Mineralogy and genesis of Kutinga manganese deposit, South Orissa, India

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Manganese ores at Kutinga occur as distinctly conformable bands in the khondalite suit of rocks of Eastern Ghats complex. The dominant manganese ore minerals include cryptomelane, psilomelane, pyrolusite, hausmannite, lithiophorite and wad. Quartz, chalcedony, orthoclase, garnet and kaolinite are the associated gangue minerals. Presence of high iron, high phosphorous, low to medium silica and dominance of CaO over MgO, K₂O over Na₂O, Ni over Co, Zn over Pb and Cu over Pb are the characteristics of this manganese deposit. Phosphorous occurs as discrete apatite inclusions within the quartz and orthoclase; and also adsorbed in the secondary manganese and iron minerals. Field characters, mineralogy and geochemistry of manganese ores suggest their formation as chemical precipitates, and the source of which appears to be continental erosion. Manganese formation along with the country rocks have been metamorphosed under granulite facies conditions, affected by granitisation and subsequently undergone supergene enrichment to give rise to the present deposit. These ores will be amenable to removal of silica, but will not respond well to removal of iron and phosphorous by physical beneficiation.

Keywords: Eastern Ghats complex, India, Manganese, Phosphorous, Mineral chemistry, Geochemistry, Genesis

1. Introduction

India has a total reserve of 176 million metric tonnes of manganese ore, but most of it is either low or off grade ore, due to the presence of high amounts of iron and/or phosphorous. Around 95% of manganese ore in India is utilised in iron and steel industries (Indian Minerals Year Book, 1990). Orissa accounts for about 41 million metric tonnes manganese ores associated with Iron Ore Group of north Orissa and Eastern Ghats complex of south Orissa, of which about one third of the reserves are in latter association. The manganese deposits of south Orissa are considered to be the extensions of "Koduritic types" (manganese deposits associated with high grade meta-

morphic terrain, where manganese oxides were considered to have been derived as alteration product of manganese rich rock containing quartz, potash-feldspar, garnet, manganese-pyroxene and apatite termed Kodurite) of Vishakhapatnam and Srikakulam districts of Andhra Pradesh (Fermor, 1909; Roy, 1981), and are rich in phosphorous, on an average containing 0.3% of phosphorous (Mohanty, 1991) and as such are not suitable for even in iron and steel industries. Presence of high amounts of phosphorous in manganese ores deteriorates the mechanical properties of steel. An attempt is made in this paper to decipher the mineralogy, chemistry, and modes of occurrence of phosphorous, iron and silica which will throw light on its genesis as well as the amenability of the ore

Fig. 1. Location and index map, showing Kutinga and other manganese deposits in parts of South Orissa.

to beneficiation.

II. Geological setting

A number of manganese deposits (e.g. Devjholla, Podkana, Talidhodshi, Nishikhal, Kasipur and Kutinga) form a small manganese belt trending NNE-SSW over a strike length of about 40 kilometers in the Eastern Ghats complex. The manganese deposit at Kutinga (Lat. $19^{\circ}2' - 19^{\circ}7'N$ and $83^{\circ}7'30'' - 83^{\circ}12'E$ Long., Fig. 1) is one of the prominent deposits of south Orissa, situated at a distance of 36 kilometers from Rayagada railway station. The deposit occurs in Precambrian Eastern Ghats complex (>2600 million years), associated with metasedimentary rock types such as khondalite, quartzite and manganiferous quartzite. Calc-silicate granulite is also reported from this area. The ore body is parallel to foliation planes of migmatized khondalite and quartzite. These rock types along with the manganese ore band form

more or less banded assemblage, metamorphosed under granulite facies condition (quartz-orthoclase-garnet-sillimanite-granulite), and are permeated by quartz-feldspar neosomes and pegmatites (Fig. 2) and have experienced all the granitisation and deformational episodes of Eastern Ghats orogeny. The general strike is NNE-SSW with a steep to vertical dip. The strike swings from NE-SW to NS to even NW-SE locally.

III. Mineralogy

Mineralogical studies (supplemented by X-Ray Diffraction pattern) on manganese ores from Kutinga revealed the presence of primary as well as secondary minerals. Hausmannite and spessartite are the only primary manganese minerals recorded. Cryptomelane, psilomelane, pyrolusite and lithiophorite are the secondary manganese minerals identified whereas quartz, chalcedony, orthoclase, garnet,

Fig. 2. Quartz-feldspar pegmatite (white) is associated with manganese ore (black).

Fig. 3. Hausmannite grains (dark grey) enclosed within cryptomelane. Replacement of hausmannite by cryptomelane is distinct.

kaolinite, apatite, sphene, biotite and zircon form the silicate gangue minerals. Associated opaque minerals include goethite and graphite with traces of hematite and pyrite.

Hausmannite is present as subhedral to anhedral grains within a groundmass of cryptomelane/psilomelane. Twinning in hausmannite is very common, lamellae often intersecting each other. Cryptomelane and psilomelane replace hausmannite along margin and enclose unreplaced islands (Fig. 3). Cryptomelane is very fine-grained and mostly occurs as colloform bands along with psilomelane, goethite and/or pyrolusite (Figs. 4-6). Replacement of psilomelane by cryptomelane and vice versa has been observed.

Fig. 4. Cryptomelane (light grey), psilomelane (dark grey) exhibit olloform bands.

Fig. 5. Pisolitic texture of psilomelane (dark grey) associated with cryptomelane (light grey).

Fig. 6. Cryptomelane (light grey), goethite (dark grey) and pyrolusite (whitish) are interlayered and exhibit colloform bands. Oxy-hydroxides of iron-manganese (dark grey to black) is at the left bottom corner.

Fig. 7. Pyrolusite (light grey) exhibits branching, kinking and micro-veins in psilomelane (dark grey).

Fig. 8. Lithiophorite (L; showing strong reflection pleochroism) associated with goethite (G) and cryptomelane (white).

This indicates their simultaneous formation. At places thin veins of cryptomelane cut across psilomelane, goethite and earlier formed cryptomelane, suggesting two stages of cryptomelane development. Cryptomelane as well as psilomelane are present in botryoidal manganese ores and show colloform, oolitic and pisolitic texture. In botryoidal ores psilomelane also shows mammillary texture. Pyrolusite is present as cryptocrystalline bands interlayered with cryptomelane/psilomelane or goethite. It is also present as stout crystals exhibiting strong reflection pleochroism and anisotropism. Pyrolusite replaces cryptomelane, psilomelane and goethite, and contains their unreplaced islands. The replacement

boundary between pyrolusite and gangue minerals often shows a saw-teeth texture. Veins of pyrolusite are observed within cryptomelane/psilomelane and fine-grained lithiophorite. Branching and kinking of pyrolusite are recorded in rare instances (Fig. 7). Microfolding of pyrolusite veins is also noticed within psilomelane. Lithiophorite is characterised by very strong reflection pleochroism in dark grey to greyish white, low reflectivity, strong anisotropism and mostly occurs as fine-grained aggregates (Fig. 8). It is common in lateritic types but also recorded in massive manganese ores along with cryptomelane. It is replaced by cryptomelane, psilomelane and pyrolusite.

Most of the iron in these manganese ores is contributed by goethite and is intimately associated with manganese phases. It occurs either as colloform bands or in oolitic, pisolitic forms within cryptomelane and psilomelane. Scales, flakes and tablets of graphite are noticed along the grain boundaries and intergranular spaces of gangue minerals. Cryptomelane, psilomelane and goethite replace graphite along cleavage and kink planes and enclose flakes and tablets within them (Figs. 9-10). Branching in graphite enclosing silicate minerals is common. Graphite is curved, kinked and folded.

Quartz, chalcedony, orthoclase, garnet, kaolinite, apatite with traces of biotite, sphene and zircon are the gangue minerals associated in these ores. Many of the quartz and orthoclase grains show undulose extinction, indicating effect of stress. Chalcedony shows fibrous structure, some times sheaf-like aggregates, leafy aggregates or spherulitic (Fig. 11) and colloform texture. It is replaced by manganese minerals along grain margins and fractures. Replacement of quartz and orthoclase by secondary manganese minerals (Figs. 12-13) is noticed along grain boundaries, cleavage and

Fig. 9. Cryptomelane (light grey) replaces graphite flakes along margin and cleavage planes and encloses within it. Goethite (dark grey) is very intricately intergrown with cryptomelane.

Fig. 10. Flakes and scales of graphite in silicate gangue minerals (dark grey) associated with cryptomelane (white) and garnet (Gar). Alteration of garnet along fractures to cryptomelane is very distinct.

fracture planes often resulting in box-work type texture. Apatite, zircon and sphene are found as inclusions within quartz and orthoclase (Fig. 12). Grain size of apatite varies from 3 to 20 microns. Zircon is observed as rounded to subrounded or elliptical grains. Orthoclase has been altered to kaolinite in a number of places. Garnet occurs as subhedral to anhedral grains and present along with quartz and orthoclase. Alteration of garnet is very conspicuous. It proceeds from grain margins, fractures and at times completely alters to biotite, and oxy-hydroxide of manga-

Fig. 11. Chalcedony shows spherulitic texture and is replaced by manganese minerals (black). Transmitted light, under crossed nicols.

Fig. 12. Quartz and orthoclase are replaced by manganese minerals along grain boundaries and enclosed by manganese minerals (black). Note the fine crystal of apatite within quartz and orthoclase at the centre of the photomicrograph.

Fig. 13. Cryptomelane (white) replaces a silicate mineral (dark grey) along grain boundaries, fractures and cleavage planes.

nese-iron, cryptomelane (Fig. 10) and/or goethite.

IV. Mineral paragenesis

The sequence of mineral formation or paragenesis observed in a mineral deposit helps in the interpretation of ore genesis. An attempt has been made here to establish the paragenesis of different ore and gangue minerals on the basis of their textural relationships. The earliest mineral assemblage (recognisable) belongs to the granulite facies, and is represented by quartz + orthoclase + garnet + hausmannite $\pm$ hematite $\pm$ graphite. Garnet (spessartite), hausmannite and hematite represent the primary minerals. Textural equilibrium relationship among primary manganese oxide and silicate minerals could not be established due to their isolated nature enclosed in a matrix of secondary manganese and iron minerals. During granitisation some amounts of quartz, orthoclase, biotite, apatite and graphite might have also been added. Secondary manganese and iron oxide minerals are formed from the primary minerals by weathering and supergene enrichment. Goethite, cryptomelane, psilomelane, pyrolusite show colloform texture suggesting their simultaneous formation. Possibly there could be two stages of cryptomelane development; the earlier one occurs simultaneously with psilomelane and the later veins cross cut the psilomelane, goethite and the earlier formed cryptomelane. Later veins of pyrolusite are found to cut across the cryptomelane, psilomelane, goethite and earlier pyrolusite. Pyrolusite II is later to cryptomelane II and both are later to lithiophorite. Cryptomelane, psilomelane, pyrolusite and goethite are later to graphite is evidenced by their presence along the cleavage and kink planes of graphite and the enclosures of graphite within the former minerals. Wad is the latest mineral developed by weathering process.

V. Mineral chemistry

A few selected mineral phases (cryptomelane, psilomelane, goethite, garnet and iron-manganese oxide/hydroxide) were analysed by JEOL EPMA Super Probe JXA-8600 model with the help of pre-set automatic programmable point scanner using international standards (minerals of manganese oxides, iron oxides, manganese silicates etc.), with an accelerating voltage of 15 kV and a specimen current of 2×10^{-8} mA. On line ZAF correction procedure was adopted. Electron probe data along with their structural formulae are presented in Table 1.

Electron probe analytical results indicate that *cryptomelane* is essentially potassium bearing manganese oxide, on an average containing 94.58% MnO₂, 4.33% K₂O and traces of SiO₂, Al₂O₃, Fe₂O₃, TiO₂, P₂O₅, CaO and Na₂O. Small quantities of MgO and BaO are recorded in some cases. High amounts of P₂O₅ is detected in cryptomelane. Ba and Na in cryptomelane may be due to substitution for K, while Al and Fe substitute for Mn. Higher amounts of barium and lower potassium distinguishes *psilomelane* from cryptomelane. It contains less P₂O₅ (0.21%) and more Al₂O₃ than cryptomelane. Goethite analyses show uniform Fe₂O₃ content with variation in MnO₂, SiO₂ and Al₂O₃. CaO, MgO and BaO are in minor traces. It contains significant amount of P₂O₅ (0.64 to 1.62%). The phosphorous content in goethite may be due to adsorption or chemisorption (Mookherjee, 1961; Acharya *et al.*, 1990) or in solid solution (Graham, 1973). Goethite has the ability to accept phosphorous into solid solution as the structure is based on a closed packed hydroxyl (oxygen) lattice, in which the tetrahedral interstices are of suitable size to accommodate the phosphorous ion, and the charges could be balanced by converting some hydroxyl to oxygen when phosphorous is

Table 1. Electron probe analyses of cryptomelane, psilomelane, goethite, garnet and oxy-hydroxide of iron and manganese

	Cryptomelane			Psilomelane		Goethite		Garnet	\$
	1	2	3	4	5	6	7	8	
MnO ₂ (wt%)	96.59	94.18	92.97	80.82	2.87	7.30	0.28	3.41	20.79
MnO	-	-	-	-	-	-	-	-	-
Fe ₂ O ₃	0.20	0.11	1.45	1.33	76.91	79.34	77.50	73.46	48.59
FeO	-	-	-	-	-	-	-	-	-
SiO ₂	0.07	0.23	0.07	0.21	3.31	2.65	0.42	1.08	2.60
Al ₂ O ₃	0.32	0.26	0.21	0.74	0.95	0.48	2.04	5.41	1.85
K ₂ O	4.33	4.25	4.42	0.64	0.01	-	-	-	0.77
P ₂ O ₅	0.56	0.75	0.58	0.21	0.84	0.64	1.62	1.47	2.05
CaO	0.45	0.42	0.43	0.31	0.18	0.31	0.04	0.06	0.32
Na ₂ O	0.08	0.11	0.13	0.02	-	0.01	0.03	0.03	0.01
MgO	0.04	-	0.04	-	0.02	0.03	0.05	0.07	0.05
TiO ₂	0.02	0.02	0.03	0.29	-	-	-	0.03	0.08
BaO	0.05	0.08	-	15.57	0.05	0.05	0.04	0.04	0.16
H ₂ O	-	-	-	-	14.86	9.19	17.98	14.94	22.82
Total	102.70	100.41	100.33	100.14	100	100	100	100	100
Based on	16(O)	16(O)	16(O)	16(O)	8(O,OH)	8(O,OH)	8(O,OH)	8(O,OH)	24(O)
Mn ⁺²	-	-	-	-	-	-	-	-	3.4820
Mn ⁺⁴	7.6986	7.6515	7.5928	7.2760	0.0793	0.2305	0.0099	0.1249	0.4055
Fe ⁺²	-	-	-	-	-	-	-	-	0.2398
Fe ⁺³	0.0166	0.0099	0.1292	0.1299	2.3127	2.7812	2.9934	2.8723	5.9335
Si	0.0083	0.0276	0.0085	0.0266	0.1323	0.1234	0.0213	0.0570	0.0012
Al	0.0443	0.0353	0.0298	0.1143	0.0451	0.0263	0.1233	0.3382	0.0054
K	0.5682	0.6370	0.6660	0.1064	0.0004	-	-	-	0.0076
P	0.0540	0.1248	0.0582	0.0235	0.0283	0.1900	0.0703	0.0656	2.0977
Ca	0.0547	0.0501	0.0531	0.0423	0.0077	0.0157	0.0022	0.0032	0.0012
Na	0.0194	0.0240	0.0298	0.0470	-	0.0012	0.0024	0.0054	0.0018
Mg	0.0062	-	0.0071	-	0.0012	0.0020	0.0040	0.0054	0.0018
Ti	0.0014	0.0014	0.0021	0.0282	-	-	-	0.0009	0.0101
Ba	0.0021	0.0035	-	0.7945	0.0007	0.0008	0.0009	0.0006	0.0018
OH	-	-	-	-	7.9192	6.1062	6.1570	5.2880	-
Total	8.4738	8.5651	8.5766	8.5887	10.5269	9.4773	9.3847	8.7593	16.1378
* H ₂ O by difference	-	-	-	-	-	-	-	-	-
		\$	Oxy-hydroxide of iron and manganese						

added. Manganese is mostly present substituting for iron, whereas silica may be due to admixtures and/or impurity (Deer *et al.*, 1963). Other trace elements like Na, K, Ti are present in some analysis and absent in others.

Garnet analysis reveals that it is dominantly a spessartite, having end member composition of 54.60 mole% spessartite, 32.92 mole% grossularite, 3.92 mole% andradite, 6.36 mole% almandine, and 2.23 mole% pyrope. The presence of phosphorous in garnet may be due to replacement of SiO₄ group by PO₄ (Deer *et al.*, 1963). The analysis of *oxy-hydroxide of iron-manganese* phase indicates that it is essentially constituted of iron, manganese and water with minor amounts of SiO₂, Al₂O₃, P₂O₅ and traces of K₂O, CaO, MgO and BaO. It contains highest amount of phosphorous (2.05 % P₂O₅) amongst mineral phases analysed.

VI. Geochemistry

Major, minor and trace elements of eight samples were analysed in duplicate and the average values are reported in Table 2. Major elements are analysed by conventional wet chemical methods; K₂O, Na₂O, CaO and Li₂O were analysed by Flame photometer (Systronics, model K-III); P₂O₅ by colorimeter (Systronics) following Vogel (1961) and trace elements (Cu, Ni, Co, Zn, Pb and Cr) were done by Varian Tectron AA-1475 ABD Atomic Absorption Spectrophotometer. In case of major elements there was excellent agreement between the values. The analytical error in case of minor and trace elements was found to be within 2.3% of the average value.

The analyses of Kutinga manganese ore samples show wide variation in their manganese and iron contents. Phosphorous content in these ores is very high in comparison to

Table 2. Major, minor and trace element analyses of Kutinga manganese ores

	1	2	3	4	5	6	7	8
MnO ₂ (wt%)	55.78	85.62	63.58	51.57	54.59	66.05	65.66	57.99
Fe ₂ O ₃	24.13	0.60	11.68	28.02	25.34	14.43	12.52	18.11
Al ₂ O ₃	0.64	0.25	2.48	1.15	1.65	1.81	1.43	1.30
SiO ₂	4.48	0.15	5.13	3.16	2.41	3.68	5.28	4.93
CaO	1.13	1.68	1.85	1.23	0.98	0.88	1.12	0.72
MgO	0.19	0.11	0.18	0.14	0.19	0.36	0.12	0.10
K ₂ O	2.13	3.99	2.35	2.20	2.23	1.07	2.44	2.23
Na ₂ O	0.25	0.31	0.23	0.26	0.25	0.23	0.25	0.30
P ₂ O ₅	0.32	1.08	0.44	0.35	1.15	0.37	0.63	0.80
TiO ₂	0.01	0.01	0.05	0.05	0.05	0.01	0.01	0.02
Li ₂ O	0.22	0.31	0.22	0.22	0.20	0.14	0.21	0.25
LOI	10.42	5.65	10.57	10.86	11.06	11.05	10.23	12.76
Total	99.70	99.76	98.76	99.21	100.10	100.08	99.90	99.51
Cu (ppm)	59	90	59	99	142	174	75	125
Ni	214	135	317	341	230	492	406	210
Co	170	202	216	198	177	277	172	144
Zn	274	171	218	247	303	288	351	423
Pb	17	19	42	47	49	39	37	43
Cr	73	149	33	145	121	96	57	104

other deposits, e.g. Western Koira valley, North Orissa, India (Mohapatra, 1992); North Kanara and Chiknayakanahalli Green stone belt Karnataka, India (Machigad, 1990; Anantha Murthy and Devraju, 1990); Groote Eylandt, Australia (Varentsov, 1982); Islay, Argyllshire (Nicholson, 1988); Urkut, Hungary (Varentsov *et al.*, 1988); Tokoro belt of Japan (Choi and Hariya, 1992) and more or less comparable with Nishikhal manganese ores, south Orissa, India (Acharya *et al.*, 1990 and 1994) as well as manganese ores of central India (Gonditic types of M.P.- Maharastra belt; Sahoo *et al.*, 1982). Presence of high iron, high phosphorous and dominance of CaO over MgO, K₂O over Na₂O, Ni over Co, Zn over Pb and Cu over Pb are the characteristics of Kutinga manganese ores. Similar behaviour is also reported from the gonditic manganese ores of M.P. and Maharastra, India (Mookherjee, 1961). The higher concentration of trace elements like Cu, Pb and Zn are considered to be the diagnostic of

hydrothermal and/or volcanogenic manganese deposits (Zantop, 1981; Nicholson, 1986 and 1988; Ajmal, 1990). Lower concentration of the above trace elements in these manganese ores may suggest that the contribution of hydrothermal and volcanogenic origins is minor or insignificant.

VII. Genesis of the deposit

The genesis of this deposit is discussed briefly under source and deposition; metamorphism; granitic and pegmatitic activities and supergene enrichment.

1. Source and deposition of manganese

Continental erosion, volcanic activity and/or hydrothermal process have traditionally been cited as source for most of the manganese deposits of the world. The classic problem one encounters while attributing any such source is the association of iron along with manganese. Unusual huge accumulations of either of these two or often to the mutual inclusion, have

prompted many authors to propose volcanic activity as a probable source. However, manganese derived from the volcanogenic and/or hydrothermal sources are ruled out for this deposit because of the following facts:

a) Non-existence of rocks derived from volcanic activity in the near vicinity of the area under investigation.

b) Concentrations of Cu, Pb and Zn in this manganese ores are much lower than that of hydrothermal and volcanogenic deposits (Zantop, 1981; Nicholson, 1986 and 1988; and Ajmal, 1990).

c) Absence of wall rock alteration and manganese sulphide minerals, such as alabandite do not indicate this deposit to be of hydrothermal origin (Roy, 1981).

Occurrence of well defined manganese band having same strike and dip with that of the country rocks (metasediments, e.g. khondalite and quartzite) having signatures of deformation on both, strongly suggest for a metasedimentary parentage for this deposit. Manganese ore bodies appear to be confined to a definite stratigraphic horizons in khondalite suite of rocks in this part of Eastern Ghats complex. Continental erosion appears to be the most probable source. This fact is supplemented by the Na vs. Mg plottings of the manganese ores which lie in the freshwater field of Nicholson (1988; Fig. 14). The scatter of plots of Na against Mg clearly distinguishes manganese oxides deposited in marine, shallow marine and fresh water environments (Nicholson, 1988).

In Kutinga deposit, both metamorphic mineral assemblages (relics of primary minerals such as hausmannite and spessartite) and their supergene derivatives (secondary manganese and iron minerals like cryptomelane, pyrolusite, psilomelane, lithiophorite, goethite) have been observed. However, no mineralogical and textural features are preserved to indicate that these primary oxide and the sili-

Fig. 14. Kutinga manganese ore sample (●) plotted on the discrimination diagram of Nicholson (1988). F/W-Fresh Water.

cate minerals existed in the original sediments (syngenetic minerals). It is unlikely that these minerals themselves existed in the original sediments and simply recrystallized during metamorphism.

The existence of oxide and silicate minerals only in the Kutinga manganese ores suggest that an oxide facies was dominating (without any manganese carbonates or manganese sulphides) during original sedimentation. Absence of any manganese carbonate mineral further indicates that the deposition of the ores took place under highly oxidising environments. Presence of different silicates in the manganese ores indicates that the manganese-rich sediment which was rich in iron probably also contained abundant admixtures of sand and/or clay.

The mode of transportation of Fe and Mn and their deposition under oxidising conditions has long been known (Rankama Sahama, 1950; Krauskopf, 1957). Fe and Mn might have been transported as finely divided particles in river waters, as adsorbed compounds on clay particles, as sols, gels and so on. Manganese com-

pounds are soluble in neutral and acid solutions (Sivaprakash, 1980) while not so soluble under alkaline conditions. Fe is more readily precipitated than Mn under suitable Eh-pH condition. Mn and Fe might have been precipitated in the form of compounds such as $\text{Mn}(\text{OH})_4$, MnO_2 , $\text{Fe}(\text{OH})_3$, and Fe_2O_3 . $\text{Mn}(\text{OH})_4$, MnO_2 sols and gels being negatively charged readily adsorb cations such as K and Ba (Rankama and Sahama, 1950). Such manganese precipitates with adsorbed materials during diagenesis could transform into oxides of higher valency states such as cryptomelane, psilomelane etc..

2. Metamorphism

After deposition and diagenetic changes, the manganese minerals of higher valency states were metamorphosed under granulite facies conditions along with conformable, psammitic and pelitic sediments of Eastern Ghats. Metamorphism of manganese oxides is relatively a simple process. With an increase in pressure and temperature during metamorphism, the manganese minerals of higher valency states were transformed to oxides of relatively lower valency (Roy, 1981), and this is essentially a case of isochemical metamorphism except for any redox changes. Temperature, pressure and oxygen fugacity are the important parameters in controlling the manganese oxides/silicates stability boundaries during metamorphism. The manganese formation along with the associated country rocks have been affected by polyphase metamorphism and deformation (Acharya and Dash, 1984). Quartzofeldspathic neosomes pervade and obliterate parts of the other rock types including manganese bands and occur as laminae, discrete patches, stromatolitic bands, veins and dykes. Some are coarse grained quartz-feldspar-mica pegmatites.

The presence of some of the primary minerals can be used to estimate their tempera-

ture of formation. For instance, hausmannite could result from the direct transformation of an early formed Fe-Mn hydroxide, (which donot transform to intermediate oxides such as bixbyites) at 600°-750°C (Okada, 1960) which is in agreement with the temperature of metamorphism. The temperature and pressure conditions of metamorphism of Eastern Ghat rocks in parts of Orissa is determined to be >650°C and >6 Kb (Park and Dash, 1984; Dash *et al.*, 1987). The granulite facies metamorphism is followed by retrograde metamorphism.

3. Supergene enrichment

During the post-metamorphic period, prolonged exposure of the deposit to atmospheric oxygen and percolation of meteoric waters has caused the primary minerals to undergo supergene alteration. While all the primary minerals have undergone supergene alteration, most of the primary manganese oxide minerals are totally obliterated by weathering and supergene process. However, the manganese silicates like spessartite is partly affected by weathering and supergene process. Alteration of manganese garnet is intense where fractures and microfractures are present. Under supergene condition and because of strong oxidation effects, the manganese oxides of lower valency states (primary minerals) might have transformed to higher valency oxides, e.g. cryptomelane, psilomelane, pyrolusite etc. (Sivaprakash, 1980; Acharya *et al.*, 1990). Lithiophorite might have produced by a low temperature reaction of clay minerals and primary manganese oxides during the weathering process (Ostwald, 1980, 1988). Presence of chalcedony showing colloidal texture is also related to weathering process.

VIII. Discussion and conclusion

Mode of occurrence, mineralogy, texture and chemical characters of Kutinga manganese ores suggest their formation as chemical precip-

itates, and the source of which appears to be continental erosion. Manganese formation along with the country rocks have been metamorphosed under granulite facies conditions, affected by granitisation and later subjected to supergene enrichment to give rise to the present mineral assemblages.

A direct relationship appears to exist between phosphorous content and metamorphic grade of Indian manganese ore deposits. Low or unmetamorphosed manganese ores contain very small amounts of phosphorous whereas the high grade metamorphosed ores contain higher amounts of phosphorous (Krishnan, 1982). This is in agreement with the fact that the Kutinga deposit which has undergone granulite facies metamorphism also contains high amounts of phosphorous. Phosphorous in the Kutinga ores is present as fine apatite crystals within the silicate gangues and also adsorbed with various manganese and iron phases. The original manganiferous sediments probably contained some amount of phosphorous (Sivaprakash, 1980) and some more phosphorous in the form of apatite might have been introduced into the manganese ores through granitic and pegmatitic activities (Acharya *et al.*, 1990), preceeding the supergene enrichment. A primary manganese silicate mineral, spessartite contains small amounts of phosphorous. During supergene enrichment, the phosphorous content in the secondary manganese phases have been relatively increased (Acharya *et al.*, 1994). The hydrous oxide of iron and manganese, which has probably derived from the primary manganese oxide and silicate minerals, contains highest amount of phosphorous (2.05% P_2O_5). Goethite, cryptomelane, psilomelane are in decreasing order of phosphorous content.

These ores are amenable to removal of silica and silicates by physical beneficiation (magnetic or gravity routes). Removal of iron by this process is not possible because of fine

size and intricate association of goethite with manganese ore minerals. As the apatite is in small quantity and majority of the phosphorous is in adsorption with manganese and iron phases, the ore will neither respond well to removal of phosphorous by physical beneficiation nor to acid leaching methods. However, this ore is likely to respond well to dephosphorisation by roast-alkali leaching methods (Banerjee *et al.*, 1990).

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