# Abstract

Set in the milieu of the northern part of the eastern Dharwar Craton in southern India, the late Archaean Hutti-Maski greenstone belt hosts the largest, presently operational gold mine in India, namely Hutti. Two other smaller mines, Uti and Hira-Buddinni are also producing gold in this belt. The main objective of this research work is to study aspects relating to metamorphism, fluid evolution and mineralization and to propose coherent genetic models for the above three orogenic gold deposits in the broader spectrum of crustal scale tectonic setting.

Several, kilometer scale, NNW-SSE trending, steeply westward dipping, and parallel strike-slip shear-zones are the main controlling structure in Hutti. Four different generations of veins were identified, amongst which, the isoclinally folded quartz veins in the biotite alteration zones and the laminated fault fill veins are auriferous. The deformation history constitutes five successive stages ($D_1$-$D_5$). $D_1$ represents the earliest phase during which the regional schistosity ($S_1$) was developed. After that ($D_2$), the main shearing took place followed by $D_3$ when these shear zones were reactivated together with the formation of laminated fault-fill veins. Minor broad folds and regional-to-local scale faults represent $D_4$ and $D_5$ respectively. Thin anastomosing shear zones with a general N-S orientation and four deformation episodes ($D_1$-$D_4$) characterize the Uti deposit. The first two events ($D_1$ and $D_2$) produced shear foliations at low angle to each other but with different slip directions. $D_3$ and $D_4$ had similar structural manifestations as $D_4$ and $D_5$ in Hutti. The structure of the Hira-Buddinni mine is also dominated by a large E-W oriented steeply dipping, reverse, brittle-ductile shear zone. Here, steeply dipping fault-fill veins running along the shear zone and shallow dipping, sigmoidal extension veins are the most important auriferous vein structures. The first deformation episode produced the regional foliation and the next phase involved development of the shear zone. The flat lying extensional veins were sigmoidally rotated during cyclic pressure fluctuation and ductile creep in the shear zone. The deformation history culminated with the formation of large faults crosscutting the earlier structures.

Careful examination of the micro-textures followed by individual thermobarometric calculations using suitable mineral pairs and multi-equilibrium thermobarometric (MET) computations on pertinent mineral assemblages were pursued to deduce the metamorphic conditions. The metabasites from Hutti record amphibolite facies conditions (3-5 kbar / ~ 650°C) as the probable peak metamorphic P-T. Major and trace element whole rock geochemical data of these amphibolites indicate that the precursor rock was tholeiitic basalts with an island arc tectonic signature. A clock-wise P-T-t path could be established from garnetiferous amphibolite and garnet biotite schist, with peak P-T reaching amphibolite facies conditions (6 kbar / 650-700°C) at Uti. In the prograde sequence, garnet formed from calcic amphibole and plagioclase 4.9 ± 1.0 kbar and 507 ± 35°C ($X_{CO_2}$ = 0.2). On the retrograde sector, garnets altered to chlorite along cracks (550°C). Continued retrogression of garnet to form Fe-Mg clinoamphiboles took place at 3.1 ± 0.5 kbar and 367 ± 28°C. Further lowering of P-T into sub-greenschist facies conditions aided by hydrogen ion metasomatism led to stabilization of secondary Ca-Al silicates such as prehnite, pumpellyite and hydrogarnets within biotites. The deduced clock-wise P-T-t path can be explained by a subduction related compressional tectonic setting, invoked by several authors for similar greenstone belts in other Archaean terrains.

Gold mineralization at Hutti took place on the metamorphic retrograde path beginning with initial alteration (and sulfidation) at upper greenschist facies and after a protracted fluid activity the mineralization culminated with the formation of auriferous laminated quartz veins at lower greenschist facies. The $fS_2$- buffered arsenopyrite + pyrite + pyrrhotite assemblage in the biotite zone constrained the temperature (350–477°C) and $\log fS_2$ (–5 to –8.7) of ore formation. Geochemical mass balance calculations indicate an increase in mass but a decrease in volume of the shear zone during alteration. The alteration was accompanied by intense potash metasomatism along with addition of S, As, Rb and LOI. Theoretically computed $\log fO_2$-log $a_{H_2S}$ and $\log fO_2$-pH diagrams suggest that the ore fluid had

a total S content near 0.1m and decrease in both $fO_2$ and pH was necessary to precipitate gold from a hydrothermal solution containing $Au(HS)_2^-$ complex. Wallrock sulfidation reaction also involved similar $fO_2$ and pH decrease in order to precipitate gold. Fluid inclusions in folded quartz veins in these biotite alteration zones show a unique assemblage of five distinct types of carbonic inclusions containing variable proportion of $CO_2$, $CH_4$, fluid deposited graphite and $H_2O$. Precipitation of thin films of graphite in the inner walls of carbonic inclusions is interpreted to be the result of heterogeneous reaction between $CO_2$ and $CH_4$ ($CO_2 + CH_4 = 2C + 2H_2O$) within those inclusions that were trapped at temperatures in excess of 400°C and had sufficient amount of $CH_4$ in them. Entrapment of these carbonic and aqueous inclusions succeeded phase separation that the initial aqueous-carbonic fluid underwent following a decompression event. The P-T condition of formation of the auriferous laminated quartz veins (1.0 -1.7 kbar / 280-320°C) was estimated by the method of intersecting isochores of coeval and co-genetic aqueous and carbonic inclusions. Simultaneous entrapment of these inclusions was again a consequence of phase separation of an initial fluid of broadly similar composition, but at lower temperature. Accordingly, gold precipitation in these veins was primarily due to decrease in total sulfur content in the aqueous part, rather than the wallrock sulfidation and $fO_2$ decrease as in the biotite zones. Thus, gold precipitation at Hutti, in the alteration zones and laminated veins occurred at different temperature regimes and followed different mechanisms.

Mineralization at Uti is intimately associated with biotite- and sulfide- rich alteration zones developed in unsheared lenses between N-S oriented anastomosing shear zones. Temperature (357 to 466°C) and $\log fS_2$ (−8.3 to −12.2) were estimated from arsenopyrite composition in the $fS_2$-buffered assemblage arsenopyrite + löllingite + pyrrhotite. Like Hutti mineralization occurred on the metamorphic retrograde path. Mass balance calculations indicate introduction of $SiO_2$, $K_2O$, S, As and Zr and depletion of CaO in the mineralized portion. There is virtual absence of carbonic inclusions in the thin quartz veins of Uti and the aqueous inclusions in veins within and outside the mineralized zones have broadly similar fluid characteristics. Estimated P-T variation for mineralized quartz veins are 1.0-2.5 kbar and 250-300°C. Fluid evolution in Uti followed a two-stage process where the first stage witnessed simple cooling from a heated (≥ 400°C) low saline fluid, followed by its near-isothermal (≈ 200°C) mixing with a high saline granitic fluid. Mineralization and characteristic hydrothermal alteration was primarily a product of remobilization due to the interaction of heated meteoric water with suitable host rock, where gold was already available. Although the meteoric fluid mixed with the granitic fluid, fluid mixing had no ore genetic significance, since such mixing was clearly post-mineralization and took place at a lower temperature.

Gold is recovered both from the wall rock mylonites as well as from the fault-fill and sigmoidal extension veins at Hira-Buddinni. Here the alteration mineralogy is rather complex with a wide range of minerals occurring at various locations without any observed systematic disposition. The sigmoidal extension veins contain numerous aqueous as well as carbonic inclusions in close association, showing large density variation within single clusters. Such variation is indicative of pressure cycling or operation of fault-valve mechanism during the formation of these extensional veins. Occurrence of gold within these veins implies phase separation during sudden pressure drops that acted as the governing factor leading to gold precipitation at Hira-Buddinni.

Summing up, the Hutti-Maski greenstone belt constitutes orogenic gold deposits that formed on the retrograde paths after the greenstones underwent amphibolite facies metamorphism. However, deposit-wise variations in fluid evolution and mineralization style also strikingly characterize this belt.