The Manganese vein of Mount Brandnuten, Botnedal, South Norway.

by

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Abstract.

The manganese deposit on the NE. slope of Mt. Brandnuten near the head-waters of Botnedalen in western Telemark has the shape of a massive vein of vertical attitude. It is conformably intercalated between arkoses of the Precambrian Telemark suite of metamorphic supracrustal rocks. Granite invades the wall rocks in the immediate neighbourhood of the deposit. The manganese vein strikes N30—35° E across Botne brook, has been traced over a distance of more than 300 m, and has a thickness between zero and 2.10 m. There are a few parallel veins of minor importance and also some smaller veins striking obliquely or perpendicularly to the bedding of the arkoses, which latter show intercalations of amphibolite. The main ore body mainly consists of coarsely crystalline rhodonite and spessartite carrying lenses of Mn-oxides to a quantity of about 15 %. Braunite is the main Mn-ore and is associated with some hausmannite and jacobsite. There are, in addition, a few subordinate and secondary Mn-silicates of unknown composition replacing rhodonite, small quantities of metasomatic fluorspar and rhodochrosite; furthermore small amounts of, respectively, a mineral of the psilomelane group, an unknown Mn-oxide, pyrite, hematite, and native copper. Rhodonite replaces braunite, which is also earlier than hausmannite and jacobsite. Spessartite seems to be partly earlier and partly later than rhodonite.

The primary ore shows granoblastic and poikiloblastic textures and is of metamorphic origin, being a true gondite very similar to the manganese protores of Central India. Fluorspar, rhodochrosite, pyrite, etc., are of later hydrothermal origin and probably genetically connected with the intrusive granite.

I. Introduction.

The manganese deposit on the NE. slope of Mt. Brandnuten near the head-waters of Botnedalen in western Telemark, which belongs to a group of occurrences of a similar type developed along and in the environment of Saetesdalen, was discovered in about 1890 (A. O. Poulsen, unpublished report). A preliminary exploration was carried out in 1903 and a limited quantity of manganese ore was exported for experimental purposes. Mr. Poulsen visited the occurrence, which

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seemed to be one of the most promising in southern Norway, in October 1950 and furnished some data on the situation, the Mn-content, and the mineralogy of the deposit (unpublished report and Poulsen 1956, p. 292). The locality was visited again and re-sampled by Dr. J. F. Brondijk in 1952 and 1953, and in 1953 also by Mr. Immink, both working for a private company.

A representative collection of ore material and country rock of the Brandnuten manganese vein was put at the disposal of the present author through the kindness of Dr. Brondijk, who also delivered a short field description and some chemical data concerning the deposit, while the writer also had the opportunity to inspect Mr. Poulsen's and Mr. Immink's reports. At the present writer's laboratory, Dr. Brondijk's material was subjected to a mineralogical and petrographical investigation, the results of which are given in the present essay, together with the writer's opinion concerning the origin of the deposit.

II. Situation of the Brandnuten manganese deposit.

The Mt. Brandnuten manganese vein has been traced in a side-valley of the Botne valley at a height of about 1000 m above sea-level, on the NE. slope of the Brandnuten mountain ridge. The manganiferous region lies about 11 km WNW of the township of Mo in Telemark, and about 3 km E of the provincial boundary between Telemark and Aust Agder. According to Mr. Poulsen's report to the Geological Survey of Norway, it may be reached from the township of Dalen in Telemark by first following the good road to Froland in Botne valley (17 km), and afterwards the roads and pathways through this valley over a distance of 13—14 km (Fig. 1).

Another, analogous deposit was discovered in the Bykleheia at about 12—14 km W of Brandnuten, in a region which according to Poulsen (1956) deserves to be further investigated. In the southern Saetesdal area, a group of manganese veins is known to exist N of Kristiansand, while more westward some small manganese deposits are besides recorded from the equally little explored area N of Mandal (Foslie 1925, p. 33). Only the Kvivigdal vein N of Kristiansand seems to have been eploited for some time.

Although the South-Norwegian manganese occurrences probably belong to a province of mutually similar deposits, their comparative mineralogical investigation still remains to be done.

III. Geology of the environment of Mt. Brandnuten.

The country rocks of the Saetesdal manganese veins are formed by Precambrian granite and gneiss in the Kristiansand—Mandal area, but farther north, in the region W and principally in that E of Mo, a broad belt of mineral deposits, comprising, e.g., the Brandnuten manganese veins and various small, but apparently often rather rich deposits of copper, molybdenum, and on a minor scale also of lead, arsenic, and bismuth, sometimes carrying in addition some silver and gold, is developed in the metamorphosed quartzitic sedimentaries of the Telemark suite of supracrustal rocks along their contact with a younger granite. There are besides some fluorspar deposits near Dalen, and pegmatite veins carrying a good quality of mica (written communication by Dr. Brondijk). This mineral belt has a width of approximately 25 km and the quartzites are likewise cut by veins of granite near the granite contact, and furthermore by predominant quartz veins (Foslie 1925, p. 16).

Following Dr. Brondijk's written communication to the present author, the almost vertical main Brandnuten vein could be traced in a N 30—35° E direction across Botne brook. On the S. side of this rivulet, the vein zone is exposed at intervals over a horizontal distance of about 275—300 m on the steep slope of the U-shaped valley. It could equally be followd on the N. side of the Botne valley, where the manganese ore has been found exposed in the same direction above the moraine blanket covering the rock basement near the valley bottom.

The country rocks of the manganese deposit are quartzitic arkoses of the Telemark suite carrying narrow seems of intercalated amphibolite. The mineralized area lies very near to an intrusive contact of a younger granite, of which veins, bosses, and embayments are found cutting the metamorphosed sedimentaries in profuse quantity. The main manganese ore body generally is almost conformable to the schistosity and bedding of the quartzites; where it meets granite, it is always interrupted. Narrow manganese veins, however, sometimes cut the bedding of the quartzite obliquely or even perpendicularly (Dr. J. F. Brondijk, written communication).

The manganese ore of the main deposit constitutes a compact ore band of some width and occurs besides as impregnations and pockets alongside the main ore body. On the higher part of the southern slope of the U-shaped valley, where Mr. Poulsen took his samples in the
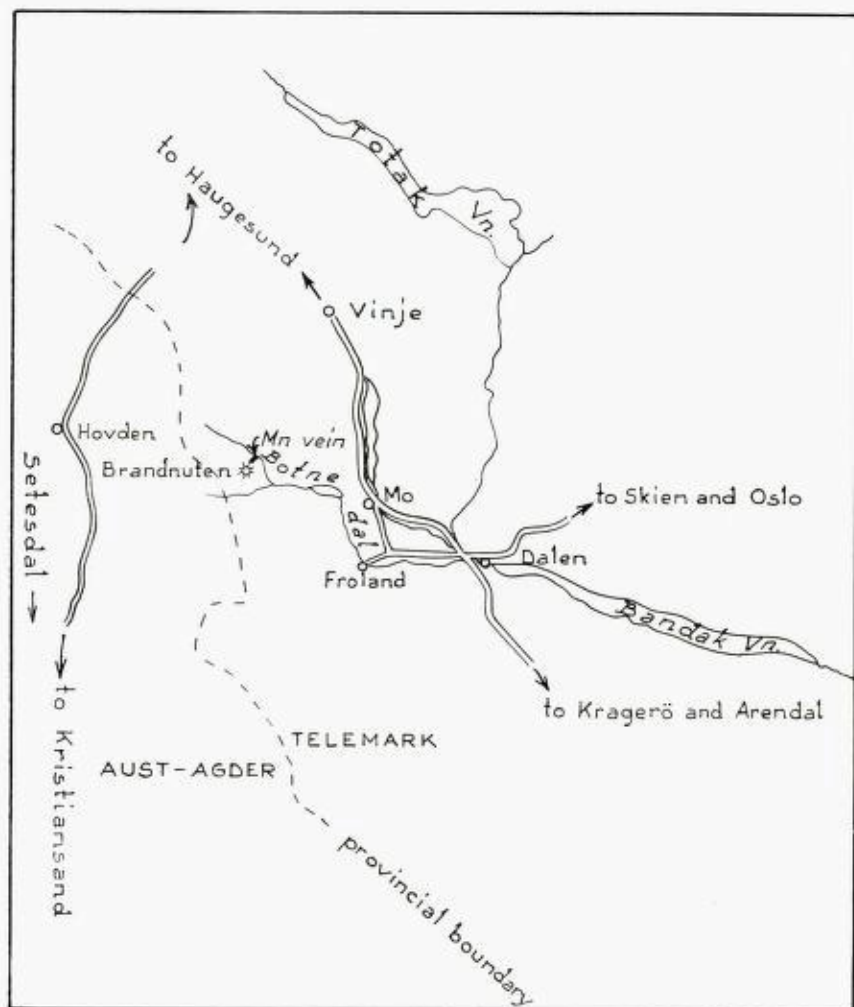
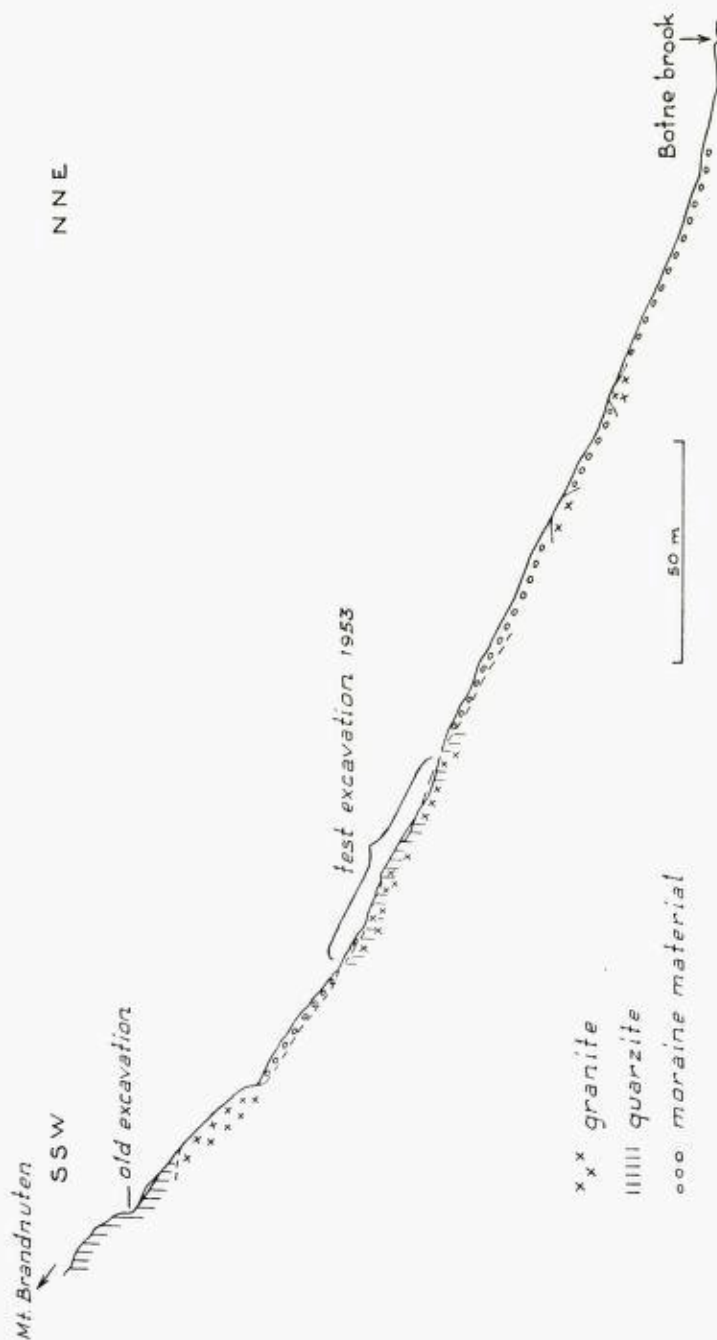Fig. 1. Situation of the Mt. Brandnuten manganese vein. Scale ± 1 : 563,108.

Fig. 2. Longitudinal wall-rock profile along the main manganese vein on the NE. flank of Mt. Brandnuten in western Telemark (after Dr. J. F. Brondijk).

old exploration excavation, the main ore body has a width of 1.60 m (fig. 2; Plate I, A), whereas at other places the latter may vary between zero and 2.10 m. It is accompanied by a few parallel seams of much reduced width and lacking in continuity. One of these parallel occurrences is found at about 60 m ESE of the main body, at the same altitude as the old excavation.

IV. Chemical composition of the ore.

The bulk of the Brandnuten manganese ore consists of a mixture of rhodonite, spessartite, rhodochrosite, some fluorspar, sometimes rather much microcline, and Mn-oxides with some hematite. In Mr. Immink's report it is stated that the Mn-oxides are concentrated in lenticular masses with a maximal length and width of a few metres and 50 cm, respectively. Most of the Mn-oxide lenses are, however, much smaller, and the average oxide content of the vein-filling is evaluated at not more than 15 %.

According to Mr. Poulsen's report, samples taken from the vein in the old excavation averaged 40.3 % Mn and 1—2 % Fe, P and S being absent. A few of the richest specimens assayed 58—60 % Mn, whereas the country rock appeared to contain 1.17 % Mn. It is not clear from these data whether the assay values refer to samples especially rich in Mn-oxide or to samples taken over the entire width of the vein.

During Dr. Brondijk's visit to the area, the old excavation was resampled over its entire width and the material thus obtained split into a macroscopically rich and a macroscopically poor part. The rich part, rich in Mn-oxides, assayed 51.23 % Mn, 1.45 % Fe, and 20.29 % SiO_2; the poor part, poor in Mn-oxides, 13 % Mn, 1.43 % Fe, and 60.8 % SiO_2. The rich ore occupied about 60 % of the width of the vein at this place; the poor ore about 40 %.

Assays were equally made of samples taken from the test excavation 1953, from the continuation of the Brandnuten vein N of the Botne valley, and from the parallel vein at about 60 m E of the old excavation. The results are tabulated in Table I, together with a more complete analysis of a sample taken from the old excavation. It ought to be understood that the qualifications rich and poor refer to material rich and poor in Mn-oxides, respectively.

Table I.

Assay values of manganese ores from the Brandnuten veins.

Sample	Fe %	Mn %	Cu[1]) %	Al %	P %	S %	SiO$_2$ %
I	1.79	47.15	0.29	2.50	+	0.04	14.93
II	4.38	55.61	0.10	0.54	—	0.05	10.48
III	2.86	18.51	+	3.16	+	0.12	50.38
IV	2.64	33.96	0.01	3.49	+	0.12	32.86
V	1.72	4.10	0.04	5.00	—	0.18	68.02
VI	4.59	48.03	0.04	3.80	—	0.18	17.22
VII	2.28	49.48	0.07	2.32	—	0.09	15.23

[1]) Pb and Zn are absent   — absent   + trace.

I. Sample taken from the old excavation, main vein.

II. Richest ore from a spot 1 m S of a small tributary of Botne brook, test excavation 1953, main vein.

III. Average of a few tons of poor ore from a spot 40 m N of the small tributary of Botne brook on the NE. slope of Mt. Brandnuten, test excavation 1953. main vein.

IV. The same from a spot some 5 m higher in the main vein zone.

V. Poor ore from the continuation of the main vein N of the Botne valley.

VI. Rich ore from the continuation of the main vein N of the Botne valley.

VII. Sample taken from the parallel vein at 60 m E of the old excavation.

Judging from the mineralogical composition of the ore, more detailed analyses would certainly also have detected the presence of small quantities of Ca, K, Na, F, and CO$_2$.

V. Petrography and mineralogy of the main ore zone.

General character of the manganese ore and its country rocks.

The greater part of the vein-filling sampled in the test excavation 1953 consists of rhodonite, spessartite, and rhodochrosite, with some fluorspar and occasionally rather much microline. Rhodonite sometimes builds crystals with a length of more than 10 cm. Fine-grained, honey-coloured or reddish-brown spessartite forms distinct, vein-like masses associated with rhodonite; both minerals are also mutually intergrown in fine-grained aggregates. Fluorspar and rhodochrosite occur in narrow veins between rhodonite and spessartite or may fill up irregular interstices; they are fine- to medium-grained. Fluorspar veins also cut rhodonite (Plate I, B; Plate II, A).

The transparent minerals enclose masses and pockets of Mn-oxides, part of which latter are likewise developed as thin films around crystals of the Mn-silicates. Adjacent to their contacts with the Mn-oxide lenses, pink rhodonite crystals exhibit a border zone of "black" rhodonite, which latter acquired its colour through the infiltration of secondary Mn-oxide along its cleavage planes and small cracks. An X-ray diffraction diagram of the black variety gave the same d-values and intensities as one made of the adjacent pink rhodonite.

The wall rocks of the main ore body consist of greyish, fine-grained arkose, which near its contact with the ore body contains strings of fine-grained rhodonite and spessartite. Judging from the material available to the present author, these Mn-silicate bands seem to run parallel to the walls of the main ore body and to the strike of the arkose beds. Samples taken at the contact between the ore body and its country rock show a transition zone about 5 cm wide containing much rhodochrosite and fluorspar in addition to the Mn-silicates. This zone also appeared to contain some jacobsite.

The lenses of Mn-oxides forming concentrations of rich manganese ore in the mixed main ore body mainly consist of a hard, massive mineral aggregate with a dull appearance, which is only freshened by numerous, scattered specks of a black mineral with a metallic luster. Braunite and in a minor degree hausmannite are the main constituents of the dull parts, whereas the shiny specks mark the sites of what seems to be mainly a psilomelane variety and perhaps some hematite.

In the arkose forming the wall rock of the main vein, quartz and abundant potassic feldspar are the chief constituents. The granites occurring as profuse intercalations between the arkoses show a pink to greenish colour in samples taken on the E. side of the vein. They are medium- to coarse-grained, devoid of a gneissic structure, and composed of potassic feldspar, acid plagioclase, quartz, mica, and some sphene as the main mineral consituents.

Petrography of the country rocks.

The arkoses.

The arkose at the border of the main vein in the 1953 excavation consists for about 30 % of quartz grains with an undulatory extinction, and for about 50 % of grains of a potassic feldspar showing a patchy microcline quadrille structure. At some places, the microcline

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individuals are veined in one direction by strings of albite, which give them the aspect of a replacement perthite. Albite is besides found as separate grains. The remaining part of the rock consists of parallel impregnation seams containing either blastic spessartite or porphyroblastic rhodonite. The latter mineral is veined by patches of Mn-oxide and by a secondary, brownish Mn-silicate mineral of unknown character (see later). The spessartite grains sometimes enclose quartz, whereas the rhodonite porphyroblasts enclose both quartz and feldspar.

The granites.

The granites exposed in the vicinity of the main vein contain a pink potassic feldspar and a greenish plagioclase. The average mineral composition is about 25 % quartz, 35 % potassic feldspar, 30 % plagioclase, and 10 % mafic constituents.

Quartz generally builds rather small grains between the feldspars, but may also be enclosed by the latter. At some places it appears to replace both potassic feldspar and plagioclase. All quartz has a strongly undulatory extinction.

Plagioclase (albite-oligoclase) shows a hypidiomorphic development and a twinning according to the albite law. The polysynthetic lamellae are frequently very irregularly shaped; they wedge out towards both ends and are frequently more or less bent. The plagioclase individuals are corroded by microline.

Potassic feldspar, probably all microcline, shows a xenoblastic development, and mostly occurs as rims around plagioclase crystals. The core of a microline xenoblast sometimes consists of a plagioclase relic. The microcline usually has a fresh appearance, whereas the plagioclase is often dull by partial sericitization. The quadrille structure of the microcline individuals is mostly badly developed.

A partial albitization of the feldspars completed the process of feldspar crystallization. Albite veinlets penetrate into the microcline individuals, starting from the borders of the older albite-oligoclase cores, thus giving rise to the formation of replacement perthites. Clear, late biotite likewise grew around the borders of the earlier-crystallized feldspars.

The dark constituents of the granite are formed by biotite and sphene. Biotite is accompanied by some sericite. Both micas are replaced by chlorite. Apatite and zircon are minor accessories.

Transparent minerals of the vein-filling.

Rhodonite.

Rhodonite is the principal non-opaque mineral, which may build porphyroblasts with a diameter up to more than 10 cm (Plate I, B; Plate II, A). Macroscopically, it shows its typical pink colour, crystal habit, and perfect cleavages. In thin section, it displays a weak pinkish colour, and frequently a strong pressure shadowing in large individuals forming part of mixed rhodonite-spessartite-Mn-oxide ore. Aggregates of smaller rhodonite grains, on the other hand, may show crystallographic orientations deviating only slightly from an average direction, so that in this case larger crystals of this mineral were probably broken up as a result of compressional forces.

Optical and specific weight measurements on Brandnuten rhodonite gave the following results: $2V_z = 66°$, $n_z = 1.74$, $n_y = 173$, $n_x = 1.72$ (calculated), $G = 3.65$ (± 0.01).

According to diagrams given by A. N. Winchell (1951, Fig. 346, p. 457; Id., Fig. 348, p. 458), after N. Sundius, these physical data characterize a rhodonite with about 86 % $MnSiO_3$ and 14 % $CaSiO_3$ (incl. $MgSiO_3$ and $FeSiO_3$). The rate of accuracy of our measurements does, however, not allow the evaluation of a possible Mg and Fe content in proportion to Ca. The presence of Zn ought to be excluded on account of its not having been detected during bulk ore sample analysis.

Rhodonite is generally composed of much larger crystals than spessartite. The Mn-garnet may be observed to be enclosed poikiloblastically and sometimes in great quantity by large rhodonite individuals (Plate II, B). Occasionally, spessartite enclosed in rhodonite displays clear idiomorphic outlines (Plate III, B), but in other instances the garnet seems to have intruded into rhodonite in the shape of parallel streaks following a cleavage direction (Plate III, A). The general impression is that both minerals crystallized about simultaneously, although part of the spessartite apparently grew at an earlier stage than rhodonite. The general aspect of rhodonite-spessartite intergrowths reveals their crystalloblastic origin.

In massive Mn-oxide ore, rhodonite has been observed to fill the interstices between frequently rounded grains of opaque ore substance, which is mainly braunite. In addition, rhodonite sometimes forms worm-shaped intergrowths with opaque Mn-oxide substance, which latter in this case is almost certainly hausmannite, according to

a microscopical study under the ore microscope (Plate V, B). These relationships show that the rhodonite-Mn-oxide intergrowths, too, represent crystalloblastic textures.

Spessartite.

The Mn-garnet comes second in abundance among the non-opaque minerals. Macroscopically, its colour varies between reddish-brown with an orange tinge and honey-coloured. In thin section, the garnet displays a yellow to greenish or reddish colour.

The mode of appearance of spessartite tends to be idioblastic with regard to rhodochrosite and sometimes also to rhodonite and fluorspar (Plate III, B; Plate IV, A, B).

Spessartite either occurs as massive streaks composed of more or less xenoblastic grains (Plate I, B) or as crystal intergrowths with rhodonite. Spessartite enclosed by rhodonite frequently shows a darker colour than vein-building spessartite, with phenomenon possibly indicates successive crystallization periods for this mineral. X-ray diffraction diagrams of both types of spessartite, however, appeared to be identical.

Measurements of specific weight, refractive index, and unit cell size gave the following result; $G = 4.16$ (± 0.02 or 0.03), $n = 1.82$, $a_0 = 11.64$ Å.

As for rhodonite, the specific weight of our spessartite was measured with a picnometer, the refractive index by means of the immersion method. The unit cell size was calculated from X-ray powder diagrams obtained with CuKα radiation, using a camera with a radius of 57.3 mm.

Using Frietsch's (1957, Fig. 2, p. 48) diagram for the determination of global compositions of garnets by means of the values obtained for n and a_0, the above figures for these constants appear to produce a point situated inside his spessartite ($+$ almandite) field. As in Frietsch's graphs, his Figs. 1 and 2, specific weights are left out of consideration, it is not possible to use them for more precise derivations of garnet compositions, although the denomination spessartite is sufficiently confirmed by them for the mineral here discussed. Further proofs that the Brandnuten vein garnet is a true spessartite were afforded by X-ray analysis and by the partial chemical analysis of two samples of isolated material, which latter gave an average of about 28 % MnO.

Applying H. Winchell's (1958, Figs. 1 and 2, pp. 597, 598) graphical representations of garnet compositions as a function of n and a_0, in which specific weights are, moreover, indicated by contour lines drawn across the triangular fields representing 3-component combinations (leaving uvarowite out of consideration), the n-a_0 point for our spessartite appears to correspond with the following three 3-component combinations:

(a) $Spess_{55}Alm_{33}And_{12}$, with $G = 4.19$
(b) $Alm_{70}And_{12}Gros_{18}$, with $G = 4.12$
(c) $Alm_{55}And_{25}Pyr_{20}$, with $G = 4.05$

Our specific weight (4.16) is, therefore, in agreement with two mixtures, each of two 3-component combinations:

I. 0.6 (a) + 0.4 (b) = $Spess_{35}Alm_{45}And_{12}Gros_8$
II. 0.8 (a) + 0.2 (c) = $Spess_{45}Alm_{36}And_{15}Pyr_4$

Mixture I gives an MnO content of 13.1 %, mixture II one of 19.4 %. Since partial chemical analysis gave an average of about 28 % MnO, it may be assumed that our spessartite corresponds in a rough way with mixture II, although with a higher spessartite content. The latter is apparently of the order of about 60 %, the other components being essentially almandite, the chief minor component, and andradite. Grossularite is probably entirely lacking.

Unknown Mn-silicate mineral.

As indicated before, rhodonite has been found partly replaced by a secondary, brownish Mn-silicate mineral in arkose adjacent to the main manganese vein. This mineral is delevoped in veinlets carrying, in addition, a small amount of Mn-oxides. Its true nature could not be established with certainty on account of its very fine-grained appearance, which makes it difficult to isolate. It shows the following features : prismatic development with cleavage // longitudinal direction; extinction // longitudinal direction; negative elongation; high relief ($n \approx$ or $\geqslant 1.7$); $2V_z = \pm 60°$; $\Delta = 0.035—0.040$; $X \approx Y$ orange-brown, Z reddish-brown; $X \approx Y < Z$.

As another alteration product of rhodonite there sometimes appear very fine-grained aggregates of a brownish to colourless micaceous substance.

Fluorspar.

Macroscopically, fluorspar may be observed to constitute veinlets cutting through rhodonite or formed at the contract between rhodonite and spessartite (Plate II, A). The same phenomenon appears in thin sections; fluorspar fills up voids between rhodonite grains and penetrates as veinlets into the latter mineral, which it replaces (Plate III, B), whereas spessartite remains much less attacked by the fluoride (Plate IV, B).

Fluorspar appears to have been formed earlier than rhodochrosite, since the latter sometimes forms rims around fluorspar.

Both fluospar and rhodochrosite are replacive minerals and do not show crystalloblastic habits. They, therefore, apparently crystallized from late hydrothermal fluids, which attacked the manganese silicates after the process of metamorphism responsible for the formation of the latter had ceased to operate.

Rhodochrosite.

In hand specimens rhodochrosite in the Brandnuten ore shows a pink to dirty-brown colour. It, therefore, probably contains rather much siderite in solid solution. In thin section it has a dirty greyish colour, and sometimes a faint pink hue. Rhodochrosite crystallized later than all other non-opaque Mn-minerals and, as said above, also appears to be later than fluorspar. It forms veinlets cutting through the Mn-silicates, but also fills voids between, e.g., idiomorphic crystals of spessartite (Plate IV, A).

Opaque minerals of the vein-filling.

Braunite.

In one sample of massive Mn-oxide ore from the 1953 excavation braunite appeared to constitute approximately 70 % of the opaque substance, and hausmannite about 20 %. In rich ore, braunite builds massive, almost monomineral aggregates exhibiting a mosaic texture of polygonal or rounded grains (Plate V, B). Octahedral cross-sections are sometimes observed and octahedral zoning is, in addition, sometimes revealed by an alternation of opaque braunite layers and non-opaque gangue material according to an octahedral pattern. The grain-size is very variable, mostly 0.1—0.2 mm. In reflected light, braunite shows

a grayish-white colour with a creamish-brown hue; pleochroism and anisotropy are rather weak, but distinct, and a brown internal reflection is occasionally visible with strong illumination. The X-ray diffraction diagram of Brandnuten braunite corresponds very closely with those given by various authors (for instance Ramdohr 1956, p. 39) for braunite. As has been said before, braunite may form poikiloblastic intergrowths with large rhodonite individuals. It is sometimes equally poikiloblastically enclosed by hausmannite (Plate V, A), which latter mineral also occupies voids in massive braunite aggregates (Plate V, B). Occasionally, braunite crystals have been observed to be surrounded by jacobsite (Plate VI, A).

Hausmannite.

Hausmannite can be recognized in reflected light by its distinct and rather strong pleochroism (from clear grayish-withe to darker gray with a brownish hue) and by its ansiotropy (in yellowish brown and gray); besides by its frequently observable polysynthetic twinning in one or two directions (Plate V, A) and by its frequent blood-red to red-brown internal reflection. As has been said in what precedes, hausmannite occasionally forms crystalloblastic, worm-shaped intergrowths with rhodonite in voids between aggregates of massive braunite (Plate V, B). In these intergrowths, the hausmannite particles show a similar optical orientation over areas of some extent, so that groups of adjacent hausmannite particles apparently form part of one crystal.

Jacobsite.

Jacobsite is a minor constituent of massive Mn-oxide ore, but has also been observed in the border zone of the main vein against the arkose wall rock. In one sample of massive ore, which beside Mn-oxides contains interstitial Mn-silicate (mainly rhodonite), jacobsite appeared to constitute about 30 % of the opaque minerals.

The octahedral structure of the jacobsite is revealed by a triangular pattern of cleavage planes (Plate VI, A, B). In air its colour is grayish-white with a yellowish hue, but in oil the colour changes to a distinct olive-green. The mineral is completely isotropic and with very strong illumination occasionally shows a red internal reflection. Along the octahedral cleavage planes, jacobsite grains contain enclosed lamellae of silicate gangue (Plate VI, A, B), while a replacement by hematite

reminding of "martitization" equally starts from these structural partings (Plate VI, B). The development of hematite indicates a partial oxidation of the jacobsite.

The features of the Mt. Brandnuten jacobsite agree with those given by Ramdohr (1955, p. 718) for this mineral, which marks our jacobsite as a typical occurrence. As has been shown by Roy (1960) for Mn-ores near Kodur in Central India, a change in the Mn_3O_4-content in jacobsite apparently changes its colour in reflected light, a high hausmannite content giving it a brownish-grey hue, and a high magnetite content a pinkish-brown tinge. Pinkish-brown jacobsite, without hausmannite exsolution lamellae, has also been noticed by Roy (1959) in gondite ore from Dongari Buzurg, and a deep brownish-yellow variety (Roy 1958), equally without hausmannite lamellae, in related gondite ores near Tirodi, both also occurrences in Central India. Colours deviating from the normal have, however, not been observed in our Norwegian material, and neither have the intergrowths of olive-green jacobsite and hausmannite known as "vredenburgite", which latter are very common in the Central Indian manganese ore province.

When associated with braunite, jacobsite encloses more or less rounded grains of the latter mineral (Plate VI, A). Hausmannite may be observed as interstitial filling between braunite and jacobsite grains (Plate VI, B). In samples taken from the border zone of the main vein, jacobsite has been observed locally to be the main Mn-oxide mineral and to cut as aggregates of hypidiomorphic grains through the Mn-silicate gangue.

An X-ray powder diagram of Mt. Brandnuten jacobsite gave the d and I values recorded in the left-hand column of Table II. For comparison, the central column shows the corresponding values for Jacobsberg jacobsite as calculated from $\sin^2 \vartheta$ figures presented by Johansson (1928, p. 114), whereas the right-hand column contains the d and I values for magnetite, according to Torre de Assunção and Garrido (1952—53, p. 81). The figures show that Mt. Brandnuten jacobsite stands closer, as regards d and I values, to Jacobsberg jacobsite than to magnetite. The d values for Jacobsberg jacobsite stand in between those for the Mt. Brandnuten occurrence and those for magnetite, so that the jacobsite of the Norwegian deposit is apparently richer in Mn than that of Jacobsberg.

Table II.

X-ray diffraction data obtained with Mt. Brandnuten and Jacobsberg jacobsite, and with magnetite.

Jacobsite, Mt. Brandnuten		Jacobsite, Jacobsberg		Magnetite	
d(Å)	I	d(Å)	I	d(Å)	I
4.91	2				
				4.85	1
3.43	—1				
3.29	—1				
2.99	6	2.98	6	2.97	3
2.55	10	2.54	10	2.53	10
2.44	1	2.43	1	2.42	1
2.12	6	2.11	6	2.10	3
		1.88	1		
1.72	3	1.72	4	1.71	2
1.63	5	1.62	8	1.61	6
1.58	1				
1.49	8	1.49	10	1.483	8
		1.42	1		
1.34	—1	1.33	2	1.326	1
1.29	—1	1.28	4	1.279	2
1.28	—1	1.27	1		
		1.22	3	1.21	—1
		1.13	4	1.121	1
		1.10	9	1.092	3
		1.05	6	1.049	1
		0.99	4	0.97	2
		0.97	7	0.966	1
				0.940	1

Unknown Mn-oxide mineral.

A Mn-oxide mineral which it was not possible to identify by ordinary microscopic examination appeared to be locally developed as an interstice filling between more or less rounded crystals of braunite in samples of mixed Mn-silicate-oxide ore. Its colour is a somewhat darker gray than that of braunite, without the creamy-brown hue commonly shown by the latter. Both its reflection power and polishing hardness are lower than those of braunite. It, furthermore, shows a

weak reflection pleochroism and a weak anisotropism, both in shades of gray. A few grains of hausmannite were found associated with the unidentified oxide.

Psilomelane.

Among the secondary Mn-oxides a mineral of the psilomelane group seems to be the most wide-spread. It replaces the primary Mn-oxides. The psilomelane-like mineral is also found as veinlets cutting through the Mn-silicate gangue. Sometimes, this mineral also builds larger aggregates of very fine needles.

The psilomelane-like mineral shows a more greyish colour than hematite, while its reflection power is greater than that of jacobsite.

In air, it shows a very distinct and rather strong pleochroism from white to dull-gray, whereas in oil the pleochroism increases. Between crossed nicols its colours vary in shades of gray, combined with a parallel extinction. Incidentally, a brown internal reflection has been observed.

Hematite.

Hematite is occasionally developed along grain boundaries of braunite, and another mode of occurrence is represented by its martite-like intergrowths with jacobsite. It frequently shows red internal reflections.

Pyrite and native copper.

Pyrite grains are occasionally visible in the Mn-silicate gangue, and the same holds for rare grains of native copper. The latter are probably responsible for the low copper content of bulk ore samples (Table I) and may be explained by the oxidizing effect exerted by the Mn-oxides upon circulating, slightly Cu-bearing hydrothermal solutions.

VI. Mineral facies and origin of the Mt. Brandnuten manganese veins.

The situation of the Mt. Brandnuten manganese veins at the western extremity of a rather varied mineral province characterized, e.g., by the occurrence in quartzitic rocks of the Telemark suite of sulphidic vein deposits of Cu, Mo, Pb, As, Bi, etc., and besides of fluorspar deposits and mica-bearing pegmatites, at a first glance might give

rise to the opinion that the manganese veins are hydrothermal vein fillings genetically connected with the adjacent intrusive granite. The mineral association of our manganese deposit, together with the poikiloblastic and granoblastic textures of its primary Mn-silicate and Mn-oxide components, speak, however, in favour of its metamorphic origin. A few late, hydrothermal minerals (fluorspar, rhodochrosite, late Mn-silicates replacing rhodonite, perhaps also hematite) and supergene psilomelane play only a subordinate part.

The primary Brandnuten manganese minerals together represent a typical example of the manganiferous rock facies known to be of widespread occurrence in the Precambrian metasedimentary series of India and designed as "gondite" by Fermor (1909) in a classical memoir. According to Fermor (l.c., p. 307), a true gondite type of rock is marked by the association spessartite-rhodonite develoved in a noncalcareous metamorphic series of sandy, argillaceous, and conglomeratic strata. As a result of recent studies of the Indian gondite series, Straczek et al. (1956, footnote on p. 67) prefer to extend the denomination gondite to a rock with variable proportions of rhodonite and other manganese-bearing silicates, which in addition commonly carries braunite.

The term "gondite" has, unfortunately, been used rather arbritarily by other authors. Dorr II et al. (1956), for instance, apply it to the manganese-silicate-carbonate protores of Minas Geraes, Brazil, which are described by them as not containing the primary Mn-oxides (braunite, jacobsite, hausmannite, bixbyite, etc.) typical for the Mn-protores of India. In their opinion, the Minas Geraes Mn-deposits were originally deposited in a reducing environment, as is indicated by the abundant occurrence of rhodochrosite and, in addition, of graphite and small quantities of sulphides (including alabandite) and sulpharsenides. The Indian protores, on the contrary, were derived from manganiferous sediments deposited in an apparently oxidizing environment. The Indian gondites, therefore, represent a mineral facies slightly different from that of the Brazilian protores. Park (1956, p. 370) even uses the denomination "gondite" for spessartite rock intermingled with largely supergene Mn-oxide ores of the Serra do Navio district north of the Amazone river in Brazil, without even having any certainty about the mineralogical composition of the primary ores in depth.

In the primary crystallization sequence of the Mt. Brandnuten vein braunite preceded hausmannite and jacobsite, since the latter two miner-

als enclose more or less rounded relics of braunite. Rhodonite equally encloses braunite poikiloblastically, whereas with hausmannite it forms irregular, worm-shaped intergrowths. The Mn-silicate crystallized, therefore, apparently later than braunite, but at about the same time as hausmannite. Its relation to jacobsite is less clear. Spessartite seems to be partly earlier and partly later than rhodonite. Rhodonite porphyroblasts enclose euhedral as well as anhedral spessartite grains, which latter sometimes seem to replace rhodonite.

Fluorspar and rhodochrosite, and possibly hematite, were probably formed as the result of the attack of the protore by late hydrothermal solutions. Narrow psilomelane vein fillings may be regarded as supergene.

The crystallization scheme of the Brandnuten vein agrees in a striking way with that established for the Mn-protores of some important manganese districts of India. In the Mn-ore region near Vizagapatam (Kodur, Srikakulam district, Andhra Pradesh) on the east coast of the Indian Peninsula, for instance, the bulk of the primary oxides in the ore bodies intercalated between the metamorphic strata of the Khondalite series is described by Roy (1960) as being constituted by braunite (main constituent), jacobsite, and hausmannite. The last-named species only occurs as an ex-solution product in jacobsite-hausmannite intergrowths known as "vredenburgite". As in the Brandnuten vein, jacobsite and hausmannite appear to be later than braunite. The only difference between the Indian and Norwegian occurrences is that in the Brandnuten vein there apparently did not crystallize vredenburgite, but separate grains of the common variety of jacobsite characterized by an olive-green hue in reflected light, and of hausmannite. Concerning the Madhya Pradesh area in the central region of the Indian Peninsula west of Vizagapatam, it is stated, furthermore, by Straczek et al. (1956) that in mixed Mn-silicate-oxide ores braunite, again the main oxide, is replaced by spessartite and subordinate jacobsite, whereas rhodonite replaces both braunite and spessartite.

According to the last-named authors, the generally E-W trending Madhya Pradesh ore belt traverses three different zones of regional metamorphism in the Precambrian series. Most deposits lie within a sillimanite zone, but eastward the ore belt crosses a staurolite-kyanite zone and a chlorite-biotite zone, respectively. In the least metamorphic area, the chlorite-biotite zone, the manganese ore is devoid of Mn-silicates and consists of fine-grained intercalations of braunite and quartzite, whereas

in the staurolite-kyanite zone braunite and quartzite become more coarse-grained and associated with abundant Mn-silicates (gondite). In the sillimanite zone, finally, the coarseness of the ore textures increases, gondite becoming in addition more abundant. It may be concluded from these observations that the replacement of braunite by gondite (rhodonite, spessartite, etc.) when going from east to west in this Indian province resulted from a gradual rise of temperature-pressure conditions in that direction in the course of Precambrian metamorphism, and that a similar process was responsible for the replacement of braunite by gondite in the Brandnuten vein. In the latter there are equally indications that spessartite was, at least partly, earlier than rhodonite.

It ought to be remarked in the context of this discussion that the phenomenon of the replacement of Mn-oxide minerals by rhodonite and other Mn-silicates as a result of regional metamorphism of a manganiferous series is by no means restricted to Precambrian Mn-occurrences. According to Zvéreff (1953), for instance, Devonian sedimentary and volcanic beds of the Urals between Miass and the upper course of the Ural river are described by A. Betekhtine to contain conformable intercalations of metamorphic manganese ore associated with jasper, in which it can be observed that rhodonite replaces Mn-oxides and cements lumps of jasper in brecciated textures. Rhodonite in its turn is replaced by bustamite and Mn-garnets, piedmontite being besides developed in tuffs adjacent to the ore beds.

The comparison of the Central Indian Mn-ore province with our Norwegian occurrence leads, moreover, to the conclusion that as a mineral facies the Brandnuten vein body belongs to the almandite-amphibolite facies as outlined by Turner (1958, pp. 228—232). The coarseness of the rhodonite in the Brandnuten vein and the apparent scarceness of muscovite in its immediate neighbourhood equate this deposit rather more with the sillimanite-almandite than with the comparatively lower-graded kyanite-muscovite-quartz or staurolite-quartz subfacies of Turner's subdivision of the alamandite amphibolite zones of high-grade progressive regional metamorphism.

It may consequently be supposed that the manganese vein of Mt. Brandnuten received its primary mineral content through regional metamorphism of a low-temperature Mn-oxide deposit conformably intercalated between the arkoses of the Telemark suite. Our present state of knowledge precludes, however, a decision concerning the mode

of formation of the original manganese bed; whether it was formed as a result of the sedimentation of Mn-oxides derived from a continental mass subjected to weathering, by the accumulation in a basin of Mn-oxides produced by some sort of volcanic exhalation process, or possibly by the deposition at low temperatures of Mn-oxides of subvolcanic origin in a bed vein at a relatively shallow depth below the earth's surface. As has been outlined by the present author in a previous publication (Westerveld, 1951), most of the Alpine manganese deposits are related, primarily or secondarily, to basic or intermediate volcanism, whereas conformable manganese deposits of some importance between Mesozoic and Tertiary strata, of which the origin can only be ascribed to pure weathering of older rocks, without any relation to volcanism, seem to be an exception. Whether this view also holds for the Precambrian era, is at present difficult to settle.

Since a few of the narrower manganese veins in the Brandnuten area have been observed to cut perpendicularly or obliquely through the stratification of the wall-rock arkoses, it might be suggested that the original low-temperature Mn-deposits were formed epigenetically with regard to the enclosing clastics. The clue to this question could only be afforded by a careful examination of the mineralogy of these cross-cutting veins, which could also have been formed through the transport of material out of the conformable main vein by hydrothermal circulation during post-metamorphic time. The influence of hydrothermal action after the formation of the main Mn-silicates, probably exerted in connection with the intrusion of the adjacent intrusive granite, is clearly indicated by the occurrence of late fluor-spar and rhodochrosite, together with minor quantities of pyrite and native copper, in the main vein.

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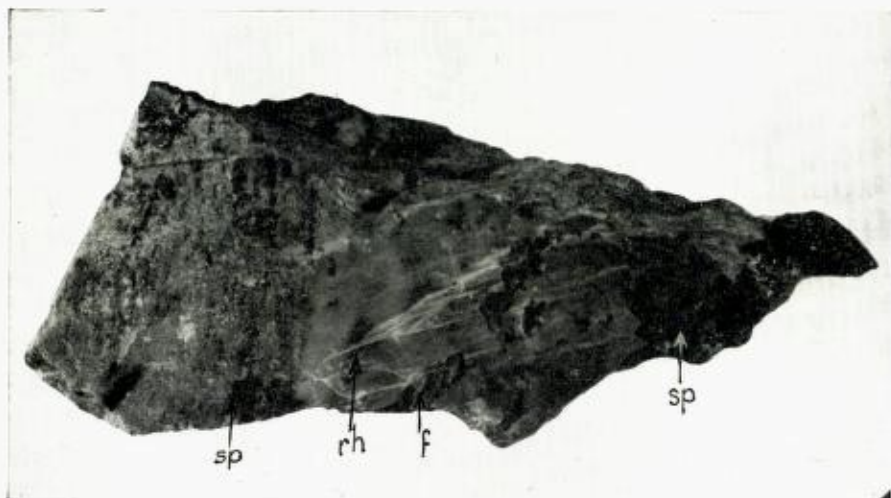
Plate I

A. *Mt. Brandnuten manganese vein; old test excavation. (Photo Dr. J. F. Brondijk.)*
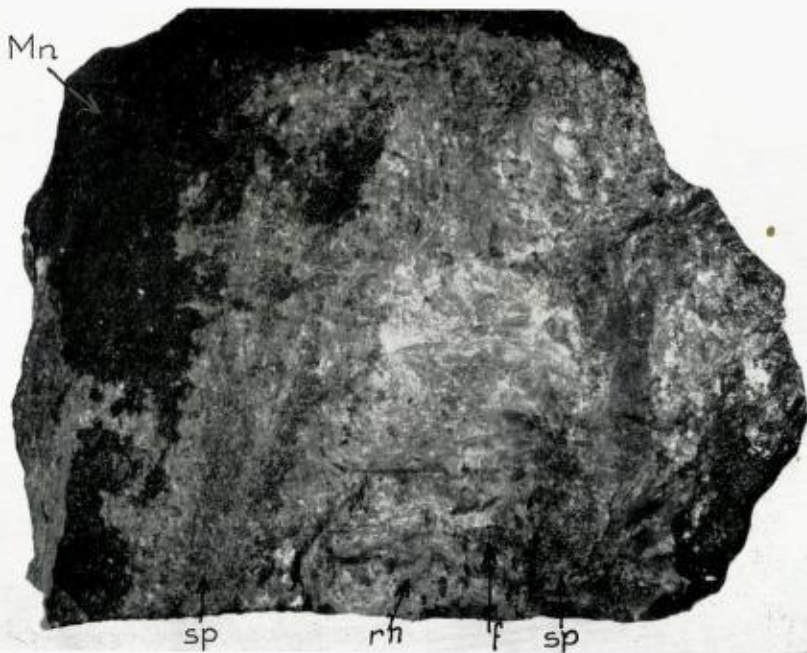
B. *Sample of massive Mn-silicate ore from the Brandnuten vein, taken 15 m N of where the latter crosses a tributary of Botne brook (rh = rhodonite; sp = spessartite; f = fluorspar; Mn = Mn-oxides). x 0.73.*
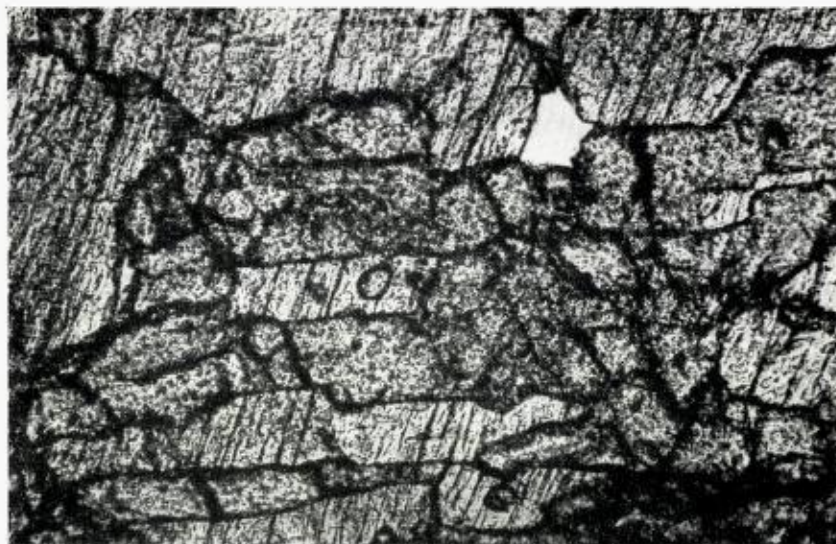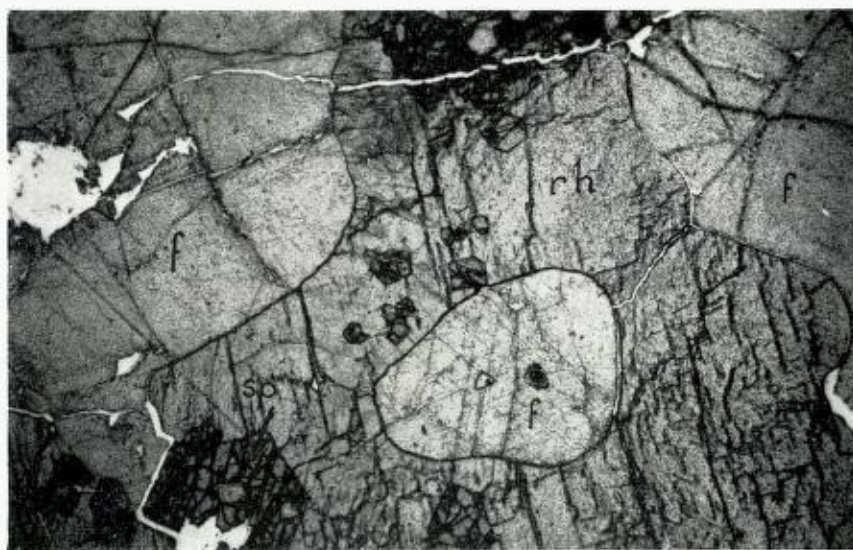
Plate II

A. *Cross-section of sample illustrated by Plate I, B (rh = rhodonite; sp = spessart-ite; f = fluorspar). x 0.57.*

B. *Large crystal of rhodonite (with marked cleavage) poikiloblastically enclosing abundant spessartite. 1 nicol, x 22.*

Plate III

A. *Lamellae of spessartite developed in almost paralell arrangement (// cleavage direction?) in rhodonite host. 1 nicol, x 123.*
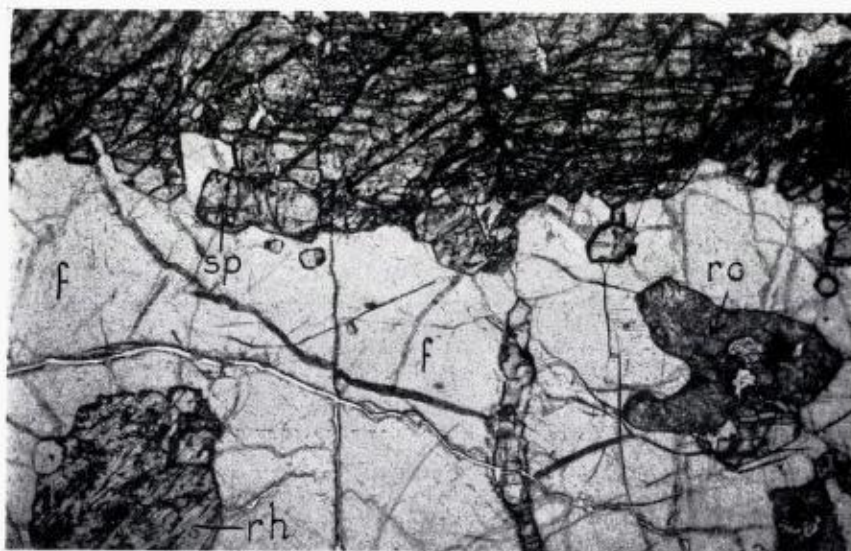

B. *Euhedral spessartite grains (sp) enclosed in rhodonite (rh) host, which is partially replaced by fluorspar (f). 1 nicol, x 17.*
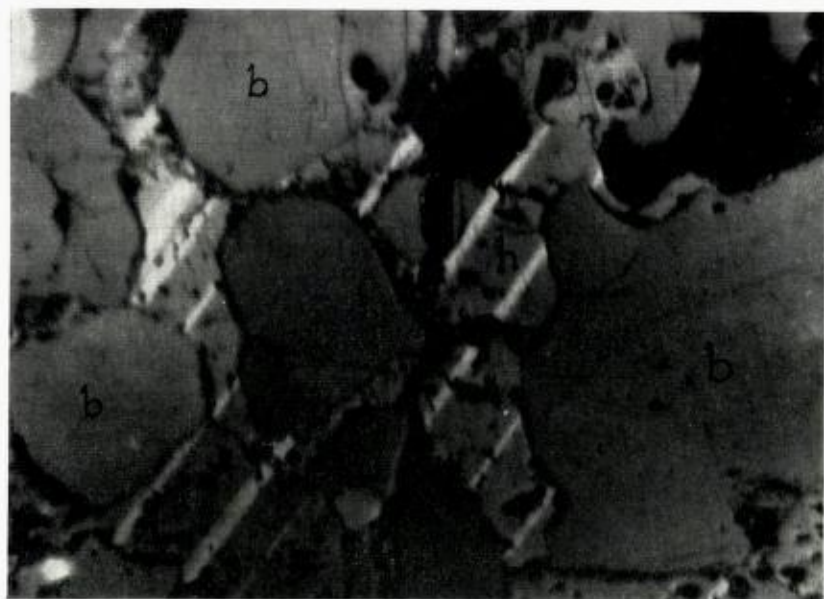
Plate IV
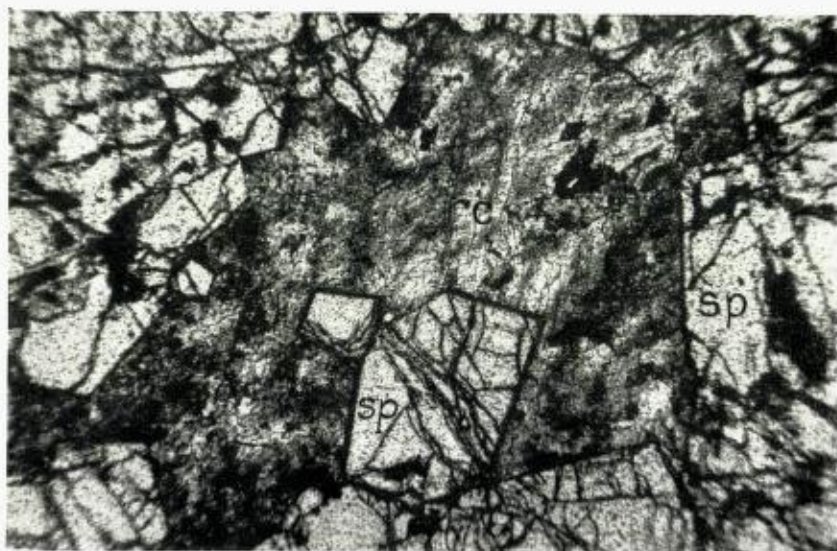
A. *Interstice between more or less euhedral spessartite (sp) occupied by rhodochrosite (rc) and subordinate fluorspar. 1 nicol, x 22.*
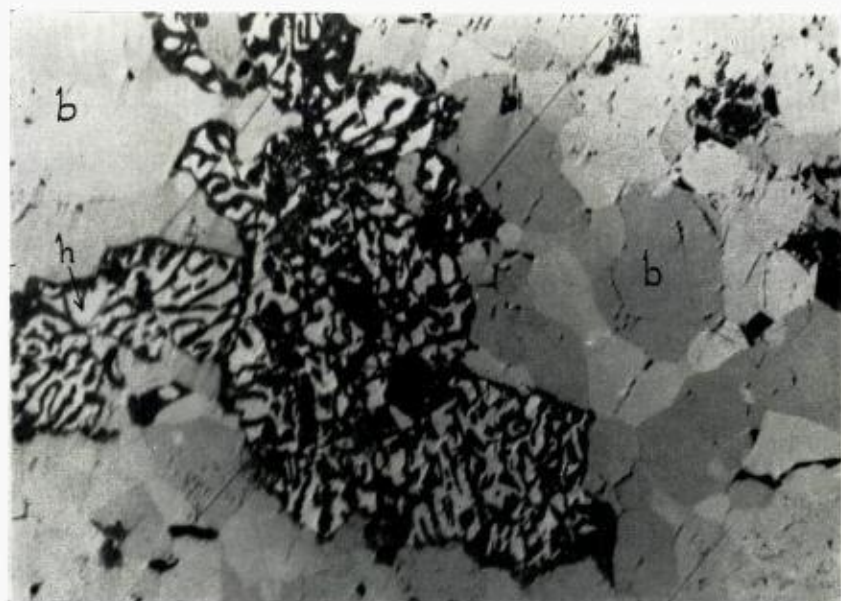

B. *Spessartite (sp), in part with euhedral crystal faces, in contact with fluorspar (f) enclosing some rhodochrosite (rc) and rhodonite (rh). 1 nicol, x 17.*

Plate V

A. *Rounded grains of braunite (b) poikiloblastically enclosed by hausmannite (h) exhibiting twinning lamellae. 2 nicols, x 167.5, air.*

B. *Mass of granoblastic braunite (b) enclosing intergrowth of hausmannite (h), apparently forming one crystal on account of simultaneous extinction of all lamellae, and Mn-silicate gangue (rhodonite). 2 nicols, x 61, air.*

Plate VI

A. *Rounded grains of braunite (b) enclosed by jacobsite (j) showing (111) cleavages filled up with gangue material. 1 nicol, x 277, oil immersion.*

B. *Jacobsite (j), partially replaced by hematite (he) along cleavage directions, and hausmannite (h) developed between braunite (b). 1 nicol, x 300.*