CHAPTER 10
SUMMARY AND CONCLUSIONS

The demand of manganese, one of the important components of steel making process, is increasing with steel production. India is 7th in the world production of manganese ore, with a production of about 2.5 million tonnes per year. The export of manganese has been restricted to cater to the domestic consumption and future requirement. The state of Madhya Pradesh contributes about two third of the total production of ferro-grade manganese in India, and a major portion of comes from the Balaghat mine. Multidisciplinary approach was adopted by the author to find out new manganese prospects in and around Balaghat deposit. Detailed geological studies including the metallogenesis of manganese which had a direct bearing on techniques and norms to be adopted for exploration of manganese was used to achieve this. Under this backdrop, current research work is attempted on manganese ores in and around Balaghat deposit in Central India.

The manganese deposits of Bharweli area of Balaghat District, Madhya Pradesh, occur as synsedimentary banded sequence, conformable with the enclosing metasediments like phyllite, sericite schist, quartzite, schistose quartzite and gritty conglomerate. The deposit occurs as Banded Manganese Formation (BMnF) with bands of jasper and manganiferous quartzite, alternating with the manganese ore. The physical properties of the manganese ores vary widely because of the association of the ore with different gangue minerals in different proportions. Mineralogical studies reveal that braunite is the main manganese ore mineral which was formed during sedimentation and was also developed during later metamorphism as second generation along with hausmannite, hollandite, manganite, and bixbyite; pyrolusite and psilomelane were formed during supergene enrichment of the metamorphosed ores. Geochemical studies show that the MnO\(_2\) % is high (i.e. 57% to 78 %) with very low amounts of phosphorous. The high concentration of manganese in all ore samples is derived from braunite, hausmanpite, hollandite, manganite, bixbyite and pyrolusite. MnO\(_2\) shows relatively negative correlation with Al\(_2\)O\(_3\), SiO\(_2\), K\(_2\)O, and P\(_2\)O\(_5\) indicating reduction with increase in manganese content. Presence of Al\(_2\)O\(_3\) and SiO\(_2\) is attributed to the alumino-silicate minerals and quartz feldspathic rocks.

The observations made through the major, trace and REE analysis provided typical geochemical signatures of ore genesis and environment of deposition of manganese ore. Comprehensive geochemical studies were carried out on a number of manganese ore samples collected across the strike and dip of the deposit from surface mines, boreholes and underground
faces. Most of the samples provide evidence for a hydrothermal source of manganese in the sedimentary basin. Sub-marine hydrothermal affinity of Mn-oxide ores is also supported by their high concentration of trace elements like Cu, Ni, Co and Zn, compared to their relatively lower concentration in hydrogenous deposits. The ~2.2 to 2.4 Ga Sausar Group, India hosts large Mn oxide deposits in different stratigraphic levels of a Proterozoic sequence. Large scale deposition of manganese started during the early part of Paleoproterozoic. This was possible due to oxygenation of the atmosphere and stabilization of the stratified ocean system. At that time dissolved Mn$^{2+}$ could have concentrated in anoxic deep water and the source was hydrothermal or terrigenous. Ocean-floor spreading and hydrothermal activity is thought to be responsible for the supply of manganese to most of the Proterozoic manganese formations.

Hydrothermal processes also include exhalative or volcanogenic deposits and are products of rapid precipitation from hot mobile metal- enriched fluids, close to the interface between the ocean and the seafloor REE and other trace element data when viewed along with the information obtained from detailed study suggest that Balaghat manganese deposit has been derived from some nearby volcanic hydrothermal vent. Large positive Eu anomalies are characteristic of seafloor hydrothermal vent fluids. The REE patterns shown by the ores represent the end product of complex series of events that record the properties of the Mn rich solutions subsequently precipitated with volcaniclastic sediments. The high concentration of barium reflects its oxidizing environment resulting from the development of pyrolusite and also could be due to volcanogenic source. Detailed study of geological, petro–mineralogical, structural, and geochemical aspects of the deposit it is inferred that the manganese deposit of Balaghat area was initially volcano-sedimentary origin and was later modified by metamorphism.

The manganese bearing horizon of Balaghat extends almost for about 2.8 km in length. The general strike is N 25°E - S 25°W, and the dip is towards west. The economically mineable zone has some local isoclinals folds, which increase the total thickness of the pay horizon making it economically viable for mining. The ore bed is thicker in the middle portion because of development of a regional S-shaped fold, thinning out in the extremities and ultimately disappears. The maximum thickness in the middle portion is about 20 m and minimum is about a meter giving average thickness about 10 m. A recumbent fold, between 4th to 6th level, with east–west axial plane and subhorizontal plunge towards SSW is the main structure which controls the down depth variation of the mineralized zone.
The entire deposit can be divided into two blocks on the basis of dip amounts. Due to the recumbent fold, the ore deposit is flat (very sallow dip of 10°-30°) in the north section where the ore horizon is very wide; on the other hand the south section dips steeply (dip amount 60°-85°) and has narrow width.

Deformation and metamorphism takes place in three stages in this area. Deformation and metamorphism (D$1$-M$1$): The first folding generated isoclinals folds with axial planar schistosity. These folds on the ore band have NNE-SSW trend (recumbent fold). Deformation and metamorphism (D$2$-M$2$): Tectonic deformation of second generation developed folds on schistosity and reoriented early folds. These folds were mostly upright with NNE-SSW trend (i.e. drag folds and asymmetrical folds). Deformation and metamorphism (D$3$-M$3$): These folds with NS to NNW-SSE axial planes caused swing of regional trend. The ore body is predominantly affected by both D$2$ and D$3$ fold patterns producing at places narrow and wider ore bands. Other folds like recumbent isoclinals, asymmetrical, symmetrical and drags have affected the mineralization locally, and have formed pinch-and-swell geometry. Joints present in the deposit have little effect on mineralization, but affect mining operations by reducing wall rock strength and increase the cost of mining by the requirement of more support system. Some minor faults are also observed with throw of less than 10 m.

The mining method used in Balaghat mine is overhand flat back cut fill. The ore is mined in horizontal or slightly inclined slices, and then filled with waste rock or sand. The interval between each level is 30 m and the size of the stope block is kept 45 m × 30 m × width of the ore body in the southern part and 60 m × 30 m × width of the ore body in the northern part. Due to weak nature of hanging wall the slice of ore body is kept restricted to 3 m. The void created by the slice is packed by fill material before taking the next slice only after the completion of packing. To prevent the caving in the mine various types of supports are generally used, depending upon the character of wall and the ore. In Balaghat mine medium hard rocks require less support. But due to jointed strata various types of supports are used such as sand stowing, roof bolting, cable bolting, timbers, waste filling/waste packing, steel support with concrete, chock, pillars and ribs. The contact between the ore body and hanging wall is very weak. Presently concrete support is being used. It is recommended to use pre-cast concrete slab support in this weak zone, which will be much faster.
and safer for future mine development work. Pre-cast concrete slab can be also be used in the footwall side.

The problems of mineral beneficiation of manganese ore have direct relation to their mineralogy and genetic history. The study of genesis, ore mineral characterization and nature of manganese ores helped us to understand the locking pattern, shape, size, mineral fabric and chemical composition and liberation characteristics of gangue minerals from the manganese ore and ultimately help to formulate the right strategy for their beneficiation and utilization. There are several types of ore textures associated with manganese ore of Balaghat manganese deposit, such as, mutual boundary, contact, colloform-colloidal-banding and replacement textures. This type of ores require only proper sizing of beneficiation before they are used for metal extraction. In Balaghat mine, two types of beneficiation methods are in use, hand picking and gravity concentration or jigging. The jigging is being done by air pulsed jig, and by this process sub-grade material of more than 0.9 million tones can also be used for extraction of concentrate or sailable grade.

With the help of extensive geological studies along with interpretation of several lithologs, detailed exploration plan was made to intercept the ore body at about 50 m along the strike and with about 100 m in dip interval. The point of intersection was prefixed and accordingly inclination surface has been arranged so that the borehole intersects the target horizon. The general strike direction of the deposit is N25°E – S25°W but changes from chainage 2300 and moves towards north-western direction and ultimately crosses the lease area due to the recumbent fold pattern. The curved geometry of the ore body is increasing with the depth. So the north-western part of the deposit is can be developed with the help of concept based exploration that will help to add new reserves in the Balaghat manganese deposit and to find new prospects in the analogous zones.