

The Ore-Deposits of Sudbury, Ontario.

BY CHARLES W. DICKSON, COLUMBIA UNIVERSITY, NEW YORK CITY.*

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I. THE RELATION OF NICKEL TO PYRRHOTITE.

Introduction.

The Sudbury district is to-day one of the two great sources of nickel in the world. The peculiar geological relations of

the ores have long attracted attention, and widespread interest has been aroused by the differences of opinion regarding their origin, whether as igneous segregations or as precipitates from solution. The writer has endeavored to attack this problem with the aid of microscopical and petrographical methods. The field-work of these investigations was carried on during the summers of 1901 and 1902, and the material collected was worked up at Columbia University, New York, during the sessions of 1901-'02 and 1902-'03.

As a necessary preliminary, it was thought advisable to investigate carefully the chemical composition and geological relations of pyrrhotite, as well as the mineralogical associations of the Sudbury ores.

Minerals of the Sudbury Nickel-Region.

Pyrrhotite and chalcopyrite, associated with fragments of the enclosing rock, are the predominant minerals of the Sudbury deposits. The nickel-mineral pentlandite, which is the principle source of this metal, is distributed through all the ore-bodies in greater or less amount. Its matrix is almost universally pyrrhotite, though a number of exceptions occur, notably at the Copper Cliff mine.

This mine, which has furnished a number of interesting minerals, contains in the lower levels some massive ore, composed very largely of chalcopyrite intimately associated with pentlandite. Other samples from the same place consist of pyrite and marcasite, also with an intimate mixture of pentlandite.

Millerite is encountered, though rarely. In a sample from the Copper Cliff mine, the writer found small bunches of hair-like crystals of this mineral in the cavities of some radiating pyrite mixed with calcite. It has also been reported in a number of other cases. The millerite is undoubtedly secondary, and was probably derived from pre-existing pentlandite.

Polydymite (Ni_4S_8 , with one part of nickel replaced by iron) containing platinum, was described by Clark & Cattlett.*

Niccolite, gersdorffite, danaite and arsenopyrite (containing cobalt) occur in several localities in Denison township, though

* This paper was presented by the author as a dissertation for the degree of Ph.D. at Columbia University, New York City.

* *Am. J. Sc.*, vol. xxxvii., 1889.

the association is not exactly similar to that of the typical deposits.

Pyrite is by no means uncommon, and Walker has described a nickeliferous variety (over 4 per cent. nickel) from the Murray mine. A number of samples of this mineral from the Copper Cliff mine were associated with secondary quartz, calcite and millerite. On analysis, they yielded from a trace to over 3 per cent. Ni, which, however, may be due to an intimate mixture of pentlandite or millerite.

Samples of a compact, whitish or steel-grey mineral, containing a considerable amount of pentlandite, were submitted by the writer to Prof. Penfield, who considers them to be massive marcasite. The analyses conform to the formula FeS_2 , and show the presence of from 2 to 4 per cent. Ni, probably as pentlandite.

Sperrylite (PtAs_2) was originally found in the gossan at the Vermilion mine. The writer has also isolated it from the unaltered chalcopyrite of the Victoria mine (see p. 9).

Galena occurs rarely in streaks through the pyrrhotite, *e. g.*, at the Mount Nickel mine, Blezard township.*

Native copper is reported in a few instances in leaves in the associated rocks. Secondary copper-minerals are rare; but bornite is occasionally seen.

Small masses of titaniferous magnetite (with as much as 18 per cent. TiO_2) are at times found.

This list is probably not complete, but represents the most important minerals found by the writer or recorded by others.

S. H. Emmens† describes what he calls several new species of nickel-minerals from Sudbury. But the doubtful purity of his material and the analytical methods employed do not warrant the recognition of these new species.‡

As a preliminary to the discussion of the relation of the nickel to the pyrrhotite and its associates, a brief review of our knowledge of pyrrhotites will be given; since the uncertainty

* Specimen kindly furnished by Prof. W. G. Miller, Provincial Geologist of Ontario.

† *J. Am. Ch. Soc.*, vol. iv, No. 7.

‡ S. L. Penfield, "On Pentlandite from Sudbury, Ont., Can., with Remarks upon Three Supposed New Species from the Same Region," *Am. J. Sc.*, vol. xlv, June, 1893.

which prevails regarding the exact chemical composition of pyrrhotites is probably not generally appreciated by students of ore-deposits.

Pyrrhotites in General.

For many years the composition of pyrrhotite has presented to chemists and mineralogists a most difficult and interesting problem, to a large extent still unsolved.

Various writers have applied to this mineral formulas which range from Fe_3S_4 to $\text{Fe}_{16}\text{S}_{11}$. In general terms it is usually expressed as $\text{Fe}_n\text{S}_{n+1}$. By some it is regarded simply as FeS with impurities.* Others consider it as varying molecular mixtures of different sulphides, as $n\text{FeS} + \text{Fe}_2\text{S}_3$ or $n\text{FeS} + \text{FeS}_2$. Bodewig's† and Doelter's‡ formula was $\text{Fe}_{11}\text{S}_{12}$.

In other words, "pyrrhotite" is regarded, not as a mineral in the true sense of the term, but as a series of minerals, differing slightly from each other in the relative proportions of their constituents. If this is the correct view, the case is unique. Homologous chemical series are by no means uncommon, but in these there is always a gradual change in the properties of the different members; the extremes being so entirely unlike as hardly to be recognizable components of the same group. There seems, however, to be little, if any, difference between pyrrhotites represented by Fe_3S_4 and $\text{Fe}_{16}\text{S}_{11}$. It should thus be possible to grade imperceptibly from the monosulphide FeS to the disulphide FeS_2 , when a pyrrhotite with the composition of pyrite would result. But such a view does not seem reasonable, and is opposed to some of the fundamental laws of chemistry. It seems more reasonable to consider many of the so-called "pyrrhotites" as mixtures of other sulphides with this mineral, and to regard the latter as of a definite composition.

A fact which may have an important bearing on this question is that of the magnetic permeability of different pyrrhotites. In the preparation of various samples, as noted later in this paper, some were observed to be much more magnetic than others, the strength of attraction by a small magnet being, in a

* Weinschenk, Groth's *Zeit.*, 17, 499; Lorenz, *Berg. d. chem. Ges.*, 1891, 612.

† Groth's *Zeit.*, 7, 180.

‡ *Tsch. Mitth. N. J.*, 7, 544. A synopsis of the results obtained by different writers will be found in the *Handbuch der Mineralogie*, Hintze, vol. i., p. 621 et seq.

general way, proportional to the percentage of iron. Further investigation along this line may lead to important results.

It should be borne in mind, however, that lack of care in the preparation of samples for analysis may account for many discrepancies, especially as few pyrrhotites are entirely free from other sulphides in more or less intimate mixture.

The inaccurate methods of analysis, and difficulties of manipulation, will also cause many errors. That the reliability of many analytical methods is open to question is shown by the animated controversies of experts in recent years.* Errors amounting to 0.75 per cent. in the estimation of sulphur are not uncommon, and in many cases they are possibly larger. The iron-results are also apt to be unreliable.

In a number of determinations on the same sample Habermehl† obtained results in which the sulphur varied from 39.10 to 39.71—a difference of 0.61, and iron from 60.28 to 60.79—a difference of 0.51 per cent. When we consider the theoretical compositions represented by the compounds varying from FeS to FeS₂, it is seen that a comparatively small error would change the formula calculated from the analysis. The calculated composition for different formulas would be as follows:

Formula.	Iron. Per Cent.	Sulphur. Per Cent.	Formula.	Iron. Per Cent.	Sulphur. Per Cent.
FeS,	63.61	36.39	Fe ₈ S ₉	60.80	39.20
Fe ₁₅ S ₁₆ ,	62.06	37.94	Fe ₇ S ₈	60.40	39.60
Fe ₁₁ S ₁₂ ,	61.60	38.40	FeS ₂	46.60	53.40

A few analyses made by prominent workers (see Table I.) will show the wide variation, both in the analytical results and in the recorded specific gravity of the mineral. The latter varies very widely (3.98 to 4.80) and probably indicates the doubtful purity of the sample. Where the total (as in analysis No. 1) is over 101 per cent., any calculations based on the result will be wholly misleading, and it is safe to say that many others recorded, while not indicating such an excess, are equally unreliable for this purpose.

* Gladding and Lunge, *Journal Am. Chem. Soc.*

† *Oberrh. Ges. Nat. u. Heilk.*, 1879, 18, 97.

TABLE I.—Analyses of Pyrrhotite.

	1.	2.	3.	4.	5.	6.	7.	8.	9.
Fe.....	63.82	63.15	63.35	62.62	63.41	62.04	61.17	60.83	58.00
S.....	37.86	36.35	35.91	37.38	36.29	38.08	38.83	39.17	42.00
Total.....	101.18	99.50	99.26	100.00	99.70	100.12	100.00	100.00	100.00
Sp. gr.....	3.98	4.62	4.787	4.80	.....	4.497	4.546	4.580	.....
Formula	Nearly FeS.	Nearly FeS.	Nearly FeS. (Fe in excess.)	Nearly FeS.	FeS.	Fe ₁₃ S ₁₄ .	Fe ₉ S ₁₀ .	Fe ₈ S ₉ .	Fe ₄ S ₅ .

No. 1. Nenntmamsdorf. Geinitz, *N. Jahr.*, 1876, 609.

No. 2. Tavetsch. Gutknecht, by Kenngott, *N. Jahr.*, 1880, 1, 164.

No. 3. Seelaesgen, Rammelsberg, *Pogg. Ann.*, 1864, 121, 368.

No. 4. Brazil, Bertier *Ann. Mines*, 1835, 7, 531.

No. 5. Jeliza, Servia, Losanitsch, *Berg. d. Chem.*, 1892, 15, 880.

No. 6. Borév, Pálffy, *Groth's Zeit.*, 30, 184.

No. 7. Bodenmais, Graf Schaffgotsch, *Pogg. Ann.*, 1840, 50, 533.

No. 8. Hartzburg, Rammelsberg, *Pogg. Ann.*, 1864, 121, 356.

No. 9. Chile, Mennier, *Cosmos*, 1869, 5, 581.

The above results are taken from C. Hintze's *Hdb. der Min.*, vol. i, 1901, p. 653.

Altogether apart, however, from the considerations outlined above, pyrrhotite, as we know it, is not constant in composition; and an adequate explanation of the variations in its composition is one of the problems of the future.

The Origin of Pyrrhotite.

Little is known of the conditions under which pyrrhotite is formed in nature, except that a strongly-reducing atmosphere is necessary. Those synthetic reproductions of the mineral, which have not been made under conditions analogous to those of nature, do not aid materially in explaining its origin.

Doelter,* however, by heating ferrous chloride to 250° C. in an atmosphere of carbonic acid and hydrogen-sulphide gas, produced pyrrhotite much like the natural mineral and having a composition represented by Fe₁₁S₁₂. He also produced it by the action of H₂S gas on solutions of ferrous sulphate, carbonate, chloride and silicate. Other methods of preparation do not appear to have any direct bearing on the natural formation of the mineral.

* *Tsch., Min. u. Pet. Mitt.*, vol. vii., 85, 86.

Nickel and Cobalt in Pyrrhotite.

Nickel is universally recognised as an associate of pyrrhotite, and in few cases has it proved, when looked for, to be entirely lacking. Whether the nickel is an essential constituent of the pyrrhotite, replacing part of the iron, or whether it is present as a separate compound, is still a disputed question. It is hoped, however, that the results here presented will help to clear this matter up to a great extent.

The percentage of nickel varies widely in different pyrrhotites. Those occurring in metamorphosed sedimentary and acidic schistose rocks are notably low in nickel, while in those associated with basic igneous rocks, especially of the gabbro family, it may range from a trace to a proportion economically valuable. Cobalt nearly always accompanies the nickel, though usually in very subordinate amount.

Tables II., III. and IV. give the nickel-contents of representative pyrrhotites of these two classes. Those of the first class rarely carry more than 0.5 per cent. of nickel, while those from basic eruptives usually exceed this limit,—some of the Rossland examples being notable exceptions.

TABLE II.—Percentages of Nickel and Cobalt in Pyrrhotites Generally.

	Ni.	Co.		Ni.	Co.
ONTARIO.			BRITISH COLUMBIA.		
1. Dalhousie twp. Lanark co.	0.23	trace	1. West Kootenay	0.16	0
2. " " " "	0.11	"	2. Kennedy Lake, V. I.	0.16	trace
3. Angleseawtp. Addington co.	0.16	"	3. Deer Creek, V. I.	1.70	"
4. Galway twp. Peterboro' co.	0.16	"	4. West Kootenay	0.14	"
5. " " " "	0.10	"	5. Crawford Bay	0.05	"
6. " " " "	0.05	"	6. Jarvis Island	0.28	"
7. Victoria co.	0.15	"	7. Rossland	0.23	"
8. Rainy River District	0.13	"	8. " "	0.13	"
9. District of Nipissing	3.30	"	9. Kootenay Lake	0.68	"
10. " " " "	2.10	"	SWEDEN, ETC.		
QUEBEC.			1. Klefva	1.08	0.07
1. Ottawa co.	0.13	0	2. " "	1.50	0.08
2. " " " "	1.68	"	3. " "	2.03	0.10
3. Calumet Island	1.48	"	4. Sagmyrna	0.50	"
4. " " " "	4.06	0.33	5. Krageroe	0.80	"
5. Pontiac co.	1.50	trace	6. Varallo	1.75	"
NOVA SCOTIA.			7. " "	1.20	"
1. Cape Breton co.	0.10	"	8. " "	1.44	"
NEW BRUNSWICK.			UNITED STATES.		
1. St. Stephen	1.82	0.17	1. Gap Mine, Pa.	1.75	0.10
2. " " " "	trace	"	2. " " " "	1.00	"
3. " " " "	4.00	"	3. Anthony's Nose, N. Y.	3.00	"
				0.30	"

NOTE.—The nickel-mineral gersdorffite occurred in association with some of these pyrrhotites, so that in part the nickel found may mean an admixture of this mineral.

Ontario.—1. Pyrrhotite with pyrite in white translucent quartz and hornblende; 2. Pyrrhotite with pyrite in quartz-mica-diorite (Nos. 1 and 2 occur in dark-grey diorite, which cuts gneiss); 3. Pyrrhotite in dark-grey gneissoid rock; 4. Massive pyrrhotite; 5. Massive pyrrhotite with pyrite, chalcopyrite and quartz; 6. Massive pyrrhotite with chalcopyrite, quartz and feldspar (Other samples from Galway gave from a trace to 0.15 nickel. The pyrrhotite is associated with bands of gneiss, mica-schist and quartzite; i.e., the deposits are "fahlbands," like those of Norway, which are likewise poor in nickel.); 7. Massive pyrrhotite; 8. Massive pyrrhotite with a small amount of quartz from the Huronian schists of English river; 9 and 10. Pyrrhotites with small amounts of chalcopyrite in a gangue of greyish-green diorite. (Pyrrhotites occurring in light and dark-grey gneissoid rocks from Frontenac county, Ont., Schreiber (Thunder Bay), Darlington Bay (Lake of the Woods), and numerous other localities all contained nickel, but only in traces.)

Quebec.—1. Massive pyrrhotite from Eardley township; 2. Pyrrhotite in part massive, in part disseminated through a gangue of quartz, feldspar and hornblende; 3. Small quantity of pyrrhotite, etc., in a quartz-amphibolite; 4. Massive pyrrhotite with a little quartz-gangue (The associated rocks of 3 and 4 are diorites, which cut a series of gneisses and limestones.); 5. Massive pyrrhotite.

Nova Scotia.—Pyrrhotite in a siliceous gangue from Leitch's Creek.

New Brunswick.—Pyrrhotite with a little chalcopyrite and a small amount of quartzose-gangue, or diorite and quartz. (The association is much like that of Sudbury. Various samples from the same locality yield from a trace to 4 per cent. of nickel.)

British Columbia.—1. Pyrrhotite in quartz, feldspar and hornblende; 2. Massive pyrrhotite in a gangue of quartz, garnet, calcite and hornblende; 3. Massive pyrrhotite with chalcopyrite in a quartzose-gangue (from the Two Sisters and Crow claim); 4. Pyrrhotite and chalcopyrite in a dark-green rock; 5. Pyrrhotite in association with a small amount of chalcopyrite, graphite, quartz, mica and feldspar; 6. Pyrrhotite with chalcopyrite in a gangue of quartz-green diorite; 7 and 8. Massive pyrrhotite with chalcopyrite in massive eruptive rocks, the ore-bodies lying between gabbros and surrounding porphyries and diabases; 9. Pyrrhotite with pyrite and chalcopyrite in garnet and quartz.

The above Canadian examples are taken from vols. vi. to xi. of the *Reports of the Canadian Geological Survey*.

Sweden, etc.—Pyrrhotites in dark eruptive rocks, principally gabbros (authority, Schnabel's *Handbook of Metallurgy*).

Gap Mine, Pa.—Pyrrhotite with chalcopyrite, pyrite, etc., in the outer portions of basic igneous rock-masses, which may be metamorphosed to amphibolites.

Mine at Anthony's Nose, N. Y.—Pyrrhotite in association with feldspar, pyroxene, hornblende and quartz; the walls being acidic gneisses. (Authority for this and the preceding examples, "The Nickel-Mine at Lancaster Gap," by J. F. Kemp, *Trans.*, xxiv., 620, 883, October, 1894.)

The relation of the nickel-content to the mode of origin of the pyrrhotites and the enclosing rock will be considered subsequently.

One of the purposes of this investigation has been to test the validity of the view generally held, that in the Sudbury

pyrrhotites the nickel and cobalt replace the iron isomorphously. Another purpose has been to try to find a definite formula for the sulphide of this district, with the idea of comparing it with similar minerals from other localities.

The Sudbury Pyrrhotites.

The Sudbury nickel-region, as treated in this paper, will be considered, for convenience, as including the deposits of similar nature in the adjoining Algoma district, as well as those in the immediate vicinity of the town of Sudbury.

The ore mined in this region consists chiefly of a mixture of pyrrhotite and chalcophyrite, intimately associated with more or less country-rock. The pyrrhotite carries the nickel, while the chalcophyrite appears to be quite free from that element.* Table III. gives the nickel and copper in typical samples of the ore of some of the leading Sudbury mines, as taken from the catalogue of the Ontario mineral exhibit at the Buffalo Pan-American Exposition of 1901, and similar data regarding a number of nearly pure pyrrhotites from claims in various parts of Algoma, taken from the reports of the Canadian Survey. These Algoma deposits have the same geological relations—i. e., they are closely associated with an altered gabbro or norite.

The average contents of nickel, copper and cobalt in the ore smelted since 1892 are given in Table IV. The statements of Messrs. Turner and Walker, Table V., show that gold, silver and the metals of the platinum group are constant constituents of the ore, though present only in small quantities.

Sperrylite, the arsenide of platinum, (PtAs_2), was first recognized in the decomposed products of chalcophyrite and pyrrhotite at the Vermilion mine. The platinum in the unaltered ore occurs as sperrylite, as proved by the writer.† Mr. T. L. Walker‡ has shown that the sperrylite is associated with the chalcophyrite, rather than the pyrrhotite. Recent investigations seem to confirm this view, as sperrylite has been found associated with copper-minerals in several other places.

* Thus, Nos. 3 and 5 in Table III., which are largely chalcophyrite, contain but little nickel.

† *Am. J. Sc.*, February, 1903.

‡ *Am. Jour. of Sc.*, February, 1896.

Mr. Turner's estimate, given in column A and B, Table IV., probably presents fair averages of the general run of the ore. The figures under A may give a good idea of the ore of the Creighton mine, while that from Copper Cliff may run up to 7 per cent. copper and 3 per cent. nickel, according to the particular level from which the ore was taken (copper predominating in the upper, and nickel in the lower levels). Column B is based on the composition of the matte produced, as shown in Table V, column I.

TABLE III.—*Nickel and Cobalt in Sudbury and Algoma Pyrrhotites.*

	Ni. Per Cent.	Cu. Per Cent.		Ni. Per Cent.	Cu. Per Cent.
SUDBURY.			ALGOMA.		
1. Victoria mine.....	3.50	4.50	1. Lorne township.....	1.95	0
2. Copper Cliff mine.....	9.25	0.51	2. " ".....	2.30	0
3. " ".....	1.25	23.78	3. Nairn township.....	1.95	trace.
4. Stobie mine.....	2.99	0.37	4. Drury ".....	2.01	"
5. " ".....	0.64	24.23	5. Denison ".....	1.80	0
6. No. 2 mine.....	4.70	0.38	6. Levack ".....	4.13	.....
7. " ".....	1.87	13.76	7. " ".....	3.00	trace.
8. No. 3 mine, Frood.....	4.85	0.42	8. " ".....	1.96	.....
9. No. 4 mine.....	4.33	1.39	9. Morgan ".....	3.30	.....
10. " ".....	4.15	2.49			
11. Creighton mine.....	7.03	1.81			
12. No. 2 extension.....	4.32	0.35			
13. Worthington mine.....	3.00	3.00			

NOTE.—The Sudbury figures are from the catalogue of the mineral exhibit of Ontario at the Pan-American Exposition of 1901, except those of the Worthington mine, which are the result of a number of analyses of average samples, obtained through the kindness of Mr. R. E. Booraem, N. Y. city.

The Algoma figures are taken from reports of the *Geological Survey of Canada*. Most of the samples were massive pyrrhotite, with a small amount of chalcophyrite. The copper per cent. was not reported.

TABLE IV.—*Averages of Smelters' Assays of Sudbury Ores, from 1892 to 1900.*

	1892	1893	1894	1895	1896	1897	1898	1899	1900	A	B
	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.
Cu.	3.19	2.38	3.14	2.73	2.54	2.86	3.43	.....	1.59	1.50	2.00
Ni.	3.36	2.21	2.92	2.67	2.67	2.08	2.28	.....	1.67	3.50	2.50
Co.	0.10	0.08	0.07	.....	.....	.....	.....	.....	.....	.....	.....

NOTE.—The figures for the several years are taken from the Sixth Report of the Ontario Bureau of Mines (1896) and *Mineral Industry*, 1900. The returns for 1900 seem too low. Columns A and B, furnished by President A. P. Turner, of the Canadian Copper Co., contain (A) an estimate of certain ores of that company, and (B) a general average based on the composition of the matte produced from a mixture of all its ores.

TABLE V.—*Composition of Sudbury Mattes.*

	I.	II.
		Per cent.
Copper,	14 per cent.	25.92
Nickel,	17 " "	} 48.82
Cobalt,	0.5 to 0.6 per cent.	
Gold,	trace	0.000075
Silver,	0.5 to 1 oz. per ton.	0.001775
Platinum,	0.25 to 0.5 oz. per ton.	0.000430
Palladium,	0.25 to 0.5 " " "	present
Iridium, . . . . .	.....	0.000056
Osmium, . . . . .	.....	0.000056
Rhodium, . . . . .	.....	present
Iron, . . . . .	.....	2.94
Sulphur, . . . . .	.....	22.50

I. Average furnished by President A. P. Turner for mattes of the Canadian Copper Co.

II. Analysis of the matte from the Murray mine, given by Mr. T. L. Walker, *Am. J. Sc.*, February, 1896.

To ascertain as accurately as possible the average nickel and cobalt contents of the general run of the pyrrhotite from the whole region, a number of analyses of carefully-selected material were made by the writer.

The pyrrhotite was coarsely crushed and the mineral picked out as pure as possible, under a lens when necessary. From the massive varieties good samples were easily obtained; but in other cases the pyrrhotite was so intimately mixed with chalcopyrite and rock that it was very difficult to obtain satisfactory samples, some rock always adhering to the sulphide. The results, given in Table VI., show that the percentage of nickel and cobalt in the pyrrhotite, calculated to the pure mineral, is fairly constant over a wide area, embracing all the principal mines and prospects. The pyrrhotites include both coarse- and fine-grained massive varieties, and those mixed with more or less rock and chalcopyrite. The object was to determine, as far as practicable, only the nickel existing as a component of the pyrrhotite, if it occurred as such. In the case of the coarse-grained varieties, where the nickel-mineral pentlandite is often to be recognized, this was carefully rejected, as far as possible. But the difficulty of this separation accounts for the fact that some of these varieties show less nickel than the fine-grained ones, although the former are usually considerably richer. Had the coarse-grained samples been treated in their

original condition, the results would have been more uniform. Subsequent work proves that a large part, at least, of the nickel is not a constituent of the pyrrhotite. The results of these tests, therefore, represent the nickel which is most intimately associated with pyrrhotite and does not appear in visible particles of pentlandite.

Cobalt is always very subordinate in amount, bearing a ratio of between 1:40 or 50 to the nickel.

TABLE VI.—*Nickel, Cobalt, etc., in Sudbury Pyrrhotites.*

Location.	Insol. Per Cent.	Cu. Per Cent.	Ni. Per Cent.	Co. Per Cent.	Ni. in Pure Pyr- rhotite. Per Cent.
1. Elsie (a).....	2.00	trace.	2.40	0.06	2.46
2. " (b).....	3.45	"	2.35	0.05	2.44
3. Stobie (a).....	1.50	"	3.00	0.08	3.05
4. " (b).....	4.00	"	2.05	0.05	2.15
5. Frood, No. 3 mine (a).....	0.40	"	2.35	0.05	2.40
6. " " (b).....	5.00	"	2.34	0.06	2.48
7. Mount Nickel.....	2.20	"	3.00	0.07	3.06
8. Copper Cliff, No. 4 mine (a).....	1.10	"	3.24	0.06	3.30
9. " " 2 " (b).....	5.00	"	3.70	0.08	4.00
10. " " 5 " (c).....	0.50	"	3.47	0.08	3.50
11. Creighton (a).....	3.25	"	3.84	0.10	4.00
12. " (b).....	0.50	"	2.26	0.06	2.32
13. Gertrude (a).....	5.00	"	3.83	0.11	4.05
14. " (b).....	6.00	"	3.61	0.09	4.00
15. Victoria (a).....	0.50	"	3.36	0.07	3.40
16. " (b).....	0.40	"	3.14	0.08	3.20
17. Levack.....	3.20	"	2.80	.....	2.88
18. North Range.....	4.10	"	2.22	.....	2.32

NOTE.—These analyses, and others by the writer, were made in duplicate or triplicate to insure the greatest possible accuracy.

1. Coarse pyrrhotite with a small amount of chalcopyrite and rock; 2. Compact fine-grained pyrrhotite, with a small amount of rock; 3. Massive fine-grained pyrrhotite; 4. Pyrrhotite and chalcopyrite in diorite; 5. Pure, coarse pyrrhotite; 6. Fine-grained pyrrhotite; 7. Massive pyrrhotite; 8. Coarse pyrrhotite. 9. Massive fine-grained pyrrhotite; 10. Massive fine-grained pyrrhotite; 11. Massive fine-grained pyrrhotite; 12. Coarse pyrrhotite; 13. Massive pyrrhotite; 14. Massive pyrrhotite; 15. Massive fine-grained pyrrhotite; 16. Coarser than No. 15, but with more chalcopyrite; 17. Massive pyrrhotite (Tuff & Stobie's property); 18. Coarse, massive pyrrhotite from Wisner township.

The Magnetic Separation of Nickeliferous Pyrrhotite.

Many experiments have been performed in recent years to effect a commercial magnetic separation of the nickel in pyrrhotite ores; or, for scientific purposes, to determine the con-

dition of the nickel in this mineral. The commercial elimination of the nickel is probably an impossibility, and the scientific problem is only now approaching a solution.

S. H. Emmens* refers to the work of Habermehl (1879), who effected a separation of European nickeliferous pyrrhotite into magnetic and non-magnetic portions.

T. J. McTighe, in 1890, applied magnetic separation in the treatment of Canadian ores; and in 1892 T. A. Edison, in applying for a U. S. Patent, said:

"I have discovered that where magnetic pyrites, called pyrrhotite, is nickeliferous, as it usually is to a more or less extent, the nickel is not distributed generally throughout the whole body of the pyrrhotite, but certain crystals are pure pyrrhotite or magnetic pyrites, while other crystals have some of the iron replaced by nickel and sometimes by cobalt, and that the crystals containing the nickel and cobalt are considerably less magnetic than the pure pyrrhotite."

Emmens himself made some crude experiments on material from the Gap mine, Pa., and from Sudbury, and obtained two products, the non-magnetic being considerably richer in nickel than the original ore.

Shortly after, David H. Browne† contributed a very valuable article on the same subject. He shows the existence of a rich nickel-mineral in the ores from the Copper Cliff, Evans and Stobie mines, in the Sudbury district, and also that it can be separated by rough-crushing and hand-picking, after first removing the magnetic part. His analyses‡ show that the non-magnetic residue bears a close resemblance to the pentlandite described by Penfield.

Probably the most extensive series of experiments for a commercial separation were those made by Mr. J. N. Judson, of the Wetherill Separating Co., in 1900. The results have never been published; but Mr. Judson has very kindly placed them in the hands of the writer and a partial abstract is here presented.

The material operated on was nearly pure pyrrhotite from Copper Cliff, containing, by analysis, Ni, 3.14; Cu, 0.42; and

* 2d Rep. Bureau of Mines, Ont., 1892, p. 163. Jour. Am. Chem. Soc., vol. xiv., No. 10.

† Eng. and M. J., December 2, 1893.

‡ Nos. 5 to 8 in Table XI. of this paper.

Fe, 49.78 per cent. The magnetic-separation products, with different current-strengths, and the analysis of each, are given in Table VII.

TABLE VII.—*Magnetic Separation of Pyrrhotite by the Wetherill Separator. First Experiment—Material Crushed to 30-Mesh.*

Product No.	Amperes.	Magnetic Product, Per Cent.	Analyses.					
			Magnetic Portion.			Total Percentage of Metal in Magnetic Portion.		
			Ni.	Cu.	Fe.	Ni.	Cu.	Fe.
1	1	90.11	2.46	0.22	58.60	70.58	47.48	97.02
2	15	7.65	10.83	0.78	14.80	28.38	14.37	2.27
3	15	0.78	9.68	2.55	13.25	2.42	4.79	0.21
4	28	0.92	1.76	13.58	20.10	5.87	29.99	0.87
5	tails	0.54	0.70	2.64	11.25	0.13	3.35	0.12
1*	1	90.11	2.46	0.22	58.60	70.58	47.48	97.02
2-5*	...	9.89	9.33	2.21	14.97	29.42	52.52	2.98

The results show that with a current-strength of 1 ampere 90.11 per cent. of the total sample was magnetic, and this contained 2.46 per cent. Ni, or the equivalent of 70.58 per cent. of the total metal in the original pyrrhotite; that is, only 29.42 per cent. of the total nickel was concentrated in the non-magnetic portion (making only two products). The second and third products (15 amperes) were highly nickeliferous; but as they contained less than a third of the total nickel in the ore, the loss in the magnetic portion was very heavy.

In the next experiment, the first magnetic product, at 1 ampere (amounting to 90.11 per cent. of the total), containing Ni, 2.46; Cu, 0.22; and Fe, 50.62 per cent., was again treated, using a weaker current. The results are shown in Table VIII.

TABLE VIII.—*Magnetic-Separation Product No. 1 of Table VII. Second Experiment (No. 30-Mesh).*

Product No.	Amperes.	1. Magnetic Portion of Part Treated.	2. Magnetic Portion of Total.	Analyses.		
				Ni. Per Cent.	Cu. Per Cent.	Fe. Per Cent.
1	2	33.61	30.28	1.93	0.08	56.65
2	15	54.15	48.79	2.08	0.13	55.60
3	15	4.64	4.18	3.46	0.18	53.00
4	15	1.79	1.61	3.70	0.51	41.25
5	1	2.35	2.12	3.95	0.90	23.80
6	tails	3.47	3.13	10.60	2.44	20.20

* Making only two products—i.e., magnetic and non-magnetic—at one ampere.

Column 1 gives the percentage of the part treated, which was magnetic with the different current-strengths indicated; column 2, the percentage of the total sample which was magnetic under the same conditions (e.g., $90.11 \times 33.61 = 30.28$). The magnetic portion at $\frac{1}{8}$ amperes (about $\frac{1}{2}$ of the total) still contained nearly 2 per cent. Ni; so the loss was still very great, while the non-magnetic concentrate was not very greatly enriched.

All the products of these two experiments were then mixed, crushed to pass through 60-mesh and treated as shown in Table IX.

TABLE IX.—*Magnetic Separation of Mixed Sample Crushed to Pass No. 60-Mesh. Third Experiment.*

Product No.	Amperes.	Magnetic Portion, Percent. of Total.	Analyses.		
			Ni.	Cu.	Fe.
1	$\frac{1}{8}$	44.26	1.69	0.13	55.50
2	$\frac{1}{4}$	41.96	2.16	0.18	54.80
3	$\frac{1}{2}$	0.37	2.16	0.26	50.30
4	$\frac{3}{4}$	0.37	4.19	0.70	32.50
5	1	0.49	5.29	0.93	24.55
6	2	1.13	8.96	0.97	20.85
7	3	1.38	13.55	0.76	21.55
8	4	3.95	10.29	0.46	22.35
9	5	4.19	12.71	0.60	19.60
10	6	0.89	4.17	3.18	12.65
11	28	0.77	1.53	14.36	19.65
12	tails	0.52	0.38	1.64	8.25

At $\frac{1}{8}$ ampere, 44.26 per cent. of the sample was magnetic, and product contained 1.69 per cent. Ni. At $\frac{1}{4}$ ampere, 41.96 per cent. was magnetic, and the product contained 1.92 per cent Ni. If the remainder, 13.78 per cent., were considered as the non-magnetic concentrate, we would have a comparatively rich nickel-ore, but the losses in the magnetic portion are so great that a commercial separation by this method is out of the question. All the other experiments led to the same conclusion. Intermediate products, rich in nickel, were easily obtained; but in no case was the nickel in the magnetic portion reduced to such an extent that it could be economically rejected.

Mr. D. P. Shuler, Sudbury, Ont., has recently (1902) taken out patents for a process whereby he proposes to eliminate the

copper from the nickel-iron portion by magnetic concentration, and subsequently to convert the latter, after roasting, into a nickeliferous pig-iron. The copper-nickel concentrate will, of course, be treated separately for its metallic contents. This seems to be the most fruitful field for investigation now open in this connection, and about the only method of treatment which promises to yield results capable of industrial application.

*The Nickel-Bearing Mineral.**—Prof. S. L. Penfield† first definitely proved the existence of pentlandite in the ores from the Sudbury nickel-copper mines. Later, Mr. David H. Browne‡ showed that pentlandite was the principal nickel-bearing mineral. On the assumption that the ores were the result of a magmatic segregation from an original fused magma, he tried to show that the coarser the grain of the pyrrhotite, and the deeper it lies below the surface, the more nickel exists as pentlandite. On the other hand, the finer-grained the ore, and the more rapidly it has cooled from the fused state (i.e., the nearer it is to the surface), the more nickel exists as an element replacing the iron in the pyrrhotite. As will appear later in this paper, however, this relation does not hold good.

In order to determine as nearly as possible how much of the nickel occurs as a separate mineral, and how much, if any, replaces iron, and also to ascertain the composition of the nickel-mineral, several series of experiments were made by the writer.

First Series of Experiments.—A number of representative samples of pyrrhotite were ground to pass through 100-mesh and the non-magnetic portion was removed as completely as possible by repeated treatment with a small horse-shoe magnet. The nickel-contents of the original samples are given in column I., and those of the magnetic concentrate in column II., Table X. The nickel is seen to have been materially reduced, and the results seemed to indicate a pretty constant quantity remaining with the magnetic part. Further experiments, however, showed that this was purely an accidental relation.

Second Series of Experiments.—The original samples were coarsely crushed and the magnetic portion was sized between

* A preliminary note on this subject was published in the *Eng. and Min. Jour.*, May 10, 1902, by the writer.

† *Am. Jour. Sc.*, vol. xlv., June, 1893.

‡ *Eng and Min. Jour.*, Dec. 2, 1893, and *Sch. of Mines Quart.*, vol. xvi., 1895.

40- and 60-mesh, then freed as well as possible from non-magnetic material, crushed between 60- and 80-mesh and again concentrated. By successive treatments the mineral was finally reduced to a fine powder. The ultimate product was then assayed for nickel. As shown in column III., Table X., the nickel was much reduced, but not entirely eliminated.

Third Series of Experiments.—To see if it were possible to still further reduce the nickel-contents, a number of samples were very carefully prepared. They were coarsely crushed and the purest mineral selected. This was crushed to pass through 10- on 20-mesh, and the finer material was rejected. All the non-magnetic portion was eliminated and the concentrate was then crushed to 20- on 40-mesh, the finer part being again rejected. The operations were repeated until the ore was finally ground in an agate mortar, the non-magnetic part being very carefully removed each time. The nickel in the final concentrate is given in column IV., Table X.

TABLE X.—*Experiments in the Magnetic Concentration of Nickeliferous Pyrrhotite.*

Location.	I. Ni.*	II. Ni.	III. Ni.	IV. Ni.	
1. Elsie mine.....	2.44	2.22	0.98	.....	Fine-grained pyrrhotite.
2. Stobie mine.....	3.05	2.14	0.68	.....	"
3. Frood mine.....	2.40	2.07	1.05	0.65	Coarse-grained pyrrhotite.
4. Mount Nickel mine.....	3.06	2.14	0.75	0.70	Medium-grained "
5. Copper Cliff, No. 2 mine.	4.00	2.00	0.70	.....	Coarse-grained "
6. " " No. 4 " "	3.30	2.32	0.83	.....	" " "
7. Creighton mine (a).....	2.32	2.25	1.20	0.70	" " "
" " (b).....	4.15	.....	.....	0.45	Fine " "
8. Gertrude mine.....	4.00	2.30	1.10	.....	Massive pyrrhotite.
9. Victoria mine.....	3.40	2.46	0.80	.....	Fine-grained pyrrhotite.

The results show conclusively that the nickel present is not replacing part of the iron in the pyrrhotite, but exists as a separate mineral. The fact that all the nickel could not be eliminated by the methods used does not indicate that even the amount that remained was an essential part of the pyrrhotite, as several factors enter which render its complete removal practically impossible. In the first place, the nickel-mineral is very intimately associated with the magnetic pyrites; and

* Nickel with a trace of cobalt.

even a minute adhering fragment of the latter will cause it to be carried over with the magnetic portion. It is also to be noted that the nickel-mineral itself is slightly magnetic, and in the form of a powder is attracted by even a small magnet.

As a result of these experiments I feel justified in saying that all the nickel, in the Sudbury ores at least, occurs as a separate mineral, and that in this district there does not exist a true nickeliferous pyrrhotite, in the sense that the nickel isomorphously replaces part of the iron in that mineral.

Experiments on Swedish and Norwegian ores of a similar nature show that a large part of the nickel can be eliminated by magnetic concentration; and taking these results, in connection with the foregoing, it is pertinent to ask: "Is there such a thing as a true nickeliferous pyrrhotite?"

The results show that even with the most careful treatment, a commercial separation of the nickel by magnetic concentration is prohibited by the considerable loss of nickel involved.

*The Non-Magnetic Residue.**—Analyses of the non-magnetic residues, roughly freed from impurities, were made to get an idea of their compositions.

The small amount of copper was estimated as chalcocopyrite, and the necessary amounts of iron and sulphur deducted. The ratios of Fe:Ni:S (taken as 1) were then calculated, and the results are given in Table XI.

TABLE XI.—*Analyses of the Non-Magnetic Residue from Pyrrhotites.†*

Location.	Cu. Per Cent.	Total Fe. Per Cent.	Total S. Per Cent.	Ni. Per Cent.	Co. Per Cent.	Fe.‡ Per Cent.	S.‡ Per Cent.	Ratios. (S. = 1.00.)		
								S.	Ni.+Co.	Fe.
1. Victoria mine.....	0.95	28.50	31.92	31.65	0.65	27.66	30.96	1.00	0.570	0.514
2. Frood mine.....	0.84	29.36	32.85	32.25	0.84	28.65	32.04	1.00	0.565	0.512
3. Creighton mine.....	1.20	29.50	34.25	33.00	.....	28.45	32.80	1.00	0.550	0.50
4. General sample.....	0.80	27.11	30.30	29.71	0.60	26.40	29.46	1.00	0.565	0.515
5. Copper Cliff mine.‡	0	.....	.....	.....	.....	25.05	34.35	1.00	0.56	0.50
6. " " " " " "	0	.....	.....	.....	.....	25.00	30.30	1.00	0.571	0.52
7. Evans mine.....	0	.....	.....	.....	.....	24.90	33.35	1.00	0.571	0.51
8. Stobie mine.....	0	.....	.....	.....	.....	24.70	33.90	1.00	0.56	0.505

* The residue is spoken of for convenience as being non-magnetic, although in reality slightly so.

† For the sake of uniformity the following revised atomic weights are used throughout: Ni, 58.69; Co, 58.99; Fe, 56.02; S, 32.07.

‡ After deducting the necessary amounts to form chalcocopyrite with the copper present.

§ Analyses by D. H. Browne, *Eng. and Min. Jour.*, December 2, 1893, Nos. 5 and 8, contained some pyrrhotite; Nos. 6 and 7 were purer.

The striking uniformity of the ratios obtained at once indicated the similarity of the mineral in all these cases; and further work on carefully-purified material confirms this view.

The pyrrhotite from the Creighton, Worthington and Frood mines shows considerable amounts of the non-magnetic mineral, in pieces up to $\frac{3}{4}$ in. in diam., fairly pure, and specimens from these localities were chosen as affording the best material to work on.

The ore was first roughly crushed and the pyrrhotite removed by a magnet. The larger non-magnetic fragments were taken and picked over under a lens, carefully discarding any that was even suspected of containing pyrrhotite.

The samples were then crushed successively to pass through No. 20-, No. 40-, No. 60-, No. 80-, and No. 100-mesh, each time discarding the fines and going over them with a magnet, examining under a lens, and removing all foreign material till they were too fine to treat in this way. They were finally ground in an agate mortar and again gone over with a weak magnet, which attracted the mineral but little and served to remove any traces of pyrrhotite that might remain. In this way the samples were obtained as pure as it is practically possible to get them, and they were ready for analysis; the results are shown in Table XII.

TABLE XII.—Analyses of Nickel-Bearing Mineral.*

Location.	Cu.	Ni.	Co.	Fe.	S.	Ratios. (S.=1.00.)		
						S.	Ni.+Co.	Fe.
1. Creighton	0	34.82	0.84	30.00	32.90	1.00	0.589	0.518
2. Worthington....	0	33.70	0.78	29.17	32.30	1.00	0.583	0.517
3. Frood.....	0	34.98	0.85	30.04	33.30	1.00	0.588	0.513
4. Copper Cliff†...	0	34.23	0.85	30.25	33.42	1.00	0.573	0.518

The composition of the non-magnetic residue at once suggests pentlandite, and as such Penfield described the sample he examined (No. 4 in Table XII.).

* The small amount of residue consisted of siliceous gangue. These analyses were made in the laboratory of the School of Mining, Kingston, Ont., which was kindly placed at the writer's disposal.

† Penfield, *Am. J. Sc.*, vol. xlv., 1893, p. 493.

The pentlandite from Lillehammer, Norway, corresponds very closely to it in physical properties, but carries a lower percentage of nickel (20 to 22 per cent.).

The Sudbury mineral occurs, in part, finely disseminated through the pyrrhotite, so that it cannot be detected, even with the aid of a lens, and partly in larger grains and segregations, at times an inch in diam. Usually it possesses the characteristic platy structure and octahedral parting, though this is at times obscured. On fresh fracture, the mineral has a light steel-grey or silver-white color, which soon changes on exposure to the peculiar and characteristic light bronze-yellow. When fresh and massive it is with difficulty to be distinguished from the fresh pyrrhotite, but on a slight superficial oxidation the difference becomes quite pronounced.

The Lillehammer pentlandite has a ratio of FeS : NiS about 2 : 1, and its formula is given as $2\text{FeS} + \text{NiS}$. Penfield* gives the ratio of the Sudbury mineral as $(\text{Fe} + \text{Ni}) : \text{S} = 1 : 1$, or $(\text{Fe} + \text{Ni}) \text{S}$.† By a reference to Table XII. it will be seen that the ratio $(\text{Fe} + \text{Ni}) : \text{S}$ is (1) 11.07 : 10; (2) 11 : 10; (3) 11.03 : 10; and (4) 10.91 : 10; that is, there is an excess of the metallic constituents over the amount required by the formula $(\text{Fe} + \text{Ni})\text{S}$. The same excess is indicated in the analyses of less pure material given in Table XI. This relation is constant and cannot be regarded as accidental, especially since the analyses of the purest samples from different localities show the ratio to be constant at 11 : 10. Just what this peculiarity signifies it is difficult to say; but it seems to indicate that the structure of the pentlandite molecule is more complicated than that represented by $(\text{Fe} + \text{Ni})\text{S}$, even though it is advantageous to represent minerals by the simplest possible formulas.

An excess of sulphur over the metal is by no means uncommon in minerals (*e.g.*, in pyrrhotite, polydymite, beyrichite, etc.); but an excess of metallic contents seems unique.

* *Loc. cit.* The analysis given by Prof. Penfield, in this paper, agrees almost exactly with those made by the writer, but by a slight error in calculation, his analysis worked out exactly to the formula $(\text{Fe} + \text{Ni}) \text{S}$, instead of showing an excess of metallic constituents, as is actually the case; that is the ratio of $(\text{Fe} + \text{Ni}) : \text{S}$ in the material examined by Prof. Penfield is almost 11 : 10, instead of 1 : 1 as given.

† Nickel and cobalt being taken together.

Such a formula as $(\text{Fe} + \text{Ni})_{11}\text{S}_{10}$ is not convenient; but it appears to be the only means of expressing the results of analysis.

Another interesting feature is the ratio of nickel to iron, which is quite constantly also, nearly 11:10, while that of nickel to cobalt is about 42:1.

An intimate admixture of some sub-sulphide with what might be regarded as normal pentlandite $[(\text{Ni} + \text{Fe})\text{S}]$ is, of course, a possibility; but if this is the case it must be in a definite and constant ratio, as the mineral shows the same phenomenon throughout the whole district.

But this is a mere speculation. There is no direct evidence on which to base the assumption, and at present it seems most reasonable to imagine a peculiar molecular arrangement of the atoms of the mineral itself. As the matter now stands, however, the relations are unexplained, and must be the subject of further investigation before a satisfactory conclusion is reached.

The Formula of the Pyrrhotite.

A large number of the magnetically-separated samples were analyzed, in an attempt to determine the formula of the pyrrhotite, and with a fair amount of success. A number of factors had to be taken into consideration, and tended to render the results in some cases rather unsatisfactory, so that absolute uniformity was not attained.

The nickel present was calculated to pentlandite on the basis of the ratios given above, and the necessary amounts of iron and sulphur were deducted. As there was a persistent, though varying amount of magnetite in all the samples, it was necessary to determine this. The estimation of the oxide (Fe_3O_4) in the presence of the magnetic sulphide presented considerable difficulty, and this is probably the main cause of the discrepancies.

After a number of experiments, it was found that by treating the sample with a dilute (10 per cent.) solution of nitric acid, the pyrrhotite could be largely removed, while the magnetite was but little affected. The separated sulphur was removed by means of bromine and carbon-bisulphide; and after several treatments the residue of magnetite was obtained pure, and the iron was estimated by titration. The nature of the various

operations involves the possibility of some loss, especially as the amount of magnetite is comparatively small; but, on the whole, the method answered very well. The great majority of the analyses indicated that the pyrrhotite could be represented by the formula Fe_8S_7 , while two or three worked out to Fe_7S_6 and Fe_6S_5 ; so that the former can be regarded as the most probable for the pyrrhotite from the Sudbury district.

For purposes of comparison, a number of pyrrhotites, as pure as it was possible to obtain them, from various localities, were further purified by magnetic concentration and analyzed. One from Rossland, B. C., conformed to Fe_8S_7 , one from Anthony's Nose, N. Y., to Fe_7S_6 , as did also a sample from Enterprise, Ont.*

As absolute uniformity, even in the material from a limited district, was not obtained, it would not be wise to draw general conclusions, or attempt to make any general applications, without an exhaustive study of more representative material.

It seems, however, a justifiable conclusion from the work so far that the pyrrhotite from the nickel-region of Sudbury is of fairly uniform composition, and is best represented by the formula Fe_8S_7 .

Summary.

In recapitulation, the main facts may be summed up briefly as follows:

1. Our present conception of the constitution of pyrrhotite is very unsatisfactory. The nature and associations of the mineral are such that analyses are often misleading, and a great deal of careful, systematic work is necessary as a basis for generalizations of any value.
2. The conditions under which pyrrhotite is formed in nature are still very little understood.
3. Nickel is universally associated with pyrrhotite in greater or less amount, though in but few instances is it present in quantities of economic importance.
4. The Sudbury pyrrhotites are very uniform over large areas, as to metallic contents and associated minerals.
5. Aside from the copper- and nickel-minerals, the others

* This pyrrhotite is associated with a remarkable deposit of molybdenite, which has recently been exploited.

are of small economic importance, except, perhaps, sperrylite, which is furnishing an increasing amount of the world's supply of platinum.

6. The magnetic separation of the nickel from pyrrhotite is out of the question commercially.

7. The nickel occurs in the pyrrhotite as the so-called pentlandite, and not as an essential constituent of this mineral.

8. Nearly all the pentlandite can be separated from the pyrrhotite by magnetic methods; but peculiar physical conditions seem to render its absolute elimination an impossibility.

9. The pentlandite does not conform to the generally accepted formula $(Fe + Ni)S$. The metallic constituents are always in excess of the sulphur by a constant ratio of 11:10. But, as yet, no satisfactory explanation of this phenomenon can be advanced.

10. The pyrrhotite from Sudbury can best be represented by the formula Fe_9S_8 .

11. Pyrrhotite and magnetite can be separated by a 10 per cent. solution of nitric acid with fairly satisfactory results.

II. GENESIS OF THE SUDBURY ORES.

General Considerations.

For convenience pyrrhotites may be divided into two main classes, according to their geological relations.

1. Those of the first class occur, often with more or less pyrite and chalcopyrite, as lenses in acidic gneisses and schists. These lenticular masses generally conform to the foliation of the schists, and are often repeated and connected by leaner zones, like fahlbands. Such deposits are of world-wide distribution; and, wherever found, generally carry pyrrhotite low in nickel, seldom containing more than 0.5 and usually less than 0.25 per cent.

2. The second class also is widely distributed. The deposits are likewise lenticular in shape, but they are associated with basic igneous rocks, usually of the gabbro type, or their metamorphic equivalents. Another characteristic feature is, that while they lie well within the limits of the eruptive rock, they generally occur at or near its contact with other rocks, such as granite, mica-schist, porphyry or diabase. The pyrrhotite is

always associated with more or less chalcopyrite and pyrite, and at times with the rarer minerals, pentlandite, sperrylite and gersdorffite. The characteristic minerals of the basic rock are also intimately mixed through the prevailing sulphides. Nickel is almost invariably present, at times reaching the amount of 10 per cent. Generally, however, from 2 to 4 per cent., as at Sudbury, would be a fair average. In Norway and Sweden the average is lower.

It should be added that the above general statements as to the nickel-contents of the two classes of pyrrhotite-deposits is subject to some important exceptions.

3. Outside of these two classes, pyrrhotite is found at times in considerable quantity in true fissure-veins; but this occurrence is relatively unimportant.

Types of the first class, as represented by the Phillips mine, at Anthony's Nose, N. Y., the Ducktown, Tenn., deposits, and numerous *fahlbands* in various parts of Ontario, Norway and Sweden, are believed to be replacement-deposits along crushed zones.

To the second class of deposits an igneous origin has been attributed in recent years by some of the ablest workers in this field of geology. The sulphides are regarded as original rock constituents, and it is thought that, being among the first minerals to crystallize in a cooling rock-magma, they became concentrated in their present position before the rock solidified.

It is well established that rock-magmas—especially the more basic—tend to divide into fractional parts of varying acidity. What forces produce this "magmatic differentiation" are not clearly understood.

There seems to be excellent evidence to prove that many deposits of magnetite (always titaniferous), chromite and corundum have originated in this way. That is, they are simply excessively basic developments of magmas, in which the mineral in question is a normal, or common, accessory constituent.

These deposits, however, consist of oxidized compounds; and their segregation presents fewer theoretical difficulties than does that of the sulphides.

Value of the Classification.—Quite apart, however, from theories of origin, the distinction above made as to geological relations is of the utmost importance from an economic standpoint.

This view of the relative value of the pyrrhotites in acid and basic rocks, as nickel-ores, is strongly urged by Profs. Adams and Kemp in valuable papers which appeared about the same time.*

The Sudbury Pyrrhotite Deposits.

In studying the origin of pyrrhotite of the second class, particular attention has been paid to the Sudbury deposits. Reference will, however, be made to similar deposits elsewhere when necessary.

Before proceeding with the consideration of the origin of the ores, it will be necessary to give a brief account of the geology of the deposits, especially as the ideas formerly held have been recently much modified. The Canadian Geological Survey has lately paid particular attention to the district, and it is now recognized that its relations are much more complex than was at first thought. In his preliminary report on the district, Dr. A. E. Barlow,† who has had charge of the work, gave some general ideas of the nature of the rocks and the extent of the ore-bodies. But the field-work was not completed at the time, and many new facts have been collected during the past season; hence, his final views on the subject will not be presented until the full report is issued. Meanwhile, the question must be considered with the understanding that some of the previously-presented conceptions are subject to revision.

The deposits are prevailingly lenticular, pinching out in both directions and conforming to the general strike of the enclosing Huronian strata. The ore always occurs in, and contains fragments of, a basic and altered eruptive of the gabbro-type.

The ore-bodies may occur either well within this eruptive or at its contact with the other prevailing rocks of the district, namely, granite or granite-gneiss, quartzite, or the metamorphosed representative of a series of basic sedimentaries, now termed "greenstones" by the Survey.

Dr. Barlow says his investigations prove that the normal

* F. D. Adams, "Prel. Rep. on the Geol. of a Portion of Central Ont.," *Geol. Sur. Can.*, vol. vi., (3); "On the Igneous Origin of Certain Ore-Deposits," *Proc. Min. Assoc. Que.*, 1894. J. F. Kemp, "The Nickel-Mine at Lancaster Gap," *Trans.*, Oct., 1894.

† *Summary Rep. of the Director of the Geol. Survey of Can.*, 1901.

or type-rock associated with the deposits is a member of the gabbro family of rather exceptional character. It nearly always has traces of a broad, ophitic structure,* and the presence of hypersthene or enstatite justifies its classification as a norite. Considerable original quartz is, at times, present. In general, the rock consists of a basic plagioclase, hypersthene, or enstatite, augite, biotite, hornblende and quartz, with smaller quantities of accessories. Associated with the nickel-bearing norite and grading into it, is a rock which is called "micro-pegmatite." Microscopically studied, the change consists in the gradual assumption of a reddish color and an increase of quartz and feldspar. The hornblende is replaced by biotite and the plagioclase by orthoclase.

The Nickel Belts.—Three main belts of these norites and associated micro-pegmatites are now recognized, designated as the Northern, Middle and Southern belts respectively. They are, at present, mapped as separate, but genetically and mineralogically they are essentially identical. The northern belt runs from the old Ross Mine (Foy township) ESE. to Bowell, where it branches. The limits of the smaller branch have not been ascertained, but the larger trends to the N. and connects with the large area of basic rocks to the W. of Lake Wahnipitae. The middle band begins in Levack township to the SW. of the northern, and runs in a southwesterly direction across Windy Lake to Trill.

The southern and most important belt begins in scattered patches in Drury township (S. of Trill), which unite and extend unbrokenly NE. for over 32 miles into Denison township, where a maximum width of over 4 miles is attained. Here it is divided into two by an intrusion of coarse "augen" granite-gneiss. The northern, or more important branch, pursues a northeasterly direction through Garson township (S. of Lake Wahnipitae). The southern branch crosses the Vermilion river and passes through Copper Cliff, where it rejoins the other.

It will thus be seen that the norite belt forms a sort of rough and somewhat disconnected ellipse, the center of which is occupied by the basin of later silicified volcanic tuffs, and surrounded by the so-called Laurentian acidic gneisses.

* This was found by the writer, also, to hold true as a general rule.

The unraveling of the complex, which was formerly included under the general name of "greenstone," has proved a very difficult problem. The results seem to show that it can be broken up into several series, comprising eruptives, metamorphosed sediments, and some as to whose true nature it is difficult to decide.

The relation of the granite intrusions also presents a difficult problem. These granites in many places, undoubtedly, cut some of the basic rocks in close proximity to the ore-bodies, but in other places they seem to be earlier than these.

The geologists of the Canadian Survey are now of the opinion that these granitic rocks are intruded into rocks, largely of sedimentary origin, and classed as greenstones, but that these intrusions are earlier than the ore-bearing norite. The problem is complicated by the close similarity in mineralogical and chemical composition of the so-called altered sediments and the basic eruptives, and by the excessive metamorphism which all have undergone.

The points at issue are probably not yet finally settled, and a great deal of careful work will, no doubt, be necessary before the last word is spoken. In the absence of the full Survey report, the matter is in a very unsatisfactory state, but we may confidently expect, in Dr. Barlow's final utterance, a contribution of great scientific and practical value, shedding much light on the question.

Various Theories of the Origin of Nickeliferous Pyrrhotite.

A brief statement of the views held hitherto by prominent workers in this field is appropriate here.

Dr. Bell* brings out the following points:

1. That this area was the seat of volcanic activity, with explosive violence on a large scale.

2. The greenstones along certain lines hold an abundance of angular fragments of other rocks, especially quartzite, and this brecciated condition appears to be favorable to the accumulation of ore. (Bleazard, Stobie, Copper Cliff, etc.) In fact, the ore-masses always consist of a breccia, of sulphides and country-rock in angular and rounded fragments of all sizes.

* *Geol. Survey of Can.*, vol. v., 1890-91.

3. The ore-bodies are lenticular and parallel to the strike of the enclosing rocks.

4. The chalcopyrite in large masses is generally nearly pure, but the pyrrhotite is always mixed with a certain amount of stony matter. This may indicate that the former has segregated from the original mixture by some secondary process.

5. The chalcopyrite is often in the form of branching strings and partially surrounds stony inclusions. In some of the brecciated ore-deposits in Levack township, the spaces between the greenstone fragments are filled, partly with sulphides and partly with light-colored crystalline granitic vein-matter.

6. The intimate association with the greenstone appears to indicate that they have originated first from a state of fusion, but have been more or less modified by other agencies. The presence of crystals of feldspar, quartz, apatite, etc., together with laminated iron pyrites and galena, indicates the action of solutions.

7. Both clastics and eruptives have suffered extensive metamorphism.

Von Foullon* also calls attention to the metamorphosed and brecciated condition of the diorite (more properly norite, or altered gabbro; Bell's greenstone) and to the fact that this appears to be the most favorable place for ore-deposits. Along a line of fracture which can be traced from the Dominion (Bleazard) mine to the Vermilion, very similar deposits prevail, so it must be considered that the fracture caused them. There is also a fracture-line from the Copper Cliff to the McConnell mine in Denison township, along which ore-outcrops, accompanied by diorite, and a breccia of gneiss and quartz-syenite. He then adds that the ores are not deposited from solution, but are of igneous origin, because they occur in an eruptive rock.

Dr. F. D. Adams,† speaking of "The Igneous Origin of Certain Ore-Deposits," claims such an origin for both the Sudbury and Norwegian pyrrhotites in gabbro. He thinks the ores segregated according to Soret's principle, and the formation of the minerals was determined according to Fournet's series.

* *Jahr. der k.k. Geol. Reich.*, vol. xlii., 1892.

† *Can. Mining Rev.*, February, 1894.

Philip Argall* also points out the faulted nature of the district. He considers that a leaching out of the nickel and copper from the greenstones in which they were originally formed, and a concentration and precipitation along favorable zones, is a more reasonable explanation than that of magmatic differentiation.

E. Renshaw Bush† says, the schists in Denison and Graham townships in the vicinity of the nickel-bearing greenstones carry pyrrhotite in grains and aggregates between the layers. He suggests the aqueous origin of the ores for the following reasons:

1. Because of the tendency of the sulphides to occur along planes of contact and fracture, and the impregnation of the rock near such planes.
2. Because the ore-bodies occur at the contact between structurally different rocks.
3. Because of the impregnation of the schistose areas near the greenstones.

Merritt‡ thinks that a secondary concentration is necessary to explain certain features of the ore-bodies, viz.: the presence of native copper; the "horses" of barren country-rock, cemented by ore; the "flucan" observed across certain deposits; and the sharply brecciated nature of some of the "horses."

D. H. Browne,§ in an article on "Segregation in Ores and Mattes," seeks to draw an analogy between a pot of matte, in which he found that the nickel- and copper-sulphides tended to separate somewhat, and the Sudbury ore-bodies, where it is seen that pyrrhotite and chalcopyrite, to a certain extent, form separate masses.

Prof. J. F. Kemp|| appeals to the laws of thermo-chemistry to explain the Sudbury deposits. As is well known in a fused mass or solution, the order of formation of compounds is determined by the amount of energy (heat) which they develop

* *Proc. Col. Sc. Soc.*, December, 1893.

† *Eng. and Min. Jour.*, March 17, 1894, "The Sudbury Nickel-Region."

‡ *Trans.*, vols. xvii. and xxiv.

§ *School of Mines Quart.*, vol. xvi., 1895.

|| "An Outline of the Views Held To-day on the Origin of Ores," *Min. Ind.*, vol. iv., 1895.

on crystallizing. If, now, the gabbro magma is considered as an intrusion in which the bases have been concentrated near the walls by Soret's or some other principle, and a stream of sulphuretted hydrogen and sulphurous anhydride gases finds a way of escape along the contact, the sulphides would form in the order indicated above. This should give in order, the sulphides of iron, copper and nickel. Prof. Kemp, however, recognizes that in this case nickel should be associated with the copper, not the iron sulphide.

Professor Vogt's views on this subject are well known.* He considers that on account of the close chemical and mineralogical relations of these deposits the world over, they can be explained only by a common general chemical process. He also emphasizes the fact that there is a regular transition from the pure ore, on the one hand, to normal rock, on the other, by a gradual decrease of sulphides. He claims further support for his theory in the facts that titaniferous magnetite is often present in the ore; that the platinum metals, which are regarded as essentially of igneous origin, are found in Sudbury; and that eruptive magmas can dissolve considerable quantities of sulphides. This last seems to be shown by the fact that basic blast-furnace slags often contain, 3 to 5 per cent. CaS and MnS; 4 to 6 per cent. FeS; and 6 to 8 per cent. ZnS, etc. His conclusion is that the sulphides are undoubtedly derived from original eruptive magmas, by a process of differentiation according to Soret's principle, influenced by other factors of which gravity may be important.

T. L. Walkert† says that near the nickel deposits the basic eruptives are more or less completely altered by metamorphism, while farther away the change is less, till practically unaltered rock is found. He also brings out the very important fact that some at least of the granites, in contact with the nickel-bearing greenstones, formerly held to be of Laurentian age, are really younger than the greenstones. This is well seen at the Murray mine, where the "younger granite" sends apophyses into the surrounding greenstones.

* "*Sulphidische Ausscheidungen von Nickelsulphiderzen.*" *Zeit. für prak. Geol.*, 1893. For other papers see bibliography, below.

† "Geological and Petrographical Studies of the Sudbury Nickel District." *Q. J. G. S.*, vol. liii., 1897.

Breccias are also formed in places by the inclusion of angular fragments of greenstone in the granite. Similar examples are seen in the granites south of the Blezard mine and the coarse-grained gneiss north of the Copper Cliff, which is essentially the same rock.

In direct opposition to the views of Professor Vogt, another eminent European geologist, Professor R. Beck* (Freiberg) may be quoted. Professor Beck in his admirable work on ore-deposits (Fig. 18) pictures a polished section of mixed ore and rock from the Murray mine, near Sudbury, showing its brecciated nature. Such an association, he claims, could not result from a direct magmatic segregation, but must have been due to a separation of the ore, *during* or *after* the metamorphism.

Speaking of the Norwegian nickel-deposits, Professor Beck says there are weighty considerations opposed to the theory of a direct igneous origin of the ores.

1. On physical grounds it is very difficult to understand how the molten sulphides penetrated so far into the cool, surrounding rocks (schists), as Vogt figures it.

2. On the basis of a microscopical examination of the ore, he considers that the corrosion of the residue of the rock minerals in the ore, is due to solution by water, especially as most of the ore occurs in very strongly metamorphosed parts of the gabbro, and that here the ore-separation appears later than the metamorphism. In Figs. 16 and 17† the relations are shown. The gabbro and norite, associated with the ore, is nearly always changed to amphibolite, or garnet-amphibolite, and the ore seems to have followed the metamorphic changes, or in some cases to have been contemporaneous with them. The conclusion is that the important concentration of the ore took place *during* the regional metamorphism, and *later* by the aqueous method.

Posepny,‡ referring to the Sudbury ore-bodies, claims that an igneous origin is a "chemical impossibility." But the contention is not borne out, when we consider that pyrrhotite is one of the commonest of the early crystallizations from the gabbro magma.

* *Lehre von den Erzlagertstätten*, 1st ed., 1901.

† *Op. cit.*, page 41 and 42.

‡ "The Genesis of Ore-Deposits," *Trans.*, xxiii, 1893.

S. F. Emmons* is of the opinion that the ore has been concentrated by percolating waters along lines of faulting and brecciation.

The Rossland Pyrrhotite Deposits.

By way of comparison, a word about the Rossland, B. C., pyrrhotites may not be out of place. The writer has to thank Mr. R. W. Brock, of the Geological Survey of Canada, who has been one of the chief workers in this province, for the latest data.

The ore-bodies here, while not carrying nickel in any quantity, have the same general associations as at Sudbury; and it is now fully established that they are of secondary aqueous origin.

During the trial of the suit of the Iron Mask Mining Company against the Centre Star Company, in 1899, evidence was submitted by Messrs. Clarence King, Waldemar Lindgren and R. W. Raymond as to the nature of these deposits.†

Stated briefly, the Rossland district forms part of a huge system, reaching from Cape Horn to the Arctic, and has been involved in the enormous dynamic and volcanic effects which this region has undergone from early geological times. Following the folding of the dynamic periods, the deposition of mineral matter in the fissures and along lines of weakness took place. In connection with most of the ore-bodies 3 types of rocks are represented.

1. A monzonite, often carrying pyrrhotite, and with the original structure more or less obliterated.

2. A darker, coarser-grained rock of the gabbro family, consisting of augite and triclinic feldspar, with little or no orthoclase.

3. The third is composed largely of hornblende and orthoclase. These types are doubtless local variations of the same magma, but of successive flows.

The veins are considered as distinctly of the fissure-type, and many of them are of the "shear-zone" variety—*i. e.*, consisting of a number of more or less parallel seams, with little displacement and no open fissures. The depth of the fissuring

* "Geol. Dist. of the Useful Metals in U. S.," *Trans.*, xxii, 1893.

† *Records of the Supreme Court of British Columbia*, 1899.

FIG. 1.

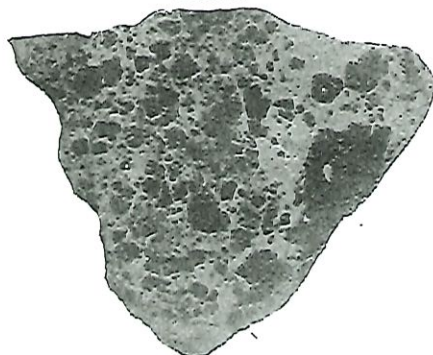
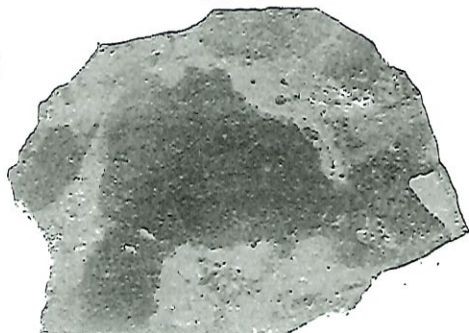


FIG. 2.



Mount Nickel Mine. Photograph of polished section of ore. The light is chalcopyrite and pyrrhotite; the dark is gangue and rock. Slightly enlarged.

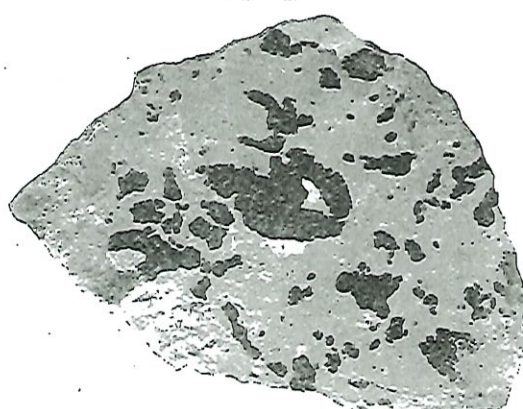
Mount Nickel Mine. Photograph of polished section of ore and rock, showing brecciated character. Slightly enlarged.

FIG. 3.



Mount Nickel Mine. Polished section of massive ore with unreplaced rock (dark). Pyrrhotite and chalcopyrite indistinguishable in the photograph. Slightly enlarged.

FIG. 4.



Stobie Mine. Photograph of polished section of ore (light), with angular and rounded rock-fragments (dark). Slightly enlarged.

FIG. 5.



Mount Nickel Mine. Photomicrograph of rock containing ore, showing the ore in parallel veinlets through the rock-minerals. The white is feldspar containing ore (dark), and granular and fibrous hornblende and hypersthene (shaded). Field, 2.5 mm.

FIG. 6.



Stobie Mine. Photomicrograph of ore-rock. The dark is ore in veinlets, etc. The white is feldspar, and the shaded is hypersthene, often with ore in the cleavages. Field, 2.5 mm.

FIG. 7.



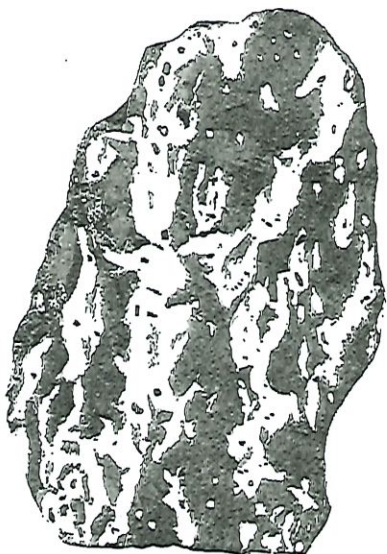
Mount Nickel Mine. Drawn from blue-print of photomicrograph, showing the ore in veinlets through the rock-minerals. The dark is mostly pyrrhotite, the white is feldspar, and the shaded is hypersthene. Field, 2.5 mm.

FIG. 8.



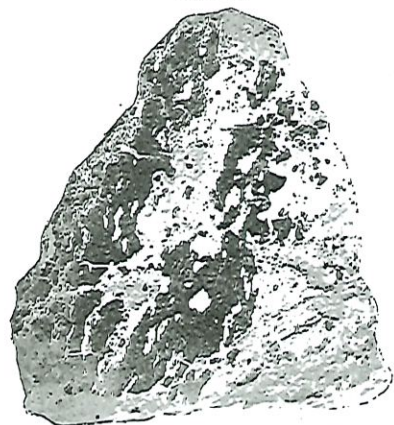
Stobie Mine. Drawn from blue-print of photomicrograph, showing the ore (dark) sharply outlined against the fresh hypersthene (shaded) and feldspar (white), and entering the cleavages. Field, 2.5 mm.

FIG. 10.



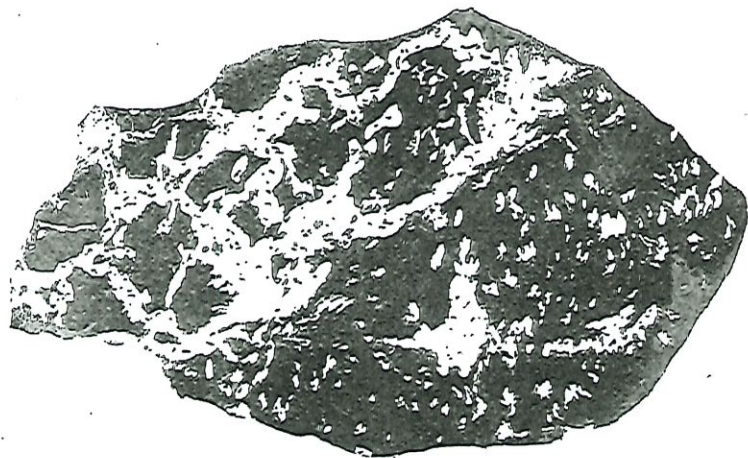
Copper Cliff Mine. Photograph of polished section of ore, showing the vein-like character of the sulphides. The pyrrhotite has been touched out with Chinese white to form a contrast with the chalcopyrite (dark). Slightly enlarged.

FIG. 9.



Elsie Mine. Photograph of polished section of ore (light), showing the irregular, vein-like replacement of the rock (dark). Slightly enlarged.

FIG. 11.



Copper Cliff, No. 2, Mine. Photograph of polished section of ore and rock, showing the brecciated character, and the vein-like nature of the ore (light), and the centers of unreplaced rock (dark). The sulphides are brought out by touching up with Chinese white. Slightly enlarged.

FIG. 12.



Elsie Mine. Photomicrograph of ore-rock, showing altered feldspar (white) with parallel veinlets of ore (dark) and irregular patches of pale-green hornblende (shaded). Field, 2.5 mm.

FIG. 13.



Copper Cliff, No. 2, Mine. Photomicrograph of ore-rock, showing ore (dark) replacing fibrous and granular hornblende (shaded), and entering cracks and cleavages. The white is feldspar and quartz. Field, 2.5 mm.

FIG. 14.



Creighton Mine. Drawn from blue-print of photomicrograph, showing the ore in veinlets, through altered hornblende, chlorite and biotite (shaded). The white is feldspar and quartz. Field, 2.5 mm.

FIG. 15.



Victoria Mine. Drawn from blue-print of photomicrograph, showing sulphides (dark) between and surrounding fibers of hornblende and biotite (shaded), and entering cleavages. The white is quartz and feldspar. Calcite is also present. Field, 2.5 mm.

FIG. 16.



Gertrude Mine. Drawn from blue-print of photomicrograph, showing the sulphides (dark) parallel to the fibers of the hornblende (shaded). The white is feldspar. Field, 2.5 mm.

FIG. 17.



Gertrude Mine. Drawn from blue-print of photomicrograph, showing sulphides (dark) parallel to the cleavages of the fibrous hornblende (shaded), and following the changes of direction. Field, 2.5 mm.

FIG. 18.



Creighton Mine. Photomicrograph of ore with small residues of hornblende, feldspar and quartz, partly replaced. Field, 2.5 mm.

FIG. 19.



Gertrude Mine. Photomicrograph of ore-rock, with ore (dark) replacing the hornblende and biotite (shaded) along cracks and cleavages. The white is feldspar and quartz. Field, 2.5 mm.

FIG. 20.



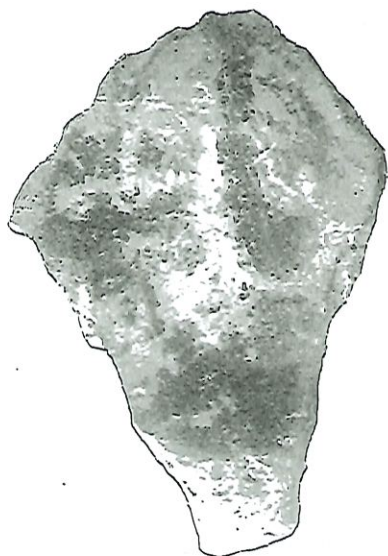
Gertrude Mine. Photograph of polished section of ore, showing unreplaced rock (dark). The light is pyrrhotite and shaded is chalcopyrite. Slightly enlarged.

FIG. 21.



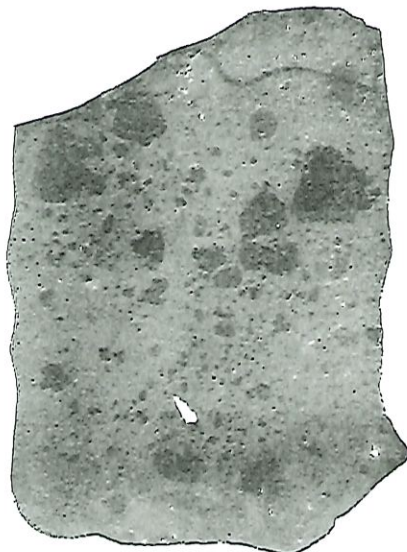
Creighton Mine. Photograph of polished section of ore, showing the vein-like nature of the sulphides. The light is pyrrhotite and the dark is chalcopyrite. Slightly enlarged.

FIG. 22.



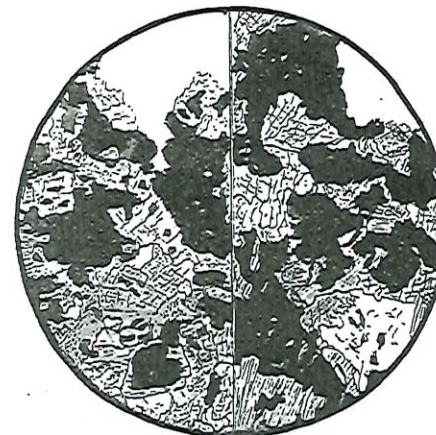
Worthington Mine. Photograph of polished section of ore, showing irregular patches of unreplaced schistose-rock. Slightly enlarged.

FIG. 23.



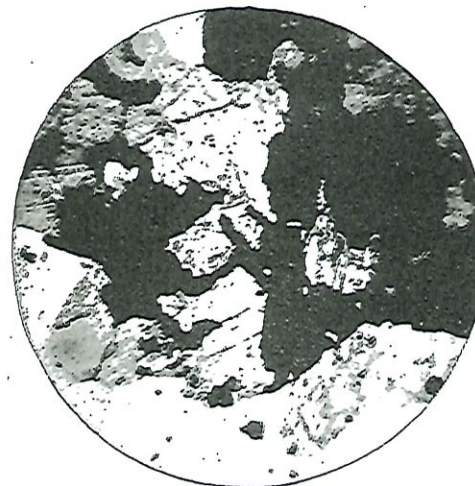
Worthington Mine. Photograph of polished section of ore, showing round and angular fragments of unreplaced rock. Slightly enlarged.

FIG. 24.



Copper Cliff Mine. Drawn from blue-print of photomicrographs, showing ore (dark) between the grains and fibers of the rock-minerals. Field, 2.5 mm.

FIG. 25.



Photomicrograph of ore from the East Tennessee Mine. The white mineral is calcite. The dark mineral is chalcopyrite, which has entered cracks and fissures in the calcite. Magnified 40 diameters.

FIG. 26.



Photomicrograph of ore from the East Tennessee Mine. The white mineral is actinolite. The dark mineral is chalcopyrite, which has filled even minute cracks in the shattered actinolite and has replaced it when crushed and altered. Magnified 17.3 diameters.

permitted a circulation of deep-seated thermal waters and a deposition of the chemicals carried in solution along the lines of weakness by a decomposition and replacement of the rock-minerals. The final result is either: (1) a deposition of the ore on one plane or fissure of the "shear-zone," or (2) a replacement of the rock between two planes, or (3) the replacement of a whole zone, and so on with endless variations. The replacement of the rock-minerals by ore (largely chalcopyrite and pyrrhotite) took place molecule by molecule, producing what is really a pseudomorph. The replacement is well seen near the Iron Horse mine, where large diallages or augites have changed to ore, while the surrounding country-rock was only partially transformed.

The replacement has, at times, been so intense that an almost solid body of sulphides (with quartz and calcite) results. In other places the original rock, more or less modified and silicified, has been only partially replaced and impregnated with ore.

Messrs. King, Lindgren and Raymond were practically unanimous in their interpretation of the phenomena of the district, which agrees very closely with that of the Canadian Geological Survey, though the more recent work shows that slight modifications of the rock relations are necessary.

Briefly, the geology and relative ages of the rocks of the mining district are as follows:*

1. The oldest series represented is classed as the Kootenay volcanic group, consisting of augite-porphyrates, tuffs, ash-beds, etc., of Paleozoic age.
2. Next comes a granite or grano-diorite (Nelson granite), probably Jurassic.
3. The Rossland monzonite, probably post-Jurassic.
4. Conglomerate, probably Tertiary.
5. Alkali (Rossland), granite and syenite.

The ores may occur in any of the rocks older than the alkali granite. This granite, whose main development is outside the limit of the Trail Creek sheet, is probably a tertiary eruption, and its dykes have penetrated all through the Rossland district. As it happens, the principal mineralization is in the augite-

porphyrites and monzonite, probably on account of the fracturing and cutting of these rocks by dykes, together with their relative solubility. The chief factor controlling the location of the mineralization seems to have been the alkali-granite contact and its system of dykes, the eruption of which *immediately preceded the formation of the ore-bodies*. The deposits are found where the dykes are particularly abundant.

The monzonite is the chief centre of mineralization, but it is not to be considered as a volcanic neck, with the augite-porphyrates and tuffs as part of the cone. These latter are much older and are cut by the Nelson granite. The occurrence of the ore has no relationship to the contact of the monzonite, being found both *outside* and *inside* its boundaries and in the younger rocks.

While magmatic differentiation has gone on to some extent, the *sulphides are not the result of it*, as is proved definitely by the work of the Survey.

A peculiarity of the rocks in which the ore occurs is that, while sheared and fractured, they are not brecciated, the dynamic movement having doubtless taken place under an immense load.

With reference to the ore-bodies themselves, some interesting points are brought out. The ore replaces the country-rock, partially or completely, starting from some fissure or line of fissures and often fading out gradually, the only "wall" being a commercial (economic) boundary. It may end abruptly at a fissure, in some cases due to a slip, which brought an unmineralized face against the ore.

Deposits very similar to those in the eruptives are found in the conglomerate (No. 4), which cannot be regarded in any other way than as of secondary origin.

The marked similarity of the geological relations in Rossland and Sudbury help to make clear some of the more obscure points in the latter district. As the conditions of metamorphism, however, were not identical, the dynamic movements have manifested themselves in different ways, and it is not surprising that there should be striking dissimilarities. This difference is seen in the characteristic structures of the ore-bodies in the two districts. In Rossland, the fissure or shear-zone type of vein is predominant, with little or no sign of brecciation.

* See Trail Creek map, 1897, and *Summary Reps.*, 1896-1900, of the *Geol. Surv. Can.*

In Sudbury, on the other hand, where the dynamical movements probably took place under a very small load, a brecciation from faulting on a large scale and, probably with considerable movement, is characteristic. This will be brought out more clearly in speaking of the individual deposits.

This brief review indicates the wide differences of existing opinion as to the origin of pyrrhotite and the various interpretations which have been put upon the same phenomena.

Microscopical Evidence of the Origin of the Ores.

The evidence on which the secondary nature of these ores is here advocated is mostly altogether different in character from that already presented. It consists in the relations between the ores and the rock-minerals, brought out by microscopical examination. As no investigation of this kind has been previously made, the results will be given in some detail. Material from all the principal mining locations has been studied, in order to avoid laying too much stress on local phenomena and to emphasize the genetic similarity of all the deposits of the district. The character of the ore-bodies in a large way will also be briefly noted as throwing much light on the general nature of the deposits.

Sudbury District.—The following separate localities in this district will represent its character:

1. Mount Nickel Mine, Blezard Township.—The ore consists of pyrrhotite (both coarse- and fine-grained) and a smaller amount of chalcopyrite, through which occur masses of almost barren rock, varying in size from minute particles to large "boulders," or "horses." Near what is considered as the foot-wall, the chalcopyrite increases in amount and the proportion of barren rock is greater.

The deposit is a good example of what is best described as a "*breccia ore-body*." Rounded and angular rock-fragments of all sizes, with sulphides as a cementing material, are everywhere a striking characteristic. Besides the brecciation as a whole, the rock is often broken and fractured, and little seams and veinlets of ore occur all through it in a very typical manner.

In some of the open cuts the ore is seen to run in particular streaks or bands, and may end very abruptly against barren rock.

The brecciated character, as it is seen in a large way, is also faithfully reproduced in hand-specimens. Figs. 1, 2 and 3, from photographs of polished sections, show these features very well.

While brecciation is one of the most striking characteristics of the deposit, evidences of faulting and shearing are not wanting in the slickensided and schistose nature of some of the rocks. There are a number of clayey seams, and some of the samples are decidedly fibrous. Along certain of the lines of crushing the rock is partly brecciated and partly slickensided, and here the ore occurs in veinlets and as a cement for the rock-fragments.

Under the microscope, the rock associated with the ore is black and dense, and belongs to the gabbro family. Hypersthene in fresh idiomorphic grains is very abundant, while augite and diallage are in subordinate amount. The pyroxenes have, in part, been altered to green fibrous hornblende. The feldspar forms an irregular mosaic, among the grains of which are fragments of hypersthene.* Biotite and quartz are sparingly present.

The relations of the sulphides to the rock-minerals is well shown. Where the pyroxene is somewhat altered it becomes fibrous; and here the sulphides are best developed.

Chalcopyrite and pyrrhotite form numerous veinlets between the fibers and cleavages of the rock-minerals. In places, where not too massive, the sulphides reproduce very faithfully the fibrous structure of the hornblende, though little of this mineral may remain, so that really a pseudomorph results. In one place or another all stages of replacement can be seen, from a few dust-like particles of sulphides in the hornblende to complete replacement. Where the pyroxene is fresh, the sulphides are outlined sharply against its margin, and only enter cleavages. In this way grains of pyroxene are more or less completely isolated. Figs. 5 and 7 show veinlets of sulphides through the fibrous minerals.

The relations seem to indicate a crushed zone, in which the feldspar has yielded and formed a mosaic, and along which the

* The rocks from all the localities examined show a more or less pronounced migration of the dark silicates, especially secondary hornblende, into the feldspar.

solutions carrying the sulphides have acted; the greater the alteration of the rock, the more complete being its replacement.

2. Blezard (Dominion) Mine, Blezard Township.—The character of the deposit is very similar to that of the Mount Nickel, showing the same brecciation and shearing. Under the microscope, however, the rock shows a more advanced stage of alteration than that of Mount Nickel. The pyroxene has changed to greenish fibrous hornblende and chlorite, which, in some cases, makes up nearly the whole rock. The feldspar is largely labradorite, and often contains irregular fibers of hornblende. The pyrrhotite forms reticulating networks among the hornblende fibers, the veinlets of ore lying parallel to the fibers.

3. Stobie Mine, Blezard Township.—The brecciated character is here very pronounced, and the ore contains a large proportion of barren-rock masses of all sizes, as usual filled around with sulphides. Fig. 4 shows the prevailing nature of the more massive ore, with its residual angular and rounded rock-fragments.

Under the microscope, sections of rock, with a small proportion of ore, are made up largely of a fine-grained mixture of plagioclase (labradorite and anorthite) and hypersthene, with small amounts of augite, diallage and biotite; and magnetite, apatite and zircon as accessories. Quartz, in varying amount, is also characteristic. The hypersthene is quite abundant, and forms idiomorphic and rounded grains and irregular aggregates; it shows the usual microscopical characters of this mineral. The pyroxenes are, as a rule, quite fresh, but form a mosaic with the feldspar, probably due to crushing. Along certain lines, however, the pyroxenes have altered to a pale-green uraltic hornblende or chlorite.

The relations of the sulphides to the rock-minerals are striking. Following the direction of the altered zones, the sulphides are most prominently developed. A veinlet of chalcopyrite can be traced across one of the sections, following the cleavages, and between the fibers of hornblende and around the fresher grains of the other minerals (Fig. 6). In other cases the partly altered pyroxene has been more or less replaced by ore, the particles of which are elongated in the direction of the cleavages, and follow these even when they change their direction

abruptly. When found in connection with the fresher grains, the sulphides simply enclose them, following their irregularities and larger cleavages (Fig. 8).

An increasing proportion of ore is accompanied by a corresponding change in the character of the rock. The pyroxenes decrease notably in quantity and finally disappear, giving place to secondary green hornblende, chlorite and biotite. Both hornblende and biotite are fibrous, and often show deformation, due to strain. The hornblende and other secondary products, in their turn, disappear as the ore increases, and various stages of their replacement can be traced from an almost pure silicate, containing a few specks of ore, to pure sulphide. In intermediate cases the sulphides may preserve very perfectly the fibrous structure of the hornblende or biotite, with little shreds of the mineral marking its original form. In purer ore, still, the dark silicates disappear almost entirely, and the feldspar is filled with inclusions of ore and changed to a confused aggregate of secondary products.

In the latter cases the amount of quartz has increased notably and remains as clear irregular patches through the ore.

4. Frood, or No. 3 Mine, McKim Township.—The ore consists of coarse- and fine-grained pyrrhotite and chalcopyrite. The latter at times occurs in almost pure masses, and is most abundant toward the walls. Barren-rock fragments occur all through the ore-body, presenting the usual breccia, cemented by sulphides.

Microscopic sections show that the rock has undergone considerable alteration. No traces of original pyroxene could be found. The secondary hornblende is bleached and ragged, and is intimately associated with the sulphides, as is the biotite, which is also plentiful. Feldspar in many cases is subordinate, while there is a notable amount of clear quartz, which is apparently secondary. Calcite also appears in small quantities. The sulphides are always found in connection with the dark silicates, and replace them to a greater or less extent.

5. Elsie Mine, Snider Township, and Murray Mine, McKim Township.—The ore-body (Elsie) is situated well within the basic rocks, the granite contact being some distance off. The ore is largely pyrrhotite, with a varying amount of chalcopyrite, which increases towards the footwall. The ore is in

places largely mixed with rock and may become subordinate in amount, even in the midst of the deposit. Nearly every piece of ore shows a characteristic breccia of rock in a matrix of sulphides, the rock being either practically barren or having veinlets of mineral irregularly through it (Fig. 9). There are many evidences of movement, as shown by the numerous clay seams impregnated with sulphides and in the schistose and slaty character of the gabbro, which is often polished and slickensided. There are also examples of what appear to be fault-planes and fissures, filled with a mixture of tremolite, quartz, calcite and ore, the latter very evidently having been introduced subsequent to the movement. The structure at the Murray mine is very similar to that at the Elsie, except that the granite contact is close to the ore-body. The granite pierces the associated "greenstones" (altered sediments?) and is undoubtedly younger.

Microscopic sections of rock with a large amount of ore show that most of the pyroxenes have changed to green fibrous hornblende, though original hypersthene more or less altered is still recognizable. The feldspar is much crushed, and is in an advanced stage of alteration, and often contains hornblende fibers, and parallel veinlets of pyrrhotite along the cleavages (Fig. 12).

The relation of the sulphides to the rock-minerals is of the usual type, *i.e.*, the replacement proceeds along and between the hornblende fibers and lines of weakness and cleavage in other minerals.

6. Mines Around Copper Cliff in Snider and McKim Townships.—This group includes the following mines of the Canadian Copper Co.: Copper Cliff, No. 1, No. 2, No. 4 and No. 5; in different stages of development. Some of the deposits are entirely surrounded by "greenstones," while others have the granite-gneiss as one of the so-called "walls." Dr. Barlow, of the Geological Survey of Canada, is of the opinion that the ore-bearing norite often occurs in more or less completely isolated patches in the "greenstones," and may consist almost entirely of ore.

No. 2 mine (and extension) affords a typical example of the "breccia ore-body." The contact is right at the granite, and the ore-bearing rock has numerous small dykes of the latter through it, and in this case, at least, it seems to be indisputa-

ble that the granite is the younger. Near the contact the granite contains a small amount of ore, and samples at times consist of both acid and basic rock impregnated with sulphides. The brecciated structure is very pronounced, and veinlets of ore occur everywhere through the rock (Fig. 11). There is also evidence of shearing, and secondary quartz-stringers are common.

The Copper Cliff mine belongs to the same brecciated type and has yielded a large number of minerals of secondary origin. (See Part I.)

No. 1 mine in places exhibits a very abrupt transition from rich ore to barren-rock. A short distance from the ore-body the rock is slightly mineralized, but on a close examination it is seen that the ore always occurs in small crevices or parting-planes, or other lines of weakness.

Under the microscope, thin sections show that the rock varies from an almost pure hornblende variety, with other minerals in subordinate amount to more acid varieties, but in all, the dark silicates are in excess. Nearly all the pyroxene has been altered to fibrous green hornblende, though in some sections traces still remain. Quartz is often quite abundant, and the usual accessories are present. The granular nature of the feldspar, and the bent and twisted hornblende and biotite indicate severe crushing. The sulphides abut sharply against the fresher minerals, but where they are fibrous and broken, they tend to occur between the fibers and grains, more or less complete replacement resulting (Fig. 13).

As the amount of ore increases, the dark silicates disappear largely, leaving areas of clear quartz and feldspar, with the ore sharply defined against their boundaries (Fig. 24). Where the effects of crushing are most pronounced, the sulphides are best developed, and then the replacement extends from these centers along the cleavages and between the hornblende-fibers, resulting in a more or less complete substitution of ore.

7. Creighton Mine, Near the Boundary Between Snider and Creighton Townships.—This mine, which has recently been developed by the Canadian Copper Co., is perhaps one of the most remarkable nickel-deposits in the world. The ore-body is very large, and the ore is above the average in richness and purity. Mining is carried on in a huge open-cut, 200 ft. or

more across and about 100 ft. deep in solid ore, with a shaft from the bottom of the pit.

The ore, which is largely pyrrhotite with more or less chalcopyrite, however, contains many masses of barren diorite (norite) all through it, presenting a very characteristic breccia. The rock-fragments vary in size from minute particles to large "boulders," and are both rounded and angular. Where the ore is not too massive to obscure the relations, it presents much the appearance of a conglomerate cemented by sulphides, with numerous ramifying veinlets along the fracture-planes of the rock. Through the ore-body are a number of intrusions of a coarse granitic rock, which often includes fragments of the diorite (norite) breccia. This rock is itself not heavily mineralized, but where it has included fragments of the basic-rock these are more or less replaced by ore, and the replacement may extend to the acid-rock itself to a lesser extent.

From the evidence collected it would appear that this granitic rock had been intruded into, and had included fragments of the diorite at the time of, or after, its brecciation. These fragments have then been partly replaced by ore, the mineralization extending slightly to the acid-rock.

There are also two dense fine-grained diabase dykes cutting sharply through the ore-body and having well-defined contacts. These are considered as among the youngest rocks of the district. While they are usually considered to have cut through the ore after its formation, there is a possibility, if the theory of igneous origin is left out of the question, of their being previous to the formation of the deposits.

They do not include fragments of the ore, and their only mineralization is along fissures and joint-planes, the introduction of the sulphides being very evidently later than the intrusion. There has also been a movement in the dykes themselves since their formation, as they are composed of numerous vertical and parallel divisions with smooth polished faces, along which sulphides at times occur. If the dykes were in place previous to the formation of the ore, their compact fine-grained texture would be unfavorable to the action of the ore-bearing solutions, except along parting-planes, while the more coarsely crystalline and crushed diorite would offer an easy passage for the circulating-waters.

No conclusive evidence of faulting or shearing could be found in the main pit, but in several of the test-pits sunk in the vicinity, to determine the extent of the ore-body, abundant proof was available. In these, the rock associated with the ore has been severely crushed and squeezed, so that it presents a schistose and slickensided appearance, and is often much like an amphibolite schist, with seams of ore on the parting-planes.

If these pits are in a continuation of the main body of ore, as seems probable, we have two different structures resulting from an unequal distribution of the dynamic force which caused them, and probably also due to local differences in the rocks themselves.

In the neighborhood of the Creighton mine, and towards Copper Cliff, the granite frequently cuts the basic rocks and sends dykes through them. What the relation of these rocks is to the ore-bearing variety could not be accurately determined.

Under the microscope the diorite, or altered norite, presents a somewhat gneissoid appearance, with a large part of the pyroxenes altered to fibrous green hornblende and chlorite. Quartz is present in variable amount.

The sulphides (Fig. 14) are best developed where the effects of crushing are most apparent. Some of the dark silicates have altered to indefinite aggregates of secondary products, which are spotted all through with ore and may even be entirely replaced. The veinlets of sulphides typically follow along the cleavages of hornblende and feldspar, which shows in some cases an advanced stage of alteration. Fig. 18 shows massive ore, with only small residues of unreplaced rock minerals.

The coarse granitic dykes contain abundant quartz and feldspar, and where they include fragments of the basic rock these show partial replacement, which also extends to the minerals of the acid rock.

8. Gertrude Mine, Creighton Township.—Besides the usual breccia which is very pronounced, there is abundant evidence of shearing in the different deposits under development (Fig. 20). In No. 1 pit the ore ends very abruptly against a wall of sheared diorite, which is only slightly mineralized along the shear-planes.

Along this contact and penetrating the rock breccia, a num-

ber of small granite dykes have been intruded, which are slightly mineralized. Sheared diorite, together with actinolite and other secondary minerals, impregnated with ore are noticeable in all the pits which have been opened up. As these pits are in line, it is probable that the faulting movement embraced them all, but from lack of exposures between, the fault-line could not be traced.

The brecciation and shearing, as well as the intrusion of the granite, evidently took place previous to the introduction of the ore, as all are more or less impregnated with mineral, either as veinlets or between parting-planes.

Under the microscope, the ore-rock is seen to consist very largely of actinolitic and chloritic hornblende, with other minerals in lesser amount.

The relation of the sulphides to the rock minerals is quite typical (Figs. 16, 17 and 19). Where the hornblende is of the fibrous variety, it is usually associated with ore, and all stages of progressive replacement can be seen. In samples with a large proportion of the ore, the more compact grains of hornblende, as well as the feldspar and quartz, are left as isolated patches in a ground mass of sulphides, while the fibrous variety has nearly all disappeared.

9. Victoria Mine, Denison Township.—The ore consists of pyrrhotite with chalcopyrite, which increases in quantity towards the footwall in a typical rock breccia. There is a fault passing through the deposit, and in the secondary minerals formed (actinolite, mica, etc.) the ore occurs in veinlets clearly later than the movement. There is also a considerable development of quartz and calcite intimately mixed through the ore, which cannot be considered as original igneous products.

The microscope shows the ore-rock to be the usual altered norite with the minerals of a diorite. Green fibrous and granular hornblende is predominant. One of the most noticeable features is the large amount of quartz and calcite, which remains spotted through the ore when the other minerals have largely disappeared. The replacement of the hornblende and biotite by sulphides is well shown (Fig. 15). The pyrrhotite has many hornblende fibers through it and enters the cleavages of the other minerals in a typical manner.

10. Worthington and Mitchener Mines, Drury Township.—The ore-rock at the Worthington is bounded on the S. by a band of dark schistose rock of sedimentary origin, and to the S of this there is quartzite. The Mitchener mine, about a half a mile W. of the Worthington, is surrounded by the quartzite. Two varieties of rock are met with in the ore-bodies, namely, coarse- and fine-grained. The coarse-grained variety is sheared and slickensided, and, as a rule, contains little ore, but when it does, it is in the form of veinlets and along the parting-planes. The fine-grained rock has been brecciated, instead of sheared, and numerous rock-fragments of different sizes, surrounded and cemented by sulphides, remain in the ore-body (Figs. 22 and 23). Through the ore-body there are also numbers of small lenticular masses of schistose diorite giving the ore somewhat the appearance of an "augen" gneiss. These are evidently residual portions of the rock which has escaped replacement, and clearly show that the introduction of the ore was subsequent to the movement which caused the shearing and brecciation.

The ore at the Worthington is often very rich, and the nickel-mineral pentlandite occurs quite abundantly.

The fault which occurs at the Victoria seems to be continued through Denison township, embracing the deposits containing niccolite and gersdorffite, through the Worthington, and gradually dying out toward the Mitchener.

Under the microscope, it is seen that the original structure of the rock has been almost entirely obliterated, and green fibrous-hornblende and chlorite are the most abundant minerals, and often show the effects of severe crushing. As the quantity of ore increases, the amount of secondary products (epidote, etc.) increases also, and the feldspar is more or less altered and peppered with sulphide grains. Quartz is often present in large amount. Progressive replacement can be traced both in the irregular aggregates and fibrous masses of hornblende and biotite. In many cases, the introduction of the sulphides appears to start along cleavages, gradually spreading and uniting till only isolated patches of rock-minerals remain, or the whole may be replaced, leaving no trace of the original structure. In this way, reticulating networks of sulphide-veinlets form all through the rock, oftentimes ramifying through the areas of

quartz and separating the individual grains. Samples of the coarse diorite containing ore present much the same features—*i. e.*, a branching network of sulphide-veinlets between the fibers and along cleavages of hornblende, etc., and separating the different rock-minerals.

11. Levack Township Deposits.—On the NW. are the large deposits in Levack township on the western side of the nickel-belt. These deposits have been thoroughly prospected and opened up to show their extent, and promise to be large contributors of ore in the future.

To the N. and W. the contact is on the large granite-area, formerly mapped as Laurentian, but which may prove to be much later. At the contact the ore-bearing diorite and granite are mixed up, and the acid-rock is impregnated with ore for a short distance, though not to the same extent as the basic-rock.

The brecciated nature of the ore-body is very pronounced, and is emphasized on the weathered exposures, where pebbles and boulders of rock stand out from the oxidized sulphides of the gossan.

The vein-like nature of the sulphides is everywhere seen, and is especially well shown in the diamond-drill cores.

As seen under the microscope, the rock consists, as usual, largely of secondary fibrous green-hornblende, and shows many evidences of severe crushing in the bent and twisted hornblende-fibers and the granular aggregates of hornblende and feldspar. The minerals, also, have a marked undulatory extinction. The feldspar is, at times, in idiomorphic individuals, giving the rock a somewhat diabasic aspect.

Good examples of the relation of ore to rock-minerals are presented in some of the sections. One shows a large fragment of fibrous hornblende which has been bent and twisted, with pyrrhotite between the fibers, following all the curves and leaving the comparatively fresh fibers intact. In other places the pyrrhotite has replaced the uralitic-hornblende to a greater or less extent, in some cases with such delicacy as to preserve the original fibrous structure perfectly. Where the feldspar and hornblende form granular aggregates, the sulphides form a mass of radiating veinlets around and between the grains, leaving the nucleus unreplaced.

12. North Range. Location, W.D. 16, Wisner Township.—On the northern extension of the nickel-belt a number of promising deposits have been opened up, but so far have not passed the "prospect" stage.

Deposits with good showing have been exploited in lot 6, concession 3, Norman township (Whistle mine); in Bowel township, W.D. 35, 150, 151 and 155, but lack of transportation facilities has been a serious drawback to more active work. The ore-rock is a fine-grained altered norite, shading to a coarser and more granitic variety to the S., and bounded on the N. by the so-called Laurentian granite.

As far as could be determined from the limited exposures, the ore-bodies are very similar to those farther S. That is, they consist of a breccia of almost barren-rock cemented by sulphides and with irregular veinlets of ore running through them. Besides the prevailing brecciation, there has been shearing and numbers of samples of schistose-rock are found seamed with ore, especially on the parting-planes.

Microscopically, the rock is seen to be composed largely of secondary hornblende and chlorite, both fibrous and granular. Feldspar is often in idiomorphic crystals, giving the rock a decided ophitic structure. The structure of the sulphides is decidedly vein-like, some of the veinlets continuing across the sections and having numerous accessory ramifications. The ore is most closely associated with the hornblende, and follows between the fibers and grains, conforming to all the irregularities and replacing it partly or wholly, often preserving the fibrous structure very well. As the amount of ore increases, the alteration of the rock-minerals becomes more pronounced, and the sulphides spread all through the section, forming a very characteristic secondary network of reticulating veinlets.

The Wallace Mine, Near the Mouth of the Whitefish River, Lake Huron.—This deposit lies outside what is commonly understood as the "nickel-belt." While essentially the same in some respects, so that it must be considered as genetically similar, it presents certain peculiar features of its own.

The mine is of historic interest, and was opened up as early as 1847 for copper. A year later it was discovered that the ore carried nickel, and a sample containing about $\frac{2}{3}$ rock, analyzed by Dr. T. Sterry Hunt, yielded over 8 per cent. of this metal.

After a series of disasters, and the loss of trial shipments on Lake Huron, the mine was abandoned in 1867, and work has not since been resumed. The deposit occurs at the junction of two small dykes of so-called diorite, intruded in the country quartzite. The quartzite at the contact is very black and dense, and has been sheared and slickensided.

Some large masses of heavily mineralized ore-rock on the dump, which have resisted oxidation, show a decidedly brecciated structure, with sulphides (pyrrhotite, pyrite and chalcopyrite) cementing the fragments.

The junction of the dykes seems to have been the center of dynamic disturbances, which caused the brecciation and shearing, and formed a favorable place for the circulation and concentration of ore-bearing solutions on a small scale.

There seems little doubt that the ore was precipitated from solution, and the relations are very suggestive when compared with those of the Sudbury deposits.

The microscope shows that the rock has been severely crushed and presents a typical mosaic in places. The hornblende is both granular and fibrous, and gives the rock a schistose appearance. The rock is also much more acidic than the Sudbury types, and contains a good deal of orthoclase and quartz, often in the form of a micropegmatite, differing in this respect also from the others. The ore is mainly in veinlets, surrounding and penetrating the remaining rock-fragments, and replacing the dark silicates (hornblende and biotite) to a greater or less extent. As the amount of ore increases, the dark silicates largely disappear, and the feldspar is broken up into grains, enclosed by ore, and this, together with quartz, is left to a large extent unreplaced, while the remaining fragments of hornblende contain sulphides along the cleavages and between fibers.

*The Rossland, B. C., District.—The Josie Mine.**—The micro-structure of the Rossland ore is so strikingly similar to that from Sudbury that a brief reference will be made to it.

The rock usually associated with the ore is a monzonite, more or less altered. The specimens examined were samples of vein-matter from the Josie (Le Roi No. 2) mine, and presented a

* Material kindly furnished by Mr. George H. Dickson, Rossland, B. C.

decidedly altered and schistose appearance, and contained pyrrhotite and chalcopyrite. Thin sections show that the rock is more or less silicified, and consists largely of secondary fibrous hornblende and biotite, and a smaller amount of feldspar with many fragments of the dark silicate through it.

The relation of the sulphides and rock-minerals is also very similar to the Sudbury examples.

They are intimately associated with the dark silicates and form veinlets between the hornblende and biotite fibers, and extend from these in the form of reticulating networks which in places wholly replace the minerals involved. Where associated with the more granular silicates and quartz, the sulphides form veinlets along the cleavages and around the grains and present the same features as the Sudbury ore, and can only be explained as due to a secondary introduction by means of circulating, ore-bearing solutions.

The Ducktown, Tenn., Deposits.—Figures 25 and 26* show the relations of the ore- and rock-minerals in the Ducktown copper-deposits.

An inspection will show that these are very similar to some of the Sudbury examples. Professor Kemp considers that ore-bearing solutions entered along zones of crushing or faulting, where the material was of a more or less open texture, and replaced silicates and other minerals; the sulphides often insinuating themselves into the broken silicates and abutting sharply against the fresher specimens. In this connection he says, "It therefore seems probable that the replaced material consisted of the crushed and greatly comminuted country-rock, which in this condition would prove an easier prey to the ore-bearing solutions. Where the crushing was most severe, the large ore-bodies are found. Unless some factor of this sort exercised an influence, it seems strange that the process of replacement should cease so sharply against perfectly fresh and unchanged representatives of the presumably replaced minerals."

Summary.

The above results are given in some detail, even at the risk of repetition. But in a problem of this kind it is all import-

* From Professor Kemp's paper on "The Deposits of Copper-Ores at Ducktown, Tenn.," *Trans.*, February, 1901.

ant that the facts should be clearly presented, so as to obtain a grasp of the entire situation and avoid a narrow interpretation based on one or two occurrences, which might not be typical of the whole.

The investigations covering the whole field of the nickel-range show that all the deposits have certain prominent features in common.

1. Brecciation with accompanying faulting and shearing are everywhere characteristic. This is shown not only on a large scale, but is also corroborated by the microscopical relations.

2. The main brecciation and shearing took place previous to the formation of the ore-bodies proper.

3. The abrupt change from massive sulphides to barren-rock, so often noticed, seems irreconcilable with the theory of magmatic segregation, and it is also difficult to imagine how the included rock-fragments could retain their angular form if they were once part of, or floated in a molten magma.

4. The ore prevailing occurs as a cement for the brecciated rock-fragments and along shear-planes.

5. The rocks associated with the ore are all members of the gabbro family and can generally be referred to norite.

6. The rocks are more or less altered and now resemble diorite, the original pyroxene having in nearly all cases changed to a fibrous green-hornblende and chlorite. Where original pyroxene remains (*e. g.*, at the Stobie and Mount Nickel mines), the structure is markedly brecciated.

7. The effects of metamorphism and the development of secondary hornblende are most marked near the ore-bodies, and diminish away from them.*

8. In general, the more complete the alteration of the rock, the more complete has been its replacement by sulphides.

9. The relation of the ore to the rock-minerals is practically identical throughout the whole district. In all cases the tendency of the sulphides is to occur along planes of weakness and in connection with the fibrous minerals.

Occasionally the relations of the pyrrhotite to the silicates suggests that it is an original constituent of the rock and one of the first minerals to crystallize from the magma. This is

seen at times in the less altered specimens some distance from the ore-bodies.

The amount of this apparently original pyrrhotite is, however, always very subordinate, and is probably no more than might reasonably be expected in a gabbro.

So that while a small percentage of the pyrrhotite may be original, the main contention still holds, namely, that the sulphides are essentially and predominantly secondary.

10. Secondary quartz and calcite are often present in the ore in appreciable amount, while they are insignificant or lacking at a little distance.*

11. Sulphides are practically lacking in the rock a short distance from the ore. The rock-fragments included in the deposit are also comparatively free from ore, except in veinlets.

12. The relation of the magnetite to the rock-minerals is in marked contrast to that of the sulphides. The former being always in more or less rounded grains in the dark silicates and generally primary.

13. With regard to the relations of the sulphides to the rock-minerals themselves, several different types might be differentiated. These types are, however, all alike in kind, and several may occur in a single specimen.

(a) Replacement starting between and extending along the fibers of hornblende, often resulting in a pseudomorph of ore after this mineral.

(b) Replacement along cleavages of the more compact and less altered minerals, breaking them up into grains and, at times, forming complete pseudomorphs.

(c) Replacement between crystals and fragments of the same or different minerals, often extending into the mineral substance, when it could be classed under (a) or (b).

(d) Replacement along planes or zones of parting and shearing, the veinlets being in general parallel and ramifying through the neighboring minerals as indicated in (a), (b) and (c).

(e) In the more crushed and granular examples, where the rock-minerals are much altered, the sulphides are peppered all through them and form an intricate and ramifying network of veinlets in the rock, at times completely replacing the minerals around certain centers.

* Compare Walker, *Q. J. G. S.*, vol. liii., 1897, p. 47 *et seq.*

(f) The dark silicates fall the easiest prey to the ore-bearing solutions, but many instances are noted in which the feldspar suffers. This is generally the case where the crushing and shearing have been most severe and the mineral is partly or wholly changed to secondary products. As a rule, though not invariably, this change is especially noticeable where the mineralization of the rock is most pronounced.

14. A comparison of the Sudbury deposits with those of Rossland, B. C., and Ducktown, Tenn., shows many remarkable and essential points of similarity. These deposits are now proved beyond all reasonable doubt to be of secondary aqueous origin, and this, aside from direct evidence, points strongly to a similar origin for the Sudbury occurrences.

Relation of Chalcopyrite to Pyrrhotite.—From the massive nature of the sulphides, very little can be accurately determined as to the paragenesis of the minerals. There are, however, certain relations existing between the chalcopyrite and the pyrrhotite which may help to explain it.

1. In a number of cases where copper is predominant, the ore consists of numerous small parallel veinlets of pyrrhotite and chalcopyrite very intimately associated. This is well illustrated by examples from the Copper Cliff and Creighton mines (Figs. 10 and 21). The same relation is a prominent feature of the Rossland ore, and hand-specimens from the two localities are almost indistinguishable.

2. The chalcopyrite is usually most strongly concentrated near the outside of the deposits, especially towards the so-called footwall. As a rule, the proportion of chalcopyrite in the main ore-body is rather small, and it tends to form fairly pure masses without much pyrrhotite. Taking these facts into consideration, it seems likely that the pyrrhotite at first constituted the largest part of the ore-body. Later, due to some dynamic movement, opening up passages through the ore-bodies, especially toward the outer limits, copper-bearing solutions entered and deposited their mineral-contents among the rock-masses and partly replaced pyrrhotite along certain lines. In some deposits, as at the Copper Cliff, where copper-minerals predominate, the fracturing may have been greater and the solutions more active or concentrated.

It is also possible that the copper disseminated in the upper

part of the ore-bodies, now eroded, has been secondarily deposited by downward-moving currents, but this does not seem to have been the case to any great extent. In the first place there is very little in the way of an oxidized gossan, and the ground water-level is comparatively near the surface. Secondly, there is little, if any, indication of this secondary change in the way of enriched sulphides which accompany the process.

Pyrrhotite is quite generally admitted to be a product of primary concentration by upward-moving solutions in a strongly reducing atmosphere, and if any considerable concentration by downward-moving waters had taken place, we would expect to find the pyrrhotite largely oxidized or removed entirely. It is, however, a notable fact that when the thin surface-covering is removed, the pyrrhotite appears perfectly fresh and with no appreciable admixture of secondary minerals, such as are formed in the process of secondary enrichment.

Source of the Metals.—What the exact sequence of events leading up to the formation of the ore-bodies and the immediate source of the metallic contents was, is not yet satisfactorily settled. The question involves many intricate problems, both of a local and general nature, and with the evidence at hand an authoritative discussion would be premature.

The metamorphic processes appear to have been very complicated, and are still more obscured by the later alteration due to the mineralizing solutions.

Pyrrhotite is a product of many metamorphic processes and may be formed in any of the classes designated by Lindgren—dynamo, hydro-thermal, solfataric or contact.*

Under which head the metamorphism of the Sudbury district could be accurately classified, it is difficult to say. Indeed, it might be considered as a combination dynamo, hydro-thermal and solfataric. From a study of the history of the district, however, it is quite evident that it was a region of vulcanism and metamorphic processes on a large scale, and the immense stores of heat and energy involved could be readily available as stimulators of the circulation and chemical activity of the mineral solutions, so that the theory of an aqueous origin presents nothing at all unreasonable.

* W. Lindgren, "Nevada City and Grass Valley Districts," *U. S. G. S.*, 1896, p. 90.

Hydrogen-sulphide is so common a constituent of mineral and thermal springs that its presence in the mineral solution can be assumed. From the nature of the deposits, the ores bearing solutions were probably highly charged with alkaline-carbonates and hydrogen-sulphide, but with subordinate amounts of carbon-dioxide.

The microscopical investigations show that the dark silicates are often bleached and robbed of iron, or else "resorbed," forming aggregates of magnetite grains. It is thus possible that a certain amount of the iron was derived from the alteration of the minerals of the replaced zone as well as from extraneous sources. The source of the nickel may, to some extent, have been the associated rocks, which contain small amounts, but it seems more probable that the larger part was derived from greater depths traversed by the circulating-waters.

Many of those who are familiar with the district, and who have discarded the theory of a direct "magmatic segregation," still consider that there was a preliminary concentration of metals with the intrusion of the norite, and that the ore-bodies assumed their present position and dimensions by subsequent processes.

This may, to a certain extent, be true, and the presence of small quantities of what appears to be original pyrrhotite in the ore-rock is cited in support of this view. Moreover, this theory does not involve many of the difficulties of the first. Still, a consideration of the whole subject and the relations involved seems to indicate that this "preliminary concentration" was comparatively slight, and appeal must be made to a more distant source of the metals, probably minutely disseminated in the rocks through which the depositing solutions passed.

In conclusion, it might be safely stated that at present the whole weight of the evidence points to the secondary formation of the Sudbury ore-bodies as replacements along crushed and faulted zones, with only minor indications of open cavities.

Previous observers have naturally been impressed by the massive character of the sulphides, in which are found the minerals of the enclosing rock, and this seems to fall in readily with the idea of an igneous origin.

The clue to the interpretation of the matter, however, appears to be furnished by the leaner material, where the relations

have not been obscured or obliterated by the excessive development of the sulphides.

The universal association of these ores with essentially similar rocks is also striking. That the norite (or gabbro) has an intimate connection with the development of the ores cannot be doubted, but in just what way they are related is not clear.

After a review of the ideas held of these and similar deposits elsewhere, it will be seen that the evidence adduced in support of the igneous hypothesis can be equally well, if not better, interpreted on the basis of replacement, while many of the observed phenomena cannot be satisfactorily explained on the assumptions of the old hypothesis.

With the additional light thrown on the subject by these investigations, there seems to be no reasonable doubt left as to the true nature of the deposits, and it may be confidently expected that future work will give additional weight to the views here advanced.

Finally, with regard to my personal connection with the matter, it may be well to say that, in taking up the work, I went into the field with an open mind and for the sole purpose of interpreting the phenomena as they were presented by the facts, without being hampered by any preconceived theories. I had always been taught to regard the deposits as essentially of igneous origin, and this theory was, of course, uppermost in my mind. But as instance after instance of the relations in the field was presented in the different deposits, the "igneous" theory was not sufficient to explain the facts. Then, on calmly studying the material collected in the laboratory, the conviction became a certainty, and I present my views only for the purpose of throwing as much light as possible on these complicated problems.

Aside from the main contention that the deposits are replacements, any arguments advanced as to the actual source, manner of concentration and paragenesis of the ore may be regarded as largely tentative and as inviting discussion, by which we may hope to arrive at more definite conclusions as to the actual processes and sequence of events, culminating in these remarkable bodies of ore as we find them to-day.

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