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Elba manganese ores and their origin, South-eastern Desert, U.A.R.

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SUMMARY. The manganese ores of Elba, South-eastern Desert, occur as numerous veins located within a narrow belt trending N.W.–S.E. Three ore-types were distinguished: hard crystalline ore consisting mainly of pyrolusite or ramsdellite or both, banded colloform ore consisting mainly of psilomelane, and in places cryptomelane, and soft nodular ore consisting of todorokite with minor amounts of psilomelane (or cryptomelane), nsutite, and pyrolusite. Black calcite and baryte occur in some of the veins and increase with depth.

Based on the field and mineralogical evidence the origin of the ore is discussed. It is suggested that the ore is a very low-temperature epithermal fissure deposit of black calcite type that occurs near the surface (oxidation zone) in brecciated zones along faults.

THE Elba mining area is situated in the southern extremity of the Eastern Desert of Egypt near the Sudan Frontier (fig. 1). The geology of the area was described by Ball (1912) and by Foley (1941), and the manganese occurrence was first recorded by Bassiuny (1958). The mineralogy of the ore was briefly mentioned by Ramdohr (1956) and by El-Shezley and Saleeb (1959).

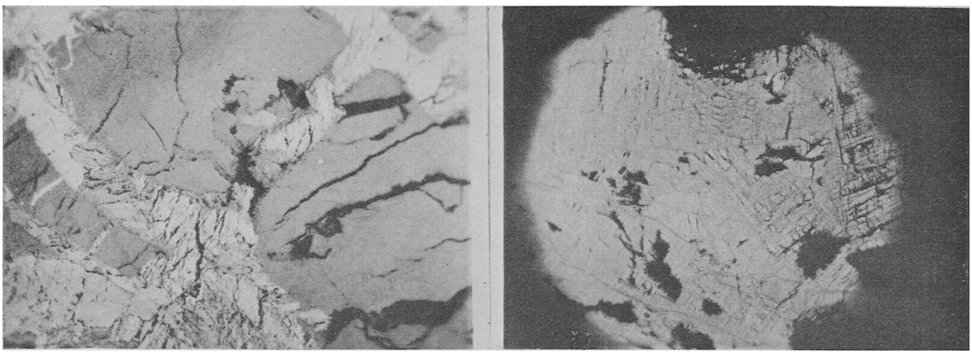
Mining of the Elba manganese ore started in 1955, and a total of 40 000 tons of high-grade ore (average MnO_2 about 74–8 % and average MnO about 2–4·7 %) has been produced. Mining is carried out by stripping the hanging wall, thus costing has limited exploitation to a depth of 20 m or less.

The present paper deals with the field, mineralogical, and chemical evidence that may have a bearing on the origin of the ore and the paragenesis of its minerals. A great number of samples were examined microscopically (in thin and polished sections) and by X-ray methods (both powder camera and diffractometer) and the results of some new chemical and spectrographic analyses are also discussed.

Mode of occurrence. More than twenty-four manganese occurrences have been mined, all being located within a featureless coastal plain consisting of sands and gravels with coral limestones and slightly raised beaches along the Red Sea. To the west of this plain occur crystalline basement rocks, consisting of an igneous and metamorphic complex. The manganese ores occur in the form of veins that are mainly found in sedimentary rocks probably of Miocene age; a few, however, occur in granitic rocks. The veins are steeply inclined and fill fault planes; their walls generally show slickensided surfaces. They have a general trend ranging from 118° to 130° and are all located within a belt of more than 70 km long and less than 7 km wide (see fig. 1), which is almost parallel to the general trend of the veins. The faults are all

amounts of cryptomelane, psilomelane, and goethite; calcite, quartz, and baryte are the main gangue minerals.

The pyrolusite generally occurs in coarse prismatic or spindle-shaped crystals with prominent transverse cracks, which may form peculiar ball-like structures due to the concentric arrangement of the cracks. These transverse cracks are somewhat characteristic of Elba pyrolusite and were considered by Ramdohr (1956) to be contraction cracks formed during the dehydration of manganite to pyrolusite. However, no trace



FIGS. 2 and 3: Fig. 2 (left). Well-crystallized pyrolusite (white to pale-grey) partly replacing cryptomelane (dark grey) along borders and cracks. Notice the strong reflection pleochroism of the pyrolusite. I-Hubal (S–644). Polished section, oil immersion, $\times 140$. Fig. 3 (right). Cell structure formed of fine grains of ramsdellite (dark grey) stacked in parallel rows and with cores of pyrolusite (pale grey). Hard well-crystallized ore from Eirongwab (S–575). Polished section, oil immersion, $\times 140$.

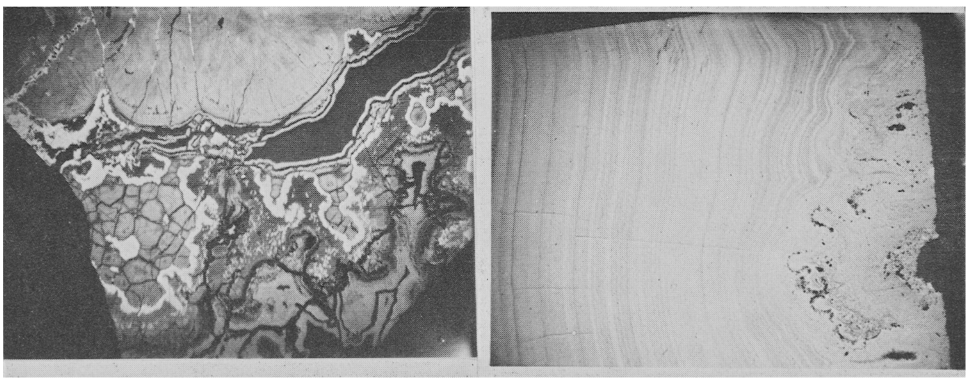
of manganite was detected in all the samples examined. On the other hand, ramsdellite is frequently observed partly altered to pyrolusite, a transformation that is accompanied by an appreciable decrease of b from 9·28 to 8·76 Å (see Bystrom, 1949). Pyrolusite also replaces cryptomelane along grain borders and cracks (fig. 2) and may form tree-like veinlets, which sometimes continue as goethite or quartz veinlets. Some pyrolusite crystals show zoning, the anisotropism of the zones being somewhat different.

The cryptomelane usually occurs in fine-grained felt-like masses with fine structures like seaweed and is almost isotropic. In occasional cases, later veinlets of porous cryptomelane are seen cutting the original cryptomelane and are themselves cut by a network of pyrolusite veins. This late cryptomelane shows strong reflection pleochroism and anisotropism and abundant internal reflections.

Some samples of the hard crystalline ore-type consist mainly of ramsdellite with minor amounts of psilomelane and pyrolusite. Ramsdellite forms big prismatic or tabular crystals, with good {110} and {010} cleavages, which sometimes show zoning and lamellar twinning. In one sample (S-575) ramsdellite exhibits a characteristic cell-structure; small grains are stacked in parallel rows and enclose pyrolusite cores (fig. 3).

The X-ray data were obtained for four representative samples of the hard crystalline ore; two from Eirongwab show pyrolusite as the main constituent, with a few foreign lines due to admixed calcite, the other two, from Einawai, consist predominantly of ramsdellite, a few weak additional lines are attributed to minor amounts of psilomelane, pyrolusite, calcite, and goethite.

The banded colloform ore is possibly the second most abundant ore-type, and is particularly common in the Alafoteib and Eirongwab occurrences, where some of the specimens consist almost completely of botryoidal masses of psilomelane in concentric bands showing typical rhythmic and colloform textures (fig. 4). Crystalline fibrous

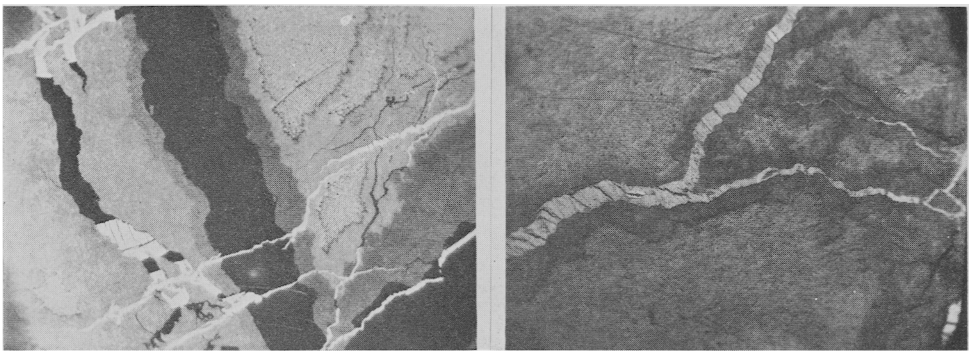


FIGS. 4 and 5: Fig. 4 (left). Psilomelane showing colloform texture of concentric rhythmic bands. The pitted, badly polished outer layer is of todorokite. Notice the fine cracks perpendicular to the layers. Alafoteib (S–559). Polished section, ×4·7. Fig. 5 (right). Colloform botryoidal cryptomelane layer of coarse fibres followed outwards by alternating undulating layers of pyrolusite (white), chalcedony (very dark grey), and goethite (dark grey). Notice the fine pyrolusite and calcite veinlets. Matet Ongwab (S–562). Polished section, ×4·7.

zones of radiating long fibres alternate with almost isotropic gel zones probably of amorphous psilomelane or wad. An outer badly polished crust of todorokite is sometimes present, and a few concentric bands of pyrolusite also occur. The identity of psilomelane and todorokite was established by X-ray examination and chemical analysis.

In a few samples, particularly from Matet Ongwab, cryptomelane is the main constituent of the banded colloform ore and forms rounded sub-botryoidal masses in which layers of coarse subradiating fibres alternate with fine-grained concentric layers. The coarse fibres are arranged with their length almost perpendicular to the layers, and may enclose small patches of todorokite. The fine-grained layers are narrower, better polished, and may form spherulitic bodies of short radiating fibres. The outer surfaces of these colloform textures frequently consist of undulating alternating bands of goethite, chalcedony, and pyrolusite (fig. 5). The identification of cryptomelane has been established by X-ray analysis of the drilled powder.

The soft nodular ore is the least common ore-type and is represented in some of the samples from Eirongwab and from Matet Ongwab, particularly from the middle of the veins. The ore consists mainly of todorokite, which occurs in the form of small rounded or oval-shaped nodules (1–3 mm diameter) embedded in pyrolusite and surrounded by a narrow crust of psilomelane or cryptomelane; the manganese minerals are cut by ramifying veinlets of calcite. The todorokite is soft (soils the fingers) and possesses a dull lustre and a dark brown streak; it is difficult to polish owing to the plucking of fibres. Microscopically, it appears in fine-grained fibres or

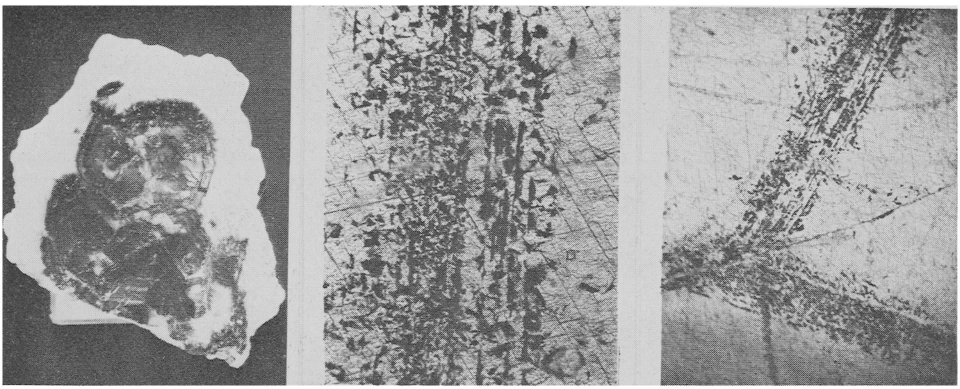


FIGS. 6 and 7: Fig. 6 (left). Pitted badly-polished todorokite surrounded by nsutite (pale grey) and this is in turn replaced by cryptomelane (dark grey). Quartz vein (black) is cut by later veinlets of pyrolusite (white). Soft nodular ore (S–518*a*) from Eirongwab. Polished section, oil immersion, ×40. Fig. 7 (right). Nsutite (pale grey) replaced by cryptomelane (dark grey) and pyrolusite (white). Eirongwab (S–518b). Polished section, oil immersion, ×140.

subparallel needles and occasionally in felt-like masses. The identity of the todorokite was established by X-ray and chemical analyses carried out on separated nodules from Eirongwab. The X-ray data compare fairly well with those given by Straczek (1960) particularly as regards the presence of the high spacing reflection (9·65 Å) characteristic of todorokite. Some foreign lines appear due to the presence of admixed psilomelane, pyrolusite, and calcite.

In a few samples, nsutite is observed replacing todorokite, relics of which appear as irregular islands; the nsutite is in turn replaced by cryptomelane (fig. 6) or by cryptomelane and pyrolusite (fig. 7). The border between pyrolusite and cryptomelane is sometimes very irregular and marked by a narrow fringe of a very fine intergrowth of nsutite and cryptomelane. According to Bricker (1965) and Roy (1968), when the oxidation gradient is low, nsutite is altered, nearer to the surface, to such stable oxides as pyrolusite and cryptomelane. The nsutite is extemely fine grained and has a much higher reflectivity and lower anisotropism than cryptomelane. The identity of nsutite and cryptomelane in the soft nodular ore was established by X-ray analyses carried out on drilled samples from Eirongwab. The X-ray data compare fairly well with those given by Zwicker *et al.* (1962) and by Mukherjee (1959) for nsutite and cryptomelane but strong lines due to much finely admixed quartz make the identification somewhat difficult.

In addition to the above ore-types, certain samples are so enriched in iron minerals that they consist almost completely of colloform cavity-filling goethite. Such samples were only encountered at the Matet Ongwab occurrence when mining reached a depth of about 17 m from the surface. X-ray powder data for two of these samples showed the goethite pattern with a few additional weak lines due to quartz and two or three strong lines that are possibly due to hausmannite.



FIGS. 8, 9, and 10: Fig. 8 (left). Well-zoned crystals of black calcite from Einawai; the black manganiferous cores are surrounded by white calcite. Handspecimen, natural size. Fig. 9 (middle). A black (manganese) band oblique to the rhombohedral cleavage of black calcite, and consisting of streaks of parallel laminae and feathery elements. Ankalidot vein (S–509), thin section. ×21. Fig. 10 (right). Bifurcating band of manganese in black calcite, part of the black streak is dispersed along the fractures and cleavage planes. Ankalidot (S–509), thin section, ×56.

Quartz and calcite are the commonest gangue minerals in the Elba manganese ores. The quartz occurs as big veinlets or filling vugs in pyrolusite and is generally contemporaneous with or later than the pyrolusite veins. In the soft nodular ore, however, thin veinlets of late pyrolusite occur cutting the quartz veins (see fig. 6). Banded spherulitic quartz and colloform chalcedony are common in the banded colloform ore type. The calcite occurs as big veinlets, as colloform crusts, or as irregular relics in the manganese matrix associated with relics of baryte.

Black calcite occurs mainly in the northern veins, which are associated with baryte, (e.g. Ankalidot and 1-Berer) and is also more abundant at depth. The crystals show black or brown cores rich in manganese surrounded by concentric zones of white or colourless calcite (fig. 8). Microscopically the black calcite reveals regular black or brown parallel bands formed of two main elements: very fine parallel laminae or regular streaks (about 10–20 in each band), and a feathery element between the regular laminae (fig. 9). The bands are generally oblique to the rhombohedral cleavage planes of calcite, but part of the feathery element occurs along some of the fractures and cleavage planes. They are 0·25–0·50 mm in breadth and are about 1–2 mm apart. Some bands show bifurcating, zigzag, or knee-structures (fig. 10); any point of junction is denser. Very locally, the feathery element becomes coarser, somewhat irregular and much denser to the extent that the laminated structure of the bands is obliterated.

Partial chemical analysis of black and white calcite samples from Ankalidot:

	Ca	Mg	Mn	Fe	Al	Ba	Sr
Black calcite	> 10	0·4	> 5	0·03	1	0·4	0·03 %
White calcite	> 10	1·0	0·01	0·02	0·1	0·01	0·03 %

It is evident that the dark colour of the black calcite is mainly due to its high content of manganese; the dispersed manganese minerals are somewhat rich in Ba.

Chemical composition

The results of five chemical analyses and semiquantitative spectrographic analyses of representative samples of the three ore-types and of the mined ore are given in table I.

The banded colloform ore (anal. 2) is composed predominantly of psilomelane, as indicated by the high content of BaO (13·27 %), with a minor amount of todorokite, shown by its high water content. The high content of vanadium agrees with the conclusion reached by Fleischer, Neuschel, and Axelrod (1945) that vanadium occurs most frequently in manganese oxides that contain Ba: 'over 2/3 of the vanadium-bearing samples are psilomelane or hollandite'.

The exceptionally high content of combined water in anal. 3 is due to the predominance of todorokite in this sample. The BaO and CaO contents are attributed to minor amounts of psilomelane and calcite. This ore-type is characterized by a high percentage of Sr, which may substitute for Ca in the todorokite structure.

The results of the analyses, particularly those of the three ore-types, confirm the mineralogical composition revealed by the microscopic and X-ray examination of the same samples. Concerning the minor elements, Pb is very low in all the analysed samples (less than 0·1 %) indicating the absence of coronadite. The K content is also low and only reaches 0·92 %, suggesting that cryptomelane is generally a minor constituent of the Elba manganese ores. The fine-grained banded colloform (psilomelane-rich) and soft nodular (todorokite-rich) ores are in general somewhat richer in minor elements than the better crystallized pyrolusite-rich ore. The following elements were not detected: Ag, As, Be, Bi, Cb, Cd, Co, Cr, Cs, Ga, Ge, Hg, In, Sb, Sn, Ta, W, and Zr.

Origin of the ore

Park (1956) classified manganese ore-deposits into five categories: hydrothermal deposits; sedimentary deposits, including those independent of volcanic activity, those associated with tuffs and elastic sediments of volcanic affiliation, and deposits associated with iron formations; deposits composed mainly of low-temperature silicates and hausmannite associated with submarine flows; metamorphic deposits; and residual accumulations and laterites.

TABLE I. *Chemical analyses of the Elba ores*

	1	2	3	4	5
MnO_2	65·76	66·85	73·16	74·04	78·53
MnO	1·03	9·17	7·49	2·09	4·71
Fe_2O_3	0·33	1·17	0·59	0·57	0·09
Al_2O_3	0·06	0·22	0·08	0·58	0·42
MgO	0·05	0·04	0·03	0·50	0·15
CaO	17·30	0·44	2·35	5·40	3·15
BaO	0·20	13·27	2·83	0·69	2·26
SiO_2	0·45	0·55	0·20	7·80	0·96
TiO_2	tr.	n.d.	n.d.	0·01	0·01
V_2O_5	tr.	0·27	n.d.	n.d.	n.d.
P_2O_5	n.d.	n.d.	n.d.	0·04	0·07
CO_2	13·80	0·40	n.d.	4·15	2·80
Comb. water	0·80	5·20	8·30	3·40	3·95
SO_3	n.d.	n.d.	n.d.	0·04	0·07
Total	99·78	97·58	95·03	99·31	97·17
Minor elements					
Cu	0·01–0·1	0·03–0·3	0·01–0·1	nil	0·002
Ni	0·01	0·01	0·01	tr.	tr.
Mo	n.d.	0·01–0·1	n.d.	n.d.	n.d.
Zn	n.d.	n.d.	n.d.	0·03	0·62
Na	n.d.	b.d.	0·01–0·1	0·18	0·89
K	n.d.	0·01–0·1	0·01–0·1	0·31	0·92
Pb	0·001–0·01	0·01–0·1	0·01–0·1	0·11	nil
Sr	n.d.	n.d.	0·1–1	n.d.	n.d.
V	0·05–0·5	0·2–2	n.d.	n.d.	n.n.

1. Hard crystalline ore (S–520) from Eirongwab (pyrolusite with minor amounts of calcite). Analyst: Pattinson & Stead, London. Recalculation excluding carbonates gives 96·1 % MnO_2, 1·5 % MnO.
2. Banded colloform ore (S–559) from Alafoteib (psilomelane with minor amounts of todorokite). Analyst: Pattinson & Stead, London.
3. Soft nodular ore (S–514) from Eirongwab (todorokite with minor amounts of psilomelane, pyrolusite, and calcite). Analyst: Pattinson & Stead, London.
4 and 5. Two chemical analyses of the high-grade ore of Elba. Analyst: G. Watson & Gray; Liverpool.

Roy (1968), on the other hand, reduced these divisions to three broad genetic types: hydrothermal, sedimentary, and superficial. The hydrothermal type includes hypogene vein deposits (Hewett and Fleischer, 1960; Hewett, Fleischer, and Conklin, 1963; Hewett, 1965) and those formed in thermal spring aprons (Hewett and Fleischer, 1960; Hariya, 1961). The sedimentary type comprises both volcanogenic (Shatskiy, 1964) and nonvolcanogenic (Strakhov, 1966; Strakhov and Shterenberg, 1966) sediments (ancient continental deposits and recent deep sea nodules) and their metamorphosed equivalents. The superficial type consists of deposits formed by residual concentration, by deposition from meteoric waters and by supergene oxidation—enrichment of pre-existing manganese formations.

The genetic classification and nomenclature given by Roy will be followed in the present paper. The results of the present field, mineralogical, and chemical study excludes any sedimentary or metamorphic origin for the Elba manganese ores. The occurrence of the ore-deposits as well-defined, steep-dipping fissure veins accompanying fault zones and the fact that they have two distinct walls that are commonly slickensided all point to a definite epigenetic origin.

A basic question is whether the mineralizing solutions are derived from above or from below. The veins occur in an exceptionally arid region where mining has not reached permanent water level and the manganese ore persists to the greatest depth of the workings. Criteria other than relation to the local water table must, therefore, be used. The following are the most important features that may throw light on the origin of the ore:

All the veins occur in a structureless plain and there is a lack of dependence of the ore on topography. Extension of the ore deposit in depth—in some veins there are signs of an increase in thickness and grade of mineralization with depth; the depth of mining is determined by cost rather than the decline in the amount and grade of the ore. Blind ore-bodies are present, and branches and stringers of the main vein may die out upwards. All the veins occur within a narrow metallogenic belt that has the same general trend as that of the veins. The surrounding rocks show no abnormal manganese content. Chalcedony, white calcite, black calcite, and baryte frequently occur in druses in the manganese minerals and are later than the main manganese mineralization; the black calcite, though richer in Mn and Ba than the white calcite, cannot, therefore, be the source. Black calcite and baryte tend to increase in the manganese veins with depth. In the northern part of the area baryte veins occur in association with the manganese veins and consist of alternating layers of black calcite and baryte. Wall-rock alteration is slight or completely lacking. The mineral assemblage is formed of stable manganese oxides in which manganese is mainly in the quadrivalent state (pyrolusite, psilomelane, ramsdellite, cryptomelane, todorokite, and nsutite), psilomelane being quite abundant while nsutite is very rare. Roy (1968) reported that psilomelane is very common in the upper zones of hypogene veins but is rather rare in supergene deposits, its place being taken by cryptomelane; he also stated that nsutite is fairly common in supergene deposits. The psilomelane-rich ore is generally rich in vanadium while the todorokite-rich ore is rich in strontium.

Most of the above features are evidences in favour of a hypogene rather than supergene origin. The manganese ore of Elba may therefore be considered as a very low-temperature fissure deposit of black calcite type that occurs near the surface. Similar vein deposits of black calcite type were described by Wilson and Rocha (1956), Jicha (1956), Hewett *et al.* (1956), and Hewett and Fleischer (1960) from the manganese occurrences in Mexico and in the Western States of U.S.A. and were mostly considered to be hydrothermal and hypogene. Hewett (1965) stated that the manganese oxides as well as the black calcite are hypogene and 'not that the manganese oxides of the deposits were formed by the superficial weathering and enrichment of black calcite', which agrees with our present result that the black calcite is later than the manganese oxides.

Roy (1968) considered that in manganese deposits formed from hot ascending solutions there is a zonal arrangement of minerals: in the deepest part of the epithermal zone rhodonite, rhodochrosite, and alabandite (with Mn^{2+}) are present, followed upwards by hausmannite, bixbyite, and braunite (Mn^{2+} and Mn^{4+}), and ultimately, in the uppermost parts, by psilomelane, cryptomelane, pyrolusite, etc. (mainly Mn^{4+}). In the Elba occurrence, the maximum depth reached during the workings is only 20 m (with the manganese ore persisting) and so no such zoning is evident; the only sign is the presence of goethite admixed with hausmannite at the greatest depth of the biggest vein in the area. The predominance of stable higher oxides of manganese and the absence of manganese silicates, carbonates, and sulphides is attributed to the abundance of oxygen and falling temperature and indicates that we are dealing with the uppermost zone nearest to surface. The low temperature is also indicated by the lack of evidence of replacement or alteration of the wall rock and by the common presence of colloform texture.

Psilomelane, ramsdellite, and cryptomelane are possibly the first manganese minerals formed and are followed by pyrolusite. In the soft nodular ore-type, todorokite is formed followed by rare nsutite and this is oxidized to a second late generation of cryptomelane and pyrolusite. The quartz is earlier than the second generation of pyrolusite but is later than all the other manganese minerals. The white calcite is generally later than the black calcite.

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