CHAPTER 1
INTRODUCTION

1.1 GENERAL STATEMENT

Manganese is an important commodity which is used all over the globe. Manganese is the most important of the ferroalloy metals, for which there is no substitute. About 95% of its consumption is used for steel making and other metallurgical purposes, 3% in dry battery industry and the rest in the chemical industry. Its chief purpose is steel making. It is one of the most important metals in an industrial economy. About 85% of total consumption in India is used by metallurgical industries.

Manganese is one of the major mineral deposits occurring in the Indian subcontinent. It has played an important role in development of civilization and industrialization. The discovery of the metal manganese and its use by man through the ages embossed a milestone in the march of civilization. The recent liberalization of the Indian economy has catapulted the Indian industry into new realms of thinking and progress. The policies of Government on economic development have given various subsidies like slashing the import duties and provisions for the Indian industry to grow indigenously.

Manganese ore is an important ingredient in the manufacture of iron and steel industry where it is used in both form of ferromanganese and silico-manganese. It is an essential constituent for the manufacturing of steel and there is no substitute of it; it is relatively low priced with outstanding benefit. It is the fourth most widely consumed metal after Iron, Aluminium and Copper. It improves strength, hardness, wear resistance and workability of steel, acts as a deoxidizer and desulphuriser and also helps in getting ingots free from blowholes as well as an alloying element. It enhances corrosion resistance of Aluminium alloy; improves copper alloy stability and strength and also can replaces part of the Nickel (Ni) in Ni-Al alloys. It is also used as coloring agent in glass and ceramics industries and produces rich brown, green and especially amethyst color. Manganese sulphate (MnSO₄) is used as micronutrient in animal feeds and plant fertilizers. Manganese metal is used as aluminum alloys and as a chemical oxidizer and a catalyst. Potassium permanganate
(KMnO₄) is used as disinfectant in water and waste water treatment, and as an oxidant in organic chemical synthesis and also used as a disinfectant in sore throat. It is also used in the manufacture of dry cell batteries in which it functions as a depolarizer of hydrogen which collects as a non-conducting film on the carbon electrode, thus facilitating the continuous flow of current within the battery. Pyrolusite is used generally to impart glaze for pottery and for making colored bricks. It also finds its use as driers for oils, varnishes and paints in glass industry for decolorizing green glass, medical preparations, carbon-monoxide gas masks etc. Manganese chloride is used in cotton textile as a bronze dry. Manganese salts are used in photography and in leather and matchbox industries. Manganese dioxide (MnO₂) is also used in the manufacture of oxygen and chlorine, and in dying black paints. Manganese compounds have been used as pigments and for the coloring of ceramics and glass. Manganese phosphating is used as a treatment for rust and corrosion prevention on steel.

Manganese (atomic no. 25, atomic weight 54.9380) is the 12th most abundant element found in the earth's crust and is estimated to be about 0.1087% by proportion of weight. Geochemically, it is a strongly lithophile element with some chalcophile characters (as shown by its presence in olhomite in meteorites). In the upper lithosphere, it is oxyophile and it also shows a biophile tendency (Rankama and Sahama, 1950). Abundance of manganese in igneous rocks has been given as 0.0086% (Clarke and Washington, 1924), 0.0980% (Hevysy, et al. 1934) and 0.1% (Rankama and Sahama, 1950). It never occurs as the native metal in nature, but instead in some combination with other elements and it may be produced by electrolysis, or by reduction of its oxides (Thermit process). These were produced by direct hydrothermal activity, sedimentary processes, continental weathering (Roy, 1981). They also occur as ferromanganese nodules on many parts of the deep ocean floor. Most of the existing demand for manganese is met from the sedimentary and residual deposits. It is a pinkish-grey metal, soft to very hard and brittle, melting at about 1060°C, boiling point 1980°C and having specific gravity of 7.2. Manganese ore minerals occur in the form of oxides, silicates and carbonates in different genetic types of manganese ores. The grade of a manganese ore represents the net manganese content and is the function of its mineralogy and geochemistry which is widely variable. Manganese tends to concentrate in the latest phase of magmatic crystallisation with reference to iron and magnesium due to its larger ionic radius in
the divalent state (Rankama and Sahama, 1950; Goldschmidt, 1954). Enrichment of manganese in rock forming minerals is recorded in pegmatites (Mn-phosphates, manganiferous columbite and tantalite, spessartine, helvite etc.) and in post-magmatic pneumatolytic and hydrothermal deposits (wolframite, rhodochrosite and different Mn-oxides and Mn-silicates) (Roy, 1981).

The formation of manganese ore deposits of the different types now resting on continents can be broadly correlated with the general pattern of the crustal evolution (Shatskiy, 1964; Strakhov, 1967, 1969; Stanton, 1972) in the early stage of basic volcanism, manganese ore bodies associated with greenstones and jasper predominated. With the development of eugeosynclines, Mn ore concentrations were formed in association with pyroclastic volcanic rocks (basalt, andesite and dacite) and stratiform iron and base metal sulphide and barite deposits on the seafloor. The most conspicuous development of manganese deposits in geological history is found on platforms which are mostly devoid of volcanic rock association (Roy, 1981).

Manganese ores come largely from China, Ukraine, Gabon, South Africa, Australia, Brazil and India and traded to Japan, France, Norway and South Korea etc. The total manganese reserves base in the world is approximately 5,200 million tonnes (Mineral Commodity Summaries, USGS, 2011) as shown in table 1.1. South Africa alone contributes the largest manganese resources of about 77% to the world's manganese resources. Only a small fraction of global manganese reserves are clearly economical. This fact continues to support mining in deep-sea manganese nodules, which constitute an enormous untapped resource. Most nodules are found in areas of deep-sea floor at water depths of 5-7 km. The Pacific Ocean alone is estimated to contain about 2.5 billion tonnes nodules containing about 25% manganese.

1.2 GLOBAL MANGANESE MINERALIZATION.

changed gradually from geosynclinals in the Precambrian to platforms in the Cenozoic (Strakhov, 1969). Manganese ore concentrations were most extensive during Cenozoic, followed by the Precambrian, the Palaeozoic and the Mesozoic in that order (De Villiers, 1971). Manganese mineralisation is also found in areas of active volcanism in the present day marine basins (Roy, 1981). Gross (1986) suggested the origin of late Archaean manganese ore deposits occur through the submarine exhalative processes. Major manganese ore deposits were formed in the early Proterozoic period which are found in South Africa, Brazil, Namibia, Botswana, Zaire, India, Gabon, China, Morocco, Canada, Finland, Australia and Russia (Gross, 1986; Roy, 1990). Majority of these sedimentary manganese ore deposits are considered to have formed in shallow water intra-cratonic basins without much temporal or spatial relation with volcanism e.g. Franceville Formation, Gabon; Morro do Urucum deposits, Brazil; Aravalli Super Group, Sausar and Gangpur Groups and Penganga beds, India (Roy, 1981). The oldest meta-sedimentary manganese ore deposits have been reported from the Iron ore group of India (3200-2950 Ma) and the Rio das Velhas series, Brazil (>2700 Ma) (Roy, 1981). Other Precambrian formations containing manganese deposits are the Graphite system, Malgasy (2420 Ma), the Birrimian system of West Africa (2400-2200 Ma), the Transvaal Super Group of the Republic of South Africa (2300-1900 Ma), the Lukoshi Complex, Zaire (>1845 Ma), the Franceville series, Gabon (1740 Ma), the Minas series, Brazil (2200-1350 Ma), the Guyana Shield (1700 Ma), the Khondalite Group (>2650 Ma), the Dharwar

<table>
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<tr>
<th>Global Ore Reserves Base</th>
<th>Million Tonnes</th>
<th>(% of Total)</th>
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<tbody>
<tr>
<td>South Africa</td>
<td>4,000</td>
<td>77</td>
</tr>
<tr>
<td>Ukraine</td>
<td>520</td>
<td>10</td>
</tr>
<tr>
<td>Australia</td>
<td>160</td>
<td>3</td>
</tr>
<tr>
<td>India</td>
<td>150</td>
<td>3</td>
</tr>
<tr>
<td>China</td>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td>Gabon</td>
<td>90</td>
<td>2</td>
</tr>
<tr>
<td>Brazil</td>
<td>57</td>
<td>1</td>
</tr>
<tr>
<td>Mexico</td>
<td>8</td>
<td>0.2</td>
</tr>
<tr>
<td>Other Countries</td>
<td>115</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5,200</strong></td>
<td><strong>100</strong></td>
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Source: Mineral Commodity Summaries, USGS, 2011
Super-group (2400-2000 Ma), the Aravalli Supergroup (2000 Ma), the Gangpur Group (1700-2000 Ma) and the Sausar Group (986-846 Ma) of India (Roy, 1981). Manganese deposits of Palaeozoic age are widely distributed in different continents in variable tectonic situations and lithologic associations. Manganese deposits of Mesozoic age are essentially of non-volcanogenic sedimentary origin. They were deposited in shallow marine environments in intra-cratonic basins. Their depositions were coincided with cycles of marine transgression/regression and periods of anoxia/oxygenation (Frakes and Bolton, 1984). The deposits of Groote Eylandt, Australia and Molango, Mexico belong to this type. During the Cenozoic period, manganese ore accumulation took place essentially in shallow water non-volcanogenic environment. The most important metallogenic epoch of manganese ore accumulations were mainly confined to formation of Oligocene age in this period represented by the deposits in the area of south European part of the Russia and Bulgaria (Vara) bordering to the Black sea (Roy, 1981). On the other hand, Ouarzazate region, Morocco is represented by a manganiferous province (Roy, 1981). Menard (1976) observed that manganese nodules were much dominant in the early Cenozoic sediments in the ocean basins and that the formation of nodules has declined since the late Cretaceous. Marginal seas and lakes also contain ferromanganese deposits; mostly of Recent age (Roy, 1981).

1.3 INDIAN DISTRIBUTION

India is self-sufficient in manganese ore and also one of the leading producers of average grade manganese ore in the world. In the beginning years of last century, India was the second largest producer of manganese ore after erstwhile USSR. Today, the country ranks fifth position in resources and occupies sixth position as far as production of manganese ore is concerned. Indian manganese ores are generally hard, lumpy and amenable to easy reduction. Though sizeable quantity of manganese ore is produced in the country, some shortage in the supplies of ferromanganese and battery grade has been faced by the domestic industries (IBM report, 2013).

Manganese ore deposits are widely distributed throughout the peninsular region of India. The deposition of manganese ore in India must have taken place in varying environmental settings and by different geological processes. Almost all the manganese deposits in India are of Precambrian age. The manganese ore deposits in
the country occur in the Sausar Group (Madhya Pradesh and Maharashtra), Gangpur Group (Odisha), Aravalli Super Group (Rajasthan and Madhya Pradesh), Champaner Group (Gujarat), Khondalite Group (Andhra Pradesh and Odisha), Dharwar Super group (Karnataka and Goa), and Iron Ore Group (Jharkhand and Odisha). The ore bearing horizons of the Iron Ore Group and the Dharwar Super Group are either unmetamorphosed or show effects of very low grade metamorphism. The deposits in Aravalli Super Group show low to moderate metamorphism, whereas in the Sausar and Gangpur Groups, the manganese deposits and other associated rocks show high grade metamorphism (up to amphibolites facies) and manganese ore bodies and other associated rocks belonging to Khondalite Group are metamorphosed up to granulite facies (Siddiquie, 1982, 1986, 2003 and 2004; Siddiquie and Bhatt 2008; and Siddiquie and Raza, 2008). Not only the manganese ore mining from the peninsular region of the country but also, started mining from the Indian Ocean as poly metallic nodules of Mn in the year 1986 (Siddiquie, 2004). Ore grade nodules occur only in the central part of the basin, which is occupied mainly by the siliceous sediments. Maximum occurrence of the nodules is reported on the pelagic clays.

1.3.1 CLASSIFICATION OF MANGANESE DEPOSITS OF INDIA

Manganese ore deposits in India can be broadly classified into four groups on the basis of their mode of occurrence and origin by Geological Survey of India.

a) Syngenetic Gonditic Deposits

They are formed by metamorphic reconstitution of manganiferous formations of Precambrian age. The manganese concentration might have taken place during the Precambrian period. These metamorphosed syngenetic manganiferous formations comprise of oxides and silicates of manganese. They are completely devoid of sulphides and carbonates (except some epigenetic rhodochoresite). The sedimentation must have taken place under strongly oxidising conditions and resulted in precipitation of tetravalent manganese oxides. These deposits are comprised of braunite, hollandite, hausmannite and vredenburgite. These syngenetic sedimentary bedded types of deposits are found in Balaghat, Chhindwara, Jabalpur and Jhabua districts of Madhya Pradesh, Bhandara and Nagpur districts of Maharashtra, Odisha, Gujarat and Rajasthan.
Introduction

b) Syngenetic Reef deposits

These deposits are of hybrid origin associated with highly metamorphosed Kodurite rocks (feldspar-spandite-apatite) in Vishakhapatnam and Srikakulam districts of Andhra Pradesh, Adilabad and Hyderabad districts of Telangana and Bolangir, Ganjam and Koraput districts of Odisha.

c) Replacement Deposits

These deposits are associated with Iron ore series in Jamda-Koira valley of Singhbhum district of Jharkhand and Odisha and also associated with Dharwar rocks in Karnataka and Goa. These deposits are also found in Keonjhar, Sundergarh district of Odisha, North Canara, Bellary, Hospet, Tumkur and Chitradurga districts of Karnataka, Ratnagiri district of Maharashtra and those of Goa belong to this group.

d) Lateritoid Deposits

These deposits and supergene enrichments are associated with all the above deposits. The lateritoid manganese ores of India also belong to the epigenetic type. They mostly overlie the other manganese deposits. i.e. primary bedded ores and secondary replacement ore bodies. As these ore bodies resemble laterite, they are named as ‘lateritoid’ manganese ores. They are always high in iron and often graded as ferruginous manganese ore. These deposits are associated with iron ore deposits. They are generally low in phosphorous. Manganese ore deposits of Sandur Schist belt in Karnataka and the deposits in Goa are examples of secondary supergene deposits.

Indian manganese ore deposits can be classified into three groups based on the systematic geological investigation carried out by earlier workers like Fermor (1909), Roy (1966).

a) Manganese ore deposits associated with the Archaean rocks including Gondite Series of Madhya Pradesh and Maharashtra. Manganese deposits of Archaean age are also found to occur in parts of Odisha, Andhra Pradesh and Karnataka. Manganese oxide ores interstratified with shale occur in the Iron Ore Group rocks at Joda, Kalimati, Gurda, Phagua and Mahulsukha areas in Odisha. These deposits are considered to have formed in cratonic shelf environment at ca. 3.0 Ga (Roy, 1981).
Large scale deposition of Mn ores started from the Early Proterozoic. The Proterozoic (ca. 2.0 Ga) Sausar Group, spreading from Maharashtra to Madhya Pradesh in central India, hosts the largest concentration of Mn ores in India, mostly in gonditic rocks. The principal ore minerals are branie and psilomelane with some amount of cryptomelane and pyrolusite. These regionally metamorphosed manganiferous sediments from central India were first described and named Gondite by Fermor in the year 1909. The gondites are quartzose rocks containing spessartite and rhodonite, usually associated with Manganese minerals like braunite, along with bixbyite, hausmannite and jacobsite. These Manganese silicate-oxide rocks are complexly deformed and interstratified with meta-pellites and ortho-quartzites in the Mansar Formation and less commonly occur as conformable lenses in carbonate rocks of the older Lohangi Formation. The litho-sequences are metamorphosed to grades ranging from low green schist facies in the east to upper amphibolite facies in the west. The well known deposits are in Ukwa and Bharweli in Balaghat district in the east, Chikla, Tirodi and Mansar in the central part of the belt and Gowari, Wadhona in Chhindwara district in the west.

b) Manganese ores associated with the “Kodurites Series” of Vishakhapatnam, Srikakulam, Andhra Pradesh. The principal minerals are psilomelane and pyrolusite with minor amounts of braunite. The Eastern Ghat sequence exposed mainly in Koduru, Garividi, Garham and Chipurupalle areas in Andhra Pradesh (Siddiquie, 1982, 1986, 2003, 2009; Siddiquie and Bhat, 2010; Siddiquie and Raza, 2008) metamorphosed to granulite facies, host Mn oxide ores in a conjectured shallow water shelf environment. The oxide ores are located in these Archaean (>2.6 Ga) high grade, pelitic and calc-silicate granulites while Mn silicate-carbonate rocks occur in calc-silicate granulites and garnetiferrous quartzites (Roy, 1981). These ores and their host rocks were described as Kodurites by Fermor in 1909. The Kodurites of Andhra Pradesh are considered to be hybrid in character, due to granitic assimilation of the manganese bearing sediments. Similar deposits are described from the Khondalites of Kalahandi and Koraput districts of Odisha. Similar Koduritic manganese ore occurrences have also been reported from Goldongri hill, north of Jothvad, Panch Mahal district, Gujarat. Manganese oxide ores interstratified
Introduction

with chert and phyllite and closely associated with stromatolitic limestone occur in Chitradurga-Tumkur, Kumsi- Hornhalli areas of Karnataka. Similar association of Mn oxide ores is also found extensively in the Sandur and Shimoga schist belts in Karnataka, spatially adjacent to the Banded Iron Formations.

c) Lateritoid manganese ore deposits of Dharwar age of Mysore, Sandur, Karnataka and Precambrian. Lateritoid manganese ores include both in situ residual ores (lateritic) and the replacement deposits formed by enrichment of manganese in meteoric water from other rocks and subsequent precipitation from solution. Thus, these ores are clearly epigenetic with respect to their host rocks. Such epigenetic ore deposits are found in fairly large quantities in Dharwar Super group rocks in Belgaum, Karnataka, Maharashtra, Goa, parts of Madhya Pradesh and in Iron ore Group rocks of Singhbhum district, Jharkhand and Keonjhar district, Orissa. In many such lateritic deposits, Al and Fe are characteristically concentrated in the upper zone and Mn in the lower zone of a weathering profile. In the Sausar Group, the large supergene deposit with a strike length of 1.5 km and the thickness exceeding 130 m occurs at Dongri Buzurg, Nagpur district, Maharashtra. The deposit was formed by oxidation of pre-existing metamorphosed Mn oxide and Mn silicate rocks (Roy, 1981).

The total resources of manganese ore in India are placed at 430 million tonnes as per the National Mineral Inventory (NMI) 2010. Out of these, 142 million tonnes are categorised as reserves and 288 million tonnes are in the remaining resources category. Out of the 142 million tonnes of reserves, 97 million tonnes were placed under proved category and 45 million tonnes were placed under probable category. Largest resources of manganese ore of India to a tune of 190 million tonnes are in the state of Odisha.
The share of Odisha in the total resource of the country is 44.20 %, followed by Karnataka with 96.20 million tonnes of resources (22.37%); Madhya Pradesh 55.72 million tonnes (12.96%); Maharashtra 34.15 million tonnes (7.94%) and Andhra Pradesh 17.60 million tonnes (4.09%) (Figure 1.3). The remaining 8.44% of total resources are contributed together by Jharkhand, Goa, Rajasthan, Gujarat and West Bengal.

Although the occurrences of manganese ore are widespread in the country, the production is reported from a few states only. Amongst these states, Maharashtra, Madhya Pradesh, Odisha and Karnataka together produced 85% of the total all India production of manganese ore of all the grades. The important areas of production of manganese ores are in Odisha, Madhya Pradesh, Maharashtra and Karnataka. Some deposits also exist in Andhra Pradesh, Goa, Gujarat, Bihar and Rajasthan (Figure 1.2). The total productions of manganese ores in India for 2013-2014 were 2.5 million tonnes increased by 11% as compared to the previous year. During this year, the production of manganese ores in India mainly came from 153 mines, eight are underground mines in which three are in Madhya Pradesh and five are in Maharashtra. Maharashtra accounted for 28% followed by Madhya Pradesh (27%) and Odisha (24%) of the total production. States like Goa which were important producers of manganese ore earlier have reduced their production because of the falling grades and increase in depth of mining.

Manganese Ore India Limited (MOIL) continued to be the largest producer of manganese ore by contributing 48% of the total production followed by Tata Iron and Steel company (TISCO) (23%), Sandur Manganese and Iron ore company (10%), Mangilal-Rungta (5% each) and Krishnapping alloys (2%). The share of these five principal producers operating 24 mines was 88% of the total production. The remaining 12% of the total production was reported by the 94 small mines (IBM report 2007).
1.4 HISTORICAL BACKGROUND OF MADHYA PRADESH MANGANESE BELT

In 1896, a British company by the name of Central Provinces prospecting syndicate was set up, at the herald of twentieth century which originally acquired the Manganese mines. The syndicate was converted into a limited liability company in 1908 and in April 1924, changed its name to the Central Provinces Manganese Ore Company Limited (CPMO). In July 1962, Government of India took control of the company and renamed it as Manganese Ore (India) Limited with its H.Q. at Nagpur. MOIL Limited is country’s largest producer of high grade Manganese ore and fulfilling 75% of country’s requirements of high grade Manganese ore.

Madhya Pradesh is India’s foremost source of manganese ore with reserve of 55.72 million tones accounting for 12.96% of the National manganese ore reserve of 430 million tonnes. The deposits are mostly located in Balaghat, Chhindwara and Jhabua districts constituting the bulk of manganese ore deposits available in the state. These deposits are associated with the Archaean rocks, included in the gondites. Three types of deposits are found viz., the primary bedded type, the supergene lode type and the boulder types. Brauneite is the chief ore mineral in the first type of deposit, while cryptomelane and pyrolusite are the subsidiary types. The “Bharweli manganese mine” in Balaghat district is the largest underground mine operating in the Asian sub-continent. The manganese ore deposits of the State are being exploited.
Introduction

mainly by the Manganese Ore India Limited. During the year 2001-02, manganese ore has contributed Rs. 1.51 crores as royalty to the State Exchequer.

In Balaghat district, conformable bedded deposits and lensoid bodies of manganese ores as well as their residual weathering products are found in intensely deformed meta-sedimentary rocks belonging to the Mansar formation (which includes the Gonditic rocks), belonging to the Precambrian Sausar Group where braunite is an important mineral. Other manganese ores noticed include bixbyite, cryptomelane, pyrrofusite, hollandite, rhodochrosite, psilomelane, spessartite, hausmanite, Vredenburgite, manganite and jacobsite. The most important manganese deposits in Balaghat district are Ukwa, Tirodi, Bharweli, Ramrama, Sethapathore-Sukri, Langar etc.

The Balaghat belts of deposits are under active exploitation by M/s Manganese Ore India Ltd. and some private enterprises. Nearly 90% of the total production of manganese ore is shared by MOIL. The bulk of reserves of manganese ore found in Balaghat belt are of blast furnace grade and the reserve of Ferro manganese ore is very limited. The MOIL has contemplated to establish a Ferro manganese plant utilizing the ores available at Balaghat by upgrading. The MOIL has also set up a plant based on indigenous technology to manufacture electrolytic manganese dioxide.

Balaghat Underground mine was started in the year 1903. The mine is operated by MOIL Ltd., one of the largest and oldest manganese ore producers of India. Balaghat mine is situated in village of Bharweli, Hirapur, Manegaon, Manjara, Awalajari and Tawejhari. It is the deepest and largest underground Manganese Underground mine in Asia. The Bharweli deposit is located at the eastern end of the Balaghat plain and near the foot of the Baihar plateau. The ore comes from two types of deposits, lode or reef type and detrital or float type deposits. The principal ores at Balaghat area are compact, massive psilomelane with some hollandite but in southern portion of the ore band a small percentage of braunite is also found along with psilomelane. The strike length of ore body is 2.80 Kms having a general strike direction NE-SW and dip varies from 25°-85° towards W. The width of the ore body is as thin as 1.0 m at the both pinching 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 ore has been explored up to 23rd level (-290 mRL). Braunite is the principal mineral
associated with other minerals such as psilomelane, pyrolusite etc. Initially, this deposit was worked by open cast method. Presently, Balaghat mine is worked by underground cut and fill mining method with pre-mining supports like cable bolts and rock bolts.

Tirodi mine is one of the mines of MOIL Limited, situated in villages of Tirodi, Jamrapani, Paunia and Chikmara, Tahsil Tirodi of Balaghat district in Madhya Pradesh. Of these, the south Tirodi includes the largest and richest mine in the area. The mining operation was started in the year 1903 by CPMO (Central Provinces Manganese Ore), from which it was taken over by MOIL, in 1962. At present mining activity is confined to opencast working with the producer of high grade and low grade manganese ore. In Tirodi group of mines, the manganese ore horizon belongs to the Lohangi zone at the contact between Tirodi biotite gneiss and Mansar muscovite schist. The rocks are intensely folded, overturned, isoclinal and recumbent folds. The manganese ore deposits are represented by meta-sedimentary beds of braunite-quartzite and gondite forming “Reef deposits” as well as ‘boulder ore’ or detrital deposit derived from the above primary deposits. The bedded deposits occur as conformable tabular bodies as well as lenses and bands ranging in thickness from a thin lamina to seven meters. The ore bands are of variable length and thickness. The ore consists of primary braunite with subordinate amounts of psilomelane-cryptomelane type oxides, pyrolusite and other minerals. The ore body was systematically explored to determine the shape, size and the depth of ore body and its quality with the 93 bore holes drilled for the purpose. The quality of ore is of International standards and caters to the needs of steel Industries and also has the Export Market.

Ukwa mine was opened and worked by private mine owners and was subsequently taken over by MOIL since 1962. The Ukwa manganese ore deposit is located near Ukwa village on the Baihar plateau. It is classified in four sections as Gudma Section, Ukwa Section, Lugma Section and Sanmapur Section. Initially this mine was run by open cast mines due to outcrop and as on today it is run by both underground oriented mine and open cast mine. The mine plays a vital role in the production of low phosphorous ore to suit the saleable quantity of manganese ores export as well as internal consumption. Both psilomelane and braunite are found. Some amount of pyrolusite is also noticed especially in the northern portion of the
Introduction

mine. The Ukwa manganese ore deposit occurs within the Sitasaongi and Mansar formations of the Sausar Group. Manganese ore is interbanded with quartzite. The ore is either massive or banded and consists of braunite, hollandite, bixbyite, pyrolusite and cryptomelane. Braunite is the dominant Mn mineral. Hematite occurs in close association of braunite and bixbyite.

In the Chhindwara deposits, the manganese deposits cover an area of 297 Sq. Km in a portion of the Kanhan valley. The ores are associated with manganese silicate country rocks (Gondites and rhodonite bearing rocks) which form lenticular bands intercalated along the strike of a complex series of metamorphic rocks traversed by granites and pegmatites.

In Jabalpur district, manganese ores are associated with quartzites traversing the phyllites and dolomitic limestones of Aravalli system. The chief ore minerals are braunite with some psilomelane, pyrolusite and hollandite. The major occurrences are at Kajlidogri, Tumdia, Mandli and Rampura. In Bilaspur district, low grade manganese ore comprising of pyrolusite, psilomelane, manganite and wad occur between Ratanur and Kori.

In Jhabua district, manganese ores are associated with quartzites traversing the phyllites and dolomitic limestones of Aravalli system. The chief ore minerals are braunite with some psilomelane, pyrolusite and hollandite. The major occurrences of manganese are at Tumdia, Mandli and Rampura. In Bilaspur district, low grade manganese ores comprising of pyrolusite, psilomelane, manganite and wad occur (Rasool, 1964).

1.5 LOCATION OF THE STUDY AREA.

Balaghat District is located in the southern part of Jabalpur Division. It occupies the south-eastern portion of the Satpura Range and the upper valley of Wainganga River. The district extends from 21°19' to 22°24' N latitude and 79°31' to 81°3' E longitude. The total area of the district is 9,245 km². Balaghat District is bounded by Mandla District of Madhya Pradesh to the North, Dindori District to the North West, Rajnandgaon District of Chhattisgarh state to the East, Gondia and Bhandara districts of Maharashtra state to the South, and Seoni District of Madhya Pradesh to the West.
Introduction

Balaghat mine is located in Balaghat district of Madhya Pradesh and is about 210 Kms from Nagpur. It is situated at 21°50' N latitude and 81°14' E longitude. The Balaghat mine is located 8 Kms away from Balaghat railway station. Tirodi Mine is located between latitude 21°43'46"- 21°43'13" N and longitude 79°43'03"- 79°44'59" E, 155 Kms northeast from Nagpur and 65 Kms from Balaghat railway station. Ukwa mine is located at 21°58' N latitude and 80°28' E longitude. Ukwa mine is situated towards northeast of Balaghat district headquarter of M.P. at a distance of 44 Kms. at state highway no. 26, near Ukwa village of Baihar Tehsil of Balaghat and about 250 Kms from Nagpur.

1.6 TRANSPORT:

Balaghat is directly connected by bus and rail. The Jabalpur-Gondia section of South East Central Railway runs north and south through the district, along the valley of Wainganga. The line was formerly narrow gauge (2 ft 6 in (762 mm)) for its entire length, but the section between Balaghat and Gondia was converted to broad gauge in 2005-2006, connecting Balaghat to India's national broad gauge network for the first time. Work is underway to convert the Balaghat-Jabalpur section to broad gauge as well. A narrow gauge branch line runs west from Balaghat to Katangi and Ramrama Tola via Waraseoni.

Bus connects important places such as Bhopal, Nagpur, Gondia, Jabalpur, Raipur etc. The nearest airport is at Gondia and 2nd nearest airport is at Nagpur.

1.7 CLIMATE

The climate of the area enjoys moderately dry and wet with well-marked summer, monsoon and winter. During summer seasons, mercury rises to 45°C, while in winter seasons it drops up to 4°C and even less during night time. Rainy seasons last between June and early October and annual rainfall is around 170 cm.

1.8 FLORA AND FAUNA

Balaghat is known as hunters' paradise due to its varied fauna. The fauna of the district are Tigers, Leopard, Bear, Neel-Gai, Deer, Wolf, Wild Pigs, Black faced Monkey, Gaur & Bison on one side and birds like Peacock, Red Bulbul and Koyal on the other. National Park lies partly within the district.
Introduction

Figure 1.4 Map showing the manganese ore deposits of Balaghat district, M.P.

Figure 1.5 Accessibility and location map of study area.
Balaghat has a very rich forest base. About 52% of the district's area is covered with forest. The major trees found here are Teak (Tectona grandis), Sal (Shorea robusta), Bamboo, Palms and Saja, the scattered alluvium plains consists of Mahuaa and Mango graves. Vegetables found in abundance in the district are potato, onion, ladies finger, tomato, beans, cabbage, cauliflower and carrot. Fruits like mango, orange, lemon, jackfruit and guava are also grown here.

1.9 MINERAL WEALTH

The district is rich in its mineral wealth. The important minerals include manganese, copper, and bauxite with minor occurrence of beryl. The area also has good potential for dimension stone. In addition, some lateritic iron ore and marble are also reported. A huge copper (Mo+ Au) mine is situated in Malanjkhand within Balaghat District. Most important Manganese ore deposits of India are located in the Balaghat district. Bharweli, Ukwa and Tirodi are some important manganese mines in this district. A number of other small occurrences of manganese have also been reported from this district. Lensoidal bodies of bauxite occurrences associated with laterite capping over the Deccan Traps are exposed in the northern part of the district. Occurrences of dimension stone have also been reported from Khelwad, Devri, Malanjkhand, Linga, and Lamta area. Occurrence of iron (associated with laterite) and limestone which are of less importance from economic point of view are also reported. Minor occurrences of beryl have been reported from a few localities in the western part of the district. Marble occurrences to the south of Lamta can be used as a dimension stone.

1.10 DRAINAGE

The main rivers which flow through the district are Banjar, Halon, Jamunia, Tannar Kanhan and Wainganga. Banjar river enters the district from Raipur district in the east and flows in the north and west direction through the main plateau into the Mandla district. The river flowing significantly is Wainganga River and its tributary Sarathi. Bagh drains the district to the east of the Wainganga, with its tributaries (Deo, Son and Ghisri).

All these rivers have their sources in the hilly area to the south of Baihar tableland. Bagh enters the district from Bhandara, forms the south-western boundary
of the district from Bhadra hills to Wainganga, till it joins it at Borinda. Nahara and Uskal rivers start from the Dhansua forest and the open area southwest of Tipagarh and ultimately join Wainganga near Chacheri. The drainage pattern in general is dendritic to subdendritic. In the study area Wainganga is the main river, which flows northeast to southeast. Another river, Chandan flows in the south-western corner of the study area. Tondia Nala flows from western corner and joins with the Chandan River.

In the Mines area, Mangardoh Nala receives maximum water from the upper reaches of the ridge. Although there are slopes in the western direction, the water draining from this slope is absorbed by the plain area and does not reach the Nala. On the contrary, prominent drainage is observed in the eastern part of the ridge. Here, the water flows in the south-eastern direction and the three streams meet the Nala in the south-eastern corner of the mines area.

1.11 OBJECTIVE OF THE WORK

Manganese mineralization since Precambrian has been a debate for the last two centuries among the earth scientists and policy makers’ world over. Previous workers like Fermor (1906, 1908, 1909, 1917, 1938; Roy, 1958, 1959, 1961, 1962, 1974, and 1981); Roy and Mitra (1964), Vemban and Nagarajiah (1974), Shau et al. 1993, Babu and Nayak (1961), Jain et al. (1990), Dasgupta et al. (1993), Banerjee et al. (2007), Kanungo et al. (2007, 2008, 2014); and Kanungo and Sutaane (2013) were some remarkable research works on various geological aspects of manganese ores and associated country rocks of Balaghath. However, there is no definite geochemical picture in the background of mineralogical blueprint of the Balaghath manganese ores and their country rocks. The present ore deposits are not assigned to any particular genetic environment in the region in the light of global manganese ore genesis. This objective could be achieved by the experimental mineralogical studies and geochemical analysis of the ores and their host rocks with significant attributes to the regional geological setting, tectonic history, stratigraphy, local geology and structure in the light of geochemistry and mineralogy of the world manganese deposits with special attention to their geological conditions.

The present work comprises of ore mineralogical and textural of manganese ore studies and the geochemical studies of the manganese ore and associated country
Introduction

rocks of Balaghat manganese ore deposits. Attempt has been made to reconstruct the possible environment of manganese mineralization and the post depositional environments of Balaghat. The geochemical analysis data including the major, trace and REE elements of the analyzed manganese ores and the associated country rocks have been used to understand variations of different elements and compositional degree of correspondence between the manganese ores and the associated country rocks. The major, minor and trace elements and their inter-elemental relationships are expected to reveal the contribution of different elements from their sources in the geochemical system. The incorporation of the selected trace elements and REE in the present manganese ores are also expected to reveal the different stages of the evolution of the manganese ores. The Balaghat manganese ore deposits hosted in the geologically complex terrain of the Sausar Group were studied in both fields with reference to the tectonic, lithological and structural controls of ore deposition as well as in the laboratory for their geochemical and mineralogical aspects to probe the possible genetic environment and the later diagenetic, metamorphic transformations and chemical alterations. Special attributes of the tectonics and associated mineralization in the sub-continent since the Precambrian were given due consideration to infer the local manganese ore genesis in the study area as a part of global manganese mineralization in the region in the different tectonic environments.

1.12 LITERATURE REVIEW

The manganese deposits of the Balaghat district were first investigated by Bose (1889; cited by Fermor, 1909), who have reported association of phyllite, sericite-schist, quartzite and jasper-quartzite and manganese ore forming the ‘Chilpi Ghat Series’, deposited over Archaean basement gneisses represented by the Baihar Gneiss and Chauria Gneiss. Fermor (1909) gave a detailed and comprehensive account of the geology, mineralogy, petrology and manganese ore deposits of Madhya Pradesh. He studied the major deposits of the area in 1903-04 and also published a detailed petrological account of the Archaean rocks of the Sausar area, Chhindwara district in 1906. Fermor (1926) proposed the Sausar Sequence and modified it in 1932. He introduced the Junewani stage in between Chorbaoli and Ramtek stages. He also introduced the Khadbikhera stage below the Utekate stage. West (1936) modified the Sausar sequence proposed by Fermor (1932). West introduced the Sitapur stage
above the Bichua stage. After completion of the first phase of mapping (in 1925) initiated by Fermor in 1911, remapping of the manganese belt of M.P. and Maharashtra began in 1951 under the overall coordination of Straczec. This Mn belt was mapped on different scales by various workers in different parts between 1951 and 1957. The detailed account of this study was presented in the Bulletin of GSI in seven parts (Narayanaswami et al. 1963; Rao, 1970; Narayanaswami and Venkatesh, 1971; Subramaniyam, 1972, Shukla and Anandalwar, 1973; Chakravarty, 1973; Vemban and Nagrajaiah, 1974). However, the principal results of the mapping of the manganese belt were presented in 20th International Geological Congress at Mexico by Straczec et al. (1956). He recognised wide spread occurrence of Biotite Gneiss of all varieties and proposed the term ‘Formation’ instead of ‘stage’. The stratigraphic succession of the Sausar series by Straczec et al. (1956) and subsequently by Narayanaswami et al. (1963) is a further modification and amplification of the succession suggested by Fermor (Pascoe, 1926) and by West (1936). Narayanaswami et al. (Op. cit.) grouped Kadbikhera, Utekata and Lohangi stages into a single Lohangi stage by giving the status of sub stages to the individual ones and also introduced new formation Sitasaongi and placed it above the formation Tirodi Gneiss. The Tirodi Gneiss considered as the lowermost unit of the Sausar Series by Straczec et al. (1956) was reinterpreted as basement gneiss by Narayanaswami et al. (1963).

Narayanaswami and Venkatesh, (1971) mapped the northern Bhandara district, Maharashtra and adjoining Balaghat district, M.P. According to them the area exposes total succession of Sausar series of which Mansar stage is most dominant. For the first time they identified Sitasaongi stage forming the basal unit of Sausar series in the area. Subramaniyam (1972) mapped the Ramrama- Sonawani area, Balaghat district, Madhya Pradesh. He is of the view that the ‘Sonawani Series’ of Burton is equivalent to Sausar Series. He also recorded total succession of Sausar Series in the area. Tripathi, et al. (1981) studied the rocks of Bharweli-Ukwa area specially exposed in Baihar area and correlated the Baihar Gneiss of Bose (1889) with the Junewani Formation of the Sausar Group and considered the Chilpi Group to be stratigraphically older and correlatable with the Sausar Group. Rao (1981) expressed the view that Sausar sedimentation commenced and ended with calcareous facies, the lower one being calcitic and the upper one dolomitic. Jain et al. (1990, 1991, 1995) mapped a major shear zone from southeast of Nagpur in the west to south of Korba,
and Hatta and Baihar in Balaghat district in the east. This shear zone is termed as the “Central India Shear” (CIS) zone. The rocks of Chilpi Ghat Group are separated from the manganese belt by a gneissic country through which this major ductile mylonite zone (CIS) passes (Jain et al. 1991). Phadke (1990) is of the view that TBG is a product of partial melting of Sausar (Pal and Bhowmik, 1998). However, Pal and Bhowmick (1998) refuted this theory and suggested that no evidence of partial melting is seen in Sausar group of rocks. Banerjee et al. (1997) proposed a two tier classification of Sausar rocks on the basis of STM carried out from Operation MP, Jabalpur. They were of the view that Sausar meta-sediments could not be given any stratigraphic status as they are strictly metamorphic in nature. The biotite gneiss was considered as intrusive into meta-sediments. The manganese mineralization was considered as structurally controlled and hydrothermal in nature.

Pal and Bhowmick (1998) worked on metamorphic history of Sausar Group of rocks. According to them metamorphic grade of Sausar rocks increases from south to north and also towards west ranging from green schist to upper amphibolite facies. This study also indicated absence of partial melting in Sausar Supracrustals. Roy et al. (2000) carried out study on Supracrustal belts and their significance in the crustal evolution of Central India. Kano et al (2001) carried out field studies in the Sakoli and Sausar Belts of the Central Indian Tectonic Zone. Chattopadhyay et al. (2001) worked on geology and structure of the Sausar Fold Belt (SSFB) covering the area around Deolapar- Mansar- Chikla. According to them Tirodi Biotite Gneiss (TBG) forming basement for Sausar Group (SSG) of rocks, records evidences of pre-Sausar tectono-thermal events also. They stated that due to intense thrusting, tectonic slicing and folding of both TBG and SSG during Sausar Orogeny, the litho-stratigraphic succession of SSG has been highly disturbed and hence created a lot of controversies regarding the stratigraphy of SSFB. Khan et al. (2003) carried out Specialised Thematic Mapping (1:25000) in the area around Deolapar and Mansar in parts of Maharashtra and presented detailed accounts of geology and structure of the area. SSG are represented by carbonate facies rocks in Deolapar and psammopelites in Mansar area. They recorded pre-Sausar folding and ductile shearing in multi components of TBG. They also recorded regionally significant events of superposed folding (SF1 to SF4), one early thrusting (Syn-SF1) and also some late stage faults in the rocks of SSG. ‘Deolapar nappe’ was reinterpreted as thrust nappe. Green schist to
Introduction

upper amphibolite facies metamorphism was recorded in SSG. The SSG rocks have been intruded by two phases of K-granite, the latter being post orogenic and of possible Mesoproterozoic 21 (950 ± 272 Ma) age. Syn sedimentary manganese mineralization was examined associated with psammopelites and carbonate facies rocks; the former association being more significant.

1.13 METHODOLOGY

1.13.1 FIELD WORK AND SAMPLING

The study area has about 20 active manganese mines. Most of the manganese mines are under the control of the MOIL and remaining mines are under active exploitation by some private enterprises. Out of these mines, three potential mines viz., Bharweli mine, Tirodi mine and Ukwa mine have been selected for present piece of research work.

Field studies include sketching structural features observed, some digital photos, GPS coordinates, notes on country rock types, landforms features, geological features observed etc., and or collect on various rocks and ores samples. Fresh ad unweathered Samples of 13 host rocks or 47 manganese ores have been collected systematically by the present author in trips to field (Feb. and July, 2011 and April, 2014). Samples collected were marked and numbered in coded form as per their respective locations and nature for laboratory use.

1.13.2 SAMPLE SELECTION

47 manganese ores and 13 host rocks were collected from the said three mines. 21 Mn ores and 6 host rocks were collected from the Bharweli mines, out of those, 15 Mn ores and 4 different host rocks were selected for the purpose of the present work. 5 Mn ores were from 9th level i.e., 2 and 3 were in the direction of N and S at the distance of 1km from the shaft in both directions. 4 Mn ores were from 10th and 11th level each, 2 and 2 were selected from N and S direction from the shaft in both level. 2 were selected from the 12th level (which was a new level) from both directions. 12 Mn ores and 4 host rocks were collected from the Tirodi mines. 6 Mn ores (2 and 4 were from the South and North Tirodi block respectively) and 2 hosts were selected for further present work. For Ukwa mine, 14 Mn ores and 5 Host rocks were collected from this mine. 10 Mn ores were from the underground mine. 6 Mn ores were selected for research work based on distance and different channels. 4 Mn
ores were collected from the open cast mine, 2 Mn ores at a distance of 100 mts were selected for research work. 3 different host rocks were selected for the present work.

1.13.3 POWDERING

The above mentioned samples, collected from the study areas were powdered in the pulverizer up to -200 mesh size. Pulverizer containing Tungsten Carbide bowls with five Tungsten Carbide balls were removed from the powdering machine and thoroughly washed by distilled water and then by acetone. The bowls were dried to remove the moisture. The samples of about (100g) were poured into the bowls and marked, then kept tightly screwed in the pulverizer. The samples were pulverized for about 30 minutes. The bowls containing samples were removed and checked for -200 mesh size. The sample powdered to -200 mesh size was then kept in marked polythene bags. If the powder size was above the -200 mesh size then the bowls were further run in the pulverizer until the sample size became -200 mesh size.

1.13.4 METHODOLOGY FOR DIGESTION AND ICP-MS ANALYSIS

Open-Acid digestion technique using PTFE Teflon beakers and Q-Block Digestion System: Acids used for digestion are HCl (10ml) & HF (5ml) for Mn Ores, HF: HNO₃:HClO₄ in the ratio of 7:3:1 for Host rocks

The following procedure was followed for the digestion of samples:

1. A known weight (50 mg) of the sample was weighed and then transferred in the clean Teflon beaker.
2. Acids of 10ml HCl & 5ml HF were added to the Teflon beaker containing Mn ore sample powder of 50mg.
3. Another Acid mixture (7ml of HF, 3ml of HNO₃ and 1ml of HClO₄) were added to the Teflon beaker containing 50mg host rock sample powder.
4. Samples were digested using Q-block system containing a Hot Block and a Q Block controller.
5. The process was repeated until the sample was clearly digested.
6. After the solution drop was cleared it was diluted with 5-10 ml of 2% HNO₃ and repeated the analysis for the complete dilution of the samples and standards.
7. The beaker content was transferred into volumetric flask quantitatively using 2% HNO₃ of 50ml.
8. 1ppb Rh was added as internal standard to the same volumetric flask and finally made up the volume (50ml) up to the mark.

9. About 3-4 ml of solution was used for the trace and rare earth element measurements using ICP-MS.

The ICP-MS was calibrated with the multi-element standards from Inorganic ventures. Rock standards and Nodule standards were used as reference standards. The results of ICPMS for the manganese ores were interpreted with the related software.

1.13.5 ORE MICROSCOPY AND X-RAY DIFFRACTION (XRD)

Ore microscopy was employed to study the minerals present in the polished ore blocks of selected manganese ore samples under reflected light using the improved version of ore microscope/image analyzer (Leica Qwin Color-RGB: 1991-2002, Taiwan Module). The sample preparation, polishing and mounting were done at the Department of Geological Sciences, Jadavpur University, Kolkata in accordance with Margolis and Glasby (1973) and Mukhopadhyay and Banerjee (1990). 30 Mn ore blocks were prepared for examining the minerals under the reflected light microscope with the help of air and oil immersions lenses. The criteria for identification of minerals followed were of Usui (1979). Thirteen manganese ore samples were selected for XRD analysis to detect the ore minerals present in the manganese ore samples. Ore samples were crushed to 200 mesh sizes using the electronic rock pulveriser and subjected to XRD tests to detect the various manganese minerals phases present in the samples. The detected minerals coincided well with the ore microscopic identification of the respective samples. XRD analysis was conducted by XPERT-PRO PHILIPS at the Department of Geological Sciences, Jadavpur University, Kolkata, analytical XRD techniques were used in operating current 40KV-30 ma and results were obtained on 28 positions in the form of peaks of account time of 30 minutes.

1.13.6 PETROGRAPHY

Nine host rocks including quartzites, phyllite, conglomerates, sericite and gneiss were prepared with standard petrographic methods. The final thin sections were studied for mineral identification and micro texture and fabric to study the various effects of regional metamorphism as declared in the available literature. The studies are expected to interpret the effect of the P-T conditions on the manganese ore mineralogy and bulk rock geochemistry of the ore and associated host rocks.
1.13.7 X-RAY FLUORESCENCE (XRF)

The major oxides of the 28 manganese ore samples and 9 host rocks samples were carried out by standard XRF techniques, analyzed by Wave Length Dispersive XRF system (Siemens SRS 3000). Lucas-Tooth and Pyne (1964) procedure was adopted for the analysis. The major oxides of manganese ore samples were analyzed using powder pressed pellets by PW 2404 PAN-analytical XRF spectrometer using a number of international standards NML standard No. 66.2, British chemical standard No. 176/2 and synthetic manganese standard at SAIF, IIT, Bombay. The major oxides data of host rocks were acquired by Axios PAN analytical X-Ray Fluorescence spectrometer at CSIR, NIO Dona Paula, Goa. International standards namely USGS standards are used for checking accuracy of the data. The accuracy of data with respect to standard is \( \pm 3-4 \% \).

1.13.8 LOSS ON IGNITION

LOI was determined gravimetrically at a temperature of 1000°C at geochemistry laboratory, Department of Geology, A.M.U., Aligarh. Using this LOI value, analytical totals remain too low for ore data sets except for the rock samples. Further LOI measurements of the ore samples were thus repeated at 1200°C (12 hours). These results showed improved totals, as the mass change values showed an average increase of 1% for the manganese-rich zones. This is explained by the fact that only at temperatures above 1000°C, most manganese bearing minerals in the Balaghat manganese ore transform into \( \text{Mn}_3\text{O}_4 \) and carbonates dissociate to \( \text{CO}_2 \) and oxide (Gutzmer and Beukes, 1996). Repeated LOI determination on selected samples indicated a reproducibility of \( \pm 1\% \) relative to earlier data.

1.13.9 DATA PLOTTING AND SOFTWARES.

The geochemical data obtained from the analysis of the manganese ores and host rock samples has been interpreted and plotted with the help of Sigma Plot, Grapher, TriDraw and M.S. Excel. Other softwares used are Photoshop, Corel draw (12) and M. S. Paint.