CHAPTER-X
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SUMMARY AND CONCLUSIONS

Singhbhum-Orissa Craton (SOC) is one of the richest mineral belts of India hosting deposits of Iron, Copper, Bauxite, Coal and minor gold (Saha, 1994, Mahadevan, 2002). Singhbhum-Orissa Craton is well studied area in terms of its geology and associated mineralization. The Singhbhum-Orissa Craton of eastern India is regarded as one of the largest uranium provinces of India where uranium mining is in operation since 1967 for mining of uranium resources which are located all along 160 km long E-W trending arcuate shaped Singhbhum Shear Zone (Gupta, 2006). However, vein type uranium mineralization is noted all along the younger Singhbhum Shear Zone, the other types of uranium mineralization finds are yet to be exploited economically. The study area forms part of older Singhbhum Orissa Craton where search for QPC-type mineralization has been initiated by AMD and met with significant success (Vasudeva Rao et al., 1988; Das et al., 1988; Mishra et al., 1997; Mishra et al., 2008; Kumar, et al., 2011a, b, and 2012).

This is important both in terms of academic and economic outlook as the quartz-pebble conglomerate (QPC) type uranium deposits share 13% of the total known uranium resources globally (Red Book, 2011) with low to medium grade uranium with large tonnages generally accompanied with either gold, REE, PGE and sometimes diamond. Two such types of deposits occur in Witwatersrand basin, South Africa (mainly Au and U as by-products) and Blind River deposit (U-Y) in Elliot Lake, Canada (Frimmel and Minter, 2002; Hazen et al., 2009). In India, QPC contribution is only 0.22 % of all uranium resources of the country (Parihar, 2012).

Although attempts have been made previously to explore QPC type uranium mineralization in this part of the SOC which resulted into identification of certain belts such as base of Iron Ore Group (IOG) and base of Dhanjori basin with shows of uranium and minor gold values (Vasudeva Rao et al., 1988; Saxena et al., 1994; Das et al., 1988; Mishra et al., 1997; Haque et al., 2001). There is a need for enhancing uranium resource base of the country as most of the deposits are of low grade (Chaki, et
al., 2010). Efforts have been made in recent years by AMD to look for QPC-type uranium mineralization (Kumar et al., 2009, 2011a, 2011b, 2012, Mishra et al., 2008; Chakrabarti et al., 2011). In this context, the area situated along western margin of Archean Bonai granite was selected for present research work.

The objective or rationale behind selection of the present research work was many folds which included, (i) Identification and delineation of radioactive (uraniferous) quartz-pebble conglomerates (QPC) at the base of Iron Ore Group (IOG) of rocks along western margin of Bonai granite pluton in Singhbhum-Orissa craton of Sundergarh district of Orissa of eastern India, (ii) Characterization of radioactive quartz-pebble conglomerates and associated quartzite with the help of field geological setup, detailed petrographic studies, mineralogical and textural features including SEM-EDS study, (iii) Identification of radioactive phase/s in QPC to find the presence of radioactive minerals responsible for radioactivity, (iv) Geochemical characterization of QPC and quartzites to understand their paleo-weathering condition, provenance and tectonic setting, (v) Analysis of selected samples of QPC and quartzites for their radioelement distribution to know the concentration levels of U, Th and potassium, hence their uraniferous, thoriferous or mixed U-Th nature, (vi) Analysis of selected samples of both radioactive QPC and associated quartzites for REE, PGE, Au and Ag analysis to decipher their economics which can be taken out as by-product during the mining of radioactive mineral mainly uranium and finally (vii) Genetic modeling with the help of geological, petrological and geochemical data to understand the origin of QPC-quartzite sequence along western margin of Bonai Granite Pluton (BGP) and genesis of uranium and associated Au-REE-PGE mineralization in this part of Singhbhum-Orissa Craton.

Geological mapping on 1:50,000 scale and then on 1:1000 scales helped in delineation of various lithounits in the area including radioactive QPC lenses. Mapping indicated that large area is covered with Archean Bonai granite (3.3 Ga -3.16 Ga) (Kumar et al., 2009; Sengupta et al.,1991) and QPC - IOG quartzite with minor meta-volcanic rocks that are exposed. QPCs occur as lensoidal body either at the base of quartzite or inter-bedded. Contact with Bonai granite is sheared / faulted. The general trend of QPC and quartzite sequence is NE-SW with 50°-80° dips towards north to NW (Fig.5.0).
Radiometric tests with Scintillometer counter revealed radioactive nature of QPC (Tables 5.2a, 5.2b, 5.2c, 5.2d, 5.3). Quartzite is non-radioactive. QPC samples (n=43) from western margin of Bonai granite indicated <5 ppm to 0.039 % U\textsubscript{3}O\textsubscript{8}, 34 ppm to 0.035 % ThO\textsubscript{2} with Th/U ranging from 0.41 to 8.17(Table 5.3). Low Th/U values are indicative of uranium bearing phases whereas higher ratios suggest thorium rich minerals. Presence of rare uraninite [(Fig.6.5(9,10,11,12)] secondary uranyl minerals[(Fig.6.5(14a,14b,15a,15b,16a,16b)]and monazite grains[(Fig.6.5(5,6)] support these analytical results. IOG quartzites with which QPC are associated are non-radioactive as indicated by scintillometer investigation of the area (Kumar et al., 2009). Petrographic study indicates pebble composition of QPC dominated by mainly white vein quartz, minor ash grey colour smoky quartz, rare chert and quartzite [Fig.6.4(1,3,4,5,7)]. The matrix is mainly composed of fine size sub-angular to sub-rounded quartz grains, chlorite flakes, sericite and iron-hydroxides like goethite, limonite and minor hematite[Fig.6.4(7,8,9,10,11)].Sub-rounded grains of pyrite[6.4(19a,b)], monazite[Fig.6.4(29);6.5(5,6)], zircon[Fig.6.4(14a,14b)], allanite, magnetite[Fig.6.4(17a,17b,18a,18b)], chromite[Fig.6.4(31)] rutile[Fig.6.4916a,16b] and tourmaline[Fig. 6.4(13)]constitute heavy mineral fractions in the QPC matrix. Quartzite is made up of mainly quartz grains with sutured grain contact, minor fine quartz and sericitic matrix and rare amount of heavies mainly zircon, sphene, magnetite [(6.2(1, 2, 3,4)].

Presence of mainly quartz, few chert and rare quartzite pebbles with moderate amounts of micaceous matrix and sub-rounded to rounded grains of heavy minerals are indicative of mature nature of QPC. High SiO\textsubscript{2} (84.94-96.73 wt % in QPC, 83.95-97.59 wt % in quartzites, lower content of alumina in QPCm (1.45 to 7.56 %) and quartzites (1.13 to 6.53%) (Tables 7.1, 7.2,7.5), high SiO\textsubscript{2}/Al\textsubscript{2}O\textsubscript{3} ratio (11.29-64.45 in QPC, 12.89-86.36 in quartzites)(Tables 7.3,7.4,7.5) also support petrographic observations. Higher contents of TiO\textsubscript{2} in QPC compared to IOG quartzite is interpreted due to presence of ilmenite, rutile, magnetite and rarely leucoxene. Comparison of trace elements in QPC and quartzite with respect to both UCC and PAAS indicated enrichment of Th, Cr, U, La, Ce, Nd and Sm and depletion with respect to Ba, Sr, Ti, Ni, Rb and Zr(Tables 7.6,7.7)(Figs.7.2a,7.2b).
Geochemical characteristics of the host litho-units indicate sub-litharenite to sub-arkose to arkose nature of QPC and arkosic to sub-arkose nature of quartzites on Log (SiO$_2$/Al$_2$O$_3$) vs Log (Na$_2$O/K$_2$O) (Pettijohn et al., 1972)(Figs.7.10a,7.10b). On Herron (1988) chemical classification scheme on Log (SiO$_2$/Al$_2$O$_3$) vs Log (Fe2O3/K$_2$O), QPCm falls mainly in sub-litharenite field, partly in Fe-sands and rest in arkose to subarkose and two to three samples in quartz-arenite field. On the other hand, IOG quartzites occupy the field of sub-arkose with barring one sample in quartz-arenite field (Fig.7.10c). In (Fe$_2$O$_3$t + MgO)-Na$_2$O-K$_2$O (Blatt et al., 1972) diagram, QPCm indicate ferro-magnesian nature whereas IOG quartzites are potassic in nature (Fig. 7.10d).

Composition of sediments is controlled by their provenance or source-rock composition from which they are derived. Secondary processes like weathering, transport, diagenesis etc. can affect the chemical composition of sediments (Cullers et al., 1987; Wronkiewicz and Condie, 1987). REE, Th and Sc generally have higher abundance in felsic rocks whereas Sc, Cr and Co are concentrated more in mafic igneous rocks. High Th/Sc ratio in QPC and low to high ratio in quartzites indicated their derivation mainly from felsic and minor mafic component in the provenance (Table 7.10). Other geochemical plots based on least mobile elements like La, Th and Sc such as La-Th-Sc diagram (after Mclennan, 2001; Condie, 1993), Hf vs La/Th values (Floyd and Leveridge, 1987)(Fig.7.13) and TiO$_2$ vs. Ni sedimentary provenance diagram (after Floyd et al., 1989)(Fig.7.14) are suggestive mainly of acidic and minor mafic provenance. Thus presence of Th, U, high Th/Sc, high La/Sc, together with elevated concentrations of Cr, Cr/Th, Cr/Zr and a rare chromite grain indicates granite-greenstone provenance for QPC-quartzites in the area. Hence somewhat mixed provenance is suggested for QPC-quartzite.

Correlation of certain trace elements suggests slightly positive relation between U and Th in QPCs which is due to presence of thorian uraninite which is also reflected in the mineral chemistry of uraninite (Kumar et al., 2012). Poor correlation of U and Zr and Th with Zr in QPC is indicative of non-radioactive or feebly radioactive nature of zircons. Presence of monazite is indicated by positive correlation among Th, Ce and P$_2$O$_5$ in QPC.
Chemical index of alteration (CIA) and plagioclase index of alteration (PIA) study are helpful in knowing the weathering history of provenance rocks in the source itself or during the deposition or at the site of deposition (Maynard et al., 1991). CIA computation of both QPC and quartzites suggest moderate to high degree of weathering in provenance rocks and also high to very high plagioclase index of alteration (PIA) (Table 7.17). High PIA is due to dissolution of feldspar in the sediments which resulted into complete disappearance of feldspar and high Rb/Sr ratios and achieving maturity of the sediments. CIA study also suggested that granite, granodioritic and tonalitic rocks were the provenance rocks which upon weathering and transportation provided the detritus to the supra-crustals in the form of QPC and quartzites (Fig. 7.20).

REE geochemistry indicates LREE enrichment and almost flat HREE pattern in QPCm (Figs. 7.16a, b) compared to IOG quartzites which shows fractionated gently sloping REE pattern with low REE and depleting trend in HREE (Figs. 7.17a, b). High values of (La/Sm)\text{CN} values ranging from 3.18-4.55 in QPC and 1.87-9.12 in quartzites and nearly flat HREE pattern with (Gd/Yb)\text{CN} ranging from 1.08-4.85 in QPC suggest LREE enrichment in QPC and quartzites (Table 7.16). The presence of negative Eu anomaly has been attributed to the presence of Eu-depleted felsic igneous rocks in the provenance such as granites.

Chondrite normalized REE plot of QPC is well comparable with REE pattern of Singhbhum Granite-B, phase-III and REE pattern of Bonai granite – phase-II whereas REE pattern of quartzite is comparable with that of SBG-A-phase-I, SBG-A-phase-II) and BG-phase-I, thus reveals that SBG-III, BG-II and PGG were the provenance for QPC and SBG-phase-I & II and BG-I were the source for IOG quartzites in the study area (Figs. 9.0, 9.1 and 9.3).

In addition to uranium and Th, QPC and quartzites have been analyzed for their Au, Ag, total REE and PGE to explore the economic viability of Archean quartz-pebble conglomerates. The gold content in QPC range from <20 ppb to 382 ppb (N = 21) (Table 8.2), which is very high compared to crustal abundance of 4 ppb. Seventeen samples of QPC indicated 1.0 to 3.5 ppm of Ag (Table 8.2).
The IOG quartzites show higher concentration of Au varying from 30 to 1527 ppb; some of the higher values of Au are 233, 238, 264, 557 and 1527 ppb (Table 8.3). Most of the IOG quartzites have low concentration of Ag (<1.0 ppm), only three of them indicated 1.0 to 1.5 ppm Ag (Table 8.3). The data suggest that the concentration of Au is more in IOG quartzites than in QPC, whereas higher Ag content and moderate concentration of Au is noted in QPC compared to quartzites.

Total REE concentration in QPC (average = 356.48 ppm) is more than quartzites (77.56 ppm) (Table 8.4). High content of REE is due to presence of detrital minerals like monazite, uraninite, zircon (Table 8.5), sphene etc. In case of quartzites, REE are mostly associated with clays as indicated by high positive correlation of REE with Al$_2$O$_3$ in quartzites (Figs. 7.8, 7.9b) The source of gold in QPC and quartzites appears to be from greenstone belt of older IOG rocks and other mafic-ultramafic rocks of OMG occurring as enclave within Singhbhum granite. One such gold deposit is located near Kundarkocha in IOG sequence of Gorumahisani-Badampahar of Singhbhum_Orissa Craton (Sahoo et al., 2009). The PGE content of QPC and IOG quartzites are given in Table 8.6. Out of five QPC samples, two samples indicated 15 to 188 ppb Pt. Similarly, three samples of IOG quartzite analyzed 220 to 692 ppb Pt. The ultramafic rocks within older IOG sequence of Daitari-Tomka basin in southern part of SOC contained elevated concentration of Au up to 6.6 ppm within chromite-sulfide assemblage (Mondal et al., 2001) and in sulfide dominated and sulfide-poor association up to 3.3 and 50 ppm respectively (Auge et al., 2002). Weathering and erosion of granitic rocks and ultramafic-mafic rocks such as Singhbhum granite, Bonai granite and OMG within SBG and ultramafic intrusive like Sukinda and Baula-Nuasahi within southern older IOG appears to have acted for the provenance for REE, PGE and Au, Ag in younger IOG equivalent QPC-quartzite sequence deposited along western margin of Bonai granite.

Post-depositional modifications are noted in the form of recrystallization of fine quartz grains between grain contact of quartz pebbles [Fig. 6.4(5,25,26)], dissolution of silica from quartz pebbles resulting into its irregular shape [Fig. 6.4(2,3)] adsorbed uranium over ferruginous material like goethite [Fig. 6.5(1,2,4)] and limonite and encrustations of secondary uranium minerals. Fracturing of quartz pebbles, magnetite grain and healing
of these fractures (Fig. 6.4(23,24,27)) also indicate post-depositional changes suffered by QPC in the area. Moderate to strong undulose extinction in quartz pebbles[Fig.6.4(5,24,25)] in QPC and quartz grain in quartzite[6.2(4,5)], minor bending in mica cleavage also favors post-depositional deformation in QPC-quartzite sequence in the study area.

Stretching and undulose extinction in quartz pebbles in QPC and quartzites, minor folding in quartzites; formation of leucoxene from ilmenite, formation of diagenetic pyrite, recrystallisation of sericite into muscovite, quartz overgrowth along grain boundary of quartz pebbles, healing of fractures in quartz pebbles and fractured magnetite by sericite and fine recrystallized quartz and quartz veins due to post-depositional activity [(6.4 (2, 5, 14a, 23, 25,26)].

The radioactive minerals identified are uraninite, secondary uranyl mineral, adsorbed uranium associated with goethite, limonite, hematite and veins of ferruginous material, monazite grains, anatase and weakly radioactive zircon. Presence of sub-rounded to muffin shape of uraninite [(Figs. 6.5(9, 10, 11)], their association with heavy minerals like zircon, monazite, magnetite, pyrite, chromite, anatase, ilmenite, rutile and tourmaline indicate the detrital origin of uraninite in QPC. Higher content of Th and REE in uraninite grain indicate their formation at high temperature. Comparable U, Th, Pb and U/Th and Ca/Th of QPC uraninite with uraninites from different environment and areas, uraninite in QPC from study area is akin to uraninite of pegmatite(Tables 7.18,7.19).Thus, the data indicate derivation of uraninite in QPC from pegmatite (Kumar et al., 2011a; Kumar et al., 2012).

Subrounded to anhedral shapes of pyrite grains and their mineral chemical data in QPC (Tables 7.24,7.25) (low Co and Ni contents and Co/Ni ratio less than 1.0) indicate their syngenetic sedimentary and diagenetic origin which is also revealed in binary plot of Co vs Ni after Campbell and Ethier,1984)(Fig.7.31)(Kumar et al., 2012).

The low Th/U ratio with less than 4.0 is indicative of enrichment of uranium and presence of reducing environment during the time of weathering and deposition of QPC and IOG quartzites(Tables 7.8,7.9) (Fig. 7.22). The presence of detrital grains of
uraninite and pyrite further support this observation in the QPC. Low Th/U ratios <3.8 suggest comparative enrichment of uranium and also indicative of K-rich granites in provenance (Taylor and McLennan, 1985). After oxygenation of atmosphere, leaching of iron from magnetite, biotite and pyrite and formation of ferruginous veins, goethite and limonite and leaching of uranium from detrital grains of uraninite and formation of secondary uranium minerals and their absorption over goethite, limonite and hematite with adsorbed uranium over it was the last activity noted in QPC-quartzite sequence formed along western margin of Archean Bonai granite in Orissa, eastern India.

Thus, research work has helped in the delineation of QPC and discovery of radioactivity associated with it, which has also resulted in the characterization of QPC-quartzite sequence from western margin of Archean Bonai granite. Geological, petrological and geochemical studies of QPC and associated quartzites indicated that QPCs are oligomictic, uraniferous, pyrite bearing which has undergone moderate to high degree of chemical weathering, and largely derived from felsic igneous rocks like Singhbhum granite, Bonai granite and Palahara granite gneiss and have been deposited in passive margin tectonic setting developed during Archean period (3.3 and 3.16 Ga or 3.16 to 2.8 Ga). The QPC– quartzite sequence in study area was also found to contain Au, Ag, REE and PGE mainly Pt which makes them economical. The geological, petro-mineralogical and geochemical character of these QPCs has similarity with those of Witwatersrand QPC of South Africa and Elliot- Lake of Canada (Mikhailov, 2006; Cuney, 2009). Therefore, there is a need to explore this area in detail with the help of detailed high resolution exploration, modern and advanced technology so as to develop this area into a good U-Au-Ag-REE-PGE prospect in future.