

MINERALOGY AND TEXTURE OF THE MANGANESE ORES OF KODUR, SRIKAKULAM DISTRICT, ANDHRA PRADESH, INDIA

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ABSTRACT

The manganese ore bodies of Kodur group of mines, Srikakulam District, Andhra Pradesh, India, have been known for a long time for their commercial importance and academic interest. A detailed study of the mineralogy of the ores of this area, not systematically investigated to date, has been attempted, by study of polished sections aided by reflectivity measurement and etch reactions, and by x -ray powder analysis. Among the primary minerals identified, are braunite, jacobsonite, hausmannite and minor pyrolusite. Later invasion of colloidal gel produced a suite of low temperature minerals like cryptomelane, coronadite and γ - MnO_2 . Cryptomelane and pyrolusite are also present as supergene minerals derived from weathering and alteration of primary minerals. The textural relationships of the ore minerals have been described and the paragenesis has been drawn up.

INTRODUCTION

The group of manganese mines at and around Kodur, Srikakulam District, Andhra Pradesh, are among the oldest working deposits in India. They have yielded a considerable amount of good quality ore since 1892, and production continues even today. In his broad classification of the manganese ore deposits of India according to origin and age of parent rocks, Fermor (1909) recognized three different types:

1. The manganese ore deposits of metamorphic origin, found associated with the Gondite Series of Central Provinces (now Madhya Pradesh and Bombay) and Jhabua State in Central India (Madhya Bharat).

2. The manganese ore deposits associated with Kodurite Series (after Kodur) of Vizagapatnam and Ganjam Dt., Madras (now Vishakhapatnam and Srikakulam Dt., Andhra Pradesh) (Fig. 1, locality 9).

3. The lateritoid manganese deposits with Dharwar rocks in Singhbhum, Sandur, Mysore, etc.

The manganese ore deposits at and around Kodur are thus a distinct type according to Fermor, and the "mother" rock of these manganese ore deposits, is what he termed "kodurite." This kodurite, named after Kodur is composed of quartz, feldspar, manganese pyroxenes, spandite

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garnet (spessartite-andradite) and apatite. Fermor originally concluded that it was of igneous origin and constitutes a whole suite of magmatically differentiated rocks, the Kodurite Series. Fermor ascribed the origin of the manganese ores of this region to the alteration of these manganese-rich rocks.

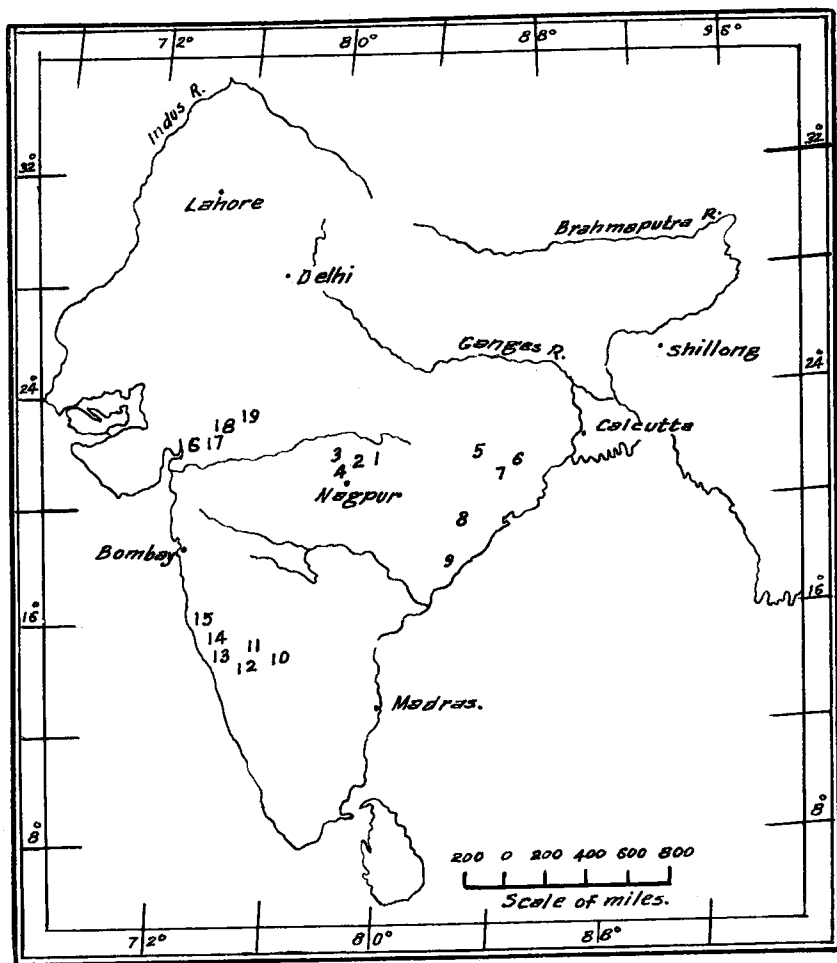


FIG. 1. Index of manganese ore localities in India (after J. A. Dunn, 1942). (1) Balaghat (2) Bhandara (3) Chhindwara (4) Nagpur (5) Gangpur (6) Singhbhum and Keonjhar (7) Bonai (8) North Koraput (9) Vizagapatam (10) Sandur State (11) Bellary (12) Shimoga (13) North Kanara (14) Dharwar and Ratnagiri (15) Goa (16) Narukot State (17) Chota Udaipur (18) Panch Mahal (19) Jhabua State.

The contention of Fermor as to the igneous nature of the kodurites was questioned by Cross (1914), who suggested a hybrid origin for them due to assimilation of manganiferous sediments by granitic intrusions. This controversy as to the nature of the kodurites also complicated the other issues vitally linked with this rock type, namely, the origin of the ores etc. The later workers in this area, Krishna Rao (1954, 1956), Raghava Rao & Srirama Rao (1955), Mahadevan & Krishna Rao (1956), and Straczek & Krishnaswamy (1956), agreed on the essentially hybrid

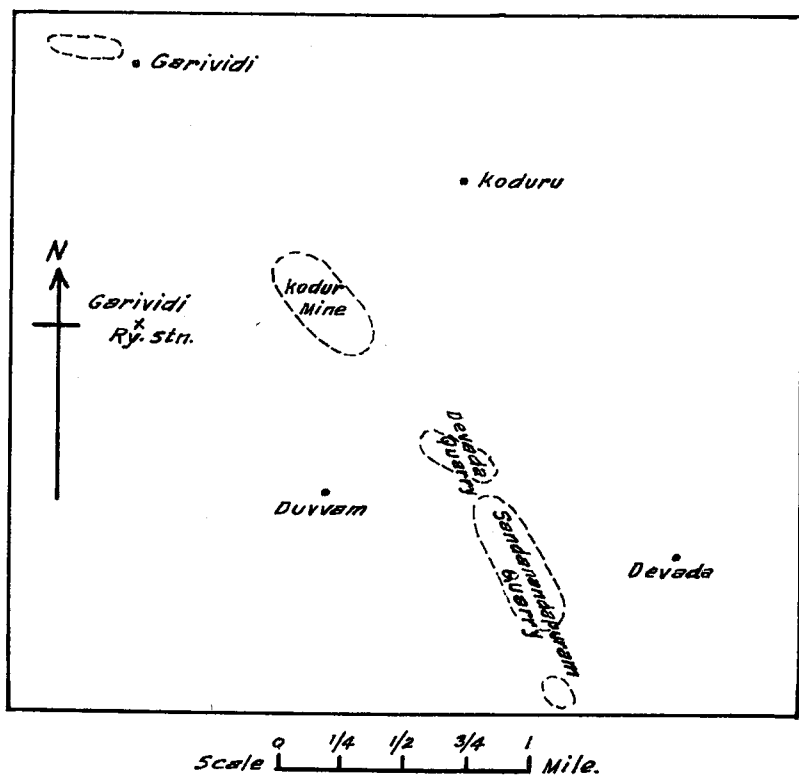


FIG. 2. Map showing locations of different ore bodies around Kodur, Srikulam district, Andhra Pradesh, India (after Fermor, 1909), locality 9 on Fig. 1.

nature of the kodurites. They also attributed the origin of the manganese ore bodies to the metamorphism of the originally bedded manganiferous sediments.

In spite of the academic and commercial interest involved in these ore deposits, no systematic study of the mineralogy and the textural relation-

ships of the ore minerals has been published up to date, save a few sporadic references in connection with the manganese minerals in general in broad based investigations (Ramdohr & Schneiderhöhn, 1931, Orsel & Pavlovitch, 1931, Dunn, 1936, Mason, 1943, etc.).

It will, therefore, be the endeavour of the author, to present in this paper a systematic study of the mineralogy, textural relationships and paragenesis of the ore minerals of this area.

GEOLOGICAL ENVIRONMENT AND MODE OF OCCURRENCE OF THE ORE BODIES

The general geology of the area has been described in detail by most of the previous workers (Fermor, 1909; Pravakara Rao, 1950; Krishna Rao, 1954; Straczek & Krishnaswamy, 1956; etc.) and only a brief and relevant reference will be made here.

The Kodur group of mines (Fig. 2) constitute the following major deposits at (i) Kodur, (ii) Garividi, (iii) Devada, (iv) Duvaam and (v) Sadanandapuram; all of these are concentrated within an area of nine square miles only. The manganese ore deposits are associated with metamorphosed sedimentary rocks of the Khondalite Series of Precambrian age. The members of the Khondalite Series are garnet and sillimanite bearing paragneisses and schists, garnetiferous quartzites and intercalated calc-silicate gneisses and marbles. As regards the kodurites, the identity of which has already been discussed, no fresh outcrop of such rock was found by the author or any other later worker (cf. Straczek & Krishnaswamy, 1956, p. 147, in the Kodur area), though Fermor (1909) described it from the Kodur mine. In highly weathered rocks in the mineralised zone, manganese garnet was however detected, which may be the remnant constituent of what was originally "kodurite." Rocks agreeing to the description of Fermor's typical kodurite, have been described by Krishna Rao (1954) from Vizayanapuram situated close to these deposits and by Straczek & Krishnaswamy (1956) who described a similar rock at the Devada mine which they called aplite.

The rocks associated with the manganese ore deposits have been invaded and transgressed by plutons of gneissic biotite granite and later pegmatites and quartz veins. These have assimilated the manganese ores at the contact to a limited degree and are also replaced by supergene manganese minerals.

According to Mahadevan & Krishna Rao (1956), p. 135), the manganese ores at Kodur are "part and parcel" of the Khondalitic suite of metamorphosed sedimentary rocks, the ore bands and lodes being conformable with members of the Khondalite Series. This feature is also

observed in adjacent localities (in Aitemvalasa, Avagudem, etc.), beyond the area under discussion in this paper. Straczek & Krishnaswamy (1956) also observed a primary layering of the ores parallel to the residual planar structure of the wall rock. The observations of the present author in the field fully corroborate this view, and in the Kodur group of mines, the primary manganese ore bands (mainly braunite-vredenburgite) are certainly conformable with respect to the enclosing rocks of the Khondalite Series. The primary layering of the ores was also conspicuous. The only unconformable relation between the ore and the wall rock was observed where the supergene ore migrated along the foliation and joint planes of the paragneiss and now presents an apparent discordant relation.

MINERALOGY OF THE ORES

The mineralogy of the manganese ores of the Kodur group of mines was studied from a suite of samples systematically collected by the author from the bedded deposits concordant with the wall rock as well as from the discordant supergene ore bodies. Sampling was done from the mines at Kodur, Garividi, Devada, Duvaam and Sadanandapuram. As already stated, no systematic account of the mineralogy of these ores has been published so far. This important aspect was mentioned briefly by Straczek & Krishnaswamy (1956), but their observations were based mostly on macroscopic characters of the ores, supported by x-ray identification in a few cases. Among the manganese oxide minerals they mentioned wad, cryptomelane, pyrolusite-type oxides, jacobsite, braunite and hausmannite. According to them, braunite is always primary, jacobsite is both primary and supergene and the manganese dioxide minerals are all supergene. Though they mention hausmannite as a member in the intergrowth in vredenburgite following Fermor's description, they did not come across any vredenburgite in the field.

The present study revealed the presence of the following minerals: braunite, jacobsite, hausmannite (and the mixed mineral vredenburgite), pyrolusite, cryptomelane, coronadite and γ - MnO_2 .

Since the optical characters of all these minerals under reflected light have been discussed by a number of workers including the present author (1957), repetition is hardly necessary. It will only be prudent, however, to mention any special character noted in any of the minerals during the investigation.

The braunites are among the most abundant minerals constituting the ore. They are primary in origin and are present as subhedral to euhedral crystals. They are fairly homogeneous without any intergrowth, but are replaced abundantly by secondary minerals. The jacobsites, which

are present both as individual free grains and also in intergrowth with hausmannite (constituting vredenburgite) are mineralogically the most interesting in this suite. The colour in polished section, reflecting power and etch characters of the mineral, vary with cell dimension, as tabulated below:—

TABLE 1

Mode of occurrence of jacobsite	Cell Dimension	Characters under reflected light
1. Jacobsite individual crystals free of hausmannite.	$a = 8.506\text{\AA}$	Colour non-pleochroic brownish grey. Isotropic. Reflecting power 19.3% in green light in air. Negative to all standard reagents.
2. Jacobsite in inter-growth with hausmannite.	$a = 8.483\text{\AA}$	Colour olive grey. Isotropic. Reflecting power 19.55% in green light in air. Negative to all standard reagents. (This agrees with the description of normal jacobsite; cf. Ramdohr, 1955.)
3. Jacobsite in inter-growth with hausmannite.	$a = 8.410\text{\AA}$	Colour rose brown. Isotropic. Reflecting power 20.01% in green light in air. HCl, after $1\frac{1}{2}$ m. etches the mineral brown and the solution turns greenish yellow HF etches the mineral black, and corrodes the specimen. The attack is instantaneous and much quicker than on hausmannite. This mineral, while yielding characteristic "d" spacings of jacobsite is very similar to magnetite in all other characters.

According to Mason (1943, p. 146), the cell size of jacobsite increases with increasing manganese in the structure, the manganese atoms being larger in dimension than the corresponding Fe atoms. In the case of the Kodur jacobsite we find that the cell size of the third type of jacobsite (Table 1) is the smallest ($a = 8.410\text{\AA}$), indicating a composition lying near the border of magnetite-jacobsite transition (Mason, 1943, p. 146), while the composition of the second type tends more to the jacobsite field and the first type may contain some manganese in excess of the ideal composition. Thus it is probable that there is slight overlapping in the optical characters and etch reactions in the transition stage between magnetite and jacobsite, and jacobsite with the smallest cell size exhibits the characters of magnetite.

Hausmannite is found in this suite only as exsolution lamellae in jacobsite (constituting vredenburgite) and is essentially a primary mineral. The slightly pleochroic (yellowish white to greyish white) grains of pyrolusite are quite common in these ores. Their high reflectance, coupled with very strong anisotropism, assists easy identification. They

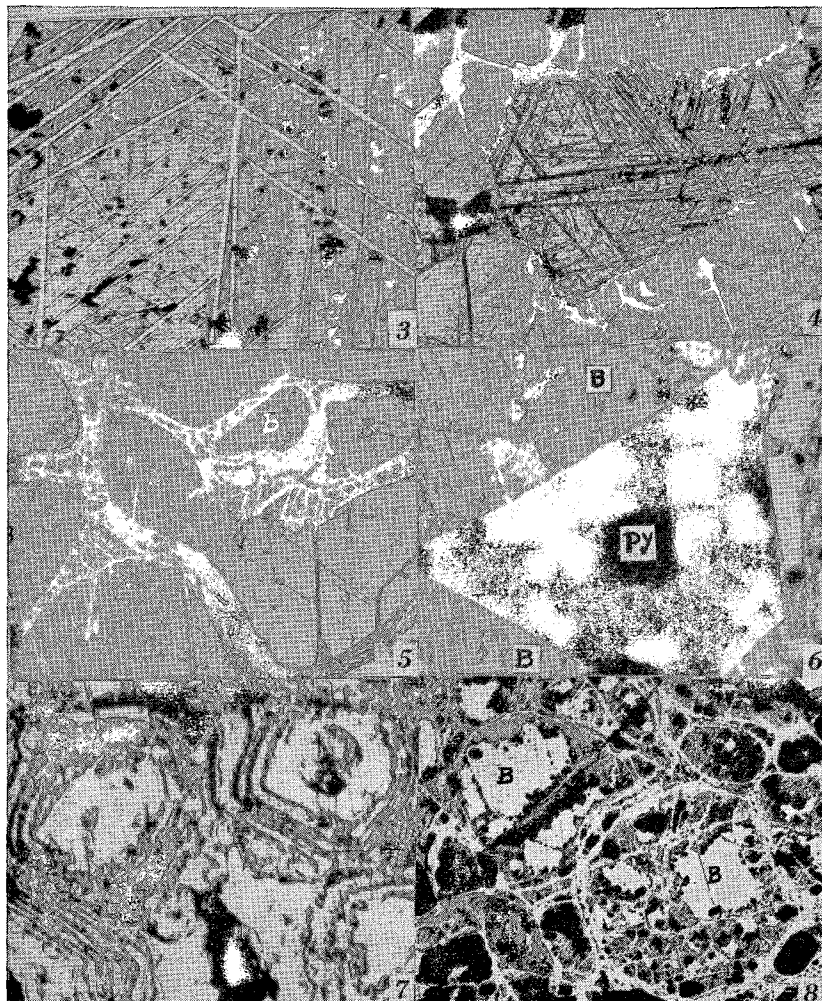


FIG. 3. Widmanstätten intergrowth of jacobsonite (host, grey) and hausmannite (white lamellae) constituting vredenburgite. $\times 155$

FIG. 4. Interstitial nature of vredenburgite (etched with SnCl_2 , sat.) in braunite (B). $\times 40$.

FIG. 5. Vredenburgite forming network in braunite (B) following interstitial spaces. $\times 30$.

FIG. 6. Euhedral grain of pyrolusite (etched black by $\text{H}_2\text{O}_2 + \text{H}_2\text{SO}_4$) interstitial in braunite (B). $\times 75$.

FIG. 7. Colloform texture of $\gamma\text{-MnO}_2$. $\times 75$.

FIG. 8. Braunite (B) replaced irregularly by secondary pyrolusite and cryptomelane (etched partially). $\times 75$.

are present either as interstitial euhedral to subhedral grains in braunite (Fig. 6), as rims around vredenburgite (Fig. 12), or as secondary minerals replacing abundantly the primary members of the suite. Cryptomelane, another common mineral, is present either as colloform aggregates with coronadite or as secondary alteration product of other primary minerals. Quite often spectrographic analysis yields a considerable amount of barium, though psilomelane could not be identified with certainty by *x*-ray powder analysis. Coronadite, a Pb-bearing analogue of hollandite and cryptomelane, has been identified exhibiting colloform texture in the interstices of vredenburgite and braunite. It is also present associated with supergene cryptomelane and pyrolusite. Another mineral, provisionally identified as γ - MnO_2 by *x*-ray powder analysis, also exhibits colloform texture and is associated with coronadite and cryptomelane.

TEXTURAL RELATIONSHIPS OF THE ORE MINERALS AND THEIR INTERPRETATION

In the course of the study of polished sections of manganese ores of the Kodur group of mines, numerous interesting textural features and microstructures were encountered. As already stated jacobsite and braunite were always found to be primary. Braunite, in subhedral to euhedral grains, evidently crystallised slightly earlier than the jacobsite, whose interstices the latter has occupied (Figs. 4 & 5). In this process jacobsite (in vredenburgite), sometimes forms a network in braunite (Fig. 5). The individual grains of hausmannite-free jacobsite occur as isolated well developed crystals, sometimes with pyrolusite. These individual grains of jacobsite have a large cell dimension ($a = 8.506\text{\AA}$ —Table 1),² which indicates the presence of manganese in slight excess of that required by the ideal composition (Mason, 1943). Since this excess manganese has not exsolved, it is evident that the proper temperature for exsolution of hausmannite was never attained. These individual grains of jacobsite are pseudomorphous after manganese garnet, various stages from initial to complete replacement along grain boundaries having been noticed. Pyrolusite has been traced as interstitial euhedral grains in braunite (Fig. 6) as rims around vredenburgite (Fig. 12) at the contact with braunite, and as secondary alteration product of braunite, vredenburgite and cryptomelane. After the crystallisation of the main primary ore body, some colloidal action is envisaged, as evidenced by typical colloform texture exhibited by cryptomelane, coronadite and γ - MnO_2 . The colloform minerals are always squeezed in the interstices of the primary

²Editor's note: Mason's (1943) higher value for jacobsite is $8.507\text{\AA}$; McAndrew (*Am. Mineral.*, **37**, 453, 1952) gives $8.505\text{\AA}$ for analysed, nearly pure jacobsite; National Bureau of Standards (Circular 539, **9**, 36) gives $8.499\text{\AA}$ for synthetic MnFe_2O_4 .

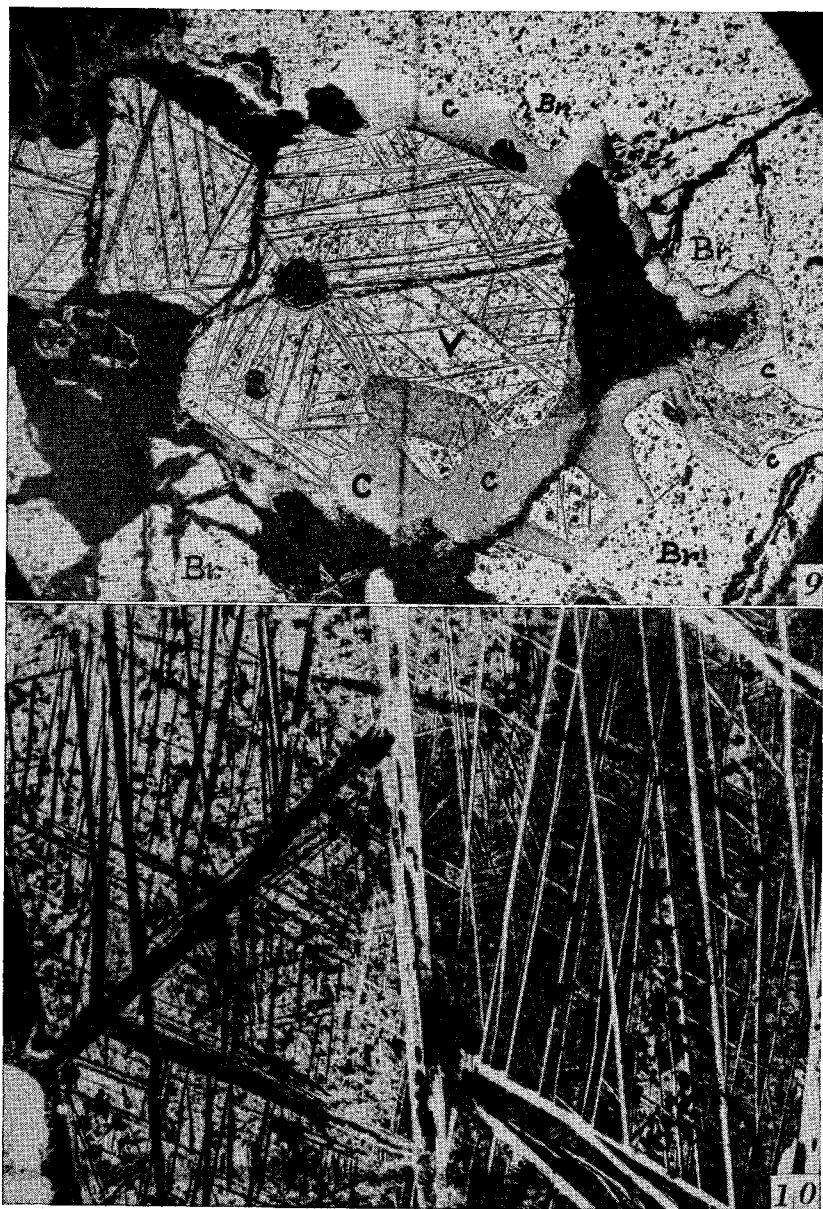


FIG. 9. Coronadite (C) exhibiting typical etch scratches and colloform texture (extreme right portion) occupying interstitial spaces between braunite and vredenburgite. $\times 95$.

FIG. 10. A single grain of vredenburgite etched by SnCl_2 (sat.) (left side) and HF (right side) in two portions. The portion etched by SnCl_2 (sat.) shows the jacobite unaffected but hausmannite lamellae are etched black. HF on the other hand, etches jacobite sooty black, but leaves hausmannite unetched when applied for short time. Etching by HF for a long time affects the hausmannite also. $\times 380$.

minerals, without intruding into them, and definitely represent a later period of deposition (Figs. 7, 9, 11 & 13). Supergene weathering, action of groundwater etc. affected the mineralogy and texture of these ores to a great extent. Supergene processes generally altered the primary minerals like jacobsite, hausmannite and braunite to pyrolusite and cryptomelane. Alteration is often irregular (Figs. 8 & 12) but sometimes show a definite pattern, e.g. in vredenburgites where the hausmannite is sometimes totally altered to pyrolusite, whereas jacobsite is not affected at all.

A paragenetic sequence can, thus, be drawn up for the manganese minerals of this suite based on the textural relationships exhibited by the different minerals. Among the primary minerals, as already stated, braunite precedes jacobsite in which again hausmannite exsolved with lowering pressure temperature condition. The present author found no evidence of the supergene nature of jacobsites suspected by Straczek & Krishnaswamy (1956, p. 149), but, in his opinion, the individual grains of hausmannite-free jacobsite suggest formation by hypogene replacement of manganese garnet at lower temperature. The association of

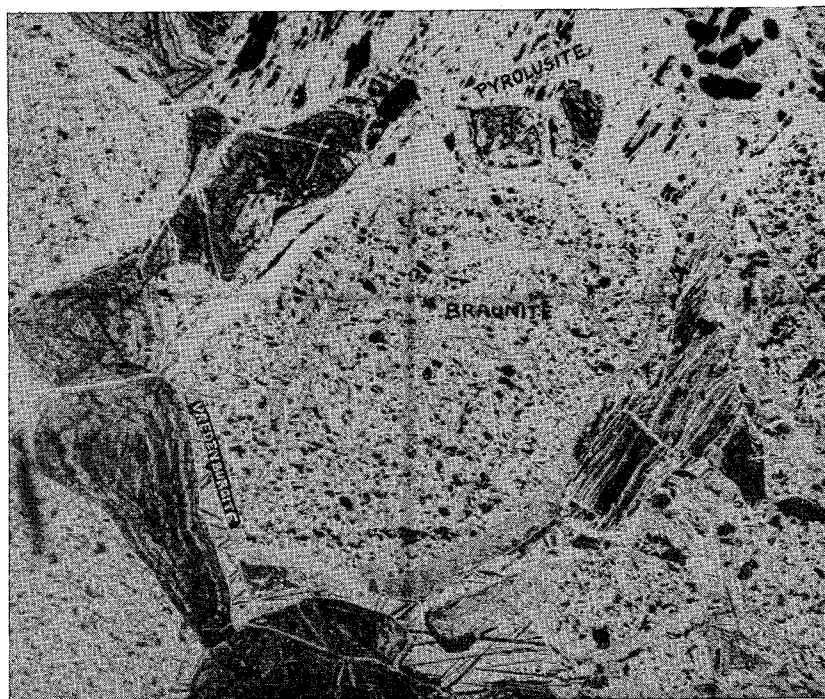


FIG. 11. Interstitial colloform γ - MnO_2 in braunite. A band of vredenburgite with hausmannite lamellae etched by $\text{H}_2\text{O}_2 + \text{H}_2\text{SO}_4$, is also interstitial. $\times 310$.

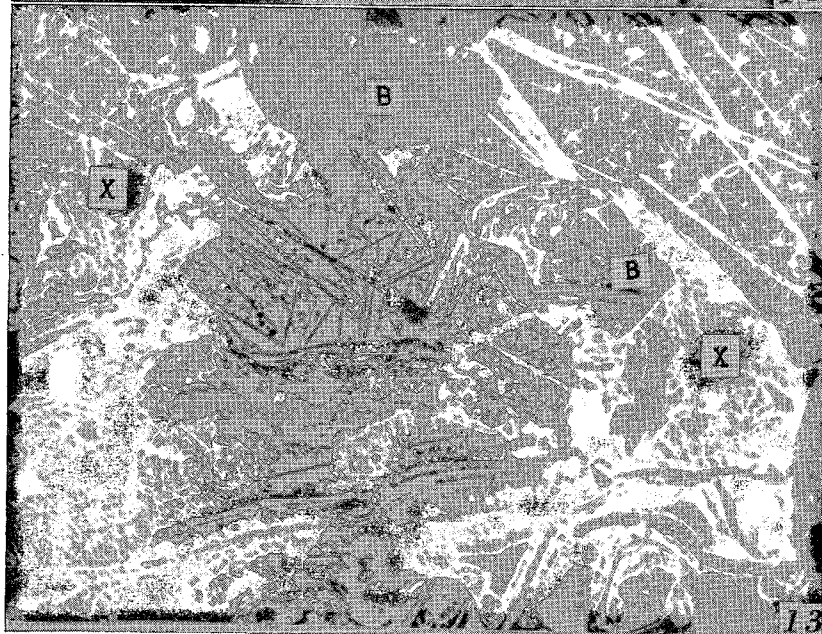
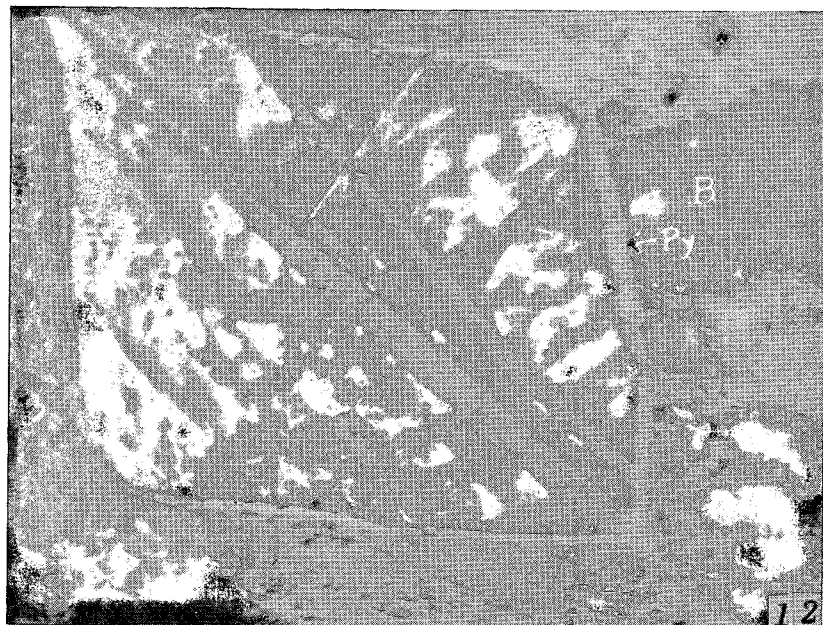


FIG. 12. Pyrolusite (white) rimming vredenburgite without replacing it. The secondary pyrolusite which replaces the braunite, is of later generation. $\times 140$.

FIG. 13. A complex ore, consisting of braunite (B), vredenburgite (with etched lamellae of hausmannite) and $\gamma\text{-MnO}_2$ (X), colloform and etched by $\text{H}_2\text{O}_2 + \text{H}_2\text{SO}_4$. Vredenburgite and braunite are intergranular and $\gamma\text{-MnO}_2$ is interstitial between them. $\times 380$.

manganese garnet with such hausmannite-free jacobsite, and their textural relationships support this. Straczek & Krishnaswamy (1956), p. 152) also mention one such occurrence of pseudomorphism of garnet by jacobsite and ilmenite due to hypogene processes. Pyrolusite, in part, seems to be of hypogene nature, particularly the interstitial euhedral grains in braunite (Fig. 6) and those formed as a sort of reaction rim at the contact of vredenburchite and braunite (Fig. 12). However, most pyrolusite forms last in the sequence with supergene cryptomelane as products of weathering.

The paragenesis may, thus, be drawn up as follows:

TIME					
Braunite	_____				
Jacobsite		_____		_____	
Hausmannite			_____		
Pyrolusite				_____	_____
Cryptomelane				_____	_____
Coronadite				_____	_____
γ -MnO ₂				_____	_____

CONCLUSION

The mineralogical study and the textural relationships of the manganese ore minerals of the Kodur group of mines indicate that the primary consolidation of the ores took place at elevated pressure-temperature conditions. From the field evidences the author agrees in full with Mahadevan & Krishna Rao (1956) and Straczek & Krishnaswamy (1956) that consolidation by metamorphism of originally bedded sediments has given rise to the ore deposits. Braunite, which is a fairly stable mineral through the different grades of metamorphism, predominates among the primary manganese oxide minerals. Jacobsite, holding hausmannite in solid solution in elevated pressure-temperature conditions, broke up into two phases with lowering pressure and/or temperature. The minor unmixed phase, hausmannite, occupies the octahedral planes of jacobsite and gives rise to Widmanstätten texture.

Colloidal gel, rich in certain elements (Ba, K and Pb), invaded the ores after their primary consolidation. The primary metamorphic ore minerals are, however, deficient in these elements. Low temperature minerals like cryptomelane, coronadite and γ -MnO₂ thus resulted at a late stage. These colloidal minerals are again altered to or replaced by supergene pyrolusite and cryptomelane. Both the colloidal and the associated resultant supergene minerals migrated, probably with the help of groundwater, into the foliation and joint planes of the enclosing rocks and presented a deceptive discordant appearance.

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