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Iron and Manganese Mineralization Associated with Archean Greenstone Belt in Joda-Noamundi Sector, Odisha, East Indian Shield

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Abstract: Iron and manganese mineralization in the Joda-Noamundi sector is associated with Banded Iron Formation of the Archean Iron Ore Group of rocks (3.5-3.0 Ga).Both Mn and Fe mineralization is stratiform and stratabound. In the Noamundi basin the estimated reserve of Fe and Mn -ores are 3.3 Gt and 130 Mt respectively. The Fe and Mn-mineralization are also genetically related to each other. A detailed petrology, mineralogy and mineral chemistry of the ores show their evolution with respect to different tectonic phases. During the first phase of deformation and metamorphism Fe-protolith generated magnetite and Mn-protolth generated bixbyite, hausmannite, jacobsite and braunite. During second phase martitized magnetite and hematite in Fe-ore and hollandite, psilomelane and pyrolusite in Mn-ore were generated. During supergene events low temperature higher oxide minerals were generated from the metamorphic and hydrothermal Fe and Mn –ore minerals. The stratigraphic status of the Fe- and Mn- ores with respect to crustal evolution has been established.

Keywords: Archean, Fe-Mn-ores, Iron Ore Group, East Indian Shield

1. Introduction

Archean iron and manganese mineralization in greenstone belts are reported from limited occurrences viz. the Rio das velhas deposit of Brazil (Machado and Carneiro [1]; Teixeira, et al.[2]; Martin, et al.[3]), the Barberton greenstone belt of South Africa (De Wit, et al.[4]; Anhaeusser and Wilson[5]), the Yilgarn and Pilbara blocks of Western Australia (Condie[6]; Hallberg and Glickson[7]), the Sebakwian-Bulawayan-Shamvaian belt of Zimbabwe (Myers and Kröner[8]; Windley[9]), the Superior and Slave provinces of Abitibi belt, Canada (Goodwin[10]; Dimroth, et al.[11]), the Isua Formation of Greenland (Gross[12]; Schidlowski[13],[14]), the Bababudan and Chitradurga belt of South India (Ramakrishnan, et al.[15]; Chadwick, et al.[16],[17]) and the Iron Ore Group (IOG) of the East Indian Shield (Roy[18]; Ghosh, et al.[19]).

The Joda-Noamundi sector of the Noamundi Iron Ore basin of the East Indian Shield bears significant occurrence of iron and manganese mineralization which belongs to Paleo-Mesoarchean (3.5-3.0 Ga) greenstone rocks of the Iron Ore Group (IOG). Sarkar [20] estimated the remaining Fe ore resource in the Noamundi basin is about 3.3 Gt (at more than 60 wt.% Fe). The total Mn-ore reserve according to Indian Bureau of Mines is about 130 Mt (25-35 wt.%Mn) (Manganese Ore Vision 2020 and Beyond[21]).

Banerji[22], Saha[23]and Roy[24] suggested the stratigraphic sequence of the IOG rocks. In this sequence Mn -minralization is bounded in upper shale which is at the upper horizon of iron formation. Beukes, et al. [25] suggested manganiferous horizon is stratigraphically at the lower horizon of ferruginous shale and iron formation in their prescribed stratigraphic model.

In this paper, the authors have enlightened the problem regarding stratigraphy of the IOG and correlated Fe and Mn mineralization in the Noamundi basin genetically with mineralogy, petrography and mineral chemistry.

2. Geologic Setting

The Precambrian rocks of the East Indian Shield are distributed in the Chhotanagpur granulite-gneiss terrain in the north, the Singhbhum granite-greenstone terrain in the south and the Singhbhum orogenic belt in between these two terrains (Fig.1). There are three major Archean greenstone belts are present at the margins of Singhbhum granitic craton viz. the Jamda-Koira belt at the west, the Gorumahishani-Badampahar belt at the east and the Tomka-Daitari belt at the south. According to Banerji[22] and Baidya[26] the Tomka-Daitari belt is the southern extension of Gorumahisani-Badampahar belt. These three greenstone belts stratigraphically belong to the IOG (Table.1). The IOG rocks overlies the Singhbhum Granite Type-A and underlies the Singhbhum Granite Type-B. The Joda-Noamundi sector belongs to central and eastern part of the Noamundi basin. Banerji[22] stratigraphically characterized iron-manganese mineralization in the Jamda-Koira belt as the Noamundi Group of much younger age (c.1500-1100 Ma) with the following sequence (ascending order) : Lower shale (tuffaceous shale - phyllite), Banded hematite jasper, Upper shale (manganiferous shale, tuff and chert), Basic intrusion, Granitic activity. Sarkar and Saha[27] & [28] described manganese ore bodies intimately associated with unmetamorphosed shales (occasionally tuffaceous) and chert of the Archean IOG. They also considered that manganese mineralization is confined to the topmost Upper shale Formation in a belt about 80 km long and 25 km wide.

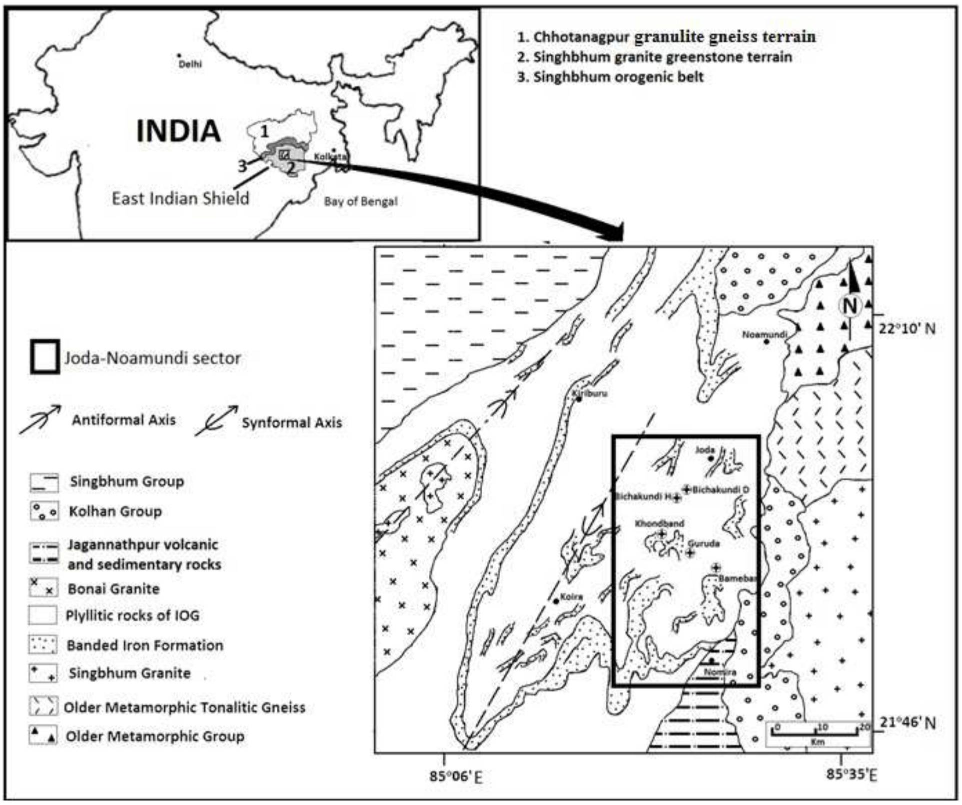

Fig.1. *Geological map of the Noamundi Basin showing the Joda-Noamundi sector.*

Table 1. *Archean stratigraphic sequence of the Singhbhum Granite-Greenstone terrain after Saha et al.[23].*

c. 3.1Ga.	Singbhum Granite Type-B (Phase III)	
c. (3.3-3.1) Ga	IRON ORE GROUP	Mafic lava, tuff, acid volcanic, tuffaceous shale, banded hematite jasper and banded hematite quartzite with iron ores, ferruginous chert, local dolomite and quartzite sandstone
--Unconformity ---		
c. 3.3 Ga	Singbhum Granite Type -A (Phase-I and Phase-II)	
c. 3.4-3.5 Ga	Folding and Metamorphism of OMG and OMTG	
c. 3.775 Ga	Older Metamorphic Tonalitic-Gneiss (OMTG)	
c. 4.0 Ga	Older Metamorphic Group (OMG)	
---------------------------------------Basement unknown------------------------------------		

The IOG rocks occupy the major central part forming the Noamundi synclinorium. The western limb of this synclinorium is more or less continuous but characteristically devoid of any significant manganese mineralization. Iron ore is associated with BIF is present in both limbs. The eastern limb is structurally much more disturbed and dissected. It characteristically contains the major manganese ore bodies in the Joda-Noamundi sector. The corresponding anticlinal core in the western part of the Noamundi synclinorium is mainly occupied by the 3.3 Ga Bonai granite (Saha[23]). The Older Metamorphic Group (OMG), OMTG and Singhbhum Granite occur mainly in the eastern part of the Noamundi Basin. Moorbath and Taylor [29] corrected the age of OMTG as 3.52-3.45 Ga. The Proterozoic Singhbhum group of rocks in the western part (mainly low grade metamorphosed volcanic and sedimentary rocks), the Kolhan Group (unmetamorphosed sedimentary rocks) and the Jagannathpur-Malangtoli volcanic rocks unconformably overlie the Singhbhum Granite Phase –III.

Due to the lack of proper geochronological data, the absolute age of the three greenstone belts of the IOG is quite uncertain. A relative age can be provided by the fact that the rocks of IOG overlie the Singhbhum Granite Type –A and intruded by the younger granites like Bonai granite in the west & Mayurbhanj granite in the east. The Singhbhum Granite Type-A, the Bonai granite and the Mayurbhunj Granite have been dated as 3328±7 Ma (single zircon Pb-Pb, Misra et. al. [30]), 3163±126 Ma (Pb-Pb age, Sengupta et. al. [31]) and 3080±8 Ma & 3092±5 Ma (single zircon Pb-Pb, Misra et. al. [30]) respectively. Mukhopadhyay et. al. [32] reported 3.51 Ga dacitic volcanics from the Tomka-Daitari belt of the IOG.

3. Geology of the Mineralized Areas

The iron and manganese ore bodies of the Noamundi basin is stratiform and stratabound in character. The Manganese ore bodies occur as lenticular bands hosted mainly by phyllitic rocks. The phyllitic rocks are very light colored and thinly banded resembling laminated shale. The host rock is composed of mainly very fine grained phyllosilicate minerals and minor ore minerals. These are actually metamorphosed tuffaceous materials (Ghosh et. al. [19]). The Mn-ores are mainly of four types: massive, banded, brecciated and colloform (pisolitic/ botryoidal/ reniform) (Fig.2A). The iron ore bodies are mainly hosted bybanded jasper quartzite.Iron ore bodies contain massive, banded, friable and colloform type ores (Fig.2B, 2C).

The local sequence encountered in the quarry sections (bottom to top) is banded jasper quartzite, manganese ore bodies hosted by phyllites, ferruginous phyllites and banded hematite jasper with iron ores (Fig.2D, 2E). The banded jasper quartzite bodies are made of centimetre thick alternate layers of jasper -rich and quartz -rich bands (Fig.2F). The overlying manganiferous phyllite (purple to cream colored) mainly hosts the Mn-ore bodies (Fig.2G). Although colloforms of secondary iron ore minerals viz. goethite, hematite etc. are also found along with Mn-ores. The ferruginous phyllite (red to yellow colored) at the upper horizon of manganiferous phyllite hosts patchy supergene hematite and goethite rich iron ores (Fig.2D,2E). The banded hematite ores hosted by BIF are at the uppermost level of the quarries (Fig.2C).

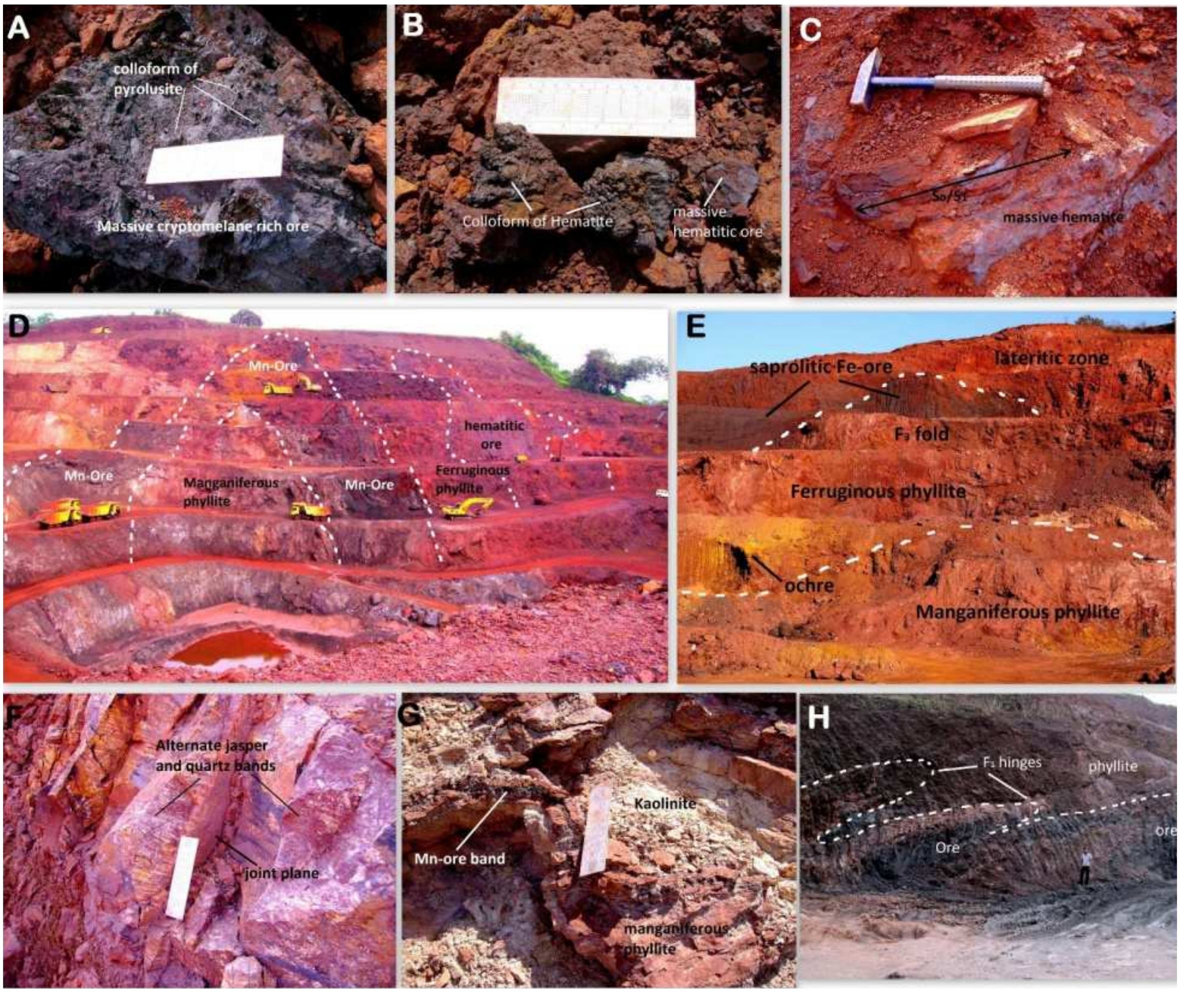

Fig. 2. Field photographs showing lithological characteristics in the mineralized zones in Joda-Noamundi sector, Noamundi Basin, East Indian Shield. A. Massive cryptomelane ore with pyrolusite colloform. B. massive and colloform hematite ore. C. Massive hematite ore is assosiated with iron BIF. D. Quarry section shows folded lithologic units of manganiferous phyllite, ferruginous phyllite and hematitic ores. E. lithologic units of manganiferous phyllite andsaprolitic Fe-ore within ferruginous phyllite. F. Banded jasper quartzite at the basement of a quarry. G. Folded Mn-ore band within manganiferous phyllite. H. Recumbent folds of Mn-ores and phyllite in a Mn-ore zone. (length of scale :16cm, length of hammer : 50cm, height of quarry bench : 15ft appx.)

During the structural study, the authors found four deformational phases. The earliest deformational phase (D_1) produced regional NNE plunging isoclinal fold (F_1) which has overturned eastern limb. The axial plane schistosity (S_1) mostly corresponds to compositional banding (So) of rock in Joda-Noamundi sector. Because of the overturned folding the lithological sequence encountered at the quarry sections inthe eastern part of Noamundi basin is stratigraphically reverse. The actual chronostratigraphic sequence should be (ascending order) banded hematite jasper with iron ores, ferruginous phyllites, manganese ore bodies hosted by phyllites and banded jasper quartzite. This stratigraphic sequence is also supported by the works of Banerji[22] and Saha[23].Some recumbent F_1 folds were also generated during D_1 stage (Fig.2H).The second deformational phase (D_2) caused NNE and SW plunging tight to isoclinal F_2 fold. The third phase of tectonic deformation (D_3) produced WNW plunging mainly open type F_3 fold. The F_2 and F_3 interference caused dome and basin structure. Subsequent to third deformational phase the rocks were subjected to faulting and shearing (D_4).

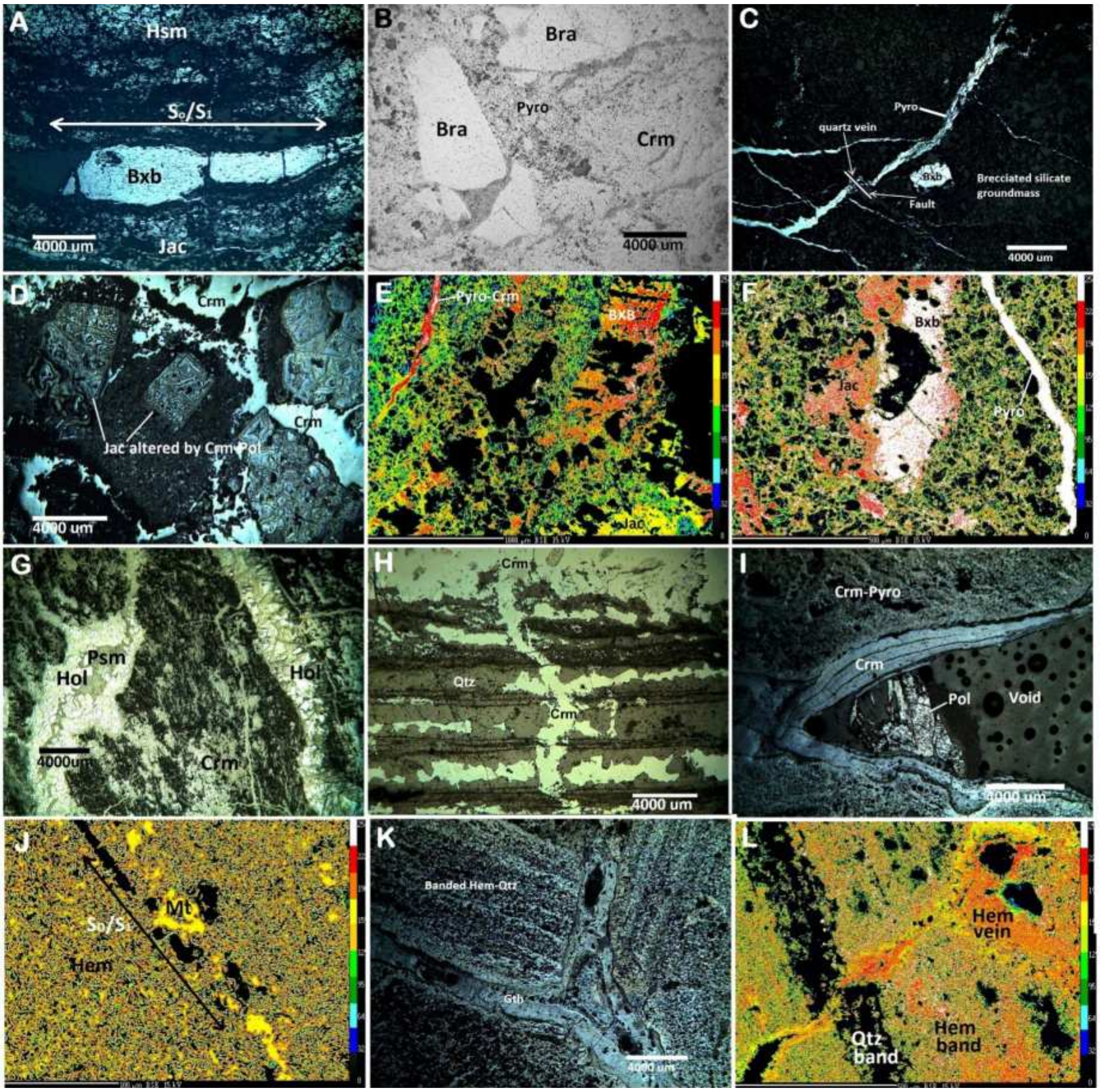

Fig. 3. *Photomicrographs of Mn- and Fe-ores. A. Banded bixbyite (Bxb), hausmannite (Hsm), jacobsite (Jac) with phyllosilicates is boudinized. B. Brecciated clasts of braunite (Bra) within cryptomelane (Crm) and pyrolusite (Pyro) groundmass. C. Bixbyite (Bxb) porphyroblast is present within brecciated silicates. Supergene pyrolusite (Pyro) vein is intruded by later quartz vein. D. Jacobsite (Jac) is altered by cryptomelane (Crm) and polianite(Pol). E. False color image (FCI) shows brecciated Bxb porpyroblasts and silicates in Pyro and silicate rich groundmass. F. Bxb and Jac porpyroblasts in brecciated groundmass. G. Hydrothermal hollandite(Hol) and psilomelane (Psm) veins intrude early ore assemblages. H. Supergene Crm is present along and across banded quartzite. I. Crm and polianite (Pol) are present as void filling colloform at the interstitial space of Crm-Pyro clasts. J. rim of hematite (Hem) over magnetite (Mt) is present as a band alternating with disorientated acicular Hem rich band. K. Void fill of goethite (Gth) at the interstitial space of brecciated banded hematite quartzite clasts. L. Void fill of Hem is present in banded hematite-quartzite.*

4. Mineralogy and Petrography of Fe-Mn-Ores

The major Mn-mineral phases in the ore deposit are pyrolusite, cryptomelane, polianite and groutite.The earlier workers i.e. Banerji[22]; Roy [18]; Mohapatra et al.[33]; Mishra et al.[34] reported mainly low temperature minerals in the ores of the present area e.g. pyrolusite, psilomelane, manganite,rhodochrosite, cryptomelane, lithiophorite, chalcophanite, goethite,todorokite, and braunite and they considered that these minerals were formed in near-surface conditions under relatively high oxidizing environment. Ghosh et al. [19] reported 15 new manganese minerals from this deposit. They also stated that formation of bixbyite, braunite, jacobsite and hausmannite is related to first stage of deformation and metamorphism (D_1/M_1), hollandite, psilomelane and pyrolusite is related to second stage of deformation and metamorphism (D_2/M_2) and pyrolusite, cryptomelane, groutite, polianite etc. is related to supergene events.

The compositionally banded character of Mn-ore is observed during petrography. Hausmannite, bixbyite and jacobsite –rich bands occur alternatingly with phyllosilicate -rich band where Mn-mineral rich more competent bands are boudinized (Fig.3A). Brecciated fragments of braunite is found in pyrolusite, cryptomelane and silicate rich groundmass (Fig.3B). Discrete grains of bixbyite and jacobsite are present in pyrolusite-cryptomelane and brecciated silicate mineral-rich groundmass (Fig.3C,3D,3E,3F). Bixbyite grains are highly altered to pyrolusite, cryptomelane etc. where cryptomelane and polianite have replaced jacobsitegrains.Pyrolusite has formed after braunite at the boundaries. Hydrothermal veins of hollandite and psilomelane are also ubiquitous (3G). Supergene cryptomelane and pyrolusite veins are common along weak planes (3H). Cavity filling of cryptomelane and polianite during supergene event is also observed (3I).

The major Fe-mineral phases in the iron ore bodies are hematite and goethite. Although Beukes et al.[25] and Upadhyay et al. [35] reported martite, limonite etc. minerals from Noamundi basin Fe-ore deposit.

Alternate bands of anhedral to subhedral martitized magnetite and acicular hematite is found in massive Fe-ore. Magnetite relicts are present inside hematite rim of higher reflectance. Acicular hematite crystals are 5-10 µm long and haphazardly oriented (Fig.3J).During D2/M2 stage major hydrothermal activity might have generated hematite in expense of magnetite. In brecciated Fe-ore goethite colloform is found at the interstitial space of the brecciated clasts of banded hematite-quartz (Fig.3K). Supergene hematite veins are present along fracture in banded hematite-

Table 2. *Generalised mineral composition of the major minerals in manganese and iron ores of Joda-Noamundi sector, Noamundi Basin, East Indian Shield.*

Points	Bxb	Jac	Hsm	Hol	Psm	Pyro,H	Pyro,S	Mgm, S	Gth-Grt-Dsp	Hem	Dsp	Mart	Gth
	n=15	n=5	n=2	n=3	n=5	n=5	n=9	n=10	n=6	n=12	n=2	n=7	n=5
Na_2O	0.21	0.17	0.10	0.21	0.15	0.09	0.15	0.71	0.09	0.14	0.40	0.20	0.35
MgO	0.09	0.23	0.14	0.40	0.36	0.15	0.22	0.17	0.40	0.50	0.69	0.55	0.69
SiO_2	0.40	3.86	0.49	0.36	0.18	0.60	0.26	0.36	3.75	0.06	0.10	0.14	0.08
Al_2O_3	3.38	7.17	0.73	1.28	0.67	0.42	1.35	0.64	10.71	1.05	97.06	0.88	1.28
P_2O_5	-	-	-	-	-	0.84	0.22	1.40	-	0.06	0.04	0.02	-
K_2O	1.47	0.65	0.23	1.08	1.53	2.90	1.90	3.43	0.50	0.01	0.02	0.12	0.03
CaO	0.32	0.24	0.27	0.90	1.02	0.40	0.42	0.11	0.17	0.14	0.10	0.11	0.22
TiO_2	0.02	0.38	-	-	-	-	0.04	0.03	0.11	0.01	0.01	0.04	-
Cr_2O_3	0.01	0.04	0.08	-	0.03	0.03	0.11	0.14	0.09	0.04	-	0.02	0.38
MnO	91.33	51.31	96.37	82.31	82.79	88.93	93.27	85.91	32.19	0.03	0.12	0.06	0.70
FeO	2.40	35.58	1.24	1.39	0.14	2.10	0.98	2.68	38.74	97.82	1.43	98.04	96.13
CoO	0.03	-	0.03	0.36	0.32	0.30	0.20	0.17	0.05	-	-	-	-
NiO	0.03	0.04	0.10	0.07	0.07	0.22	0.12	0.37	0.71	-	0.01	0.02	0.01
CuO	0.04	0.02	0.18	0.21	0.22	0.33	0.03	0.13	0.03	-	-	-	-
ZnO	0.06	0.12	-	0.05	0.07	0.66	0.01	0.60	0.08	-	-	-	-
BaO	0.04	0.04	0.01	11.34	9.33	0.89	0.34	1.05	0.13	0.04	-	0.02	0.02
ZrO_2	0.14	0.12	0.16	0.08	0.03	-	0.03	-	0.06	0.09	-	0.03	0.13
V_2O_3	0.03	0.02	-	0.03	0.03	0.15	0.02	0.22	0.05	0.01	0.02	0.01	-
PbO	-	-	-	-	-	0.57	0.13	0.97	-	-	-	-	-
As_2O_3	-	-	-	-	-	-	-	0.28	-	-	-	-	-
S	-	-	-	-	-	0.15	0.02	0.18	-	-	-	-	-
Ag	-	-	-	-	-	0.08	0.12	0.21	-	-	-	-	-
Au	-	-	-	-	-	0.17	0.04	0.24	-	-	-	-	-
Total	99.99	100.00	100.00	100.05	96.94	100.01	100.00	100.00	87.84	100.00	100.00	100.01	100.00

n : number of analyses. '-' represents not detected.

Bxb :bixbyite; Hsm : hausmannite; Jac: jacobsite; Hol: hollandite; Psm: psilomelane; Pyro, H : hydrothermal pyrolusite; Pyro, S: supergene pyrolusite; Mgm: manganomelane group of minerals; Dsp: diaspore; Mart: martite; Hem: Hematite; Gth: goethite; Grt: Groutite.

quartz ore (Fig.3L). Supergene veins of diaspore and goethite are also present.

5. Mineral Chemistry

In the Mn-ore, the major D_1/M_1minerals are bixbyite, jacobsite, hausmannite, D_2/M_2 minerals are hollandite, psilomelane and pyrolusite and supergene stage minerals are cryptomelane, pyrolusite and groutite-goethite-diaspore. Mineral chemistry of bixbyite shows they are typically Mn-rich. Although some amounts of Fe and Al are present. Ghosh et al. [19] concluded that the Fe and Al in bixbyite is due to supergene alteration by goethite-diaspore. K percent is more than Na, Ca, Mg and Ba. Zr amount is significant. Trace amounts of Cu, Ni, Cr, Co, V, Ti and Cr are also present. The mineral formula of bixbyite generated from compositional data is $(Mn_{1.88}Fe_{0.04}Al_{0.08})O_3$.In jacobsite Fe and Mn ratio is around 5:3. Significant amount of Al^{+3} is present in structure replacing Fe^{+3} and Mn^{+3} in tetrahedral site. Minor amounts of Zr, Na, K, Ca, Mg, Ti & Zn and trace amounts of Ni, Cu, Ba& Cr are also present. The calculated mineral formula of jacobsite is $(Mn_{1.62}Fe_{1.14}Al_{0.24})O_4$. The available analysis data it is clear that hausmannite structure hardly allowed other elements to occupy cation sites. This fact is also supported by other workers (Frenzel [36] and Roy [18]). Although minor amounts of Na, Mg, Si, Al, Ca, K, Ni, Cu and Zr are present (Table.2).The high Ba and minor amounts of Co, Ni, Cu and Zn in hollandite, psilomelane and pyrolusite is quite significant in D_2/M_2 stage. Minor amounts of Na, K, Mg, Ca, Al and Fe is also present. The calculated mineral formulae of hollandite and psilomelane are $(Ba_{0.81}K_{0.08}Ca_{0.06}Na_{0.01}Mg_{0.03})Mn_8O_{16}$ and $(Ba_{0.75}K_{0.12}Ca_{0.08}Mg_{0.03}Na_{0.01}, H_2O)_2Mn_8O_{16} . nH_2O$ respectively.The supergene minerals i.e. manganomelane, pyrolusite and groutite-goethite-diaspore contains almost all major and minor elements in variable amounts. The calculated generalized chemical formula of manganomelane group of minerals is $(K_{0.56}Ba_{0.17}Na_{0.11}Pb_{0.15})Mn_8O_{16}. nH_2O$. The diaspore group of minerals i.e. goethite, groutite and diaspore are present as solid solution withvariable proportion. The generalized formula of this solid solution calculated is $(Fe_{0.47}Mn_{0.39}Al_{0.13})O(OH)$.

The major minerals present in Fe-ores are martite, hematite, diaspore and goethite. The martitized magnetite and hematite grains are essentially Fe rich. Minor amounts of Na, Mg, Al, K &Ca and trace amounts of Si, P, Ti, Cr, Mn, Ba, Zr & V are also present in the grains. Analysis of two diaspore in form of supergene vein shows that they are Al rich. Minor amounts of Fe, Na and Mg and trace amounts of Si, P, Ca and Mn are also present.

6. Discussion and Conclusion

Paleo-Mesoarchean crustal evolution and corresponding metallogeny events took place in the three greenstone belts (belongs to the IOG) at the margins of the Singhbhum craton. The Jamda-Koira greenstone belt at the western margin contains significant iron and manganese mineralization associated with BIF and volcanic rocks. The synsedimentary iron and manganese ores were subjected to three subsequent phases of tectonic deformation. During first phase of deformation (D_1) the region was subjected to nearly east-west compression which ultimately formed the regional synclinorium (F_1) with NNE-trending and easterly dipping axial plane. The regional fold has overturned limb at the eastern part particularly in the Joda-Noamundi sector. That is why the lithologic sequence encountered here is actually stratigraphically reverse.

Grant et al. [37],Avasthy[38],Sarkar [39] and Raha and Moitra[40] reported algal stromatolites and spheroidal & filamentous microfossils in the BIF and manganese ore horizon of the Noamundi basin. Beukes et al. [25] studied the Fe-ores of the Noamundi basin and concluded that the original magnetite rich Fe-ore protolith evolved to high grade hematite ore in three stages i.e. hydrothermal activity and atleast two successive supergene events.According to Moriyama, et al. [41], the post-Archean average shale normalized REE patterns of IOG iron, ferro-manganese and manganese ores of Noamundi basin show HREE enrichment, negative Ce anomaly and positive Eu anomaly which are similar to modern ferro-manganese sediments near mid-oceanic ridges (Barrett & Jarvis [42]). In oxic sea water Ce is removed as CeO_2 or $Ce(OH)_4$ by oxidation reaction. Seawater has LREE depletion and negative Ce anomaly (Douville, et al. [43]). A positive Eu anomaly is a typical characteristic of modern manganese hydrothermal deposits in the ocean (Hodkinson, et al. [44]). Thus Moriyama, et al. [41] concluded that the sedimentary type ore body was deposited in presence of oxic oceanic water mixed with submarine hydrothermal components.

Detailed study in manganese mineralized areas by Ghosh, et al. [19] revealed two major facts.The manganese ore bodies are structurally (D_2/F_2) controlled. The Mn-mineralization took place in several phases i.e. syngenetic sedimentary/exhalative, D_1/M_1 stage (bixbyite, jacobsite, hausmannite and braunite), D_2/M_2 stage (hollandite, psilomelane and pyrolusite) and supergene stages (pyrolusite, cryptomelane, polianite, groutite, goethite). They also stated that the phyllitic host rocks were initially some alumina rich and silica poor tuffaceous material rather than some original argillaceous sedimentary rock.The presence of stromatolites, the concentrations of Eu & Ce in the rocks and presence of dolomite & quartz arenite at the base of the IOG rocks in the Noamundi basin indicate oxygenated shallow platformal marine environment of deposition in the Noamundi basin.

The Fe and Mn –mineralization of the present area may be compared to the other deposits in the world viz. the Isua Complex of Greenland and the Warrawoona group of Western Australia because of their similarity of ageand association.The 3800 Ma old Isua Complex of the Greenland (with earliest evidence of life) contains Fe and Mn-ores along with BIF associated with greenstone sequence of schists, phyllites, tuffs and basic volcanics (Schidlowski [13],[14]; Mojzsis, et al.[45]; Hayes [46]; Nutman, et al.[47]).The 3500 Ga Warrawoona

Group of the Pilbara craton, W. Australia contains banded iron-manganese formation associated with volcaniclastic, clastic and chemical sediments (Groves, et al.[48]; Buick and Dunlop [49]).

Compositional banding of Mn-minerals and silicates shows the Mn-ores are stratiform and stratabound in character. Boudinization in these bands indicates late phase brittle deformation event. The earliest Mn minerals found as in the ore are bixbyite, jacobsite, hausmannite and braunite formed during D_1. These minerals are altered by later hydrothermal and supergene activity. The Na, Ca, Mg, K, Zr, Cr and Ti content in these minerals are originated from original Mn-protolith but the Cu, Ni, Zn and Co are derived from hydrothermal activity. The hydrothermal veins of hollandite, pyrolusite and psilomelane formed during D_2 contains significant amounts of Ba, Cu, Ni, Co and Zn which are derived from any external source. The supergene Mn-minerals are found in cavity filling and vein form. Their chemical characteristics of having all elements in variable amounts indicates supergene recycling of early minerals. The goethite veins found in Mn-ore have originated from ferruginous shale or Fe-ore horizons.The compositionally banded Fe-ore minerals and quartz indicates startiform and stratabound character of ores. Relicts of euhedral to subhedral martitized magnetite grains (provably generated during D_1/M_1) are the earliest mineral found in the ore. The rims of hematite over magnetite and the disoriented acicular hematite grains are generated during hydrothermal activity. Goethite, hematite and diaspore are found in supergene cavity filling and vein form.

If we consider the depositional and late depositional scenario before deformations, Fe-ore protolith along with BIF underlies ferruginous phyllite which again underlies Mn-ore protolith confined in manganiferous phyllite according to field and petrographic evidences. The Fe-ore does not contain significant amount of Mn -minerals. The Fe-minerals also contains very minor amount of Mn in structure. The Mn-ore also does not contain any primary Fe-minerals although some supergene goethite veins are present. But some D_1/M_1 minerals viz. bixbyite and jacobsite contain considerable amount of Fe. It indicates that the original protolith of Mn-ore had considerable amounts of Fe during deposition.

During deposition of Fe by photochemical or biological oxidation Mn is hardly precipitated. Anbar and Holland [50] by their experimental study of showed that photoxidation precipitation of Mn^{2+} is hindered by the presence of Fe^{2+}. According to Roy [24] Fe and Mn build up took place in early Archean ocean by hydrothermal leaching of rocks but Fe precipitated first as the solution crossed Fe^{2+}/Fe^{3+}chemocline first.

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