

MINERAGRAPHIC STUDY OF THE MANGANESE ORES OF TIRODI, BALAGHAT DISTRICT, MADHYA PRADESH, INDIA

by SUPRIYA ROY, *Research Fellow, N.I.S.I., Department of Geological Sciences,
Jadavpur University, Calcutta-32*

(Communicated by S. Deb, F.N.I.)

(Received August 13, 1957; read January 5, 1958)

SUMMARY

In this paper the mineragraphy of the manganese ores of Tirodi (21° 41' 15" N.: 79° 43' 54" E.), Balaghat District, Madhya Pradesh, has been discussed. The following manganese minerals have been specifically identified in polished sections under reflected light:—Braunite, manganite, hollandite, jacobsite, hausmannite, sitaparite, pyrolusite, psilomelane and quenselite. The controversy regarding the mineralogy of the manganese minerals has been thoroughly discussed and their characters under reflected light have been given. Quenselite is rather a peculiar occurrence in this area and it is the first time that it is found in an ore body of gonditic type, the original source being Långban in Sweden where it occupies vugs and cavities in calcite-dolomite gangue. Interesting microstructures have been encountered in the ores and they have been described under the following headings:—(i) Crystallographic intergrowth, (ii) Mutual boundary relations, (iii) Colloform and replacement textures. While the already reported crystallographic intergrowths of jacobsite-hausmannite have been found in abundance, a new interesting type of crystallographic intergrowth between braunite and hausmannite has been recorded. The textural evolution of these metamorphic rocks has been determined and the following mineral assemblages have been correlated to the different types of textures:

- (i) Braunite-pyrolusite ores where pyrolusite is interstitial in massive braunite grains.
- (ii) Braunite-manganite-pyrolusite ore where excellent schistose texture has developed.
- (iii) Sitaparite-braunite-jacobsite-hollandite ore where a rude banding is observed.
- (iv) Jacobsite-braunite-hausmannite ore where vredenburgitic (jacobsite-hausmannite) are interstitial in braunites.

From textural evidences it has been concluded that braunite has a wide distribution in all the grades of metamorphism. Pyrolusite and manganite are low grade metamorphic minerals, hollandite bridging the gap with the high grade minerals like sitaparite, jacobsite, etc. Exsolution of hausmannite in jacobsite and braunite has been induced by higher pressure temperature condition. Quenselite appears to be of metasomatic origin. Second generation braunite has replaced all the primary metamorphic minerals and secondary pyrolusite and psilomelane has also invaded and replaced them abundantly. Pseudo-colloform texture has been given rise to by progressive alteration of jacobsite to psilomelane along the grain periphery. The mineral paragenesis, based on textural relationships and physico-chemical considerations, has been suggested in the paper.

INTRODUCTION

The manganese ore deposits of Madhya Pradesh (now acceded in part to Bombay) have aroused the interest of many for the last half a century. While these deposits easily claim the lion's share in the annual raising of manganese ore in India, the academic interest associated with them can never be underestimated. The ores are associated with different grades of metamorphic rocks—from the phyllites to the sillimanite gneisses—and present complicated structural problems. The mineralogy of these ores has been discussed in detail by Fermor (1909), who was the pioneering worker in India in the field of manganese ores. While Fermor's work was of classical importance, in as much as that several new manganese minerals like hollandite, sitaparite, vredenburgitic, etc., were discovered, it must also be

admitted that the tools for mineralogical investigations at that time were rather inadequate. After Fermor, mineralogical investigations on these manganese ores were carried out by Christie, Schneiderhöhn, Ramdohr, Orzel and Pavlovitch, Dunn and Mason. Among these the first five concentrated to establish the mineralogy of the ores by studies of polished sections under reflected light. Dunn, to some extent, dealt with the textural relationships and possible origin of the ores, and Mason concentrated on the X-ray investigations and phase equilibrium studies.

In spite of the valuable work done by the authors mentioned above, the data accumulated so far about these manganese ore deposits is rather scanty and much work remains to be done. In this paper the author will attempt to put forward the results of his investigations on the mineralogy, microstructure, textural relationships and mutual stability of the different manganese minerals which occur associated with gonditic rock (spessartite-quartz rock) in garnetiferous mica schist and sillimanite gneiss around Tirodi ($21^{\circ} 41' 15''$ N.: $79^{\circ} 43' 54''$ E.), Balaghat District, Madhya Pradesh. The ores were collected from South Tirodi and Tirodi East and West mines.

MINERALOGY OF THE ORES

Mineragraphic study of the polished sections of the manganese ores associated with the Gondites in Tirodi revealed the presence of the following minerals: Braunite, Hollandite, Manganite, Sitaparite, Jacobsite, Hausmannite, Psilomelane, Pyrolusite and Quenselite. The identifications were based on optical characters under polarized light, reflecting power in photometer ocular and action of standard etch reagents.

Braunite

Colour grey with a pinkish brown tint. Reflecting power 18.3 per cent in green light in air. Reflecting pleochroism faintly discernible in oil. Anisotropism weak. No twinning.

Etch Reactions

Positive — H_2O_2 —Very slow effervescence. No stain on surface.
 ——— — $\text{H}_2\text{O}_2 + \text{H}_2\text{SO}_4$ —Slightly darkens.
 ——— — SnCl_2 —Strong etching.
 Negative— HNO_3 , HCl , KCN , KOH , FeCl_3 , HgCl_2 , etc.

Braunite is almost universally present in all the specimens studied from this area. The braunites vary widely in grain size, from fine to very coarse grains constituting what Fermor termed as 'faceted ores'. The braunites occur in two generations. The first generation occurs in intergrowth with hausmannite and also intimately associated with the vredenburgite, sitaparite and other primary minerals of this suite. The second generation veins the earlier minerals like vreden-burgite, manganite, etc., and occur interstitially in them. They are abundantly replaced by psilomelane and pyrolusite.

Hollandite

Colour white with a yellowish tint. Reflecting pleochroism distinct with oil. Anisotropism strong in shades of grey and yellow. Reflecting power 28.2 per cent in green light in air. Cleavage well developed and is parallel to (110) assuming that hollandite belongs to the tetragonal symmetry. Fermor (1917) concluded that hollandite belongs to the pyramidal group of tetragonal system. The hollandite grains are often tabular and lath shaped. They occur in association with braunite,

vredenburgite, etc., and are abundantly replaced by psilomelane and pyrolusite (Pl. VI, fig. 4).

Etch Reactions

- Positive — $\text{H}_2\text{O}_2 + \text{H}_2\text{SO}_4$ —Distinctly positive, brings out cleavage.
 ——— — SnCl_2 (Sat.)—Develops cleavage particularly in sections perpendicular to *c*.
 Negative— HCl , HNO_3 , H_2O_2 , Aqua Regia, FeCl_3 , KCN , etc.

Manganite

This mineral can easily be distinguished from the other manganese minerals by its extremely strong pleochroism and anisotropism. It is strongly pleochroic from greyish white to brownish grey. Reflecting power varied from 16 per cent to 19.5 per cent in green light in air in different sections depending on the orientation of the grains. Anisotropism strong in parallel sections exhibiting lively colours—bluish grey, dark violet grey, yellowish grey, etc. Cleavage parallel to (010) and (110), often distinctly visible.

Etch Reactions

- Positive — HCl (Conc.)—Attacks the grain with development of etch cleavage.
 ——— — $\text{H}_2\text{O}_2 + \text{H}_2\text{SO}_4$ —Darkens very slightly.
 ——— — SnCl_2 (Dil.)—Darkens very slightly.
 ——— — SnCl_2 (Sat.)—Strongly etches and corrodes the grains.
 Negative— HNO_3 , H_2O_2 , KOH , KCN , FeCl_3 , etc.

Sitaparite

Fermor (1909) first described sitaparite from the manganese ores of Sitapar from the Central Provinces, India. He described it as a dark bronze grey mineral with metallic lustre, black streak, slight magnetism and good cleavage. He deduced the formula to be— $9\text{Mn}_2\text{O}_3 \cdot 4\text{Fe}_2\text{O}_3 \cdot \text{MnO}_2 \cdot 3\text{CaO}$.

Schneiderhöhn (1931) also described sitaparite from Postmasburg, S. Africa. Similar to that from India, these sitaparites also invariably contained some calcium.

Orcel and Pavlovitch (1931) and Dunn (1936) described sitaparite from India and the former are the only investigators who have compared sitaparite and bixbyite on the basis of optical criteria. They retained both these minerals as separate species.

Strunz (1943) retained both sitaparite and bixbyite as separate species though he admitted their close relationship. He distinguishes sitaparite from bixbyite by optical characters and presence of calcium and sodium in the former.

Mason (1942), however, showed by X-ray powder analysis that the structure of sitaparite and bixbyite agrees in all respects and hence he argued the abolition of the name sitaparite, since bixbyite has a clear priority. He summed up his attitude by stating '... the mineral name bixbyite may be defined precisely as including all specimens with manganese iron and oxygen as principal components and having the same crystal lattice as the original bixbyite from Utah'.

De Villiers (1943) suggested that those manganese iron sesquioxides containing less than 10 per cent Fe_2O_3 be designated as partridgeite, those containing 10–30 per cent Fe_2O_3 be called sitaparite and those with more than 30 per cent Fe_2O_3 be classed as bixbyite.

Mason (1944) put forward a phase diagram of Fe_2O_3 – Mn_2O_3 system and correlated it with different temperatures up to 1,000°C. He suggested that if the name sitaparite is to be retained, the division of manganese iron sesquioxides should be made into bixbyite and sitaparite: (i) Bixbyite with Fe_2O_3 content from 40 to

60 per cent having pneumatolytic or fumerolic origin and (ii) sitaparite with Fe_2O_3 content 0-30 per cent and having a metamorphic origin. Mason discards the name partridgeite as superfluous.

In view of the above classification of Mason (1944), the name sitaparite has been retained* for the manganese iron sesquioxides with some calcium, associated with the manganese ores of metamorphic origin in this area. The mineral, under reflected light, is non-pleochroic grey (with yellow tint) in colour with reflecting power about 21.2 per cent in green light in air. It is perfectly isotropic under crossed nicols. Sitaparite has often an idiomorphic habit showing mutual boundary relation with braunite.

Etch Reactions

- Positive — HNO_3 (Conc.)—Weak attack.
 — $\text{H}_2\text{O}_2 + \text{H}_2\text{SO}_4$ —Tarnishes the grains.
 — SnCl_2 —Weak attack tarnishes the grains.
 — HF —Develops texture.
 Negative— HCl , KCN , KOH , FeCl_3 , H_2O_2 , etc.

Vredenburgite

Fermor (1909) originally designated the name vredenburgite ($3\text{Mn}_3\text{O}_4 \cdot 2\text{Fe}_2\text{O}_3$) to a strongly magnetic mineral, found in association with other manganese minerals in Madhya Pradesh and Vizagapatam District, India. After that, up to 1928, vredenburgite was considered to be a new mineral until W. A. K. Christie first examined it in polished sections under reflected light. His study revealed, for the first time, that it contained two different minerals, one oriented in the octahedral direction of the other.

Ramdohr and Schneiderhöhn (1931) determined the two constituents of vredenburgite as hausmannite and jacobsite, the former oriented in the octahedral directions of the latter.

Orcel and Pavlovitch (1931), on the other hand, detected weak anisotropism in the host mineral of the intergrowth in vredenburgite and called them the α -constituent. They also differentiated jacobsite from the α -constituent by each reaction with HCl , which attacked the latter and was negative to the former. As regards the oriented lamellae in the vredenburgite Orcel and Pavlovitch called them β -constituent and not hausmannite.

Dunn (1936) described vredenburgite as an intergrowth of jacobsite and hausmannite.

Deb (1943) first showed by optical, X-ray and magnetic study that in vredenburgite the host mineral is jacobsite (identical with the original jacobsite from Jakobsburg) and the oriented lamellae are constituted of hausmannites.

Fermor (1938), while accepting essentially the intergrowth of jacobsite and hausmannite in vredenburgite, put forward another name 'Devadite' for the iron rich member of the series. According to him, the excess oxygen found by Iyer (cited by Fermor, 1938) over the simple $(\text{Fe}, \text{Mn})_3\text{O}_4$ formula shown by Indian vredenburgites suggests that the original material was not a spinellid and that on unmixing it broke down not to jacobsite and hausmannite alone but also gave rise to some free MnO_2 in the form of pyrolusite or psilomelane.

Mason (1947) rejected Fermor's suggestions and stated that the MnO_2 in the form of pyrolusite or psilomelane, found in association with vredenburgite, is only a secondary replacement product replacing selectively the hausmannites only. He has also shown by phase study in the system of Fe_3O_4 - Mn_3O_4 - ZnMn_2O_4 - ZnFe_2O_4 that the variation of iron and manganese in vredenburgite is continuous and therefore

* Recently B. Mukherjee (*Proc. Ind. Sc. Cong.*, 1958, p. 227) differentiated sitaparite from bixbyite by cell size, the sitaparites having a larger cell size (9.40 Å) than that of bixbyite (9.37 Å).

there is no ground for dividing vredenburgite into different species on the basis of relative content of iron and manganese. Mason has also described homogeneous vredenburgite in a metastable state from Långban (Mason, 1943b) which he calls α -vredenburgite.

The present author has come across a number of vredenburgite grains associated with braunite and hollandite in the Tirodi ores. The crystallographic intergrowth is visible in almost all the sections excepting a few and such intergrowths exhibit a more or less consistent network pattern. The host mineral, in all cases, appeared to be isotropic under crossed nicols, the reflecting power is near that of braunite and the mineral with a grey colour bears a distinct olive tint. This mineral bears all resemblance with jacobsite. The oriented lamellae in jacobsite have a slightly higher reflecting power, a grey white colour with distinct pleochroism and strong anisotropism in shades of yellow to blue. The mineral is identical with hausmannite. The author, therefore, is in all agreement with Ramdohr and Schneiderhöhn (1931) and Deb (1943) that the two constituents of vredenburgite are jacobsite and hausmannite. No homogeneous vredenburgite (of the description of α -vredenburgite of Mason, 1943b) was recorded from these ores.

Jacobsite

Colour non-pleochroic grey with olive tint in the case of those with hausmannite lamellae; deep brownish yellow in those free of hausmannite lamellae. Reflecting power 19.4 per cent in green light in air. Perfectly isotropic under crossed nicols. Most of jacobsite grains contain oriented lamellae of hausmannite, though a few are entirely devoid of them.

Etch Reactions

Negative to all standard reagents excepting $H_2O_2 + H_2SO_4$ and $SnCl_2$ which after 5 minutes develop etch scratches.

Hausmannite

Colour grey to grey white with distinct pleochroism. Reflecting power 21 per cent in green light in air. The slightly higher value is probably due to the presence of psilomelane which replaces the hausmannite abundantly. Anisotropism strong in shades of yellow to blue. Hausmannite occurs both as oriented lamellae in jacobsite and as individual grains. The individual grains often show a well defined lamellar twinning.

Etch Reactions

Positive — $SnCl_2$ (Sat.)—Grains darken much rapidly than in jacobsite.
 ——— — $H_2O_2 + H_2SO_4$ —Develops etch scratches.
 Negative— HCl , HNO_3 , H_2SO_4 , KCN , $HgCl_2$, $FeCl_3$, etc.

Though it is now established beyond doubt that vredenburgite is not a separate mineral species, but only an intimate intergrowth of jacobsite and hausmannite, the present author retains the nomenclature in order to differentiate effectively the intergrown jacobsite-hausmannites from hausmannite-free jacobsites.

Psilomelane

Colour bluish grey to greyish white. Reflecting power 28 per cent in green light in air. Reflecting pleochroism very faintly noticeable—anisotropism strong in shades of grey.

Etch Reactions

Positive —HNO₃—Stains light brown.
 ——— —HCl—Stains brown to black.
 ——— —H₂O₂—Effervesces, surface unaffected.
 ——— —H₂O₂+H₂SO₄—Etches sooty black.
 ——— —SnCl₂ (Sat.)—Blackens immediately.
 Negative—Aqua Regia, KCN, KOH, HgCl₂, FeCl₃, etc.

Psilomelane occurs abundantly in these ores in the following ways:—

- (i) As a primary mineral occurring interstitially in braunite.
- (ii) As replacement product in braunite, vredenburchite, hausmannite, etc., where it replaces the primary minerals in a random fashion.
- (iii) Exhibiting colloform or pseudo-colloform texture.

Pyrolusite

Colour white with a distinct yellow tinge: in oil a distinct pleochroism from greyish white to pale yellowish white is noticed. Reflecting power 33·7 per cent in green light in air. Anisotropism strong in shades of grey yellow.

Etch Reactions

Positive —FeCl₃ in HCl—Darkens slightly.
 ——— —H₂O₂—Effervesces, surface unaffected.
 ——— —H₂O₂+H₂SO₄—Stains black but reaction more rapid.
 ——— —SnCl₂ (Sat.)—Turns black instantaneously.
 Negative—HCl, HNO₃, KCN, KOH, HgCl₂, etc.

The nomenclature of pyrolusite has been controversial for a long time and the names polianite and pyrolusite are often confused. Both these minerals having the same composition MnO₂, Schneiderhöhn and Ramdohr (1931) called the coarse grained variety of manganese peroxide polianite and restricted the term pyrolusite to the fine grained aggregates. Orsel and Pavlovitch (1931) on the other hand followed Lacroix in restricting the term pyrolusite to the pseudomorphs of MnO₂ after manganite and calling all individual grains of MnO₂ as polianite. Later work by Vaux (1937) and Strunz (1943) have shown that X-ray studies indicate similar structure for both these minerals and on this basis Uytendogaardt (1951) has discarded the name polianite and brought all varieties of MnO₂ minerals under the common heading of pyrolusite.

Pyrolusite occurs both as a primary and as a secondary mineral in this suite. It occurs interstitially in braunite without replacing them. The other generation, however, replaces practically all the minerals including psilomelane.

Quenselite

Strongly pleochroic from pale bluish grey (c) to dark grey (a). Isolated crystals (Pl. VIII, fig. 3) show a definite geometrical contour which, according to Orsel and Pavlovitch (1931), is due to intersection of the faces (001), (110) and (010) with the plane of the polished section. Anisotropism strong in shades of grey. Simple and lamellar twinning very common. Reflecting power measured in photometer ocular in green light in air came to 23·75 per cent (maximum) and 16·35 per cent (minimum) in different crystallographic directions.

Etch Reactions

- Positive —HNO₃—Effervesces, sometimes brings out cleavage.
 —HCl—Blackens.
 —FeCl₃—Effervesces, strong attack.
 —SnCl₂+HCl—Strong attack, blackens surface.
 —H₂O₂+H₂SO₄—Tarnishes differentially.
 Negative—H₂SO₄, KCN, HgCl₂, etc.

Quenselite was originally described from Långban, Sweden, and that is the only occurrence known until now. In Långban, the quenselite was associated with hausmannite and braunite in a calcite-dolomite gangue. But in the area under consideration it has been found in gonditic ores, occupying the interstices of manganoite and braunite. This is probably the first reported occurrence of quenselite in manganese ores of metamorphic origin.

MICROSTRUCTURE OF THE MANGANESE MINERALS

The manganese minerals of this area exhibit very interesting microstructures. The common microstructures noted may be classified as follows:—

- (i) Crystallographic intergrowths,
- (ii) Mutual boundary relations,
- (iii) Colloform and replacement textures.

(i) Crystallographic Intergrowth

Crystallographic intergrowth between jacobsonite and hausmannite has been detected in these ores. Such intergrowths of these two minerals was, as a whole, named vredenburgite by Fermor (1909). Detailed discussion as to the nomenclature of this mineral has already been given. In these intergrowths hausmannite lamellae are oriented in the (111) direction of jacobsonite giving rise to widmanstetten texture (Pl. V, figs. 1 and 2). The hausmannite needles are straight, devoid of 'carries', are confined within individual grains of jacobsonite and do not continue beyond the host. Three sets of such lamellae have been found. Schneiderhöhn and Ramdohr (1931) and Orcei and Pavlovitch (1931) first noted that these intergrowths are due to exsolution of the minor member in the solid solution in the crystallographic directions of the major constituent (i.e. jacobsonite) in descending temperature. Mason (1947) has also shown that such exsolution took place at a temperature of about 600°C. or lower.

Crystallographic intergrowth has also been detected between braunite and hausmannite where the lamellae and needles of the latter are oriented in the (111) direction of the former (Pl. V, fig. 3). Such intergrowths have evidently formed due to exsolution. To the best knowledge of the author, such exsolution intergrowth between these two minerals has not been described by any previous worker.

(ii) Mutual Boundary Relations

In these ores braunite and sitaparite exhibit mutual boundary relations (Pl. VI, fig. 1). The contact between these two minerals is perfectly smooth, the crystal outline of sitaparite is prominent and there is no evidence of any replacement relation between the two. Mutual boundary relation, particularly where the members are of same grain size, is suggestive of simultaneous crystallization, but it cannot be regarded as an unequivocal evidence (Edwards, 1954, p. 133). However, in the absence of any evidence contrary to this and the intimate association of these two minerals, a more or less same age relation is suggested for both.

In a few specimens, hollandite laths and needles have been found to be included in psilomelane (Pl. VII, fig. 2). The laths are oriented in a random direction. Scattered needles and star-like bodies of hollandite have also been included in psilomelane (Pl. VIII, fig. 5). In these cases, however, it seems that the latter psilomelane has enveloped the earlier formed hollandites.

(iii) Colloform and Replacement Textures

Colloform texture has been given rise to by psilomelane, deposited in the gangue material (Pl. VII, fig. 1) and by jacobsite and psilomelane, which are inter-banded (Pl. VI, fig. 2), while the first case is rather common, no reference has yet come to the author's notice as to the 'gel' formation of jacobsite, which is considered as a high grade metamorphic mineral. Such colloform texture may not, however, be always the result of formation from a gel, on the contrary a replacement origin may often be attributed (Grigor'ev, 1953).

Replacement relations have also been noticed in the following groups of minerals :

Vredenburgite-Braunite, Jacobsite-Braunite, Manganite-Braunite, Braunite-Psilomelane, Braunite-Pyrolusite, Manganite-Pyrolusite, Vredenburgite-Psilomelane, Vredenburgite-Pyrolusite, Hollandite-Psilomelane, Psilomelane-Pyrolusite.

Vredenburgite has been invaded by the second generation of braunite and replaced along the grain boundaries and cleavage planes. Jacobsite, free from hausmannite, has also been similarly replaced by braunite. Manganite crystals have been veined and embayed by second generation braunite (Pl. VIII, fig. 2) and this braunite also occurs interstitially in idioblastic manganite grains (Pl. VI, fig. 3). Braunite is replaced by both psilomelane and pyrolusite (secondary) along the grain boundaries (Pl. VIII, fig. 4) and in an irregular fashion. Primary pyrolusite and psilomelane also occur interstitially in braunite. Manganite has been replaced by pyrolusite along cleavage planes. Vredenburgite is preferentially replaced by psilomelane, when the latter attacks mainly the hausmannite lamellae. Pyrolusite also invades the vredenburgites (Pl. V, fig. 2). Replacement of hollandite by psilomelane and alteration of the latter to pyrolusite is also common.

TYPICAL MINERALOGICAL ASSEMBLAGES

In the manganese ores of this area the following characteristic assemblages of manganese oxide minerals were found:—

- (i) Braunite-Pyrolusite ore.
- (ii) Braunite-Manganite-Pyrolusite-Quenselite ore.
- (iii) Sitaparite-Braunite-Jacobsite-Hollandite ore.
- (iv) Jacobsite-Braunite-Hausmannite ore.

The above assemblages merge gradually into one another with accompanying textural changes.

(i) Braunite-Pyrolusite Ore

This ore is characterized by braunite with interstitial pyrolusite. This interstitial pyrolusite is primary and should be differentiated from later secondary minerals which have replaced the braunite along grain boundaries due to which the idioblastic habit of the latter is often obliterated. The braunite grains vary widely in their dimensions from coarse to fine. The finer braunite grains show irregular angular outlines and seem to be a granulated product of the bigger grains. Mechanical granulation is suspected since the broken grains do not show simultaneous extinction.

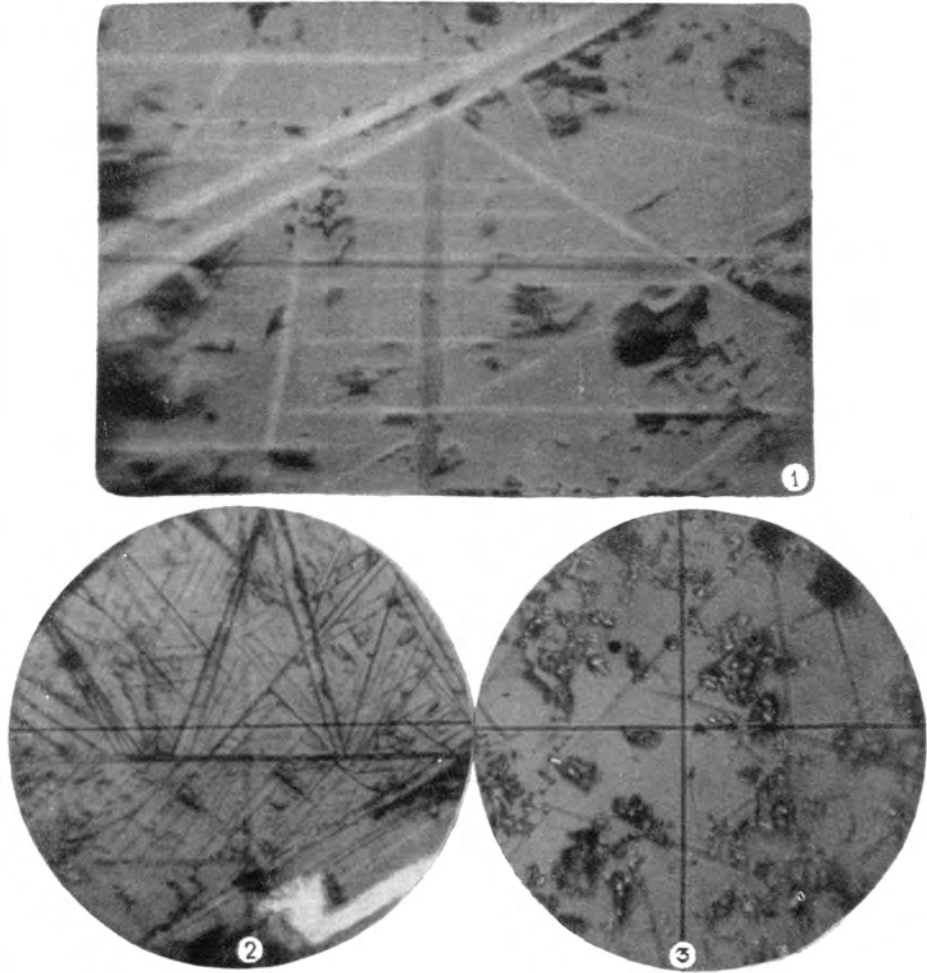


FIG. 1. Hausmannite lamellae (white) oriented in the (111) direction of jacobsite (grey) in vredenburgite. Oil immersion. $\times 800$.
 „ 2. Hausmannite lamellae (etched black) in jacobsite (unetched) in vredenburgite. At the bottom of the figure pyrolusite invades jacobsite. Oil immersion. $\times 600$.
 „ 3. Hausmannite lamellae (darker grey) oriented in the crystallographic directions of braunite (lighter grey). Oil immersion. $\times 600$.

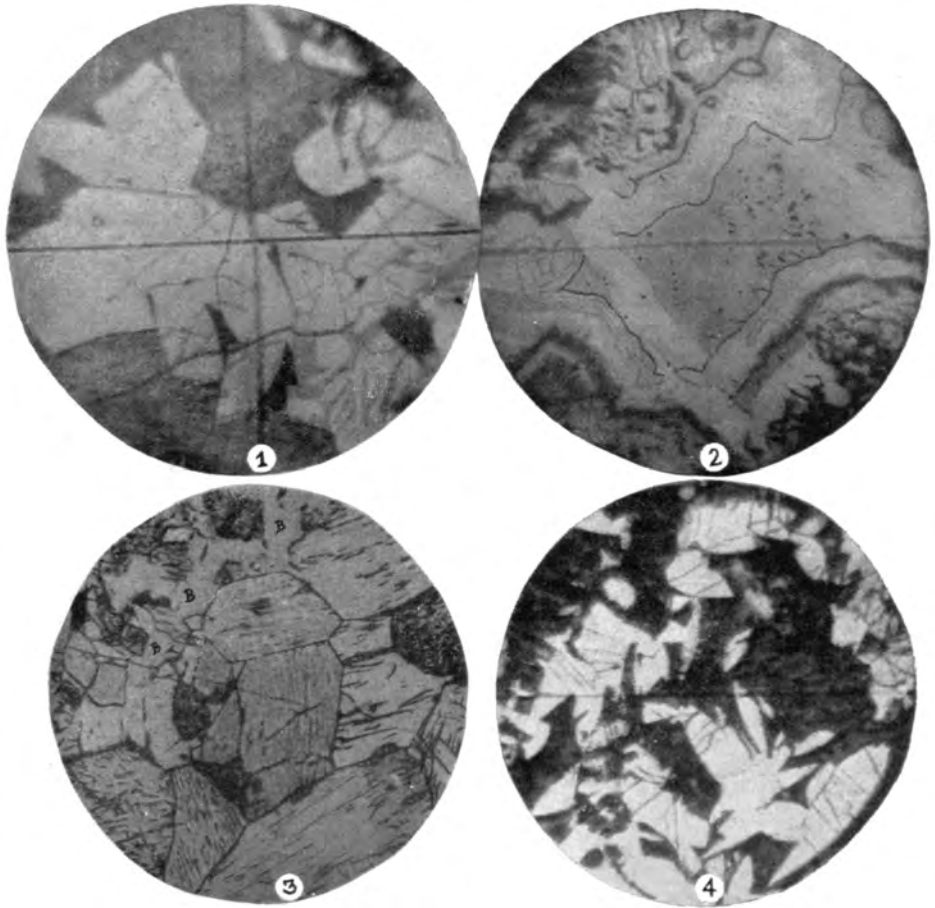


FIG. 1. Sitaparite (unetched idioblastic grains) exhibiting mutual boundary relations with braunite (etched). Oil immersion. $\times 500$.
 .. 2. Pseudo-colloform texture. Jacobsite is at the core and is subsequently rimmed by psilomelane. Later psilomelane has invaded all these minerals. Oil immersion. $\times 500$.
 .. 3. Idioblastic grains of manganite with interstitial braunite (B). $\times 250$.
 .. 4. Hollandite (white unetched) replaced by psilomelane (etched black). $\times 250$.

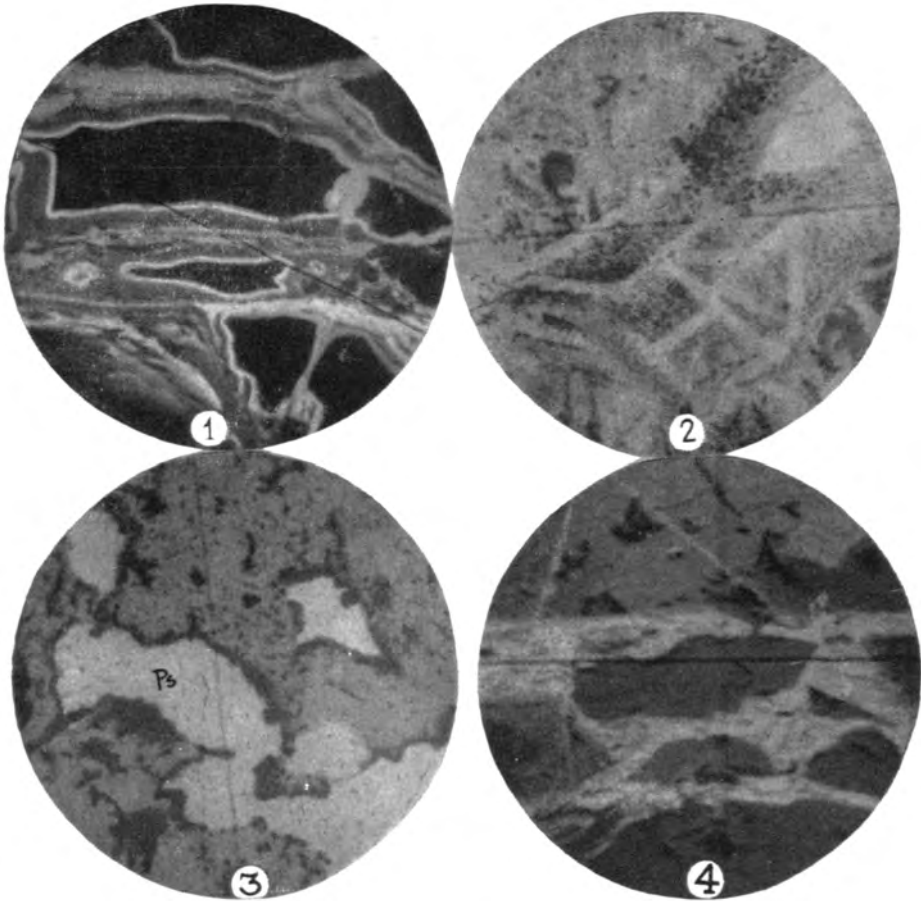


FIG. 1. Colloform texture exhibited by psilomelane (white) in gangue (black). $\times 180$.
 .. 2. Laths of hollandite enveloped by psilomelane (grey). $\times 350$.
 .. 3. Psilomelane (greyish white, Ps.) formed in vugs in braunite-manganite association. $\times 350$.
 .. 4. Psilomelane (white) replacing vredenburgite (grey) in an irregular fashion. $\times 180$.

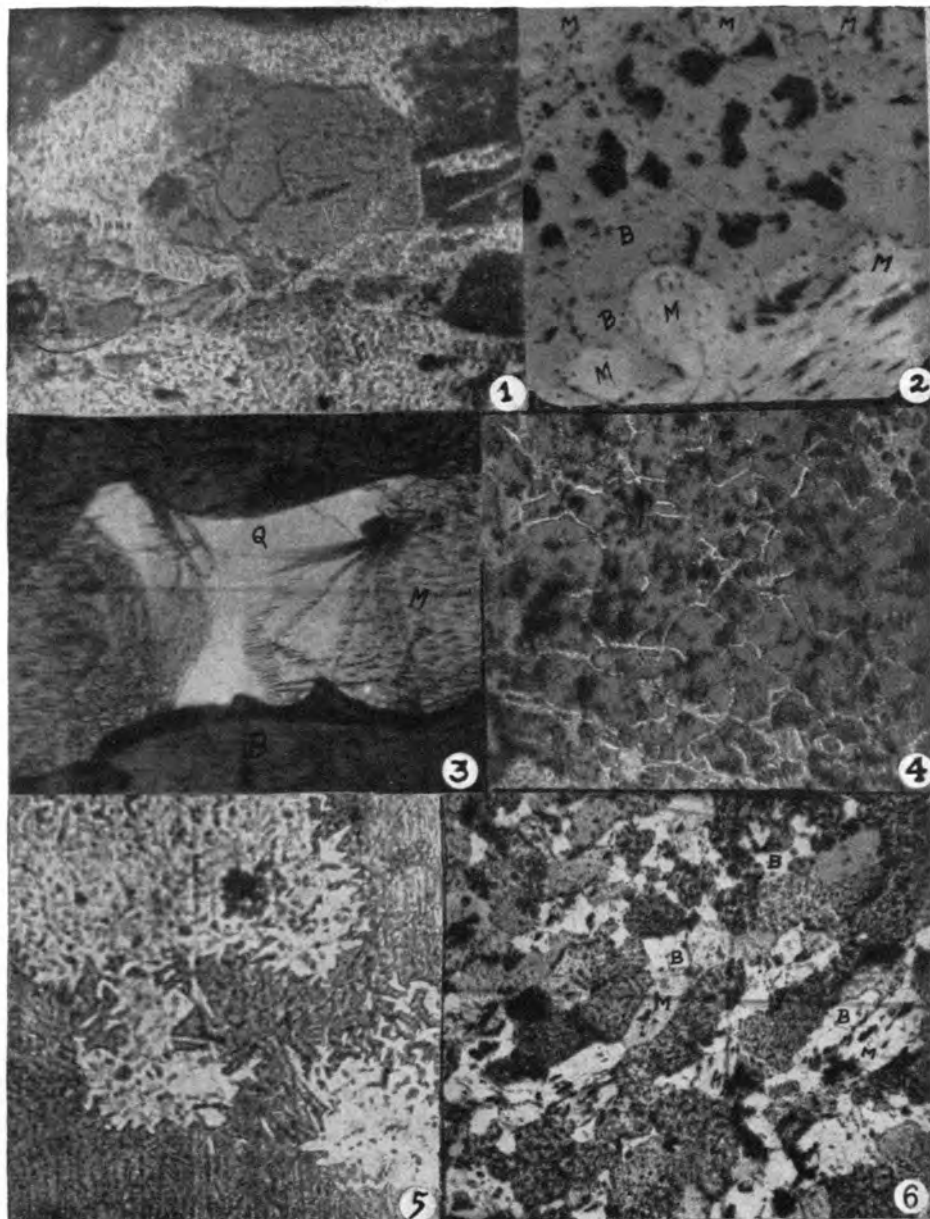


FIG. 1. Psilomelane (white) replacing jacobite (free from hausmannite lamellae—grey) in an irregular fashion. $\times 370$.
 „ 2. Braunite (B) vein replaces and embays manganite grains (white). $\times 185$.
 „ 3. Quenselite associated with manganite in a bakelite base. Quenselite—Q, Manganite—M, Bakelite base—B. $\times 370$.
 „ 4. Psilomelane (white) following the grain boundaries of braunite (grey). $\times 370$.
 „ 5. Hollandite (white) forming needles and starlike bodies in psilomelane (grey). $\times 370$.
 „ 6. Schistose texture exhibited by Tirodi manganese ore. The aligned minerals are braunite (B), manganite (M) and pyrolusite (etched black). $\times 70$.

(ii) *Braunite-Manganite-Pyrolusite-Quenselite Ore*

Braunite and manganite have been found to be intimately associated in some specimens. Braunites of two generations are found to be associated with the manganites. The first generation braunite is aligned with manganite and pyrolusite in a definite direction and exhibit typical schistose texture (Pl. VIII, fig. 6). The second generation braunite, on the other hand, veins, replaces and embays the earlier formed manganites (Pl. VIII, fig. 2) and also occurs interstitially in the idiomorphic grains of the latter (Pl. VI, fig. 3). Quenselite also occupies the interstices of manganite.

(iii) *Sitaparite-Braunite-Jacobsite-Hollandite Ore*

In these complex ores all the above-mentioned minerals are present though their relative percentage is variable. Sitaparite generally shows idiomorphic habit and exhibits mutual boundary relation with the braunites. The hollandite is found generally in tabular forms with one set of prominent cleavage. Subhedral to rounded grains of jacobsonite, free from hausmannite, are also found along with these ores. A rude banding is occasionally observed in these ores where braunite and sitaparite concentrate in one and hollandite and jacobsonite in the other. But for this rude banding the texture is intergranular.

(iv) *Jacobsite-Braunite-Hollandite Ore*

The jacobsonite-braunite-hausmannite ores are generally medium to coarse grained. Exsolution intergrowths of jacobsonite-hausmannite and braunite-hausmannite are prominent. Jacobsonite, free of hausmannite and independent hausmannite grains with rare polysynthetic twinning are also present. Second generation braunite invades vredenburghites and jacobsonite. Secondary psilomelane dominantly replaces all the minerals present. The texture is allotrioblastic granular where vredenburghites and jacobsonite have a tendency to occupy the interstices.

INTERPRETATION OF TEXTURES AND MICROSTRUCTURE AND PARAGENESIS OF ORE MINERALS

The textures and microstructure of the manganese ore minerals of Tirodi, described just now, provide sufficient clue towards the sequence of formation and to some extent the origin of the ore.

In the four typical mineral assemblages found, a gradual but perceptible variation in mineralogical constituents accompanied by textural changes, was noticed. The braunites enjoy a prolonged period of crystallization and are distributed widely in these metamorphic ores. About the interstitial pyrolusite in braunite, Schneiderhöhn (1931) suggested them to be pre-metamorphic from which the later braunite, etc., crystallized. But the textural relations in these ores indicate that braunite was definitely formed earlier and pyrolusite crystallized later in the limited interstitial space available. Manganite is a low temperature mineral formed in the braunite-manganite-pyrolusite assemblage exhibiting schistosity. The interstitial pyrolusite in braunite has evidently continued up to this stage when the schistosity developed. A second generation of braunite has invaded and embayed the manganites and also the jacobsonite, vredenburghite and other higher grade minerals. Such second generation braunite has been attributed to retrogression by Dunn (1936). Passing on to the next assemblage (sitaparite-braunite-jacobsonite-hollandite), a rudely banded texture is encountered where jacobsonite and hollandite form one band and braunite-sitaparite showing mutual boundary relations forming the other. The braunite-sitaparite band replaces the hollandite-jacobsonite band. Hollandite and jacobsonite (free from hausmannite lamellae) are considered metamorphic minerals

of this grade and sitaparite-braunite mutual boundary relations have probably been induced by recrystallization. In the next phase (jacobsite-hausmannite-braunite) widespread exsolution phenomenon is noticed and hausmannite needles and lamellae are oriented in the (111) direction of both braunite and jacobsite. It is evident that both jacobsite and braunite retained in solid solution some hausmannite molecules up to the limiting temperature-pressure condition. But with increase in pressure and temperature (about 600°C., Mason, 1947) unmixing occurred and hausmannite lamellae were exsolved in braunite and jacobsite host. The vredenborgite (jacobsite-hausmannite intergrowth) has a tendency to occupy the interstitial spaces in braunite.

Colloform and pseudo-colloform textures in these ores present a problem. While colloform texture, as the term indicates, essentially points out to a colloidal or 'gel' origin, progressive alteration of a hypogene mineral may also give rise to such a texture (cf. Grigor'ev, 1953). In the sitaparite-braunite-jacobsite-hollandite assemblage, few jacobsite grains take part in such pseudo-colloform texture, occupying the cores, the outer zones being progressively replaced by the psilomelane (Pl. VI, fig. 2). Colloform texture exhibited by psilomelane in gangue minerals (Pl. VII, fig. 1) may be due to colloidal deposition.

Thus, in drawing up the mineral paragenesis, we find that braunite crystallized first and continued up to the last stage. Pyrolusite and manganite were stable in lower pressure temperature condition and pyrolusite formed first in the interstices of braunite with manganite. Quenselite was possibly introduced into the interstices of manganite metasomatically. Hollandite belongs essentially to a medium grade of metamorphism and is stable with homogeneous jacobsite. Jacobsite and braunite contained hausmannite in solid solution, which unmixed in increasing pressure-temperature condition and occupied the crystallographic directions of the former. Some hausmannite segregated and formed individual grains. Thus hausmannite is later than both braunite and jacobsite. Sitaparite and the braunite formed after recrystallization do not show any relation with jacobsite or hausmannite except that the band in which the former occur has transgressed into that of the latter. The second generation of braunite, formed evidently by retrogression (cf. Dunn, 1936), invaded vredenborgite, jacobsite, manganite, etc., and is therefore later than all other primary minerals. Secondary pyrolusite and psilomelane, replacing the primary minerals, are placed separately. The paragenesis based on textural features and physico-chemical considerations is shown below:

TIME	→	
Braunite	—————	
Pyrolusite	—————	—————
Manganite	—————	—————
Hollandite	—————	—————
Jacobsite	—————	—————
Sitaparite	—————	—————
Hausmannite	—————	—————
Psilomelane	—————	—————
Quenselite	—————	—————
	Primary	Secondary

ACKNOWLEDGEMENTS

The author wishes to acknowledge gratefully the financial assistance afforded to him by the National Institute of Sciences of India for the scheme on 'Minera-

graphy of Manganese Ores of India' of which this work forms only a part. He is also indebted to Dr. S. Deb, under whose guidance the work was carried out. Thanks are also due to the Central Provinces Manganese Ore Company who have very kindly permitted the author to visit their mining areas and collect the specimens.

REFERENCES

- Deb, S. (1943). Optical, X-ray and magnetic studies of the mineralogical constituents of vredenburtite from different occurrences in India. *Quarterly Journal of Geol. Min. Meta. Soc. India*, **15**, 137-141.
- Dunn, J. A. (1936). A study of some microscopical aspects of Indian manganese ores. *Trans. Nat. Inst. Sc. Ind.*, **1**, No. 7.
- De Villiers, J. E. (1943). A discussion. Bixbyite—Sitaparite—Partridgeite. *Am. Mineralogist*, **28**, 468-469.
- Edwards, A. B. (1954). Texture of ore minerals and their significance. *Aus. Inst. Min. Meta. Mineralog. Obschtva*, **82**, 7-21.
- Fermor, L. L. (1909). The manganese ore deposits of India. *Memoir, G.S.I.*, **37**.
- (1917). On the crystallography and nomenclature of hollandite. *Record, G.S.I.*, **47**.
- (1938). Vredenburtite (with devadite) and sitaparite. *Proc. Nat. Inst. Sc. Ind.*, **4**, 253-288.
- Grigor'ev, D. P. (1953). Genesis of botryoidal and metacolloidal aggregates. *Zapiski Vsesoyuzn Mineralog. Obschtva*, **82**, 7-21.
- Mason, B. (1942). Bixbyite from Långban, the identity of bixbyite and sitaparite. *Geol. Foren. Forhandl.*, **64**, 117-125.
- (1943a). Mineralogical aspects of the system $\text{FeO-Fe}_2\text{O}_3\text{-MnO-Mn}_2\text{O}_3$. *Geol. Forhandl.*, **65**, 97-180.
- (1943b). Alpha-vredenburtite. *Geol. Foren. Forhandl.*, **65**, 263-270.
- (1944). The system $\text{Fe}_2\text{O}_3\text{-Mn}_2\text{O}_3$: some comments on the names bixbyite, sitaparite, partridgeite. *Am. Mineralogist*, **29**, 66-69.
- (1947). Mineralogical aspects of the system $\text{Fe}_3\text{O}_4\text{-Mn}_3\text{O}_4\text{-ZnMn}_2\text{O}_4\text{-ZnFe}_2\text{O}_4$. *Am. Mineralogist*, **32**, 426-441.
- Orcel, J., and Pavlovitch (1931). Les caractères microscopiques des oxydes de manganèse et des manganites naturels. *Bull. de la Soc. Franc. de Min.*, **54**, 108-179.
- Ramdohr, P., and Schneiderhöhn, H. (1931). Lehrbuch der Erzmikroskopie, B. II.
- Schneiderhöhn, H. (1931). Mineralbestand und Gefüge der Manganerze von Postmasburg, Griqualand-West, Sudafrica. *Neues Jahrbuch, B.B.*, **64**, A.
- Strunz, H. (1943). Beitrag zum Pyrolusitproblem. *Die Naturwissenschaften*, **31**, 89-92.
- Uytenbogaardt, W. (1951). Tables for Microscopic Identification of Ore Minerals. Princeton University Press.
- Vaux, G. (1937). X-ray studies on pyrolusite (including polianite) and psilomelane. *Mineral. Magazine*, **24**, 521-526.

Issued May 5, 1958.