U.M.

REPORT

of

Committee on Thesis

The undersigned, acting as a Committee of the Graduate School, have read the accompanying thesis submitted by Myron Amos Dresser for the degree of Master of Science. They approve it as a thesis meeting the requirements of the Graduate School of the University of Minnesota, and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science.

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5

May 25 1917

REPORT

of

COMMITTEE ON EXAMINATION

This is to certify that we the undersigned, as a Committee of the Graduate School, have given **Myron Amos Dresser** final oral examination for the degree of Master of **Science**. We recommend that the degree of Master of **Science** be conferred upon the candidate.

Minneapolis, Minnesota

May 25 1917

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THE PARAGENESIS OF CERTAIN NICKEL ORES OF SUDBURY, ONTARIO.

A Thesis Submitted to the Faculty of the Graduate School

of the

University of Minnesota

by

MYRON A. DRESSER.

In partial fulfillment of the requirements for the degree

of

Master of Science.

1917.

THE PARAGENESIS OF CERTAIN NICKEL ORES OF SUDBURY, ONTARIO.

OUTLINE.

A bibliography of literature on the region is followed by a general description of the district compiled mainly from reports of the Canadian Geological Survey. Brief mention is made of geological work that has been done in the Sudbury region. A generalized descriptive account of work which is the foundation for this paper is introduced by tables covering a study, in thin sections,of the nickel-eruptive, of ores in the norite; generalizations from thin section study are made concerning ores in rocks other than the norite. Results of study of polished surfaces are divided into a consideration of ore minerals in norite, in other rocks than norite, and in specimens from the workable deposits. In an interpretation of the data studied the development of primary brecciation and schistosity in the nickel-eruptive is dwelt upon and the probabilities that such a primarily developing schist would be subject to filter-pressing, which would explain much variation in the composition of the eruptive, are discussed. Reasons are given for considering the ores chiefly segregations from the differentiated eruptive of the region, and finally the conclusions are summarized.

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General Description.

The Sudbury Nickel District is situated in the province of Ontario, Canada, about thirty-five miles north of Georgian Bay, the town of Sudbury from which the district takes its name lying in Latitude 46° 30' West Longitude 81°. To the north of this location lie the nickel ranges which in reality are one continuous oval range fringing an interior basin or synclinal trough which has an area of 550 square miles, a maximum width of 16, and a length of 36 miles. This basin, which has been described by Coleman as "roughly boat-shaped, with a blunt bow to the southwest and a square stern to the northeast,"[1] is outlined by a fringe of norite eruptive presumed to be of Keweenawan age, which underlies and encloses the synclinal sedimentary beds of the Upper Huronian making up the interior of the trough; on the outer margin at the south and east is in contact with the older quartzites, graywackes, slates, schists, and conglomerates of the Grenville and Sudbury series as well as with the greenstones and green schists of the Keewatin; and on the northwestern and in several places on the southern boundary in contact both with younger and with older granitic rocks. The nickel and copper ores are found at the lower border of the norite sheet or "nickel eruptive" as Coleman has termed it, the greatest deposits occurring under the greatest thickness of the somewhat variable norite and in those places where the older "basement" rocks are said to form a depression beneath the eruptive.

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1. Coleman, A. P., Can Dept. Min. B. 170, p. 2, 1913.

The lithologic succession of the region embraces rocks which - in a rising scale - run from the oldest Keewatin, through the Laurentian, Lower, Middle, and Upper Huronian to those of the Keweenawan age. The greenstones and green schists already mentioned as occurring to the south and east of the outcropping norite constitute the Keewatin or the most ancient of the rocks. By some authorities two series of rocks are considered intermediate between the Keewatin and the Laurentian intrusives commonly assumed to represent the period of igneous activity succeeding the schists and greenstones. The intervening rocks in this vicinity are the Grenville and the Sudburian series. The Grenville rocks have been recognized in the township of Dill some miles to the southeast of Sudbury and include quartzites, schists, gneisses, and altered limestones.[1] The rocks of the Sudburian series, however, are much more commonly found in the region than are those just mentioned; in fact, nearly two thirds of the exposures to the south of the southern boundary of the norite and within a radius of fifteen miles from Sudbury show the bedded quartzite, arkose, graywacke, schist or slate, and conglomerate of the series mapped as Sudburian, the rocks giving a total thickness of about 30,000 feet of which the quartzites make up at least a half, and all of the rocks being metamorphosed and generally tilted at high angles to the southeast. Later than the period of sedimentary deposition and alteration of the Sudburian period, but earlier than the intrusions of the Laurentian granites, came basic eruptives of gabbro, greenstone, and an "older norite" intruding the earlier sediments and following in general - along the southern

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1.Coleman, A. P., Can Dept. Min. B. 170, p. 6, 1913.

range - the same channels subsequently to be followed by the nickel-eruptive. Some acid intrusions of granite are thought to have accompanied - probably to have differentiated from - these more basic rocks, notably portions of the large granite mass south of the norite and to the west of Sudbury. The Laurentian granites and gneisses of immense extent immediately to the northwest of the Sudbury syncline already mentioned and to the southeast of that syncline beyond the intervening band of Sudburian sediments were next in the order of succession. The Lower Huronian is so inconspicuous that its correlation is not considered final and there is some hesitation in referring the boulder conglomerates found north of Ramsay Lake just to the south of Sudbury to the Lower Huronian in preference to the Middle. In case the correlation stands, the Middle Huronian may be considered absent.

The Upper Huronian or Animikiean rocks are structurally so well distinguished from the older sediments of the region that they have received considerable attention. Occurring as they do surrounded and underlain by the sheet of norite-eruptive, they constitute the interior of the Sudbury syncline and so make up the one definite and characteristic structure of the district. Being deposited after the great interval of erosion represented by the absent members of the Lower-Middle Huronian series, these rocks of the Upper Huronian are thought to have been originally laid down upon the eroded and nearly planed surfaces of the older formations.

The "nickel-eruptive" spread out beneath the sediments of the Upper Huronian division and is thought at first to have been laccolithic in its structure.[1] Later through a withdrawal of magma, or a collapse of the sustaining lower walls, or some form of regional deformation the present syncline was formed, bounded on its outer edges by the "eruptive" and showing at its center the youngest of the Upper Huronian rocks. Although the average thickness of the eruptive where measurable is only about one and one fourth miles, the mass of this igneous rock is considerable. Considering the general dip of 38 to 40 degrees toward the axis of the syncline, Coleman has estimated that the eruptive sheet contains over 600 cubic miles. The eruptive is made up of two phases, an acid micropegmatitic one above and a basic noritic one below, both considered differentiates of the same intrusion. The nickel-copper ores of the district are found either along the outer margin of the norite or along norite dikes which cut the older rocks outside the present outcrop of the eruptive.

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1. Coleman, A. P., Can. Dept. Min. B. 170, p. 10, 1913.

Essential Contributions to the Literature on the Region.

The petrography of the region has been touched upon mainly by Walker, Williams, Coleman, Howe, and Brackenbury. Walker[1] noticed that dynamic metamorphism seemed to have affacted the norite eruptive. Williams[2] made a number of accurate petrographic descriptions of various formations for one of the earlier reports of the Canadian Geological Survey on the Sudbury field. Coleman has done extensive work both in the field and in the laboratory on the northern and southern nickel ranges. He has carefully considered the mechanics of the norite intrusion and brought out the anomalous nature of the contacts of granite at Creighton with the norite, showing that although the granite is coarse grained against the norite and the norite finer in texture against the granite, stringers of the latter seem to have penetrated the norite eruptive.[3] Howe[4] among other things took especial notice of the rocks in their relation to the ore, and pointed out the quartzose character of the norite phase. Brackenbury[5] who wrote on

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1. Walker, T. L., Geological and petrographic studies of the Sudbury nickel district: Geol. Soc. Lond. Proc. 1896.

2. Williams, G. H., Notes on the microscopical character of rocks from the Sudbury district, Canada: Can. Geol. Surv. Rept. 1f, pp. 55-81, 1891.

3. Coleman, A. P., The nickel industry: Can. Dept. Min. B. 170, p. 8, 1913.

4. Howe, E., Petrographical notes on the Sudbury nickel deposit: Econ. Geol., 9, pp. 505-522, 1914.

5. Brackenbury, C., Notes on the rocks at Levack, Ontario: Bur. Min. 23d Ann. Rept., p. 194, 1914.

the rocks at Levack in the northern nickel range made note of the presence of "older norite" as a basement for the younger eruptive and noticed the peculiar fact that hypersthene was most common not far from the norite contact, or, in other words, not far from the ore.

Literature concerning the ore deposits and their probable genesis is very extensive. There are in general two views: one favoring deposition of the ores by segregation from the norite, the other referring them to a hydrothermal origin. In the first class come Brown, Barlow, von Foullon, Coleman, Thomas, Beck, Brackenbury, Daly, Lindgren, Stokes, and St. Clair; in the latter fall Campbell, Knight, Dickson, and Beck - the latter favoring "thermal enrichment," while still others, notably Howe and Tolman and Rogers believe in some modification of the magmatic theory. Von Foullon was one of the first[1/] to point out an intimate association of ores with the rock-forming silicates of the norite. Both Browne[2/] and Barlow[3/] from an early date upheld the hypothesis of segregation, the latter admitting some rearrangement of the ores, the former drawing an analogy between the separation of a nickel-copper slag and the probable manner of formation of the Sudbury ores. Beck[4/] was an advocate also of segregation but thought that hot waters or solutions rising under the norite might have had something to do with the final arrangement of the ores. Thomas[5/] upheld magmatic segregation followed by later "aqueous rearrangement." Daly[6/] regarded the deposits as segregations through gravitative adjustment, and Lindgren[7/] suggested a division of the economic history into periods covering magmatic deposition and dynamo-metamorphism accompanied by secondary deposition of some nickel and copper ores.

St. Clair[8] examined the data generally and decided in favor of segregation. Brackenbury[9] in his work at Levack noticed that the granites of the region did not carry ore except where under the influence of the norite contact, and he too favored segregation.

Campbell and Knight[10], after studying polished surfaces, decided that magnetite formed first, then the silicates, that pyrrhotite was formed, fractured, and then pentlandite and chalcopyrite introduced in the given order. The deposition, they contended, was from hot solutions. Later Knight[11] found some indications that the granite abundant in the Creighton region was later than the norite,

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1. Von Foullon, Baron, Ueber einige Nickelerzvorkommen: Jb. d. k. k. XLII, p. 276, 1892 (quoted in Trans. Am. Inst. Min. Eng., vol. 39, p. 330.)
2. Browne, D. H., Segregation in ores and mattes: School of Mines Quar. XVI, July 1895.
3. Barlow, A. E., Origin, geologic relations, and composition of the nickel-copper deposits of the Sudbury mining district: Can. Geol. Surv. Rept. 1904.
4. Beck, R., Microscopy in economic geology: Eng. and Min. Jour., p. 1087, 1913.
5. Thomas, Kirby, The ore deposits of Sudbury: Min. and Sci. Press, 105, p. 443, 1912.
6. Daly, R. A., Origin of igneous rocks: McGraw-Hill, pp. 206, 226, 349, 1914.
7. Lindgren, Waldemar, Mineral deposits: McGraw-Hill, 1913.

8. St. Clair, Sudbury nickel ores: Min. and Sci. Press, p. 213, Aug. 15, 1914.
9. Brackenbury, C., Notes on the rocks at Levack: 23d Ann. Rept. Ont. Bur. Min., p. 194, 1914.
10. Campbell, Wm., and Knight, C. W., Notes on the microstructure of nickeliferous pyrrhotite: Econ. Geol., II, 350-366, 1907.
11. Knight, C. W., Eng. and Min. Jour., 101, p. 810, 1916.

and stated that the ore-depositing solutions were after-effects of the second period of igneous activity. Dickson[1/] stated that the ores were due to a combination of hydrothermal and solfataric processes, and that the deposition took place in brecciated and faulted zones. Howe[2/] found reason to believe the ores were separated from the norite in the magma reservoir and intruded along the lower contact some time after the rock itself had been forced into place. Tolman and Rogers[3/] thought of the sulphides as neither hydrothermal nor exactly magmatic. They pointed out that all the secondary minerals of the region - except amphibole - were later than the ores. The ores they considered magmatic in depth but brought to their present position by mineralizers consequent upon igneous activity.

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1. Dickson, C. W., The ore deposits of Sudbury, Ontario: Amer. Inst. Min. Eng. Trans., vol. 34, pp. 3-67, 1904.

2. Howe, E., Petrographical notes on the Sudbury nickel deposit: Econ. Geol., vol. 9, pp. 505-522, 1914.

3. Tolman, C. F., jr., and Rogers, A. F., A study of magmatic sulphide ores: Leland Stanford Junior University Bull. 1916.

Introduction to Results of Detailed Study.

In order to facilitate the presentation of detailed work which would otherwise involve tedious descriptions, tables were made showing the constant and variable relations of rock-forming minerals in the nickel-eruptive, and showing the relation of this eruptive to the ores. Further to illustrate points brought out in two of these tables curves were drawn. An idealized section was sketched to show the horizon in the norite of various samples, thin sections of which were studied.

The Nickel-Eruptive.

I. A study of thin sections.

While little attention has been given the economically unimportant rocks in the Sudbury district, the nickel-eruptive itself has been so carefully studied by several geologists that further detailed petrographic descriptions are unnecessary.[1] It is usually thought of as being made up of two phases more or less gradually merging into one another, the micropegmatite above being a differentiate in place from the same magma as the underlying norite. The micropegmatite, as its name implies, is made up chiefly of micrographic intergrowths of quartz and alkalic feldspars; the norite, on the other hand, is characterized by more basic feldspars, ferromagnesian minerals originally pyroxenes, and the basic constituents usually found in the rocks of the gabbro family. No little confusion of terminology has been caused, however, by the peculiar alteration which has generally affected the eruptive. As is to be expected from its composition the micro-

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1. Williams, Walker, Coleman, Brackenbury, loc cit.

pegmatite has undergone relatively little change, but the pyroxenes of the norite have been completely altered to secondary amphibole and chlorite, so that the rock is now diorite, or, as was stated by Barlow,[1] "epidiorite."

Table I of the series is intended to bring out the varying relationships that may be observed in a series of specimens taken in a traverse from the micropegmatite outward to the lower contact of the norite. The micropegmatite is known to be fairly uniform in composition; the possibility of variations in the norite was recognized by the making of two independent, widely separated traverses across that phase of the eruptive above its outer margin and by taking samples at considerable intervals in the same horizon along that lower contact - in the norite.

The table, it should be stated, is in no sense to be thought of as merely statistical. The data are primarily intended for comparison. In measurement the field of the microscope was divided into quarters, these were further subdivided into eighths and sixteenths, and the amounts of various minerals were estimated. The final results, for convenience expressed as decimals, were usually estimated between limits, the ratio in all cases being an average of a number of determinations, and the entire slide being considered 1. Possible variations in critical cases are checked up by duplicate thin sections. For comparative purposes the data should be read up and down; if, however, they are read horizontally, it should be noted that the total constituents are the quartz, the feldspar, and the mafic minerals. The graphic quartz-feldspar

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[1] Barlow, A. E., Geol. Soc. Amer. 1901, p. 145 a.

Table I

Table I. Mineralogical variations in the nickel-eruptive.

(Proportions are percentages of the entire section - 1.)

Number of Specimen	1
Amount of Quartz (free quartz and quartz in pegmatite.	2
Amount of Graphic Intergrowth (Pegmatite.)	3
Amount of Perthitic Intergrowth (this often makes up a part of the pegmatite.	4
Amount of feldspar. This includes microperthite.)	5
Ratio of Felsic to Mafic Minerals.	6
Range in Composition of the Feldspars.	

38	.375 -.5	.5 - .75	.062	.25 -.5	8 - 16	Orthoclase,Perthite, Albite,Oligoclase, Andesine 1.
39	.375	.5	.062 -.125	.5	8 - 16	Orthoclase,Perthite, Oligoclase,Andesine.
40	.25 -.5	.062	.5 - .625	.5 -.75	16	Perthite,Oligoclase 7 Andesine 3
41	.25 -.375	.062 -.125	.125-.25	.5 -.75	8 - 16	Orthoclase,Perthite, Oligoclase, Andesine.
42	.125 -.25	.25 - .5	.125-.25	.5 -.75	16	Oligoclase 2, Andesine 1.
43	.062-.125	.125	.062	.5	2	Perthite,Oligoclase 1, Andesine 1.
43d	.062	.062 -.125	.062	.25 - .5	1 - 2	Perthite,Oligoclase, Andesine
63	.25 -.375	.125	.062 -.125	.5 - .625	3 - 4	Perthite,Oligoclase, Andesine
44	.031-.062	0	0	.75 -.875	> 3 - 4	Oligoclase 1, Andesine 1.
44d	.031-.062	0	0	.75 -.875	> 3	Oligoclase 1 Andesine 1
46	.031-.062	0	0	.75 -.875	4	Oligoclase,Andesine, Labradorite.
64	.031-.062	.062	.062	.75	2 - 3	Perthite,Oligoclase, Andesine,Labradorite, Bytownite
	Base of norite group begins					
36	.25 - .5	.062	0	.375 -.5	2 - 3	Perthite,Oligoclase-Albite,Oligoclase, Andesine, Lab. Byt.
37	.125	0	0	.5 - .75	2	Oligoclase,Andesine Labradorite, Bytownite.
56	.25	.062-.125	.062	.5	2 - 3	Perthite,Olig.-Albite, Oligoclase,Andesine, Labradorite
56d	.125 -.25	.062	.031-.062	.5 - .75	2 - 3	Perthite,Olig.-Albite, Olig. Andesine,Labradorite,Bytownite.
51	.25 - .5	.062	.031-.062	.25 - .5	2	Perthite,Olig.-Albite, Oligoclase,Andesine, Labradorite.
51d	.125-.375	0	.062-.125	.25 -.375	1	Perthite,Olig.-Albite, Oligoclase,Andesine, Labradorite.
50	.062-.125	.062	.062-.125	.5 - .75	2	Perthite,Oligoclase Andesine 1
49	.25 - .5	.75	.5 - .75	.5 - .75	4	Perthite, Oligoclase-Albite Oligoclase

d = duplicate
37 = "older norite" near 36.

Table II

Table II. Fracturing.

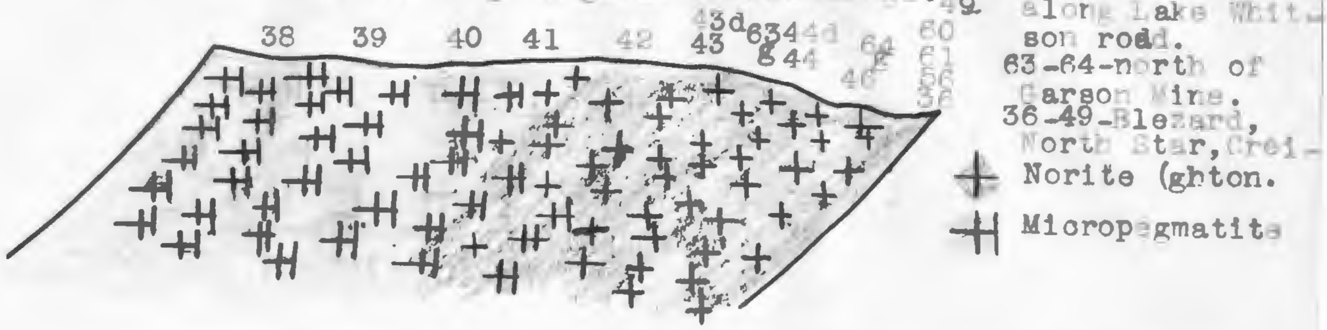
umber of Specimen	1
umber of fractures that can be raced half way across the slide.	2
rthoclase crystals fractured.	3
rthoclase crystals unfractured.	4
lagioclase crystals fractured.	5
lagioclase crystals unfractured.	6
uartz grains fractured	7
uartz grains unfractured	8
uartz-feldspar intergrowths pegmatites) fractured.	9
uartz-feldspar intergrowths pegmatites) unfractured.	10
re minerals associated with ractures or with secondary inerals in fractures.	11
re minerals surrounded by biotite uartz,etc. and not apparently elated to any fractures.	12
lagnetite associated with fractures.	13
lagnetite not associated with ractures - usually surrounded by biotite, etc.	14
re minerals enclosed in uartz-feldspar graphic intergrowth or pegmatite.	15

umber of fractures that can be

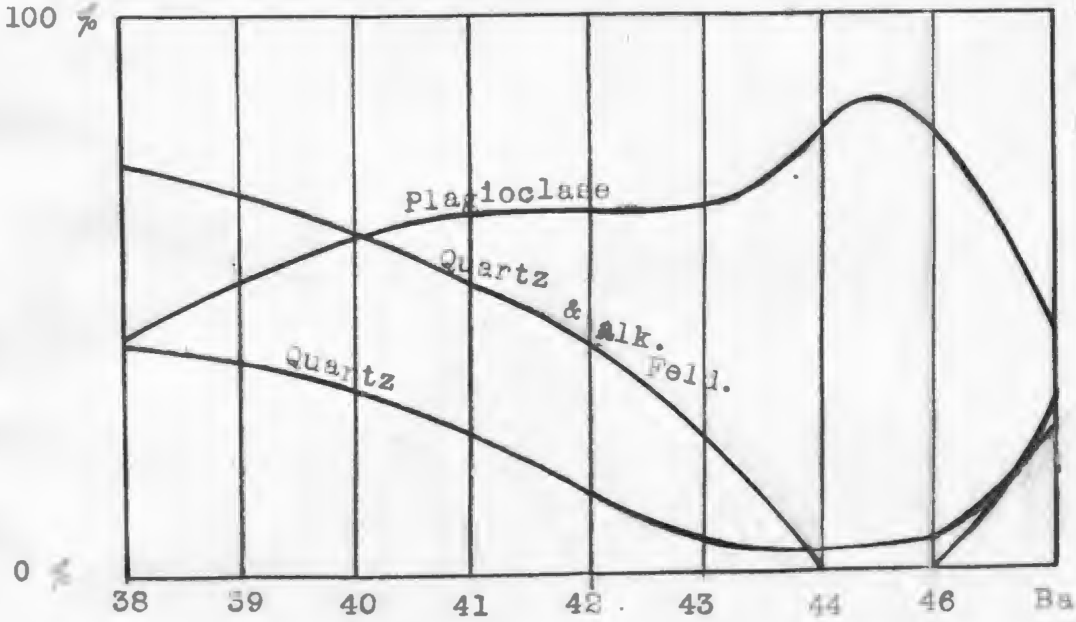
umber of Specimen

38	4	1	4	15	13	6	8	0	112	0	0	0	0	0
39	3	5	6	18	12	0	12	0	50	0	0	0	0	0
40	5	0	0	12	10	5	24	0	2	0	0	0	0	0
41	5	2	2	18	5	1	3	0	25	0	0	0	0	0
42	6	0	0	22	15	0	1	0	42	0	0	0	0	0
43	8	0	0	18	17	2	9	0	19	6	3	37	120	20
43d	6	0	0	18	15	1	3	0	14	3	3	17	115	15
3	5	0	0	16	13	3	8	0	10	0	0	30	84	0
4	5	0	0	61	25	2	10	0	0	4	0	2	0	0
4d	4	0	0	68	27	0	5	0	0	4	2	2	0	0
6	10	0	0	53	7	1	7	0	0	6	11	2	0	0
4	8	0	0	83	18	1	11	0	6	22	0	0	0	80
5	4	0	0	30	6	0	12	0	3	6	1	0	38	8
	Base of norite group begins.													
6	10	0	0	53	16	3	8	0	7	13	0	1	11	32
6d	8	0	0	37	1	4	8	0	5	6	1	8	15	15
1	11	0	0	15	16	2	17	0	14	3	1	3	12	60
1d	6	0	0	17	11	0	11	0	0	6	5	10	6	0
0	8	0	0	55	12	1	7	0	4	6	8	15	26	12
9	2?	0	0	1?	8	0	5	1?	37	13	5	3	0	300
tal	118	8	12	610	247	38	169	1	351	95	40	130	424	507
per ec.	6	.4	.6	32	13	2	9	.05	18	5	2	7	22	26
% actured		45%	60%	71%	29%	18%	82%	.26%	9272	771%	29%	23%	77%	

Ideal section showing position of certain samples with respect to geological surroundings.



Curves showing relative proportions of certain minerals and mineral combinations in eruptive.



Plagioclase-(not in pegmatite)

Quartz-(total)

Quartz plus alkalic feldspars-(mainly pegmatite)

Attention is called to the decrease of quartz and pegmatite in the "anorthosite-norite" (44-46) and to their increase again at the base of the norite.

Curve to show relative fracturing of essential minerals in eruptive.

It will be noticed that minerals last to form have suffered least fracturing.

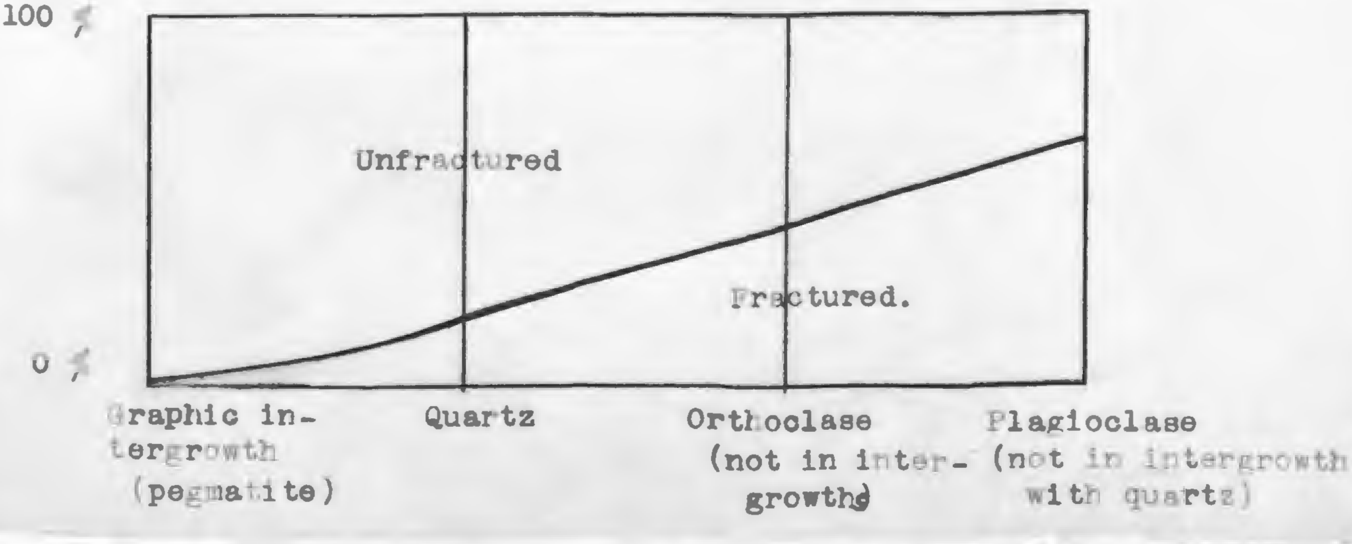


Table III

Table III. Texture of Feldspars - in millimeters.

mber of specimen	Maximum length of crystals	Maximum width of crystals	Average length of crystals	Average width of crystals

1	2	3	4	5
38	1	.7	1	.6
39	1	.4	.5	.2
40	2	1.25	1.25	.5
41	2.5	2.4	1	.5
42	3.2	.6	1	.4
43	4	.8	1.15	.5
43d	2.5	1.2	.....	.....
63	2.5	1	1.2	.6
44	2.9	1	1.5	.6
44d	3.5	1.2	1.5	.5
46	2.5	.6	1.2	.5
64	3	1.5	1.25	.4
36	1.2	.4	.6	.2
	Base of norite group begins.			
(37	2	.75	1	.4)
56	2.5	.7	2	.6
56d	3.75	1.2	2.25	1
61	2.6	.6	1	.4
61d	2	1	.7	.4
60	3.5	2	2	1
49	10	7	6	4
58	11	6		

intergrowths are included in columns for quartz and feldspar and the perthitic intergrowth with the feldspar. It was nevertheless thought advisable to list separately the proportions of micropegmatite and perthite and also a column showing the range in composition of the feldspars.

Perhaps one of the most evident generalizations that can be made is that quartz, graphic intergrowth, and micro-perthite increase and decrease together. The reason for this agreement lies partly in the fact that quartz makes up a portion, of course, of the pegmatite and in the fact that the perthitic feldspars are in most sections associated with quartz in the graphic intergrowth. The latter is interstitial between euhedral crystals of plagioclase. These perthitic feldspars frequently encountered are intergrowths apparently of potash feldspar and acid plagioclase, and are to be distinguished from poorly twinned microcline by their varying optic character, which is sometimes positive, and from any form of intermediate plagioclase by their lower index of refraction.

The transition from the zone of micropegmatite rock to norite occurs near the center of the eruptive.[1] There is a sudden decrease in the amount of quartz, pegmatite, and perthite, and increase in the proportion of ferromagnesian minerals. A short distance below this horizon the norite becomes practically an anorthosite except for the presence of a little chlorite and secondary hornblende. The texture is not diabasic. In a typical example of the phase of the norite that is composed of feldspar, coarse idiomorphic crystals of plagioclase are found generally oriented and crushed or "telescoped" into one another with but a very little

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[1] Between specimens 42 and 43.

quartz filling up the interstitial spaces. The graphic intergrowth and perthite, it will be noticed, has entirely disappeared from some parts of this "anorthosite."

But in spite of the diminution of quartz and pegmatite and perthitic intergrowths near the center of the norite, the lower norite horizon shows a very noticeable increase of the minerals and intergrowths just mentioned. Here, in comparison with the micropegmatitic phase, the quartz is less abundant, and the perthite is more common than the quartz-feldspar graphic intergrowth, the perthitic feldspars in the majority of cases being in excess feldspar ratio in the quartz-feldspar intergrowth and therefore existing separately as interstitial matter. Two specimens in the more acid part of the eruptive[1] show these same relations, but there the micro-perthitic feldspars are not interstitial; instead they form irregular anhedral grains.

The percentage of the feldspar in the rock varies with the amount of quartz and the amount of ferromagnesian minerals, the per cent of the latter being relatively constant in the norite. In composition the feldspars vary roughly with the per cent of quartz, though the greatest range of feldspars was found near the lower contact of the norite. The feldspars were studied with care as to sign, index, and extinction, but since a number were zoned, the <u>range</u> recorded does not always indicate two associated feldspars of the same generation.

The very obvious effects of dynamic action under conditions of high temperature and pressure as shown in the common occurrence of quartz replacing euhedral plagioclase and of warped, fractured,

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1. 40 and 41.

rotated, and "inter-mashed" feldspar crystals seemed to call for some sort of quantitative data in any attempt to interpret the eruptive's dynamic history. The specimens used in making Table II, covering among other things the phenomena of fracturing, were the same as those employed in Table I, and the methods, briefly, were as follows. The number of fractures that could be traced 1/4 inch or more were in each case noted. These fissures were usually filled with secondary chlorite and biotite, the latter often of the green variety, but not infrequently secondary hornblende, quartz-feldspar intergrowths, quartz - some unstrained and some fine in grain - magnetite crystals and ore minerals, especially pyrrhotite and chalcopyrite, were distinguished as fracture fillings. The number of fractured crystals or grains of feldspar and quartz having a maximum diameter of .5 mm. or over was then noted in each section and the same procedure followed in respect to the graphic intergrowths of quartz and feldspar. The idea was to determine approximately what percentage of each mineral or mineral combination had been fractured, and because the rocks were granitoid in texture, it was thought that putting some limit to the size of the grains considered would result in a fair average. In the case of the quartz-feldspar intergrowths the limitation was hardly essential, for most of those graphic structures, especially where they are less plentiful - in the basic rocks - were far above the stated diamater.[1] Since most of the ferromagnesian minerals were secondary

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[1] Inasmuch as the perthitic feldspars when in intergrowth with quartz, or when interstitial seem to have the same relation to fractures as the pegmatites and when in abundant anhedral grains show the same dynamic relations as the plagioclase, there was little to be gained by listing them separately.

and since no purpose could be served by trying to distinguish the primary biotite, the basic silicates were left out of consideration. With the purpose of bringing out any unforeseen relations, however, notation was made of the ore minerals found in fractures in relation to ore minerals surrounded by biotite, quartz, or silicates not apparently secondary. The magnetite found in fissures was contrasted with the magnetite not found in fissures. And finally the ore minerals surrounded by the quartz-feldspar graphic intergrowths were considered.

The results show that the minerals of the nickel-eruptive are generally fractured, a fact already recognized. The totals show that over half the plagioclase[1] feldspars have been fractured and with two minor exceptions the individual specimens show a balance on the same side as the grand total. A specimen from Creighton is made up largely of micro-perthite in graphic intergrowth with quartz. This micro-perthite is intruded and split apart by poikilitic quartz which is in intergrowth with other micro-perthite.

A glance at the general average for quartz shows that it is less commonly fractured that the plagioclase. The point is the more significant when it is considered that the quartz often extends poikilitically around several feldspar crystals - which are sometimes fractured.

One of the most remarkable features is the relation of the quartz and feldspar intergrowths to fracturing. With the exception of the Creighton specimen mentioned, the micropegmatites are not

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1. Orthoclase apart from intergrowths is scarcely common enough for the figures to carry the same weight as do those for plagioclase.

cut by any of the fractures developed by the dynamic metamorphism. Invariably they are interstitial among plagioclase grains, many of them fill in fractures that have developed in plagioclase, many show inclusions of secondary ferromagnesian minerals.

The ore minerals show a predominant association with fractures but the magnetite does not. It is noteworthy that ore minerals occur enclosed in micropegmatite wherever the two are to be found in the same section. The association is not invariable, for a duplicate from the North Star mine showed no pegmatite, as the original did, but more ore than the original. The association of the sulphides with this late magmatic intergrowth is important in a study of the ore.

To bring out any varying textures of the nickel-eruptive a brief tabulation was made of the size of feldspar crystals: all were included except the feldspars of micrographic intergrowths. Average dimensions much lower than the maximum in most cases indicate variation of texture in the same slide. In some specimens the presence of secondary ferromagnesian minerals made it impossible to get the average dimensions. The norite is in the average of coarser grain than the micropegmatitic phase; at the same time the norite displays greater textural variations. A specimen from the Blezard is much finer than the average, while two from the Creighton and North Star mines show exceptionally large anhedral grains of micro-perthite locally in intergrowth with quartz. The significance of this is doubtful.

Ore Minerals of the Norite.

A few distinctive relations of magnetite and sulphides to the norite in which they are often found deserve separate mention.

(See Table II.) There is a noteworthy concentration of magnetite inside the norite not far below the contact with micropegmatite. This result was checked by duplicate specimens, and similar horizons apparently were sampled on two independent traverses. From this horizon downward the magnetite varies in amount, and in a somewhat lesser ratio than that just noted is found in specimens along the lower contact.

Table II shows in a general way, also, the relative occurrence numerically of sulphide grains at the various horizons. As has been pointed out by Coleman, the size of the ore particles included in the norite increases towards the base of the eruptive so as to bring about a transition first from ore in norite to norite in ore, and finally to massive ore. Microscopically the latter is scarcely ever free from a few silicates. The most outstanding features of ore occurrences as studied in thin sections from the norite are two: first, the point mentioned in earlier papers that the ore masses often surround idiomorphic plagioclase; second, that ore particles varying from those extremely minute in the upper norite horizons to those of megascopic size in the lower portions are enclosed in the quartz-feldspar graphic intergrowths.

Sulphides in Rocks Other than the Norite.

A number of thin sections of rocks which are not norite but which nevertheless are related to the ore have been studied, and the salient facts are worthy of brief mention. A sample from west of the station on the third level of the Worthington mine shows a sharp contact of chalcopyrite with pyroxenitic wall rock; the thin section has pyroxene generally altered to chlorite and amphibole, a vein of quartz, and near it chalcopyrite intergrown with blades of chlinochlore.

Specimens taken from the dump of the Mond Nickel Company's Frood mine and from a stope in the Stobie mine, likewise a specimen from the Garson mine, southeast of the shaft on the eighth level show stringers of sulphides apparently introduced into graywacke schist. Slides from the Blezard mine show ore acting as a cement in coarse conglomeratic quartzite. A sample of metamorphosed rock near the ore is found to be chloritic schist in which veins of later spherulitic chlorite cut that of an earlier age. A comparable relation is to be seen at the Stobie mine where similar chloritic veins cut sulphides injected into schist.

Specimens taken from the Canadian Copper Company's Frood and from the Mt. Nickel mine show altered greenstones into which ores have been introduced through fissures. In the rock from the Canadian "Frood" mine an instance is noted of a rounded quartz feldspar completely enclosed by ore. No other such intergrowths are met with either in this section or in the corresponding one from the Mt. Nickel property.

Aside then from ores in norite, the sulphides are found introduced into hydrothermally altered pyroxenite, into graywacke schist, into quartzose conglomerate, and into greenstone. A still further type of rock outcrops north of the open pit at the Blezard mine and not unlikely is the "older norite" which Coleman has suggested[1] occurs here and at many places along the norite contact. The composition and texture of this rock[2] are shown in Tables I and III. The rock is characterized by unaltered hypersthene and

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1. Coleman, A. P., Can. Geol. Surv. Mines Branch, 170, 1913, p.78.
2. No. 37.

only slightly altered diallage, by the absolute lack of any shattering or strain effects in the feldspars, and by a "normal" order of crystallization, accessory sulphides and magnetite having formed first, then the mafic and the felsic silicates. In these respects there is a decided variance from the basic portion of the nickel-eruptive. The sulphides, moreover, show no signs of concentration.

II. Work on polished surfaces.

A study of the ore minerals by means of polished surfaces and arc-light illumination with the reflecting microscope has determined the relations of the sulphides to each other and in a more general way to the associated rock. For mineral determinations recourse was had to Murdoch's[1] tests by etching; in all cases acids were used for identification purposes inasmuch as color and general appearance vary to the extent of proving very deceptive criteria. At the beginning known minerals were examined and the results obtained compared with those from doubtful material. The specimens considered were classified into sulphides in the norite, sulphides in rocks other than the norite, and sulphides from the larger masses of workable ore.

Polished surfaces of ores in norite were made of specimens from the Worthington, Gertrude, Creighton, North Star, and Stobie mines. The results may be rather generally and briefly summarized. The only sulphides found were pyrrhotite, pentlandite, chalcopyrite, and polydymite. Their proportions were so variable as to permit of no definite statement concerning their relative amounts, the only constant being the insignificant but persistent quantities of polydymite. Contacts of ores with norite were both rounded and

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1. Murdoch, J., Microscopical determination of opaque minerals, J. Wiley & Sons, New York, 1916.

angular; as a rule small inclusions of rock in ore were rounded, while larger ones were defined more sharply. Much of the ore was surrounded by rock and this rock in turn surrounded by the sulphides. Repeatedly ores were found in embayments in the "silicates." In those quartz-alkalic feldspar intergrowths which by their color could be megascopically located, sulphides were found "peppered" through the intergrowths in the same relations as shown in the thin sections. One of the most striking features was the occurrence of sulphides interstitial between clearly outlined, euhedral silicates.

Between the sulphides of the norite the relations are exceedingly variable. Pentlandite surrounds pyrrhotite, and chalcopyrite cuts across pentlandite. On the other hand, nearly as many cases were encountered in which pentlandite was completely surrounded by pyrrhotite, and chalcopyrite entirely enclosed in pyrrhotite and in pentlandite. In a sample from the third level, stope 31 of the Worthington mine all three of the principal sulphides were irregularly but intimately intergrown. Lack of agreement is shown here with the work of Campbell and Knight[1] and of Tolman and Rogers,[2] for a definite order of formation: pyrrhotite, pentlandite, and chalcopyrite was asserted. Too much emphasis can not be laid upon the apparent lack of an unvarying order of formation if many cases be considered in an extensive suite of specimens.

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1. Campbell, Wm. and Knight, C. W., Econ. Geol. vol. 2, p. 350,1907.
2. Tolman, C. F.,jr., and Rogers, A. F., Magmatic sulphide ores: Stanford Univ. Bull. 1916.

Polished surfaces of ores in rocks other than the norite show the same sulphides in the same inconstant proportions, but many of the larger ore masses are connected by stringers cutting across all the intervening rock.

In the actual ore bodies the rather intimate relations of the sulphides are displayed in a sample from the Stobie mine, showing, almost in the same microscopic field, chalcopyrite intergrown with pentlandite, and pentlandite intergrown with both pyrrhotite and polydymite. In specimens of ore from the deposits of the Blezard and Mt. Nickel mines two or three fine veins of silicates were seen crossing the ore just as do the veins of spherulitic chlorite in thin sections from the Blezard and the Stobie. In the ores that are worked, in the ores in the norite, and in the ores introduced into the pre-Keweenawan rocks of the region the paragenesis of the chief sulphides seems identical.

From some of the workable deposits pyrite was added to the list of sulphides found; namely, from the Stobie, Mt. Nickel, and Worthington mines. The pyrite in the Stobie specimen was only a very small per cent. In the Mt. Nickel ore, on the other hand, masses of pyrite were often fringed by chalcopyrite which in turn was in contact with pentlandite; in one case a mass of pyrite was completely surrounded by the pentlandite. One sample from the Worthington mine showed pyrite, pentlandite, and chalcopyrite all in close association and enclosed or surrounded by pyrite. A final polished surface of "nodular" ore taken from the immediate vicinity of a slip in the Worthington mine gave massive pyrite enclosing rounded chalcopyrite unassociated with other sulphides. In the first sample from the Worthington and in the Mt. Nickel specimen pyrite and the other sulphides were cut by a few fine veins of silicate comparable to those already mentioned in ores from the Stobie and Blezard, but in the "nodular" ore no such veining was observed.

In resumé,- polished surfaces of ores in the norite, ores in rocks older than norite, such as greenstone and schist, and the ores from the deposits all show interpenetrating sulphides of no definite order of growth. In all rocks but norite, however, the sulphides have apparently been introduced along fissures or along the schistosity. In the norite, ores are definitely found to be intergrown with silicates. In one instance where associated with a fault in the ore body, the sulphides show relations to each other not at all characteristic of the ore bodies as a whole.

III. Interpretation of the data studied.

A. The Nickel-Eruptive.

There seems to be no evidence contradictory to the conclusion usually held that the nickel-eruptive has differentiated in place. Although many physico-chemical processes have been postulated by which the magma might have become separated into its acid and basic phases, the facts obtained from microscopic study do not seem to warrant any detailed consideration of the convection currents, Soret's principle, and limited miscibility over which controversy has raged. However, since differentiation took place, it probably occurred as some modification during crystallization. It might be suggested further that the great range of composition and variety of texture found at the lower border of the norite indicate less uniform cooling than at the center of that phase. The norite specimen from the Blezard mine may well be considered an example of the more rapid freezing of the magma; samples from the Creighton and North Star mines show micro-perthite in large crystals. These large crystals in the norite point to extremely slow solidification, and their presence and the field relations[1] support the possibility already suggested by others[2] that the Creighton granite and the norite are nearly simultaneous intrusions.

The general orientation and shattering of feldspar crystals in the norite indicate considerable dynamic effect on the eruptive. The common occurrence of warped and twisted crystals of feldspar and the frequent replacement of the feldspars by quartz point to conditions of extremely high temperature and pressure at the time of metamorphism. The comparative freedom of the quartz from fractures in contradistinction to the plagioclase crystals and the almost complete freedom of the quartz-feldspar intergrowths from any fractures microscopically identifiable are taken as indications of a primary or magmatic development of the brecciation and schistosity. The presence of the poikilitically interstitial quartz and pegmatite as fracture fillings in the broken feldspars is thought to support this contention.

Whatever the orogenic movements by which the formation of the Sudbury syncline was occasioned, whether by a withdrawal of a portion of the magma or by a failure of the underlying Archean

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1. Barlow, A. E., Origin, geological relations, etc. of the nickel-copper deposits of the Sudbury district: Can Geol. Surv. 1904.

2. Coleman, A. P., Can. Geol. Surv. Min. Bull. 170, p. 8, 1913.

Knight, C. W., Eng. and Min. Jour., vol. 101, p. 810, 1916.

support, some disturbance must have taken place at that period in the history of the eruptive when the plagioclase had been formed into euhedral crystals and the smaller amount of micropegmatite or graphic intergrowth and some of the quartz were still in a molten, very fluid state. Needless to say, the development of the syncline came after the differentiation of the eruptive into acid and basic phases - the magma could not have differentiated after so wholly crystallizing. Needless also again to mention in much detail the fluidity of the interstitial liquor - as seen by the warping of feldspars and their replacement by quartz - and therefore the susceptibility of the molten acid residues to removal by processes such as filter-pressing which might be brought about by any extensive dynamic disarrangement. Under conditions of the deformation of a partially plastic magma to such an extent as to brecciate the feldspar crystals there can be little question that the hot solutions and aqueous vapors usually associated with those acid residues would more or less completely alter the pyroxenes already formed. The alteration is not a superficial one; drillings have shown that at a depth of over a thousand feet the norite has been deformed and altered in the same way as it has nearer to the surface.[1] It would seem that the unshattered and unaltered norite near the marginal deposits might/be attributed to the "older norite" formed prior to the intrusion of the nickel-eruptive.

If there were such orogenic movements as have been suggested, there would not only be magmatic rearrangement and brecciation and alteration of the minerals already formed, but also a tendency of the interstitial fluid to move towards any points of relief from

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1. Coleman, A. P., Ont. Bur. Min. XIV, 1905, pt. 3, p. 111.

pressure. Such a movement or filter-pressing is especially indicated in the anorthosite-norite phase already described by the occurrence of colliding or telescoping euhedral plagioclase; it is indicated both in the upper micropegmatite phase of the eruptive and in the lower portion of the norite, where quartz and graphic intergrowths of quartz and feldspars once more come into prominence, by the occurrence of fractured plagioclase crystals entirely surrounded by the unfractured and more acid material. In the anorthosite-norite the plagioclase crystals must have been nearly formed at the time of separation and lodgment else, through additions from interstitial mother liquor, they would have grown anhedral boundaries. Originally the crystals no doubt were not well oriented and were not in close contact with each other, since they had not yet been forcibly rearranged. The spaces between them must therefore have been much greater than at present, and these interstitial spaces can have been filled by nothing but the still molten acid material - molten because since it was squezzed out by the dynamic movement, it could not have been otherwise. Furthermore, it is inconceivable how feldspars at the base of the norite and in the acid upper differentiate could have been fractured, if at the time of shattering they were surrounded by the liquid magma which is now unfractured quartz and pegmatite.

It is considered likely that differential pressures arising during the formation of the syncline resulted in the filter-pressing of residual magma at the time the primary schistosity developed, and consequently in the production of an anorthosite in that central horizon of the norite deprived of its interstitial liquids, and in the flooding or floating of the shattered feldspars along the margins of the eruptive by the expelled acid residuals. There seems no likelihood that the micropegmatitic intergrowths and quartz at the outer lower contact of the norite are in any sense "additions" to the nickel-eruptive. The interstitial quartz and pegmatite are, as shown in Table I, an essential part of the eruptive, varying only in proportion. The perthitic feldspars in intergrowth with quartz at the base of the norite are identical with those in the pegmatites of the acid differentiate. And the interstitial materials are as commonly found near the contact of the norite with the greenstone as at the contact of norite with granite; since on the whole they constitute nearly twenty per cent of the nickel-eruptive, they can be referred only to the original intrusion of the magma.

B. The ores and magnetite.

As may be seen from Table II the magnetite is most abundant at a horizon one half to three fourths of a mile in from the lower contact, or a somewhat lesser distance "stratigraphically." From that point downward it is found in varying amounts, sometimes associated with the sulphides, enclosed by them and enclosing them. Its presence in fissures in the plagioclase (see Table II) indicates that at least some of it formed after the development of the primary schistosity. Although relatively unimportant, this localization of the oxide far above the base of the norite is both interesting and difficult to explain.[1] It is thought possible that the magnetite or the part of it fluid at the time of the eruptive's deformation

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[1] A purely speculative idea that for a time seemdd attractive involved the separation of heavy minerals from the upper of two immiscible differentiates and the suspension of these separates by means of surface tension at the contact of the immiscible phases. The hypothesis was discarded because, among other things, the micropegmatite and norite were probably not immiscible.

was squeezed outward, and because of the weight perhaps mostly downward, but at a certain point began to crystallize and was locked in by the framework of plagioclase euhedra.

The sulphides are considered of magmatic origin. Their occurrence surrounding plagioclase euhedra shows that the ores formed after the plagioclase substance ceased to form distinct crystals. The abundance of sulphides enclosed in quartz-feldspar intergrowths, however, points to the solidification of the sulphides before the final solidification of the rock. The relation of the sulphides to each other in the workable ore are the same as in the norite - there is, as stated, no definite order of formation such as might be expected to result from distinct periods of deposition. There is no sign of alteration or any other evidence to suggest the two thirds of the ore making up the workable deposits is in any way distinctive from the other third associated with the norite. The introduction of <u>all</u> the ore - in the deposits and in the norite - as, for example, from the magma chamber or from some other outside source,- would require also the addition of all the felsic material which surrounds the ores in the norite, and this has already been pointed out as improbable.

Not only do the sulphides show the structural and paragenetic characteristics of segregations from magmas, but also negatively, the lack of association with any other type of activity competent to cause their deposition. The negative evidence, however, has sometimes been over emphasized. In proof of the independence of these ores from hydrothermal origin, the statement has been made by some authorities[1] that all secondary minerals with

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1. Tolman, C. F., jr., and Rogers, A. F., Study of magmatic sulfid ores: Bull. Stanford Univ. 1916.

the exception of the hornblende were later than the ores. Veins of chlorite are described as cutting both ore and rock.[1] Thin sections examined in the course of the present work show that these veins of chlorite developed at an earlier stage. There were, then, two stages of alteration, the first during the time of magmatic rearrangement and ore deposition, and the second at some subsequent period. These later veins of hydrothermal minerals are, furthermore, so small and so uncommon that they have probably little bearing upon the history of the deposits. The only effective alteration of the norite is that closely following its intrusion and differentiation, and this change took place even before the minerals last to form had crystallized. Locally there is some hydrothermal action and some redistribution of pyrite and chalcopyrite limited to a few faults in the massive ore. Locally, too, there has been some cold water solution and redeposition,[2] but on the whole both of these activities seem insignificant. The rather common appearance of ore in schist and greenstone might at first seem incompatible with magmatic origin, but these - usually uncommercial - ores are shown above to be probably injected into the older rocks. This relation is not unlikely in view of high conditions of temperature and pressure prevailing in the eruptive at the time of the formation of the syncline.

Although the segregation of the ores from the norite may have been effected by a combination of processes, the means of accumulation are limited to those changes which can have occurred

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1. Tolman, C.F., jr., and Rogers, A.F., op. cit., Pl.II, fig. 13.
2. Crustification banding of marcasite with calcite is rather frequent in the Worthington mine.

under the conditions then prevalent. These conditions made it impossible for the sulphides to accumulate by marginal cooling and fractional crystallization - since the ores were not among the first minerals to form. For the same reason the sulphides could not have separated by gravity after crystallizing; they could never have worked their way downward through the network of feldspar crystals now overlying the ore. But immiscibility with the norite below a certain temperature may have been a factor in the ore separation. Here it does not seem improbable that several stages in the physico-chemical history slightly overlapped, that while part of the ore did manage to separate through immiscibility, the remainder was retarded in its segregation and locked up still molten in the norite by the crystallizing plagioclase. At the time of the dynamic action these molten sulphides, distributed through the partly crystalline norite, were, in common with the still liquid felsic material, filter-pressed away from the interior and driven to the margins of the eruptive. These outer borders under the conditions of molten ores at the base and probably molten acid differentiate at the top would offer relief from pressure. But whereas the acid residuals, being the lightest of the still molten material, would be likely to accumulate further at the top, the ores, likewise because of specific gravity, would more likely be pressed downwards towards the outer edge of the syncline. And in going down they might very well carry with them the acid residuals below them in the norite. Thus one might account both for the ores still associated with the norite and for the quartz and pegmatite so characteristic of the lower part of the norite differentiate.

In either process of immiscible separation or filter-pressing it will be seen that there might result a sheet of molten ore below the norite while that rock was in its final stages of crystallization. There is little doubt that agitation and local weaknesses would cause blocks of norite to sink for a short distance into the molten sulphides and that, correspondingly, stringers of the sulphide would "wriggle" upward in the hanging wall. These relations are admirably displayed in various mines where coarse "norite breccias" are cemented by the ore.

Final Conclusions.

It is known that minerals of the norite are brecciated and that the fractures are limited to the minerals first to form. This limitation shows that the minerals were oriented and made schistose probably at the time the Sudbury syncline was developed, and certainly at a time before the norite had entirely solidified. Filter-pressing might well accompany such "magmatic deformation."

The ores, the quartz, and the micropegmatite are all late in period of formation. The interstitial quartz and micropegmatite form an essential portion of the eruptive; they surround the ores in norite and are later than the ores in order of formation.

The ores are chiefly of magmatic origin; they were still molten and segregating when the norite was deformed and altered; in the segregations they display the same relations as to intergrowth with each other as in the norite; they are earlier than the last hydrothermal alteration - which was insignificant; where found in rocks other than norite they are injected, possibly from the segregated mass.

The ores are known to have formed liquid masses below the norite differentiate and to have intruded and brecciated it. The separation may be due to immiscibility, but it is suggested gravity and filter-pressing may have been factors in squeezing out molten ores and acid residuals from the norite after it had begun to crystallize.

Plate I.

A. Quartz Replacing Plagioclase

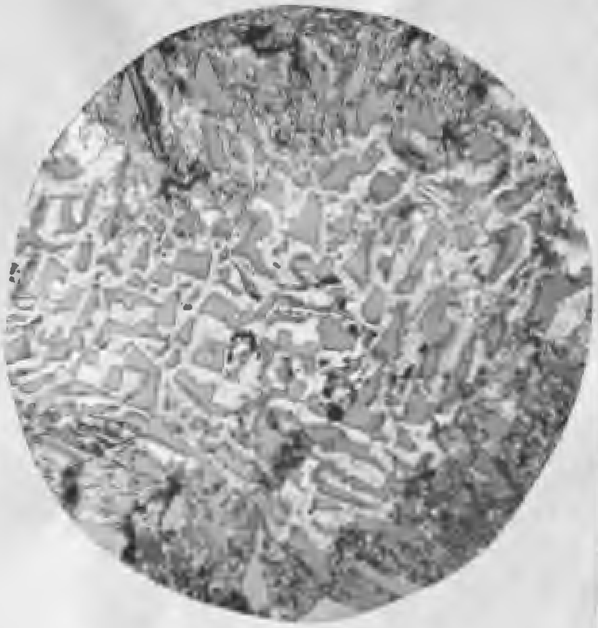
B. Warped Plagioclase

C. Fractured Plagioclase

D. Rotation of Fragments of Broken Plagioclase

Plate II.

A. Micropegmatite in Fractures in Plagioclase

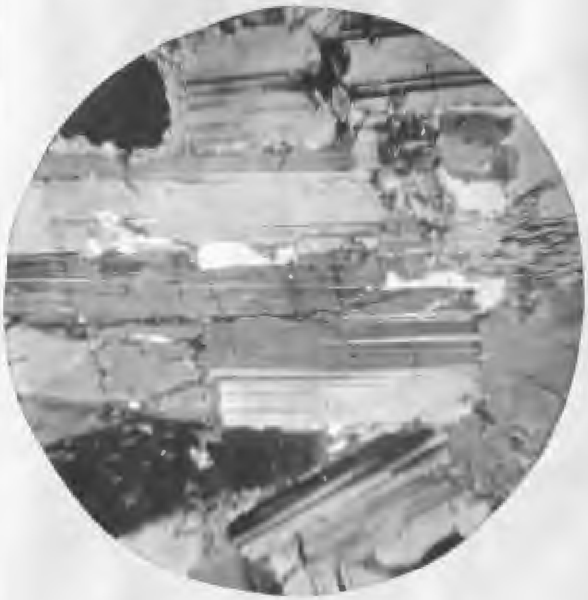


B. Ore Minerals Enclosed in Pegmatite

C. Ore Interstitial to Plagioclase

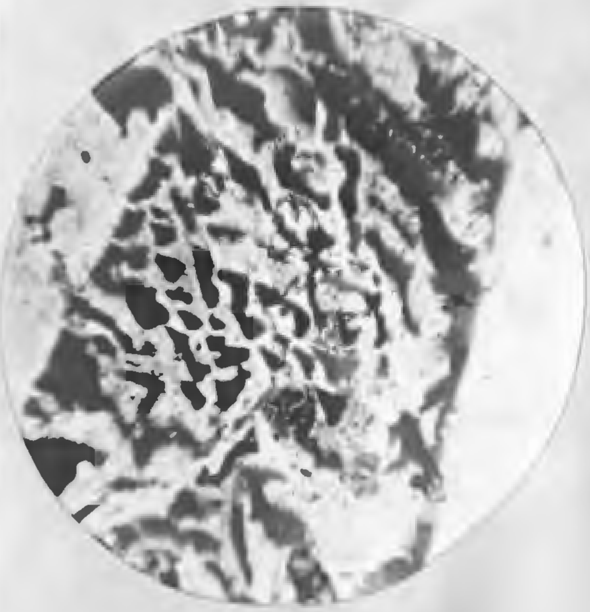
D. Fractured Plagioclase Beside Unfractured Quartz

Plate III.

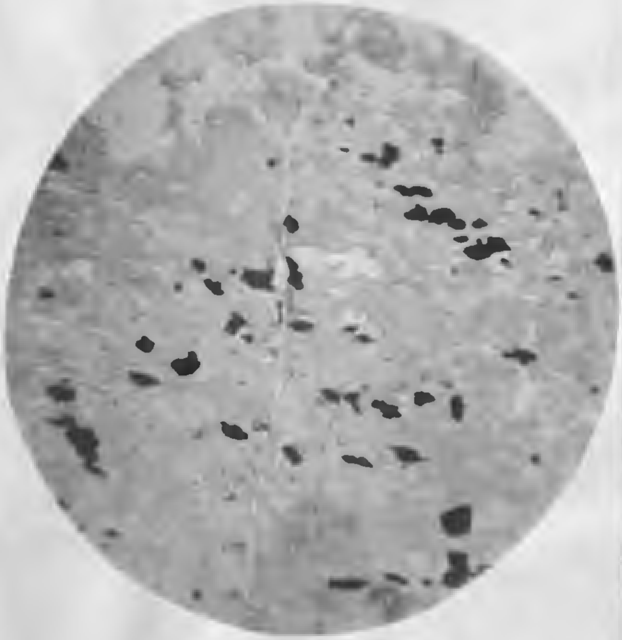


A. Oriented Feldspars in Anorthosite-Norite

B. Micropegmatite Around Euhedral Plagioclase



C. Ore in Micropegmatite



D. Chlorite Veins Cutting Chlorite and Magnetite

Page	Line	correction
17	6	1/4 inch ✓
17	next to last	plentiful ✓
18 -	last	not. ✓
22	9	Minneapolis
23	6	;
24	23	mine mine,
26 -	9	indicate
26 -	10	point
26 -	15 -	are taken as indications of
27	22	be,
28	14	omit all.