxene bearing assemblages occurred at a higher temperature. The required mineral assemblages, which got from petrographic analysis, was stable at PT range of >4.5 to 7.15 kbar and ~665 to 870°C. These peak mineral assemblages were best defined by the pentavariant field involving clinopyroxene, orthopyroxene, hornblende, plagioclase, biotite, ilmenite and quartz. The *P-T* pseudosection for mafic granulite was contoured by X_{Mg} isopleths line of Opx and Cpx; furthermore, *P-T* conditions were derived by isopleth lines. The X_{Mg} value (0.535-0.540) isopleth line of orthopyroxene and 0.615–0.625 X_{Mg} of clinopyroxene was demarcated as a PT range 6.0 to 6.78 kbar pressure and temperature 775 to 808ºC. This *P-T* range was recognized as a stable mineral phase for the peak host assemblage. Moreover, *P-T* pseudosection shows magnetite-bearing fields occurring at lower temperature. Since magnetite was also observed in mineral assemblage of mafic granulites, therefore a retrograde evolution of mafic granulite has been recorded at lower temperatures (~540ºC) and pressures (~4.5 kbar) within the magnetite-bearing field. The same system as mafic granulite is chosen for the pelitic granulites. The pseudosection is characterized by large high variance (F = 3–6) garnet-bearing fields. The *P-T* condition of pre-peak metamorphism is found at ~3.2 kbar and ~620ºC, and the *P-T* condition of this stage is derived by the X_{Mg} isopleth contour lines of garnet and cordierite which are similar to the analyzed microprobe data. The *P-T* stability field for the peak assemblage (grt + bt + plg + sill + kfs + melt + ilm + qz) ranges from 7.40 to 9.10 kbar and 815 to 835°C. Tetravariant fields dominate the pseudosection. The textural interpretation reveals that the retrograde metamorphic assemblage in *P-T* pseudosection contains grt + crd + bt + plg + kfs + melt + ilm + qz + mag, which are stable at pressure ~4.0 kbar and temperature ~790°C.

Four distinct metamorphic events (M_1–M_4) have been recognized between the Paleoproterozoic and Neoproterozoic periods and make the complex evolutionary history of CGGC terrain. The M_1 metamorphic event took place at ~1650 Ma and successively M_2 event recorded during ~1450 Ma, consecutively the M_3 stage occurred at ~1000 Ma, followed by the last metamorphic event (M_4) lies between 870–780 Ma. The CGGC preserved the oldest crustal component of Paleoproterozoic age at ~1750-1660 Ma, in this period mainly granite emplacement has been recorded from the north-eastern portion. This same age has recorded from the Mahakoshal Supracrustal Belt (MB), so, a group of workers represented as CGGC granites resulted from the extension of MB. The first metamorphic event has been recorded from the pelitic granulites at ~1680–1580 Ma; previously their protolith must have derived from the different sources which contain the variable age domains ~2400 Ma, ~2000 Ma ~ 1800-1700 Ma. In the present study, the detrital zircons represent two geochronological age of pelitic protolith as ~1840 Ma, ~1707 Ma and metamorphic zircons contain a major metamorphic event at ~1630 Ma. In the CGGC, only pelitic granulites have preserved the M_1 metamorphic event. In contrast with these metamorphic events, few magmatic intrusions also occurred in the CGGC, where the anorthositic magmatic activity recorded in older metasedimentary granulites during ~1550 Ma. The mafic granulite entrapped at ~1450 Ma within the felsic orthogneiss or other crustal component and appear as in enclaves from the north-eastern part of CGGC. The M_2 event of pelitic granulite was considered an M_1 event for mafic granulite recorded during ~1450 Ma with peak metamorphic condition at 9 kbar and 800°C. Pelitic granulites also preserved M_2 metamorphic events at ~1400 Ma, along with a huge felsic magmatic impulse ~1470–1400 Ma, this felsic magmatism engulfs the pre-existing pelitic granulites, after that, it remained as enclaves form. The pseudosection of pelitic granulite has plotted in the NCKFMASHTO system, the pelitic granulite reached peak metamorphism (M_1) and later underwent to isothermal decompression (ITD) path (M_2). Out of four metamorphic events, only three of them have been found from the high-grade gneiss. Due to the complex metamorphic history of CGGC, the M_1 metamorphic event is challenging to identify, but the M_2 event is understood as the age of protolith (~1424 Ma) of high-grade gneisses. The third phase was a pervasive metamorphic event and was affected by the Grenvillian orogeny as a continent-continent collision. The M_3 event is interpreted as the peak metamorphism with 8.65–9.42 kbar and 772–788°C *P-T* condition related to the Grenvillian orogeny (~972 Ma). Subsequently, the final phase of the metamorphic event was recorded in high-grade gneisses during 855±31 Ma, which was interpreted as retrograde metamorphism at 5.71–6.18 kbar and 745–762°C.

The geotectonic setting model suggests two Archean cratons; Bundelkhand craton and Singhbhum craton with adjacent Baster craton rifted during late Archean Paleoproterozoic period, which leads to the separation of these two cratons and consequently leads to the development of the sedimentary basin. The rift portion developed as a sink basin for sedimentation which arrived from the different sources as older craton and mobile belt. The geochronological age of detrital zircon demarcates the protolith of pelitic granulites and their origin source. It is inferred that the NW CGGC area's pelitic granulite underwent a progressive phase of tectonothermal processes where initially occurrence of crustal thickening (M_1) followed by quick exhumation of the crustal lithosphere (M_2), these both processes indicate that collision or subduction-related tectonic processes. 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 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 to the formation of HP/MT pelitic granulites at ~1.63 Ga; it was due to subduction of the oceanic lithosphere. The 1.63 Ga age considered the oldest metamorphic (M_1) 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 related to island arc as well as subduction-related setting. Our study's result emplacement of the basaltic protolith was during the orogenic (compressive) tectonism at active margins of island arcs, and their regime was subduction-related and enrichment of lithospheric-mantle source region. The basaltic magma was formed at the orogenic tectonic environment; it was a result of convergence of the CGGC and the Mahakoshal Belt, where Mahakoshal micro-plate subducted beneath the north-western CGGC crustal domain and may be breakdown into the lower lithosphere. The La/Yb vs Nb/La (Nb/La <0.5) discrimination diagram is deduced the source of magma generated from the lower lithospheric mantle. Partial melting of subducted materials in the lithospheric mantle was formed as a basaltic magma rich in LREE and LILE but depleted in Nb, Sr, and Ti. The maximum pressure of HGG is estimated ~9.0 kbar from P-T pseudosection; indicating that these high-grade gneisses were developed at a depth of about 30 km below the current surface level. If we assume the thickness of the present crust to be 35 km in the East Indian shield, it means that the crust was 65 km thick during the Proterozoic period.

The E-W-trending CITZ belt preserved an orogenic crust of ~1650–1600 Ma. The geochronological data has used to correlate the CGGC and other adjacent terrains with magmatic pulses and metamorphic events. Metamorphism and magmatic activities had been occurred simultaneously around ~1600 Ma in the CGGC and also recorded in Sausar

Mobile Belt, as well as SMGC. Late Paleoproterozoic orogenic belts have recognized from different parts of India, i.e., the Eastern Ghats Mobile Belt, Aravalli Delhi Fold Belt, and this age recorded from the Antarctica (Kemp Land) of Napier Complex, these collectively leads to the formation of Columbia Supercontinent. However, finally, it concluded that Greater India and Antarctica plates amalgamated during Paleoproterozoic age as the Columbia supercontinent. During this rifting period, many magmatic processes were obtained, viz., crystallization of anorthosite around 1550 Ma, khondalite emplaced in the quartzofeldspathic matrix around 1510 Ma, as well as charnockite gneiss emplacement during 1457 Ma. 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 plates' transpressional movement may explain the 1100–1000 Ma metamorphic events investigated from the Pinjarra orogen. It was assumed that the protolith of high-grade gneiss would be affected by the high-grade metamorphism upto granulite facies conditions (Grenville orogenesis, 1000–900 Ma) during M_3 in Daltonganj, presumably during the assembly of Rodinia. The 1000 Ma high-grade metamorphism gives evidence of tectono-metamorphic episodes in the CGGC, CITZ and EGMB of India.

Scope for Future Work

A synthesis of the geological account of CGGC has been attempted based on the present state of our knowledge, though more extensive and intrusive studies are needed, and answers must be sought to the following problems for better understanding of this little known part of the Precambrian shield:

1. Pre-Paleozoic configuration of CGGC.

2. Nature of the southern margin vis-à-vis relationship with the Singhbhum Group.

3. Nature of the primordial crust of CGGC.

4. Possibility of the continuation of Eastern Ghat Mobile Belt up to CGGC.

5. Tenability of huge basinal concept of CGGC. Nature of sub-basins at northern and western parts of CGGC. There is a lack of evidence on the existence of a subduction zone to the north of the CGGC. Absence of typical features of suture zones, like the development of melange and high-pressure metamorphic assemblage, and similarity in the composition and grade of metamorphism of the metasedimentary rocks present on either side of the Dalma Ophiolite Belt.

6. Lithostratigraphic correlation of all the metasedimentary rocks within CGGC, vis-à-vis relationship with the Singhbhum Group.

7. Deformational model of CGGC vis-à-vis younger metasediments.

8. Metamorphic history about deformational episodes to build up a tectono-metamorphic model for the evolution of CGGC.

9. Magmatic history by establishing different phases of mafic magmatism, anorthosite magmatism, granite emplacement and alkaline magmatism, with particular reference to their geochemical characters and changes in their evolutionary trend.

10. Tectonic setting as reflected by different phases of magmatism.

11. Metallogenic events within CGGC with relation to plate tectonic concept.

12. Geochemical, geophysical and remote sensing study of mineralized areas and search for new deposits.