MANGANESE ORE DEPOSIT OF BALAGHAT MINE, CENTRAL INDIA: EVOLUTION MODEL AND ITS IMPLICATION FOR EXPLORATION

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Synopsis of the Thesis Submitted to
INDIAN SCHOOL OF MINES, DHANBAD
For the award of the Degree of
DOCTOR OF PHILOSOPHY
IN
APPLIED GEOLOGY

June, 2013
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YNOPSIS

Manganese is one of the important components of steel making process. Steel is vital to the development of any modern economy and is considered to be the backbone of the human civilization. The level of per capita consumption of steel is treated as one of the important indicators of socio-economic development and living standard of the people in any country. It is a product of a large and technologically complex industry having strong forward and backward linkages in terms of material flow and income generation. All major industrial economies are characterized by the existence of a strong steel industry and the growth of many of these economies has been largely shaped by the strength of their steel industries in their initial stages of development. Prospective investors include existing public sector as well as private sector manufacturers, reputed foreign manufacturers look towards manganese business because manganese is essential raw material for steel industry.

The genetic diversity of Mn deposits in general is considerable. Genetically manganese deposit can be broadly divided into two category (i) Primary Mn deposition (ii) Supergene- residual formation. In deposit scale and commercial point of view the primary Mn deposition is most important and it can be further classified in to three sub group (a) Hydrothermal (b) Hydrogenetic (c) Diagenetic. Hydrothermal also known as exhalative or volcanogenic deposits are product of rapid precipitation from hot (100°- 350° C) mobile metal- enriched fluids, close to the interface between the ocean and the seafloor. Hydrogenetic deposits are also known as sedimentary deposits formed from slow precipitation at ambient conditions and subsequent sedimentation in rather stable fresh water or marine environments. The products of this type formation are Fe Mn crust and deep sea nodules. Diagenetic processes involve precipitation from pore fluids that have interacted with material at varying levels in sedimentary column. The products may be oxide, hydroxide, carbonate or sulphides and appear in form of cement, fracture infillings etc. The supergene and residual is secondary formation. However it is very important to know the genetic model of any deposit for find out the suitable exploration method.

The genesis of Balaghat manganese deposit is not clearly established. Most of earlier workers suggest that the deposit is originally sedimentary origin and later on it got metamorphosed,
but the source of manganese is not clear. The aim of this research is to find out the actual sources of manganese and to establish the genesis of the Balaghat manganese deposit after a scientific study on its geological, structural, petrological, mineralogical, geochemical data. On the basis structural and genetic model of the area the suitable and scientific exploration techniques to be indentify to enhance the resource base and also to explore the possibility of finding some new ore deposit in and around the Balaghat manganese deposit.

In view of this, scientific exploration of these mineral deposits has become essential for converting the “potential mineralized zones” into “proved reserves” for designing a “working mine” to produce desired “quality raw materials”. The theme of present research work: “Manganese ore deposit of Balaghat mine, Central India: evolution model and its implication for exploration” has been aimed at understanding and addressing each of these aspects along with holistic geological, metallogenetic and structural aspects combined with use of geological concepts for exploration and mine development works in details.

This work included detailed geological and structural interpretations, systematic collection of samples, detailed chemical, petrological and mineralogical studies, mainly to understand geological environment, structural set-up, geochemistry, mineralogy and genesis of manganese ores and their associated rock types besides exploration, mining and beneficiation aspects. The broad objectives of the present investigation of the manganese ores of the studied areas are as mentioned below:

1. Review of geological and structural set up of manganese deposition in Balaghat manganese belt for understanding the environment of deposition and controls of mineralization, especially in Balaghat mine.
2. Review the mineral economics of manganese resources and their present business scenario in India as well as other parts of the world.
3. Carryout detail geological and structural study different rock of the study area for understanding the lithological and structural controls on the mineralization.
4. Carryout mineralogical characterization and their textural and paragenetic relationships.
5. Carryout detailed geochemical studies of different manganese ores and associated rocks to understand inter-elemental relationships across the length and breadth of the deposits in relation to the metallogenesis.
6. Carryout detailed study on controls of mineralization vis-à-vis genetic aspects.
7. Review of suitable mining method, support system and beneficiation processes for manganese ores in Balaghat mine using the geological and mineralogical parameters.
8. Evaluation of strategies and approaches for exploration based on genetic aspects and controls of mineralization of ore deposits and to frame a suitably acceptable norms and strategy for exploration of manganese ore in the analogous areas.

To meet the said objectives, the following methodologies were adopted:

1. Literature survey and data collection on geology, structure, geochemistry, mineralogy, ore characteristics, genesis, exploration techniques, mining, beneficiation processes and market scenario of manganese ores, from Balaghat manganese mine of Central India.
2. Geological mapping and structural information from the study area.
3. Collection of manganese ore samples, followed by chemical analysis to understand the geological, petrological, mineralogical, textural and chemical characteristics.

This research work has been divided in ten different chapters, beginning with introduction of manganese ores with an overview of their present scenario, followed by geology, petrography and mineralogy, geochemistry, structural mapping, genetic aspects on these deposits and then closing in on underground mining, beneficiation, exploration techniques and conclusion.

Chapter-1 is on introduction of the studied area, covering the purpose of the project, scope of work, methodology, followed by area under investigation, accessibility, historical background of the mines, flora and fauna, minerals, climate, demography, peoples and their occupations, physiography, soils, drainage and geomorphology of the study area.

Chapter-2, deals with global as well as Indian manganese scenario, their current market status, overview on the status of resources, their production, consumption, export, import, mineral policies, substitutes and future growth potential.

In Chapter-3, apart from giving an overview of regional geology of Sausar Group, the detailed geology of the study area, is discussed. Geological environment and regional litho-stratigraphic variations have been discussed in details.

Mineralogical and petrographic studies of manganese ores have been described in Chapter-4, which include identification of minerals, their forms, nature of occurrence and their textural relationships. Mesoscopic studies followed a range of techniques, like optical microscopy, Scanning
Electron Microscopy with Energy Dispersive Spectrometry (SEM-EDS) to determine the important mineral-chemical-textural and micro-structural properties of ore minerals. Important manganese ore types, found in the area are hard and massive in nature, found in association with Jasperoid Quartzite and have high manganese content. All manganese ores contain predominantly Braunite \[3(MnFe)_{2}O_{3} MnSiO_{3}\], Hollandite \[Ba (Mn^{4+}, Mn^{2+})_8O_{16}\], Bixbyite \[(MnFe)_4O_7\], Manganite \[MnO(OH)\], Hausmannite \[Mn_3O_4\], psilomelane \[(Ba, H_2O)_2 Mn_5O_{10}\], along with relicts of pyrolusite \(MnO_2\). Quartz and jasper are mainly associated with manganese minerals in banded manganese quartzitic and jasperoid ores as gangue minerals.

Major, trace and REE geochemistry of manganese ores was performed to evaluate the physico-chemical conditions, paleo-environment of deposition, probable composition of the source rocks and inter-element variations amongst different types of ores to decipher the major deleterious elements, as described in Chapter-5. Results show that massive hard ores are high grade in nature as they contain high manganese, low iron and phosphorus contents with fringe areas are having some higher phosphorus content. Massive Hard ores typically consist of 35 – 45% Mn, 0.08-0.33 % phosphorus and 5-30% silica.

In Chapter-6, the regional and local structural set up of the deposits has been outlined. Stratigraphically ore horizon of Balaghat mine underlies the rocks of Paleoproterozoic Mansar Formation and overlain by Sitasaongi Formation of Sausar Group in Central India. The strike length of ore body is 2.80 km. having a general strike direction NE-SW and dip varies from 25º to 85º towards west. The width of the ore body is as thin as 1.0 m at the both ends whereas it increases to as high as 30 m in the central portion between ch.3000 to 1500 average thickness is 10 m. The manganese ore deposit of Balaghat mine is the richest deposit in India. The ore horizon consists of manganese ore, manganiferous quartzite and jasperoid quartzite. Different types of structure has been observed in the study area including fold, faults, joints, lineation, bedding etc. by the help of local structure the regional structure is understand. To understand the geological features surface and underground mapping has been done in various levels and various winzes. Deformation and metamorphism takes place in three stages in this area- Deformation and metamorphism (D1-M1) - 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 (D2-M2) - 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.

Genesis and controls of mineralization have been described in Chapter-7. The Proterozoic (c. 2.2-2.6 Ga) Sausar Group, India, including the manganese deposits. The ores have been complexly deformed and metamorphosed to grades ranging from low greenschist facies to upper amphibolite facies. This sequence consists of metamorphosed equivalents of a limestone-shale-orthoquartzite assemblage (Roy, 1966, 1981) indicating a shelf environment. The presence of dolomite at the top (Bichua Formation) indicates further shallowing of the basin. Interbanded Mn oxide ore bodies (braunite, bixbyite, hollandite, manganese and hausmannite) and Mn silicate-oxide rocks are interstratified with metapelites and orthoquartzites (Mansar Formation) and less commonly occur as conformable lenses in carbonate rocks of the older Lohangi Formation. The protoliths of these Mn rich rocks were Mn oxide/hydroxide sediments admixed with variable amounts of Fe, Si, and Al. The Mn silicate-carbonate rocks, derived from Mn carbonate progenitor with admixed impurities, also occur as isolated pockets in the Mn oxide ore horizon of the Mansar Formation. The Mn oxide deposits are inferred to have formed on the continental shelf during a sea-level highstand, when detrital supply was minimal. Deposition above the redox interface produced Mn oxides even on the carbonate substrate (Lohangi Formation). Mn carbonate sediments in the Mansar Formation were diagenetically derived from Mn oxides by reaction with calcareous partings in isolated pools where an evaporative condition could have developed.

In Chapter 8, underground mining method used in Balaghat mine is discussed. Geological controls have been used while developing the mine was also deliberated. Support system and sequence of mining operations are discussed. Details of fully mechanized integrated manganese beneficiation plant having 0.5 million tonnes ROM handling capacity per year is also included in the chapter considering the mineralogy. The gangue mineral and silicates produced from the jigs are being dewatered in respective vibrating screen, conveyed through belt conveyor to storage bunker and discharge the same by means of truck to yard. The product of the jig is transported to the siding by truck. After installation of air pulsated jig, ore recovery increased to 18%.

Exploration techniques, methodologies and norms adopted for manganese deposits in Balaghat Mine have been outlined in Chapter-9. Various sizes of drilling bits, reaming shell, and accessories used in Balaghat mine has been also discussed in this chapter. Lithologs of important boreholes and their cross sections are also interpreted in the chapter. Taking help from all these
studies, exploration strategies of Balaghat mine have been outlined. Genesis of the mineral deposit, including its geological complexities, structural configuration, geological, lithological, mineralogical, physiographical and structural guides have been identified for conceptualizing exploration of manganese in the region.

Chapter 10 concludes the results and discussion of the entire research work including geological and structural environment, mineralogical and chemical variations related to genesis, exploration concepts on manganese ores from Balaghat mine which are summarized as follows:

- The Proterozoic metasedimentary rocks of the Mansar Formation host the manganese deposits of the study area. Geological field investigations show that phyllite, sericite schist, feldspathic quartzite and gritty conglomerate are the main rock types. Manganese horizon is present in between sericite schist and feldspathic quartzite beds.
- The manganese ore bodies and the enclosing rocks were formed as part of the syn-sedimentary sequence and were later metamorphosed together. Banding both on macro and micro scale exhibited by the braunite rich bands indicates the original sedimentary banded nature of the manganese ores and high grade manganese minerals have been generated from Banded Manganese Formation. The manganese ore mineralisation is controlled by both litho stratigraphic and the structural features and the variable thickness of ore is attributed to the complex structural features in the study area.
- Based on the petrographic and mineralogical studies, the major minerals have been identified in the order of abundance as braunite, hollandite, hausmannite, bixbyite, manganite, pyrolusite, and psilomelane with some silicate gangue minerals. In addition to Banded Manganese Formation (BMnF), Braunite is the most abundant ore mineral in Balaghat manganese deposit. Two generations of braunite have been observed in this deposit and braunites are generally grey in colour under the microscope and vary widely in their grain sizes, from fine to very coarse grained. In the lower grades of metamorphism, it is deformed, elongated and dimensionally oriented parallel to the banding in the ore. The second generation braunite is much lighter grey in colour and is undeformed.
- MnO₂ content in the manganese samples ranges from 57.99 to 78.61% and 0.08 to 1.96 in associated rock. The silica 3.36 % to 15.56 % in the manganese ores and from 49.88 % to 66.77 % in the host rocks. In the manganese ores the alumina content varies between 0.53 to 0.98%. In
manganese ore, potassium content varies from 0.17 % to 4.87 % with an average of 3.15 % and from 5.16 to 8.34 % in the host rock with an average of 5.93%. The potassium value is may be due to psilomelane in the ores. The P\textsubscript{2}O\textsubscript{5} concentration is between 0.08 to 0.97% in manganese ore and 0.18 to 0.42 % in associated rock. The magnesium content ranges from 0.32 % to 0.64 % in manganese ores and 0.45 to 0.84 in rock samples. Phosphorous is present in very low amounts. This high grade of manganese content is very important from economic point of view and the beneficiation of low/medium grade variety is also very important based on the mineralogical characterisation.

- REE and other trace element data when viewed along with the information obtained from detail scientific 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. Thermal springs associated with young (i.e. modern-day) volcanoes do not exhibit positive Eu anomalies. The hydrothermal solutions could have added to the ambient ocean water along with the products of explosive and eruptive volcanism. These solutions moved upward and shoreward where they met variable amounts of CO\textsubscript{2} and O\textsubscript{2} and their metal content was precipitated as oxides, silicates and hydroxides.

- Balaghat mine is largest and deepest underground manganese mine in Asia and production of manganese is carried out by over hand flat back cut and fill method. The hang wall rock is incompetent and the ore body is jointed and deformed in some places. The contact between the ore body and hanging wall is very weak and hence presently concrete support is being used which is a time consuming process besides not safe as well. It has been observed that by using of pre-cast concrete slab support in this weak zone, it will be much faster and safer for future mine development work.

- With the help of detailed geological studies along with interpretation of several lithologs, cross sections, L-V sections, solid ore body modeling, 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 and changes from chainage 2300 and moves towards north-western direction and ultimately crosses the lease area due to the recumbent fold patterns. 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 and will help to add new reserves in the Balaghat manganese deposit.

- Balaghat Mine is an important mine in India and using concept based exploration, new ore reserves also can be added. The high and medium grade manganese ores are only of 15% and beneficiation of rest of low grade ores is indispensable, due to this deficiency. There is a need to increase the availability of manganese ore commensurate with projected steel production in India. For this, exploration efforts to find new or upgrade reserves of high grade, low phosphorus manganese ore is vital with a thrust on increasing proven reserves. Extensive exploratory drilling needs to be undertaken for identifying potential blocks. Holistic geological studies combined with concept based exploration programmes have been proved to be of immense use in the development of Balaghat mine.