CHAPTER 4
MINERALOGICAL CHARACTERISTICS OF HOST ROCKS AND ORE MINERALS

4.1 PETROGRAPHY OF THE HOST ROCKS AROUND BALAGHAT MANGANESE DEPOSIT

The manganese belt of Bharweli extends almost straight along a general strike direction of N25°E-S25°W for about 2.8 km. The ore bed dips towards N65°W. The maximum thickness (about 20 m) is in the middle portion and minimum is about a meter in both extremities, giving average thickness of about 10 m. In the south extremity the ore body dips steeply (about 80°), but in the northern extremity dip is very flat (about 25°).

The petrographic description of the representative rock types in the area is given here. The megascopic study of each rock type is given first, followed by the microscopic observations, which include identification of the constituent minerals and textural features.

The following rock types are found in the study area:

a. Migmatite
b. Granite gneiss
c. Amphibolite
d. Gritty-conglomerate / Arkosic grit
e. Schistose quartzite
f. Feldspathic quartzite
g. Mn-ore with jasperoid quartzite and manganiferous quartzite (BMnF)
h. Sericite schist
i. Phyllites

4.1.1 Migmatite

The migmatite and granite gneisses are parts of the basement complex (Tirodi Gneiss) of the area. These rocks are exposed to the east and south of Bharweli, and continue westward along the Wainganga river valley of the Balaghat district (Fig. 4.1 a). It is light grey in colour, very fine to medium grained, consisting of microcline, plagioclase, quartz and biotite (Fig. 4.1 b). The biotite hornblende rich migmatite shows gneissose structure (Fig. 4.1 c). The texture is granoblastic in nature.

The rock is cut by thin pegmatite veins, obliquely across the gneissic foliation (Fig.4.1 d).
Fig. 4.1 a-d: Field photographs showing migmatite and granite gneiss having massive, fine grained character, gneissosity and pegmatite vein.

4.1.2 Granite Gneiss

Granites gneisses are also parts of the basement complex (Tirodi Gneiss) of this area. The exposure of the granite rocks in the study area is less. Either they are covered by alluvium or by dense reserve forest. Recently in borehole no 75 drilled at Balaghat mine granite gneiss was encountered. The rock is medium to coarse grained, compact, with large grains of orthoclase feldspar, plagioclase and smoky quartz (Fig.4.2). Very coarse grained granite gneisses are well exposed near Gaikhuri village, south of Balaghat, and are composed of orthoclase, biotite and quartz (Fig.4.3 a, b).
4.1.3 Amphibolite

Amphibolites are well developed near Barbaspur village to the west of Balaghat Town. The rock is very fine grained, hard and compact (Fig 4.3 a). It is dominantly composed of quartz, tremolite-actinolite, and porphyroblasts of garnets. At some places quartz veins intrude the amphibolites (Fig. 4.4 b). Thickness of the quartz veins show considerable variation (Figs. 4.4 c, d).
4.1.4 Meta-conglomerate / Arkosic Grit

The conglomerate of Balaghat area comprises clasts of granitic gneiss, gneiss, corundum schist, granite, quartzite, cherty quartzite, chert, vein quartz, muscovite and orthoclase feldspar (Figs.4.5 a, b). The clasts are sub-rounded with matrix of medium to coarse grained, arkose and sericite schist (Fig.4.5 c). It is gritty in appearance and is friable, composed of light and dark colored ellipsoidal pebbles of large size embedded in a gritty matrix (Fig. 4.5 d). The grain size ranges from 0.5 cm to one meter. Some grains are rectangular in shape indicating short transport (Fig.4.5 e). In some areas clasts of corundum schist are observed (Fig.4.5 f). Some ellipsoidal quartzite fragments are fractured in a particular direction (Fig.4.5 g). Large rounded to sub-angular clasts of muscovite, K feldspar, chert, and granite (Fig. 4.5 h), are also present. Pegmatite (Fig. 4.5 i) and quartz veins intrude the conglomerate, and are also folded (Fig. 4.5 j).
Figs. 4.5 a-f: Field photographs of gritty conglomerate showing clasts of granite, gneiss, chert, corundum schist, vein quartz, quartzite, cherty quartzite, orthoclase and muscovite.
Figs. 4.5 g-h: Field photographs of gritty conglomerate showing clasts of granite, gneiss, chert, corundum schist, vein quartz, quartzite, cherty quartzite, orthoclase and muscovite.

Figs. 4.5: Field photographs of gritty conglomerate intrude by (i) pegmatite vein (j) quartz vein.

4.1.5 Schistose quartzite

Schistose quartzite is not exposed surficially in the Balaghat mine area, but found in some of the boreholes (Fig. 4.6 a). The contact between feldspathic quartzite and schistose quartzite can be easily identified in cores of various boreholes (Fig. 4.6 b). It is very fine grained, hard and compact in nature, with whitish grey to greenish grey colour. It is dominantly composed of quartz and sericite.
4.1.6 Feldspathic Quartzite

The feldspathic quartzite is milky white to light yellow with thinly bands of brown colour. It is medium to coarse grained, thinly banded, and mainly composed of feldspar and quartz (Fig. 4.7 a). The rock is very closely jointed, with two sets of joints (Fig. 4.7 b, c). The fractured character creates problem for mining activity. In some areas the rock shows dendritic structure of secondary manganese mineral, formed by leaching of primary mineral into the cracks and joints (Fig. 4.7 d).

Fig. 4.7: Field photographs of feldspathic quartzite showing (a) very thin banding, (b) two sets of joints.
Fig. 4.7: Photograph of feldspathic quartzite showing (c) fractures and (d) dendritic structures of secondary manganese minerals.

4.1.7 Manganese Ore

Manganese ore of Balaghat deposit is associated with jasperoid quartzite and manganiferous quartzite, combinedly known as Banded Manganese Formation (BMnF) (Fig 4.8 a). The jasperoid quartzite in hand specimen is brownish red in colour. It is very fine grained compact and hard (Fig 4.8 b). The manganiferous quartzites are massive, hard and compact, with black to brownish black colour (Fig 4.8 b). The main component of manganese ore of Balaghat mine is braunite, with minor amounts of hollandite (Fig 4.8 c), bixbyite, Hausmannite, manganite, pyrolusite, and psilomelane. Braunite is generally massive, compact, showing grayish black to black colour. Large variation in grain size of manganese ore minerals is observed, especially in braunite. The ore bands show fine laminations (Fig 4.8 d). In the North part of the deposit braunite showing vein replacement by pyrolusite(Figs 4.8 e-f) In some underground sections manganese ore nodule coated by silica are observed (Fig 4.8 g). In both extremities the manganese ore is of very low grade and has high silica content (Fig. 4.8 h).

Fig. 4.8 a-b: Photograph of BMnF showing alternate bands of jasperoid quartzite, manganiferous quartzite and manganese ore.
Fig. 4.8 c: Underground mine photograph of BMnF showing bands of jasperoid quartzite, manganiferous quartzite with braunite and hollandite.

Fig. 4.8 d: Underground mine photograph of showing grain size variation of braunite.

Fig. 4.8 e-f: Underground mine photomicrograph of braunite showing vein replacement by pyrolusite.

Fig. 4.8 g: Sample photograph showing manganese ore nodule coated by silica.

Fig. 4.8 h: Underground mine photograph of low grade manganese ore with quartz vein (chainage 700 at 10th level underground).

4.1.8 Sericite Schist

Sericite schists are extremely fine grained with shining grey colour, medium hardness, and compact nature (Fig. 4.9 a). These show development of schistosity (Fig. 4.9 b). Two set of joints are most prominent in sericite schists (Fig. 4.9 c). In some areas sericite schists are intruded by quartz vein (Fig. 4.9 d).
Fig. 4.9 a-d: Field photograph of sericite schist showing compact and fine grained nature, schistosity, two sets of joint and quartz vein.

4.1.9 Phyllite

The phyllites are fine grained and thinly banded (Fig.4.10 a) with silky lustre and coloured in shades of brown and yellow. These have well developed cleavage (Fig.4.10 b). Muscovite, chlorite, quartz, and garnet are the major constituents of phyllite. At some places phyllites show minor folds (Fig.4.10 c). Presence of schistosity and crenulation cleavage indicate at least two phases of deformations in phyllites (Fig.4.10 d).

Fig. 4.10 a-b: Field photographs of phyllite showing thin banding, schistosity, minor folds and crenulation cleavage.
4.2 PETROGRAPHY OF HOST ROCKS

Thin and polish sections of representative samples of manganese ores were studied under optical microscopy (both reflected and transmitted light orthoplan-microscope, Olympus CX31 make) to determine the properties of minerals and their textural relationships.

(a) Phyllite: The mineralogical composition of this rock is chlorite, feldspar, clay and some ferruginous matter. In some samples, rounded reddish brown coloured mineral is found. These minerals are weakly anisotropic in nature and are identified as spessartite garnet (Fig 4.11 a). Phyllites show well developed cleavage defined by preferred orientation of micaceous minerals, and folds on cleavage, indicating at least two deformations (Fig. 4.11 b). In some phyllites of this area, quartz showing neither recrystallization nor any directional orientation appears to be parallel to the bedding. Presence of mineral shapes resembling ‘glass shards’ indicates volcano-sedimentary origin of these rocks (Fig 4.11c). The rock suggests a greenschist facies of metamorphism.

Fig. 4.11: Photomicrograph of phyllite showing (a) spessartine garnet with snow ball texture, (b) micro-folding of cleavage (crossed nicols).
(b) Sericite Schist: Sericite schist shows brownish colour under microscope. Some euhedral opaque grains are also present parallel to foliation planes in sericite schist. The foliations are curviplanar in geometry (Fig.4.11 d). The minerals present are quartz, garnet, chlorite, actinolite, tremolite with ferruginous ground mass. Actinolite and tremolite show high birefringence in sericite schist (Fig.4.11e).

![Photomicrograph of phyllite showing (c) shapes similar to ‘glass shards’ (crossed nicols), (d) Photomicrograph of sericite schist showing euhedral opaque grains, parallel to foliation planes (crossed nicols).](image)

Fig. 4.11: Photomicrograph of phyllite showing (c) shapes similar to ‘glass shards’ (crossed nicols), (d) Photomicrograph of sericite schist showing euhedral opaque grains, parallel to foliation planes (crossed nicols).

(c) Feldspathic Quartzite: The feldspathic quartzite is very coarse grained characterized by quartz and abundance of plagioclase, orthoclase, and microcline. Calcite is also present. The feldspathic quartzite shows bluish gray colour under microscope (Fig. 4.11 f). Sericitic alteration is very prominent in some sections (Fig. 4.11 g.).

(d) Schistose quartzite: Its colour varies from light shades of gray to pink. The rock is very fine grained; composed of quartz, mica, and feldspar as major constituents (Fig. 4.11 h). Chlorite is found as an accessory mineral.

(e) Migmatite: Migmatite shows brownish colour under microscope in plane polarized light. It is composed of quartz, microcline plagioclase and tremolite. Microcline shows good cross hatched twining. The feldspar grains are altered and show slip across twin plane. Feldspars are mostly altered to chlorite and sericite (Fig. 4.12 a).

(f) Granite gneiss: The granite shows medium to coarse grained character with large grains of orthoclase, plagioclase, biotite and quartz. Plagioclase shows very good polysynthetic twining (Fig. 4.12 b).
Fig. 4.11 e: Photomicrograph of sericite schist showing rhomb-shaped opaque grains deformed along foliation planes, surrounded by tremolite, actinolite (crossed nicols).

Fig. 4.11 f: Photomicrograph of feldspathic quartzite showing large grains of calcite, microcline and plagioclase feldspar (crossed nicols).

Fig. 4.11 g: Photomicrograph of feldspathic quartzite exhibiting alteration of feldspar to sericite (crossed nicols).

Fig. 4.11 h: Photomicrograph of quartz schist showing foliation defined by fine grains of mica (crossed nicols).

(g) Conglomerate: The conglomerate of Balaghat area comprises of clasts of granitic gneiss, gneiss, corundum schist, granite, (Fig. 4.12 c) quartzite, cherty quartzite, chert, vein quartz, muscovite and orthoclase feldspar. Presence of clasts of different shape, size and composition indicate sedimentary origin of this unit. Large muscovite clasts, relative freshness of K feldspar (Fig. 4.12 d) and sub angularity also support a sedimentary origin.
Fig. 4.12 a: Photomicrograph of migmatite showing deformed feldspar which is mostly altered to chlorite and sericite (crossed nicols).

Fig. 4.12 b: Photomicrograph of granite showing inequigranular texture of quartz, orthoclase, plagioclase, microcline and biotite (crossed nicols).

Fig. 4.12 c: Photomicrograph of conglomerate showing matrix mineralogy (crossed nicols).

Fig. 4.12 d: Photomicrograph of conglomerate showing strain free microcline (crossed nicols).

(h) **Amphibolite:** The rock is fine to medium grained showing light grey colour under microscope. The large inequant quartz grains show preferred orientation parallel to the foliation (Fig. 4.13 a). At some places tremolite is altered by chlorite (Fig. 4.13 b). Two sets of foliation, one folded and another parallel to the axial plane of the fold are visible under microscope. The rock is composed of quartz, tremolite, actinolite, and garnet porphyroblast. Some garnets are fractured (Fig. 4.13 c and d).
4.3 ORE MINERALOGY

Manganese ores exhibit varied micro-structural and textural features due to multistage deformation, recrystallization. The mineralogical and petrographic studies include identification of these minerals, their forms, nature of occurrence and their textural relationships. A range of techniques were applied to the mineralogical and chemical characterization using optical microscopy. These tools provide important physico-chemical properties of the main ore minerals.

The microscopic study of the polished sections of the manganese ores of the Bharweli area reveals the following mineral assemblages: Braunite, Hollandite, Bixbyite, Manganite, Hausmannite, Pyrolusite, and Psilomelane.

4.3.1 Braunite: The composition of Braunite is \(3(MnFe)\text{O}_3\ Mn\text{SiO}_3\) and the crystal system is tetragonal. It is usually fine grained, and the grain size increases with higher grade of metamorphism. Under Microscope it gives grayish white colour with a brownish tint and the
cleavage is absent. Under crossed nicols, it shows weak anisotropism. Twinning and internal reflection are absent. This mineral is the most abundant in all the ore bodies of Balaghat manganese deposit. The braunites show wide variation in grain size, from fine to very coarse grain (Fig. 4.14 a). Some samples show massive to banded character from core to periphery (Fig. 4.14 b). The bands show individual crystals of braunite with sugary texture. At places the bands show curved nature, micro-faults and carbonate skeletons. Fine laminations of braunite are seen under cross nicols. Braunite shows local alteration to pyrolusite (Fig. 4.14 c). Bands of fine grained braunite infilled by pyrolusite grains form the opaque bands within jasper matrix. The ore minerals exhibit fold patterns at some places.

Two generations of braunite have been detected in these deposits. The first generation braunite formed earlier in the paragenetic sequence. In the lower grades of metamorphism, it is deformed, elongated and dimensionally oriented parallel to the banding. Braunite is generally grey in colour. The second generation braunite is light grey in colour and is undeformed (Fig. 4.14 d).

4.3.2 Hollandite: The composition of hollandite is \( \text{Ba(MnFe)}_8\text{O}_{16} \) and the crystal system is tetragonal. The mineral was described for the first time from Indian deposits by Fermor (1909). Hollandite has been widely present in ore bodies metamorphosed to different grades, apparently derived from low temperature oxides. Under the microscope the mineral is white in colour with a yellowish tint and is strongly pleochroic from white to grayish white with the cleavage direction giving the brightest colour. Cleavage is well developed, and is parallel to (110). It is strongly anisotropic having shades of blue, gray and yellow. These grains occur in association with braunite, and show snow ball structure (Fig. 4.14a.).

4.3.3 Bixbyite: Bixbyite forms in isometric system with chemical composition of \( \text{(MnFe)}_2\text{O}_3 \). It is very fine grained and cannot be identified megascopically. Under microscope it is non-pleochroic. Reflectivity is slightly higher than Braunite. Cleavage is not distinct. Under cross nicols, it is completely isotropic with absence of internal reflection (Fig 4.14 c).
Fig. 4.14: Photomicrograph of manganese ore showing (a) coarse grained braunite of two generations and hollandite, (b) coarse banding in braunite resembling volcano-sedimentary layering (PPL), (c) massive braunite altered to pyrolusite, and (d) braunite of two generations exhibiting planar features affected by feeble metamorphism.

4.3.4 Hausmannite: Chemical composition is $\text{Mn}_3\text{O}_4$ and the crystal system is tetragonal. Hausmannite shows grey to grey white colour, with a distinct pleochroism. Broad twins are very prominent in hausmannite (Fig. 4.15 a) and deformation twins are present in some grains (Fig. 4.15 b). Red internal reflection with strong lamellar twinning in several directions is present in some minerals (Fig. 4.15 c). It is nearly euhedral. Frequent association with braunite and jasper forming Banded Manganese Jasper (BMnJ) is common. Folding is a very common characteristic of the mineral (Fig. 4.15 d).

4.3.5 Manganite: Chemical composition is $\text{MnO (OH)}$ and the crystal system is monoclinic. It is very fine grained. Under microscope it is greyish white, strongly pleochroic from light to dark grey, and occurs parallel to length of hausmannite crystal (Fig 4.15 b). Under crossed nicols, it is strongly anisotropic in shades of blue grey and violet grey showing straight
extinction. It forms prismatic as well as lamellar crystal aggregate, radiating from a common center. In some samples pyrolusite replaces manganite in fine laminations (Fig 4.16 b).

4.3.6 Pyrolusite: The composition of pyrolusite is MnO₂ having tetragonal crystal system. It is strongly anisotropic in nature with yellowish to brownish blue colour. In some samples pyrolusite replaces manganite (Fig. 4.16 a).

4.3.7 Psilomelane: Psilomelane is a name assigned to a group of manganese minerals having composition of ((Ba, H₂O)₂ Mn₅O₁₀). It shows bluish grey to greyish white colour and strong anisotropism. It shows deformation texture with pyrolusite and exhibits it’s alteration from pyrolusite. Psilomelane shows excellent botryoidal textures depicting concentric zoning patterns (Fig. 4.16 b).
Fig. 4.16: Photomicrograph of manganese ore exhibiting (a) pyrolusite replacing manganite in fine laminations (under PPL) and (b) deformation texture (under PPL), (c) veins of jasper and quartz as gangue minerals (under PPL) and (d) bands of jasper as gangue mineral (under PPL).

4.3.8 Gangue Minerals: Quartz and jasper are mainly associated with manganese minerals. Jasper and quartz are present in vein (Fig.4.16 c) as well as in banded form (Fig 4.16 d). Some amounts of hematite and pyrite are also observed.

4.3.9 Textures

The textures, which have been observed during the study of ore sections, are given below:
(1) Banded and lamination texture
(2) Granular texture
(3) Pinch-and-swell texture
(4) Snowball texture
(5) Replacement texture
(6) Rim texture
(7) Vein texture
4.3.9.1 Banded lamination texture: It can be seen megascopically in the polished section and is a predominating texture. Microscopically, the individual bands are comprised of braunite, hollandite and pyrolusite. It is somewhere extremely fine and occurs in single grains as well as in an aggregate of one of more mineral species. The banding is seen to be very wide in the thickness (Fig. 4.17 a).

4.3.9.2 Granular Texture: It is a part of banded texture, which is shown by all the ore minerals found in the form of fine anhedral to course euhedral grains of ore minerals. Braunite is most common showing granular texture with some times euhedral grains. Hollandite also shows granular texture at many places. Pyrolusite also shows granular texture but is not well developed (Fig. 4.17 b).

4.3.9.3 Pinch-and-swell texture: In some samples manganese minerals, especially braunite, show pinch-and-swell textures (Fig. 4.17 c).

4.3.9.4 Snowball texture: Snowball texture is observed in sample no BH 65 where the manganese mineral (i.e. hollandite) occurs along with the host rock. The formation of the mineral is syngenetic type and it is banded in nature. The first formed euhedral mineral is structurally so disturbed that the euhedral shape of the mineral is transformed to a rotated ball like structure (Fig. 4.17 d).

4.3.9.5 Replacement Texture: Various types of replacement observed are as follows:

a. Vein Replacement: Pyrolusite occurs as veins in braunite, transecting several grains of the latter. Veins wall are irregular, crenulated and do not match each other. These veins show swelling in some places, and veinlets project out laterally from the principal veins (Fig. 4.18 a).

b. Guided Penetration Texture: The braunite grains have been shattered by some movement. The fractures produced serve as planes of structural weakness and as channel ways for the replacement of mineral hollandite (Fig. 4.18 b).

c. Pseudomorphic Replacement: Pyrolusite replaces manganite preserving the shape of manganite to form pseudomorphic replacement texture (Fig. 4.15 b)
Fig. 4.17 a: Photomicrograph of BMnF showing banded lamination by braunite and jasper (under CPL).

Fig. 4.17 b: Photomicrograph showing granular texture by hollandite and braunite (under PPL).

Fig. 4.17 c: Photomicrograph of manganese ore showing pinch-and-swell texture (under CPL).

Fig. 4.17 d: Photomicrograph of hollandite showing snow ball texture (under CPL).

**4.3.9.6 Rim Texture:** At places psilomelane form a rim around braunite replacing it from periphery towards center. Rim texture of pyrolusite and braunite are also seen (Fig. 4.19 a).

**4.3.9.7 Vein Texture:** Pyrolusite forms irregular veins in the braunite matrix along the cracks and fillings and also across bedding planes. Some veins could be seen megascopically along and across the bedding planes in manganese ores (Fig. 4.19 b).
4.3.9.8 Sugary Texture: The bands of braunite when magnified show individual crystals with sugary texture (Fig 4.20 a).

4.3.9.9 Colloform Texture: Pyrolusite and psilomelane are the minerals, which show characteristic colloform texture of different types. The rhythmic banding is seen prominently in the pyrolusite and psilomelane forming veins at some places (Fig. 4.20 b).

Fig. 4.18 Photomicrograph of braunite showing (a) vein replacement by pyrolusite (under CPL) and (b) guided penetration texture (under PPL).

Fig. 4.19 a: Photomicrograph showing braunite/psilomelane rim around pyrolusite (under PPL).

Fig. 4.19 b: Photomicrograph showing veins of pyrolusite fills in braunite (under PPL).
Fig. 4.20 a: Photomicrograph of braunite exhibiting sugary texture leaving behind rhombs of calcite (under PPL).

Fig. 4.20 b: Photomicrograph of psilomelane showing colloform texture (under PPL).

4.4 SCANNING ELECTRON MICROSCOPY (SEM-EDS) STUDIES

Micro-morphological and mineralogical characterization studies were conducted using Scanning Electron Microscope (SEM) with attached EDS microanalyzer. SEM-EDS is one of the variants of X-ray fluorescence spectroscopy which relies on the investigation of a sample through interactions between electromagnetic radiation and matter. Its characterization capabilities are due in large part to the fundamental principle that, each element has a unique atomic structure to be identified uniquely from one another. The Scanning Electron Microscope takes images of the sample surface by scanning it with a high energy beam of electrons in a raster scan pattern. SEM-EDS provide a combination of scanning electron microscopy and fully integrated energy dispersive microanalysis (EDS). By scanning with an electron beam across a specimen, high resolution images are obtained. Compositional analysis of a material is obtained by monitoring secondary, Back Scattered Electrons (BSE) produced by the electron-specimen interaction and thus detailed images of elemental distribution is achieved for multiphase materials. The signals are detected through detectors and results were obtained in the form of EDS graphs.

SEM analysis was carried out using JEOL JSM 6490 machine in the Department Geology and Geophysics, IIT, Kharagpur. Some data of SEM studies have been obtained from Kabi (2011). For this smooth polished sections of five samples coated with carbon, for conductivity, were used.

Back scattered images (SEM images) with EDS of the samples are presented in Figs. 4.21 and 4.22. It can be seen from the EDS graph, that iron and silica are the chief gangue
elements, where as Al is very negligible (Fig. 4.21 b and c). From the EDS graphs and the corresponding Table 4.1 it is found that the manganese mineral is hollandite (Fig. 4.21 a). From EDS graph of sample (Fig. 4.22 b, and c) the composition of mineral is found to be braunite (Fig. 4.22 a) with high percent of manganese (i.e. 73.66 Wt %), here silica and iron percentage is also high 11.72 and 12.77 Wt% respectively Table 4.2.

Fig. 4.21 a: SEM Photomicrograph showing two different points of hollandite.
Fig. 4.21 b: Photograph showing EDS data of (b) point 1 in hollandite (c) point 2 in hollandite.
Table 4.1: EDS data of point 1 and 2 in hollandite.

<table>
<thead>
<tr>
<th>Oxide (In Wt%)</th>
<th>Point 1</th>
<th>Point 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na₂O</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MgO</td>
<td>0.65</td>
<td>-</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.83</td>
<td>-</td>
</tr>
<tr>
<td>SiO₂</td>
<td>11.72</td>
<td>38.08</td>
</tr>
<tr>
<td>SO₃</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>K₂O</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CaO</td>
<td>0.46</td>
<td>1.64</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MnO</td>
<td>73.66</td>
<td>59.52</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>12.77</td>
<td>0.86</td>
</tr>
<tr>
<td>ZnO</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SrO</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BaO</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>100.09</td>
<td>100.10</td>
</tr>
</tbody>
</table>

Fig. 4.22 a: SEM Photomicrograph showing two different points of braunite.

Fig. 4.22 b: Photograph showing EDS data of point 1 in braunite.
**4.5 PARAGENESIS OF MANGANESE ORE**

The mineral paragenetic sequence was determined based on the observation of textural relationships of different minerals (Table 4.3). The first generation braunite crystallized first from the manganiferous sediments with increase in metamorphic conditions. Later on it had undergone intense deformation, and formed elongate crystals having a preferred orientation. The bixbyite present as fracture filling in the first generation braunite, and also as euhedral to subhedral grains exhibiting some shattering effect must have crystallized after the first generation braunite. It is free from any deformation. The second generation braunite is seen replacing bixbyite along the grain boundaries and crystallographic directions. It must have crystallized after bixbyite with decreasing metamorphic conditions.
after the deformational forces ceased to act. Hollandite crystallized replacing first generation braunite, bixbyite and second generation braunite. Manganite was the next mineral to crystallize. It occupies the inter-granular spaces between the late braunite and also replaces it. So it must be younger to hollandite. Hausmannite is the next mineral to crystallize. Pyrolusite and psilomelane are the minerals to crystallize as secondary alteration product of earlier formed manganese minerals at ordinary temperature and pressure. These show colloform texture indicating simultaneous deposition but the pseudomorphic replacement of manganite by pyrolusite and later psilomelane forming a rim around suggest that pyrolusite must have started crystallizing earlier to psilomelane.

Table 4.3: Paragenesis of manganese ores in the study area

<table>
<thead>
<tr>
<th>Name of Mineral</th>
<th>Sedimentation</th>
<th>Metamorphic-I</th>
<th>Metamorphic-II</th>
<th>Supergene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Braunite</td>
<td>--------------</td>
<td>--------------</td>
<td>---------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Hausmannite</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Bixbyite</td>
<td>Banded Manganese Formation</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Hollandite</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Manganite</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Pyrolusite</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Psilomelane</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

* The metamorphism possibly took place during F$_1$ deformation at ~2100-1800 Ma (Mohanty, 2011).

** The metamorphism possibly took place during F$_2$ deformation at ~1600-1450 Ma (Mohanty, 2011).