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GEOLOGY AND GENESIS OF ULTRABASIC NICKEL-COPPER-
PYRRHOTITE DEPOSITS AT THE PACIFIC NICKEL
PROPERTY, SOUTHWESTERN BRITISH
COLUMBIA¹

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ABSTRACT

This paper deals with geology and genesis of some pipelike nickel-copper-pyrrhotite deposits on the property of Pacific Nickel Mines in southwestern British Columbia. These deposits occur almost exclusively within a stocklike ultrabasic mass one and a half miles across. The ultrabasic body consists essentially of pyroxenite with cores of peridotite, with hornblende replacement phases, and with a remarkable reaction margin of pegmatitic hornblende. The mineralization consists of disseminated and massive pyrrhotite with subordinate pentlandite and chalcopyrite among fresh olivine, bronzite, augite, and hornblende. The ultrabasics intermingle with, and partly cut, a larger batholithic mass of genetically related diorites of Late Mesozoic age. Both rocks and ore are cut by small ultrabasic and gabbroic dikes, and by veins and alteration zones.

¹ Condensed and modified from a Ph.D. thesis submitted to the University of California at Berkeley in 1954.

BRONZITE - var. *Px* Enstatite ¹¹⁴ hypersthene series

Some of the ore occurs as sulfidic olivine-rich cores or shells with bronzitic borders, forming remarkably zoned, steeply plunging pipe- or parsnip-shaped magnesian ultrabasic structures 100 feet or more in diameter. These features suggest replacement origin. The remainder of the ore forms massive sulfide-silicate bodies similar in size, attitude, and mineralogy to the zoned ones but more irregular in cross section and showing flow lines, banding, drag folds, sharp contacts, inclusions, and hornblende reaction rims—all suggestive of injection origin.

Genetic characteristics of other similar nickel deposits and rocks of the world are summarized and compared, then two theories are presented for genesis of the ore at Pacific Nickel. Magmatic segregation is suggested with injection of sulfides in an incipiently molten state (perhaps 700-800° C) followed by minor replacement and reconstitution. Alternatively, a new twist is added to the hydrothermal replacement theory by suggesting that ascending water vapor above 650° C could deposit the sulfides and, by removal or addition of silica, convert bronzite to olivine or vice versa to produce the zoned structures and other features.

INTRODUCTION

THE property of Pacific Nickel Mines lies 7 miles northwest of the town of Hope and 100 miles east of Vancouver, at longitude 121° 30'W and latitude 49° 28'N in the rugged, wooded Coast Mountains of southern British Columbia, Canada (Fig. 1).

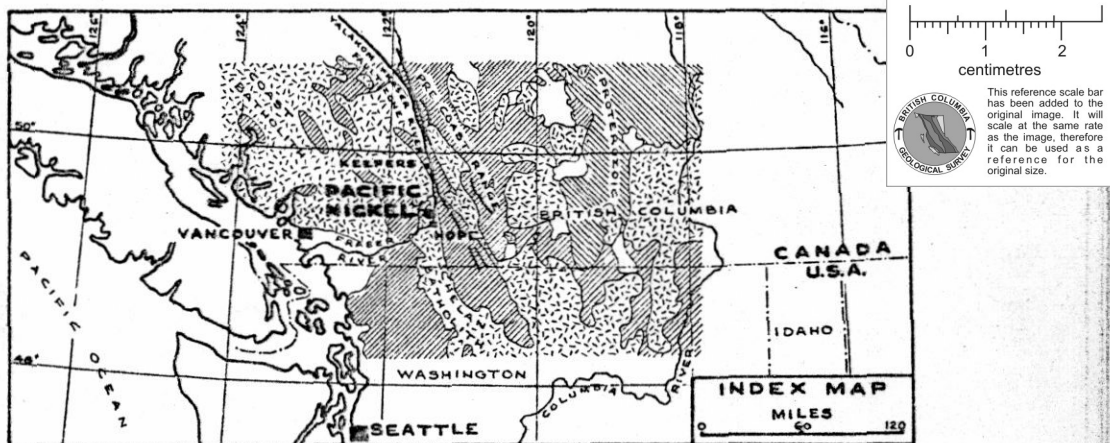


FIG. 1.

The genesis of nickeliferous pyrrhotite deposits of this general type has provoked much controversy, with theories of magmatic origin or of hydrothermal replacement origin being favored most. Such ores are all very similar to one another and are similarly closely associated with noritic, dioritic, or ultrabasic rocks. Several of the noritic or dioritic deposits have been extensively studied but, in comparison, the ultrabasic types have been somewhat neglected. Study of the geology at Pacific Nickel shows that such ultrabasic deposits can provide much new data of genetic significance.

NOTE: a VAR. of gabbro in which orthopyx > clinopyx. also Hypersthene-gabbro.

The deposits at Pacific Nickel were discovered in 1923 and were explored until 1937, then again between 1951 and 1954. The property was briefly examined by Cairnes (5) in 1924, by Cockfield and Walker (7) in 1933, and by Horwood (20, 21) in 1936 and 1937. Cairnes concluded that the ore occurred in ultrabasic rocks that cut surrounding diorite and that it was magmatic in origin. Cockfield and Walker concluded that the ultrabasic rocks were intruded by surrounding diorite and that the ore was probably hydrothermal in origin. Horwood thought that hornblendite was the principal rock type, that the sulfide ore and pyroxenite had segregated from the hornblendite and that these were injected into their present position and then later were intruded by surrounding, genetically related diorite.

AGE
REL.

The writer studied the deposits in 1951 and 1952 and found that in large part the ultrabasic rocks apparently cut the batholithic dioritic rocks as observed by Cairnes. However, some minor dioritic differentiates do cut the ultrabasic rocks. Pyroxenite and peridotite are the main ultrabasic rocks and, contrary to earlier views, hornblendite forms only a minor proportion of the ultrabasics. The hornblendite appears to have originated largely by late magmatic reaction and replacement of the ultrabasics, not by direct crystallization from a magma. The earlier writers did not recognize that the ore occurs as elongate, steeply plunging olivine- or bronzite-rich bodies, some of which are concentrically zoned with gradational contacts, others of which are relatively massive with sharp contacts.

For encouragement, cooperation and criticism in this work, the writer is especially indebted to Dr. F. J. Turner and Dr. G. H. Curtis of the University of California, Berkeley; to Dr. Christopher Riley, consulting geologist; and to R. F. Sheldon and other members of the staffs of Pacific Nickel Mines, Western Nickel (conducting recent exploration for Newmont), Newmont Mining Corporation, and the University of British Columbia. The mining companies and the University of California financed the work and granted permission to publish this paper.

REGIONAL GEOLOGY

The nickeliferous rocks at Pacific Nickel form part of the core of a 15-mile-wide block of Late Paleozoic metamorphic rocks and Mesozoic intrusives which extend north-south between the southeast end of the Coast batholith of British Columbia and the Chelan batholith of Washington (Fig. 1). Margins of this block are faulted in part against less metamorphosed volcanic and sedimentary rocks largely of Jurassic and Lower Cretaceous age (Geol. Surv. Canada, Map 737A, 1942). Serpentinities, suggestive of deep transgressive structure, occur within the block and on its east margin along faults that are southern extensions of the regional Yalakom-Fraser River fault zone. In the fall of 1954 a nickel-copper pyrrhotite deposit was discovered in a small lens of biotite diorite (of gabbroic affiliation?) in schists at Keefers, B. C., 45 miles north of Hope, along this east margin. Similar deposits might be expected elsewhere along the strike.

The nickeliferous ultrabasic rocks at Pacific Nickel form a stocklike mass about one and a half miles across (Fig. 2), bordered by a larger mass of genetically related diorites and norites, which are among the youngest of several ages of Mesozoic intrusive rocks in this area. Horwood (20, p. 2)

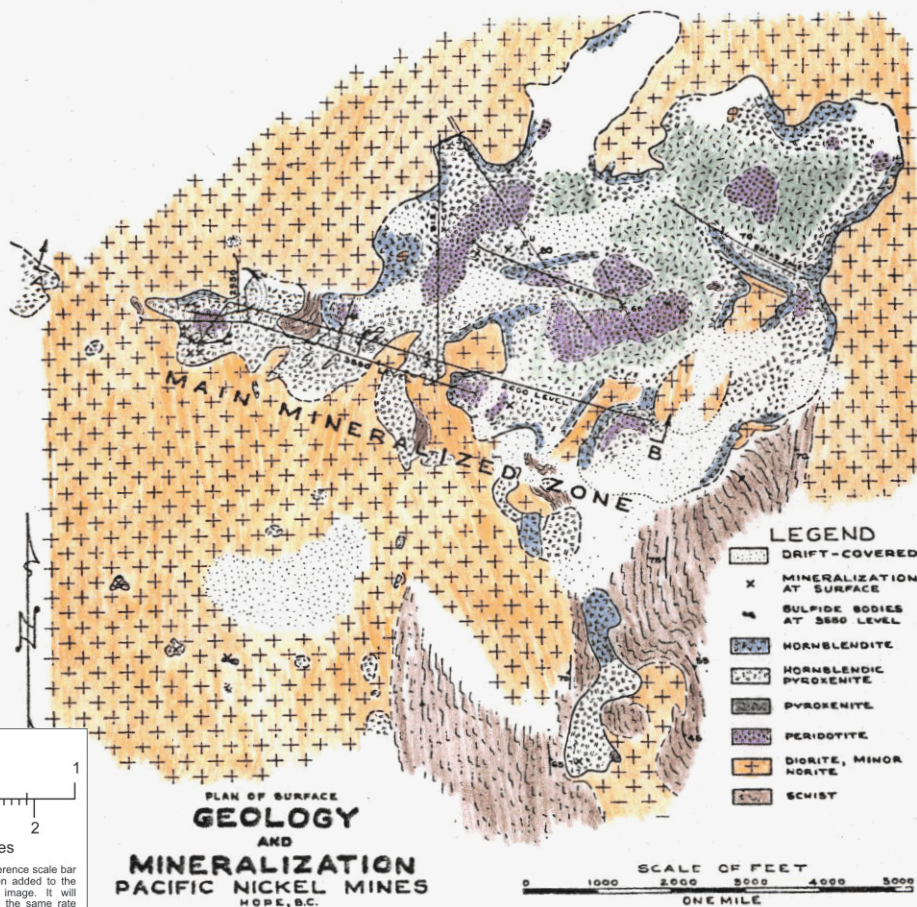


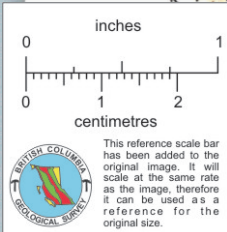
FIG. 2.

reports that the diorites cut conglomerate of probable Cretaceous age; they are grouped by the Geological Survey of Canada with other chiefly acidic intrusions that cut Upper Jurassic or Lower Cretaceous rocks. The area studied is only a part of this complex, the full extent of which is undetermined.

ROCK FORMATIONS

The following geologic units were recognized on the property (Fig. 2):

1. Metamorphic rocks, occurring south and east of the property, also represented by xenoliths in the igneous rocks (Late Paleozoic).



2. Diorites and norites, forming most of the igneous terrane; in part cut by ultrabasics, in part intermingling with them, and in minor part cutting them (Late Mesozoic).
3. Ore-bearing ultrabasic rocks—peridotite, pyroxenite, hornblende—forming a stocklike body and smaller plugs (Late Mesozoic).
4. Dikes, veins, and alteration zones.

} ACE

Plagioclase in these rocks was determined chiefly by extinction angles in sections showing centered bisectrices and by universal stage procedure outlined by Turner (34). Orthopyroxene, olivine, and augite were determined from measurements of $2V$ and some β indices using curves and nomenclature given by Poldervaart (32) and Hess (17).

Metamorphic Rocks

Most of the metamorphic rocks on the property are fine-grained garnetiferous quartzo-feldspathic mica schists of relatively uniform composition and texture, probably derived from silts. They consist of quartz, plagioclase (An_{20-35}), biotite and garnet, with minor graphite, magnetite, pyrrhotite, rutile, and tourmaline. Some contain bits of corroded staurolite or hornblende. Small amounts of muscovite and chlorite, retrogressive after biotite, are common. Pelitic types contain andalusite, some of which is corroded or has retrogressed to muscovite and chlorite. Minor basic members consist of blue-green hornblende ($z \wedge c = 25^\circ$), zoisite, minor clinozoisite, sphene, minor quartz, and secondary calcite. The above rocks probably can be classed in the staurolite-kyanite subfacies of the amphibolite facies, with perhaps a transition to the cordierite-anthophyllite subfacies (35, p. 452-456).

At some contacts with the igneous rocks, needles of sillimanite are developed in the schists. A pendant or inclusion of schist within the ultrabasics contains stubby porphyroblasts of sillimanite up to an inch long. Dark, fine-grained, granoblastic-textured xenoliths up to a few feet across are intimately intermingled with the ultrabasics and diorites along the main mineralized zone. These inclusions consist of andesine (An_{35-40}), hypersthene (Of_{30}), garnet, graphite, and magnetite. Some contain cigar-shaped eyes of andesine up to a half-inch long with central clusters of green spinel that sometimes surround corroded remnants of sillimanite—perhaps pseudomorphous after corundum and cordierite. Quartz is absent in most of these inclusions but in some it forms nodules suggestive of remnants from assimilation. The above sillimanite- and hypersthene-bearing rocks are characteristic of the pyroxene hornfels facies (35, p. 441-446), believed to indicate temperatures of at least 600 or 700° C.

Diorites and Norites

Feldspathic rocks of the Pacific Nickel property are all very similar to one another in mineralogy; they typically contain less than 40 percent mafic minerals (hypersthene, augite, and hornblende), and on the basis of plagioclase composition the bulk can be classed as hypersthene- or hornblende-diorites

with minor norite phases. These rocks are medium- to fine-grained, hypidiomorphic in texture, and locally show distinct primary lineation and foliation.

Plagioclase in the diorites ranges from An_{25} to An_{50} , averaging about An_{45} . In most of the norites it averages An_{60} but ranges to An_{35} in rarer calcic varieties. Normal and oscillatory zoning are common, with composition ranging from An_{45} to An_{25} from core to rim of some sections. Small dustlike inclusions, probably exsolved hematite, concentrated in the centres of the plagioclase give many of the rocks a pink color, which is lost, however, when pyroxene in the rocks is uralitized—probably the hematite is reduced to magnetite. Minute acicular inclusions and a few small stubby prisms of apatite are also common.

Orthopyroxene ranges from Of_{20} to Of_{56} (hypersthene) in the diorites and to Of_{15} (bronzite) in the norites. Schiller inclusions, (100) clinopyroxene exsolution lamellae, and faint normal zoning (indicated by 3 to 4° outward decrease in 2V) are common. Much of the orthopyroxene is corroded; in some rocks it is rimmed by pale green, actinolitic amphibole (uralite) and in others by greenish-brown hornblende. Subordinate amounts of anhedral augite (ca. $Wo_{43}En_{44}Fs_{13}$), partly replaced by hornblende, are present in most of the rocks. Some of it forms jackets around the hypersthene. Brown to green hornblende is almost invariably present in the diorites and norites as partial or complete replacements of the pyroxene, especially augite, or as separate grains associated with the pyroxenes. Minor reddish-brown biotite is associated with the hornblende in some specimens.

Interstitial quartz commonly occurs in the dioritic rocks in amounts less than 5 to 10 percent, but in some up to 30 percent. Magnetite is present as irregular, late primary grains and as a secondary uralitization product. Pyrrhotite and chalcopyrite, rarely found in the feldspathic rocks, form xenomorphic interstitial grains.

In general, field relations of the many dioritic and noritic rock varieties are complex and criteria for age relations are commonly uncertain or lead to contradictory conclusions. The bulk of igneous rocks surrounding the ultrabasics grade imperceptibly from pink to gray diorite to norite and from quartz-free to highly quartzose types, but in several places they show various cross-cutting relations with one another. Chilled contacts are rare, suggesting a large measure of contemporaneity. In two localities, in the 512 and 1900 crosscuts of the 3550 level, pink and gray diorites cut one another and in turn appear to be cut by, and form inclusions within, adjacent ultrabasics.

The main batholithic mass of diorite appears to be cut by the main ultrabasic body. In places the dioritic rocks are cut and embayed and their lineation and foliation are truncated by the ultrabasics. At contacts with the surrounding dioritic rocks the ultrabasics show hornblendite reaction zones up to 100 yards wide. [Rounded to subangular diorite inclusions of various sizes in various stages of assimilation can be seen in several hornblendite reaction zones within the ultrabasics.]

Some hypersthene diorite and quartz diorite along the main mineralized zone, however, show even closer contemporaneity with the ultrabasics. Here hornblendite reaction zones are absent, dioritic apophyses extend short dis-

← AGMATITE:
1. MICHAMITE C
2. FRAGMENTAL
LESS GRANITE

tances into the ultrabasics and vice versa, contacts are sharp or gradational with intermingling, and structures in the diorite and ultrabasics are concordant. Also grading into the ultrabasics are a few lenticular, discontinuous bodies of anorthositic norite a few feet or less wide, some of which form streaks and inclusions in the ore (Fig. 12).

Cutting all the other dioritic, noritic, and ultrabasic rocks are small bodies and dikes of hornblende diorite, as well as other minor differentiates (dikes and veins). These later bodies, along with cognate hornblende clots in some of the earlier diorites, may have led Cockfield and Walker (7, p. 65A) and Horwood (20, p. 5) to conclude that the main batholithic mass of diorite also cuts the ultrabasics. Horwood recognized pink diorite that was older than the ultrabasics but believed it to be Early Mesozoic in age. He thought the grey batholithic mass of diorites of Late Mesozoic age cut the ultrabasics, although genetically related to them. Many of the pink and grey diorites, however, appear to be merely color variations of the same main batholithic mass and not rocks of greatly different geologic age.

A strong genetic relation between the feldspathic and ultrabasic rocks is indicated by the close contemporaneity and intermingling, by the presence of intermediate gradations even though small in bulk, and by the presence of the same mafic minerals in the same proportions relative to one another. The various cross-cutting relations, however, suggest several successive surges of intrusion separated by enough time for partial consolidation. The feldspathic rocks and even the problems of their age relations described above are strongly analogous to those encountered in the nickel region of Sudbury, Ontario (10, 43).

Ultrabasics

Most of the ultrabasic rocks at Pacific Nickel contain no feldspar and consist essentially of fresh, undeformed bronzite, olivine, augite, and hornblende with textures that are suggestive of considerable recrystallization. In mapping, the following varieties were distinguished:

Hornblendite	Predominantly hornblende
Pyroxenite	Mainly pyroxene (commonly bronzite, with 40 percent or less augite, also minor hornblende).
Hornblendic pyroxenite	Pyroxenite with abundant hornblende, grading into hornblendite.
Bronzite	Mainly orthopyroxene (uncommon).
Olivine pyroxenite	Pyroxenite with subordinate amounts of olivine.
Peridotite	Mainly olivine with subordinate pyroxene and minor hornblende. Hornblendic variations (common) resemble schreishemite.
Harzburgite	Olivine and orthopyroxene.
Dunite ²	Over 90 percent olivine.

² The terms "dunitic" and "dunite ore" are used for mineralized dunite where sulfide content decreases the olivine percentage to less than 90.

The grain size of these rocks varies from fine to coarse but most of the rocks are medium- to fine-grained; the texture is allotriomorphic or hypidiomorphic when dominated by olivine or pyroxene, and coarsely porphyritic or poikilitic when dominated by hornblende.

Olivine in all of these rocks, as well as in the ore, has about the same composition, Fa_{14} ($2V_x = 89^\circ \pm 1^\circ$). It contains small inclusions parallel to (010) and (100)—probably magnetite or chromite—which give it a dark gray to black color in hand specimens. The olivine is corroded in contact with the pyroxenes. Bronzite (Of_{10} - Of_{19}) is the major constituent of most of the pyroxenites. In some of these rocks it is jacketed by augite but the reverse relation was also observed. In some of the peridotites, subpoikilitic bronzite encloses olivine. Some of the bronzite contains small inclusions of sulfides, magnetite, or hornblende. Augite (ca. $Wo_{43}En_{47}Fs_{10}$ - $Wo_{43}En_{42}Fs_{15}$), present in most of these rocks, is invariably mottled or peppered with hornblende, and partly to completely replaced by it as noted in the feldspathic rocks.

Hornblende in the ultrabasic rocks is olive-green to brown in color in thin section with $z \wedge c = 17$ - 21° (mostly 19°) and $2V_x = 76$ - 92° (mostly 85°). This is apparently magnesium-rich, common calciferous hornblende. In the more magnesian rocks it is paler colored with lower refractive indices and higher $2V$. In reaction zones with schists or diorite it shows conspicuous brownish cores and greenish rims. In the peridotites it almost invariably forms large poikilitic grains enclosing olivine and pyroxene, whereas in pyroxenite it is rarely poikilitic but occurs as interstitial grains or as phenocrysts. The following relations show that it has formed largely, if not entirely, by reactive replacement of augite and also of orthopyroxene and olivine:

1. Augite is invariably either partly or entirely replaced by hornblende and is absent in very hornblendic rocks—it bears a reciprocal relation to hornblende.
2. Orthopyroxene and olivine are generally corroded by hornblende.
3. Hornblende has a porphyritic or poikilitic habit and is erratically distributed.
4. Hornblendites are most common as pegmatitic reaction zones next to diorite.
5. All stages of replacement and recrystallization can be traced.

Interstitial bytownite (An_{80-85}) is found in a few of the hornblendites and pyroxenites but not in the olivine-bearing rocks. Chromite forms small octahedral grains in the olivine. Magnetite is also common as inclusions in the silicates, as interstitial grains, and as an alteration by-product. Accessory interstitial sulfides and sulfide inclusions in the silicates are also widespread. Small amounts of interstitial quartz, a contamination product, were found in pyroxenite close to the schists. Alteration products common in minor amounts in the ultrabasics are phlogopite, chlorite, talc, serpentine, tremolite-actinolite, anthophyllite, and carbonates.

According to the recognized sequence of fractional crystallization in basic magmas, a sequence of magmatic crystallization that could be suggested to fit the textural and field relations in both the ultrabasic and feldspathic rocks is:

(1) chromite, magnetite (in part); (2) olivine; (3) magnesium pyroxene, joined later by magnesium-calcium pyroxene, both becoming progressively enriched in iron; (4) plagioclase, becoming progressively more sodic, and hornblende; (5) sulfides and magnetite (in part) (Fig. 5). However, as discussed later, much of the texture may have originated by replacement or conversion.

The ore-bearing ultrabasic rocks form an irregular stock-like intrusion (Fig. 2) approximately one and a half square miles in area with outcrops occurring over a range from 2,500 feet to 5,000 feet in elevation. The stock consists of cores of olivine pyroxenite or peridotite surrounded by pyroxenite, the most common rock type, which is in turn bordered by a remarkable marginal reaction zone of coarse pegmatitic hornblendite up to 100 yards wide. This remarkable type of zoning is present locally as well as on the broader scale and is characteristic of the smaller salients and even some of the orebodies. The northeast half of the ultrabasic body is barren of mineralization and contains little hornblende except at the contacts. The southwest half, however, is a "wetter," more highly varied hornblendic assemblage which is mineralized, contains all of the known ore, and in addition contains many bodies of diorite, hornblendite dikes, and various other late differentiates.

Bowen and Tuttle (4) have concluded that ultramafics apparently can be intruded only in the solid state, which should produce considerable granulation and deformation of the silicate crystals. The ultrabasics at Pacific Nickel probably were intruded as such masses of largely solid material but internal fabrics such as banding, foliation, lineation, protoclastic structure, and strained silicates are rare. The textures described suggest considerable recrystallization of the fresh silicates after any solid state movement which may have occurred.

The ultrabasic rocks are all part of one intrusion; most of their mutual internal contacts are gradational but many are also sharp. Rounded pyroxenite inclusions that occur in peridotite and in dunitic cores of the orebodies may suggest that peridotite locally cuts pyroxenite. However, in other places irregular bodies of harzburgite and bronzitite cut the peridotite, and bronzitite borders occur at some contacts between hornblendic pyroxenite and peridotite. Some contacts between pyroxenite and hornblendite or peridotite bodies are gradational in one place and planar in another, as if governed by replacement along fractures. The above features are highly suggestive of conversions from olivine to orthopyroxene and vice versa, which Bowen and Tuttle (4) found could be produced by water vapor at high temperatures (ca. 700° C).

In several localities south of the underground workings and at 2,400 feet within the 3,550 level, hornblendite can be seen in all stages of replacement of the anhydrous ultrabasics. Pyroxene cores, relict textures, contact relations, and even plagioclase content are preserved in some rocks while in others the pyroxenes have been fully replaced and the pseudomorphs and relict textures have been reconstituted to form a medium-grained, hypidiomorphic-textured hornblendite composed essentially of prismatic brown hornblende full of small magnetite inclusions. Other bodies of pegmatitic, panidiomorphic-textured hornblendite, composed of stubby hornblende crystals up to two

inches across, have apparently been formed by similar replacement but perhaps at higher temperatures. These pegmatitic hornblendites, such as those forming the reaction zone around the main ultrabasic intrusion, grade imperceptibly into the pyroxenites and peridotites at most places. All stages of replacement can be traced, yet many of the hornblendite bodies and even the hornblendic pyroxenites show lineation, sharp contacts, inclusions, contact alteration, and dike apophyses suggestive of intrusion into the surrounding, more anhydrous ultrabasics. Subpoikilitic phenocrysts of labradorite (An_{60}), labradorite-rich schlieren, and dikelike pegmatitic bodies grading into hornblende gabbro are common near inclusions and contacts of the hornblendites (Fig. 13). Such features of the hornblendites are analogous to some fabrics of the zoned orebodies and may suggest a similar origin (see hydrothermal theory of origin of the ore).

The marginal distribution of hornblendite around the ultrabasic stock suggests that constituents of the hornblende may have been derived partly from the surrounding diorites or metamorphic rocks by addition of H_2O , Ca, and Na to the ultrabasics or that the ultrabasics assimilated these rocks slightly. Indications of limited assimilation are gradational contacts, partly digested inclusions, quartz in pyroxenite near schist, quartz knots in hornfels inclusions, and rarity of contacts between peridotite and diorite or schist (pyroxenite or hornblendite usually intervenes). Intimate mixing with pyroxene-hornfels inclusions and diorites, general lack of protoclastic structure, replacement of ultrabasics by hornblendite, bronzite veinlets, closely related dike activity, and certain features of the ore and alteration (see hydrothermal theory of origin) all suggest that the ultrabasics were emplaced at a fairly high temperature, perhaps of the order of 600 to 800° C.

Dikes, Veins and Alteration

A closely genetically related assemblage of small, aphanitic to coarse-grained dioritic or gabbroic and ultrabasic dikes cut some of the schists and all of the plutonic rocks and ore at Pacific Nickel. Many of these dikes can be traced into parent bodies that form an integral part of the exposed igneous complex. Most are less than six inches thick; a few attain a thickness of 30 inches or even 4 to 6 feet. The hornblendite dikes (Fig. 14), which are twice as common as all of the others, consist mostly of prismatic hornblende and have sharp contacts with ultrabasic wall rocks. Some consist of stubby hornblende (perhaps indicating higher temperatures) and have gradational contacts. Some cause alteration; others do not. Some contain hypersthene or bronzite phenocrysts and, rarely, serpentinized olivine with pyroxene coronas. Many grade into hornblende gabbro, and some grade into pyroxenite. The rest of the dikes vary from aplite to pyroxenite but dioritic or gabbroic types are the most common. Mafic constituents of these are brown or green hornblende, or hypersthene (Of_{20-30}), or both; rarely minor biotite or augite. The plagioclase ranges from An_{32} in aplitic types to An_{10} in very mafic types. As in the associated plutonic rocks, apatite, magnetite, and pyrrhotite are common accessories.

= REACTION RIM

All the plutonic rocks and dikes are cut by numerous small veins that rarely exceed one or two inches in thickness and which consist of combinations of oligoclase (An_{15}), quartz, tourmaline, talc, calcite or dolomite; or of fine-grained carbonate with marcasite and chalcodony. These veins show no spatial relation to ore and cut across ore and veinlets of sulfides. Quartz veinlets are the most common but, except for rare pyrite and chalcopyrite, they are barren.

Uralitization is widespread, especially in the feldspathic rocks of the complex, in which much of the pyroxene is partly or completely converted to pseudomorphs. Most of these have pale green to colorless actinolitic cores, and rims of green hornblende, chlorite, biotite and magnetite. In the uralitized ultrabasics hornblende is peripherally transformed into actinolite grown in crystallographic continuity while augite is commonly completely replaced and only cores of the orthopyroxene remain. Steatitization (talc, carbonate,

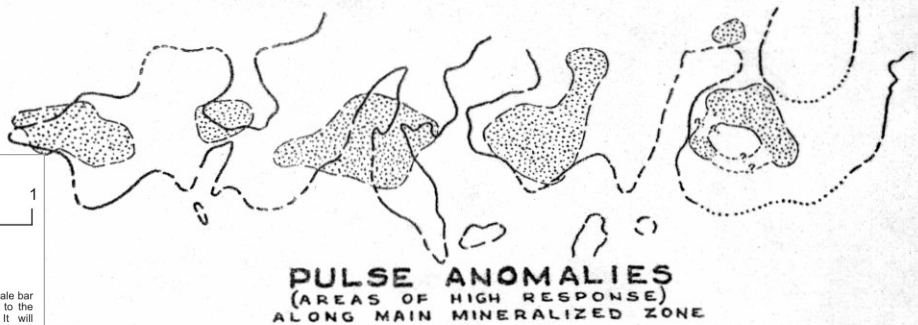


FIG. 3.

anthophyllite) affects some of the pyroxenites and locally accompanies some of the actinolitic alteration. The largest steatitized area appears to be localized along a prominent zone of shearing, uralitization, and aplite-pegmatite injection in the eastern part of the ultrabasic mass (Fig. 2). Serpentinization accompanies uralitization in some of the peridotites, some of which consist of 50 percent serpentine. Many of the remaining peridotites and olivine pyroxenites are incipiently serpentinized along cleavages and grain boundaries, and form soft, crumbly rocks (Fig. 14) which weather deeply. Poikilitic plates of phlogopite are developed in such rock in advance of this alteration, and chlorite commonly replaces the phlogopite.

All of the various types of alteration are closely controlled by, and localized along, joints, faults, dikes, and intrusive contacts and therefore could have been produced by solutions which originated elsewhere in the complex, perhaps at greater depth. Since orthopyroxene is unaffected while olivine is serpentinized, the serpentinization may be interpreted as having been produced by extraneous solutions entering the rocks below 350°C (for olivine with at least 10% fayalite) instead of by deuteric solutions (4).

Silicates.—In general, the silicates are more euhedral when enclosed completely in the sulfides than when forming barren rock, and fresh idiomorphic silicates enclosed like phenocrysts in an allotriomorphic groundmass of sulfides are more common than the earlier writers suggest (Figs. 17, 18, 19). Even fresh idiomorphic hornblende is enclosed in a groundmass of chalcopyrite in one place in the 1900 orebody. Similar textures are also common in other deposits (15, 33, 36, 40) and may suggest magmatic origin.

TABLE 1
SPECTROCHEMICAL ANALYSES

Olivine		Orthopyroxene				Hornblende						
Pride of Emory orebody		Barren peridotite, center of ultrabasic mass		Brunswick No. 1 orebody		Barren pyroxenite, N.E. part of ultrabasic mass		1600 Orebody		Barren hornblende, end of 512 crosscut		
Ni	.10	.10	.08	.09	.02	.02	.03	.02	.16	.20	.07	.08
Cu	.0008	.0006	.0002	.0002	.0002	.0003	.0007	.0007	.04	.02	.02	.02
Co	.07	.08	.07	.08	.008	.01	.007	.01	.04	.04	.05	.05
Mn	.42	.48	.25	.32	.13	.14	.18	.19	.16	.16	.18	.16
Al	0.5		0.5-1.0				5		5			
Na			<0.1				0.5-1.0		0.5-1.0			
Ca	.005		.005				.005		.005			
Cr	<.008		.008		0.5		0.8		0.5		0.1	
Ti	.001		.001				0.1		0.5-1.0			
Ba	*	*	*		*		*		.001			
Zr	*	*	*		*		*		.001			
V	*	*	*		0.1		.05		0.1		0.1	
Mo							Tr (<.002)					
Sc			Tr						Larger Tr			
Sr	*	*	Tr		Tr		*		Tr (<.02)			
2V _x = 89° Fa ₁₄		2V _x = 89° Fa ₁₄		2V _x = 90° Of ₁₁		2V _x = 86° Of ₁₄		Greenish z-c = 21° γ = 1.663 β = 1.653 α = 1.642 2V _x = 92°		Brownish z-c = 17° γ = 1.675 β = 1.664 α = 1.653 2V _x = 89°		

The figures above are percentages. Asterisks indicate amounts less than spectrographic sensitivity. Spectrographer, G. M. Gordon, University of California.

On the other hand, corrosion of the primary silicates is also common. Some of them have the appearance of having been partly replaced, resulting in skeletal forms that still retain plane crystal faces. Cockfield and Walker (7, p. 67A) describe replacement in various stages—from sulfides along cleavage cracks to “replacements” of interiors of crystals, and to where only isolated cleavage flakes remain unreplaced. Such corroded and embayed silicates could be explained either by selective replacement or by late magmatic reaction.

The silicates all appear essentially identical in optical and physical properties in both barren ultrabasics and in ore. Spectrochemical analyses of carefully separated duplicate samples of pure olivine, bronzite, and hornblende

showed most trace elements to be present in comparable amounts in each mineral in both barren rock and in high grade ore. Results of the analyses are shown in Table I. Only Ni, Cu, Co and Mn were determined accurately; the approximate order of magnitude of amounts of the other constituents is given. Pb, P, Sn, Li, Yt and Ag were not detected in any of the samples. The brownish variety of hornblende with the higher refractive indices is richer in iron than the greenish variety and both, having formed by reactive replacement in ultrabasics, contain more Ni and Cr than hornblende formed in a normal sequence of fractional crystallization. The variations in other trace elements are apparently of the order of magnitude that might be expected from normal magmatic differentiation or from experimental or sampling error (39).

Sulfides.—The grade of ore averages about 1.4% nickel and 0.5% copper with about 1% chromium, 0.10% cobalt, 0.02 oz/ton gold and 0.01 oz/ton platinum metals. Horwood (21) gives an average of analyses of eighteen selected samples of ore:

	Ore	Calculated to 100% sulfides		
Fe.....	18.38%	57.6		
S.....	10.87%	34.0	Pyrrhotite	ca. 75%
Ni.....	1.89%	5.9	Pentlandite	18-20%
Cu.....	0.70%	2.2	Chalcopyrite	6%
Cr.....	0.31%	—		
Co.....	0.14%	0.3	Ni/Cu	2.7
Total of sulfides:	32%			

Comparison of these figures with Table I shows that the sulfides contain about fifty times as much nickel, several thousand times as much copper, and about the same amount of cobalt as the silicates.

The sulfides themselves contain both corroded and euhedral grains of magnetite, some with cores of olivine. Rounded and corroded grains of "early" pyrite described by Horwood (20) were not seen by the writer, but pyrite was found in later hydrothermal veins and beaded stringers in the sulfides, and as replacements of pentlandite in serpentinized ore. Horwood described "early" pentlandite and a white mineral he tentatively called linnaeite. These were not seen by the writer but they may have been obtained from the stoped-out and flooded core of the 1600 orebody where the nickel content of the sulfides is 13 percent—near the limit of solubility of NiS in FeS. (16). A gray mineral, which may be sphalerite, was seen by the writer in one section. Supergene minerals noted by the writer or by Horwood are limonite, chalcocite, covellite, violarite, melanterite, and morenosite.

In most polished sections whether of disseminated or of massive ore, pyrrhotite, pentlandite, and chalcopyrite are generally present in similar relative proportions and consistently show the same external relationships to silicates regardless of their mutual relations. The pyrrhotite (pale nickeliferous variety) forms a medium- to coarse-grained allotriomorphic mosaic with irregular grains of pentlandite and chalcopyrite lying between the pyrrhotite grains but rarely enclosed in them. In some specimens pentlandite and,

more rarely, chalcopyrite tend to form a discontinuous mesh between pyrrhotite grains (compare 13, Fig. 89). Chalcopyrite, present in lesser amounts than the pentlandite, more commonly forms simply bounded, isolated grains, each commonly in contact with pentlandite as well as with pyrrhotite but seldom enclosed completely in either. It also forms later cross-cutting veinlets. In some sections pentlandite is found within the pyrrhotite as minute wedge-shaped plates or blebs with flame- or fungus-like outline. These are commonly localized along walls of fractures.

Pentlandite-pyrrhotite relations similar to the above are known from almost every nickeliferous pyrrhotite deposit in the world and are accepted as being a result of exsolution from a homogeneous solid solution, not a result of replacement (13, 16). Pentlandite has been found to dissolve in pyrrhotite between 310° C and 450° C upon heating and to exsolve at about 450° C upon cooling (18). The chalcopyrite-pyrrhotite relations, which are similar,

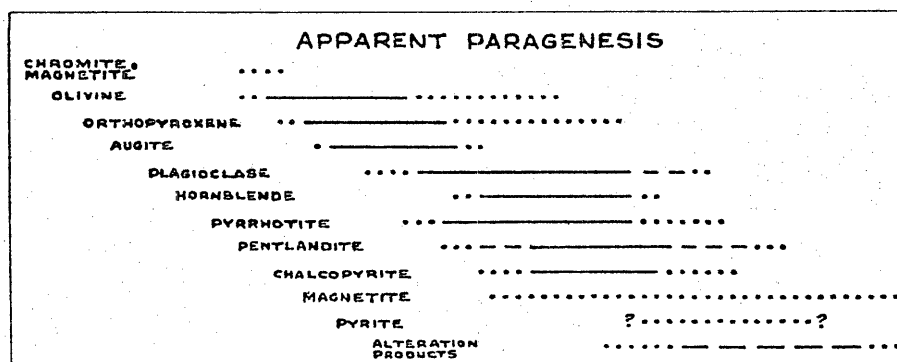


FIG. 5.

appear to be similarly explainable, at least in part. Solid solutions of pyrrhotite and chalcopyrite were obtained by Borchert (3) by heating of natural ores; by Merwin and Lombard (30) during study of the system Cu-Fe-S; and by Hewitt (18) who produced exsolution laths of chalcopyrite in pyrrhotite cooled slowly from 600° C. According to Borchert, a pyrrhotite solid solution containing about two percent copper (average for Pacific Nickel) would begin to exsolve chalcopyrite at about 400° C, and by 300° C exsolution would be virtually complete. The chalcopyrite would then apparently break down at about 250° C and under conditions of slow cooling (which must have prevailed at Pacific Nickel) it could apparently segregate into chalcopyrite and pyrrhotite leaving no direct evidence of its former presence. The solubility of chalcopyrite in pyrrhotite is much less than that of pentlandite; so separation of chalcopyrite would be complete while some pentlandite still remained in solid solution in the pyrrhotite. At Pacific Nickel the cross-cutting veinlets of pure chalcopyrite, however, cannot be explained by this exsolution process and must have formed after formation of the pyrrhotite solid solution. Still later, exsolution of the remaining pent-

landite along (0001) planes of the pyrrhotite would result in the flamelike exsolution growths observed in the pyrrhotite, and in the plates of pentlandite that extend into the pyrrhotite from fractures that cut chalcopyrite veinlets nearby.

In summary, for silicates and sulfides in the rocks and ores at Pacific Nickel, Figure 5 shows the indicated sequence of formation or stability of the minerals under the varying conditions of temperature, pressure and concentration of constituents. Although most of the textural evidence favors magmatic origin, this sequence could apply as well to a hydrothermal theory proposed later.

Field Relations

Disseminated Sulfides.—Disseminated mineralization is found chiefly in the "wetter" hornblendic southwest half of the main ultrabasic mass and in smaller subsidiary ultrabasic bodies to the south and southwest. The dioritic and noritic rocks are virtually barren except for some finely disseminated sulfides near a few contacts. The peridotites and olivine pyroxenites are the best mineralized of the ultrabasic rocks—most of the mineralization appears to be associated with peridotite, occurring especially near the margins of peridotite bodies. Many of the pyroxenites and hornblendic pyroxenites contain irregularly distributed, finely disseminated sulfides; but sulfides are plentiful in these rocks only adjacent to, or within orebodies, or at contacts with other rocks. The more augitic and hornblendic types are relatively barren. The widespread distribution, lack of associated alteration, lack of control by most fractures, as well as textural relations all seem to suggest that the disseminated mineralization may be a primary accessory of the ultrabasics. However, localization of sulfides near contacts (e.g. Fig. 12 and other localities) and near some fractures, particularly near bronzitite and hornblendite bodies, is equally suggestive of transportation of the sulfides, perhaps by water vapour at high temperatures as suggested earlier for origin of the bronzitite and hornblendite bodies themselves.

Ore.—The following is a 1937 company estimate of indicated ore: *

ESTIMATED ORE

Type	Orebody	Tonnage	% Cu	% Ni	Ni/Cu	% Ni in sulfides
Zoned	Brunswick No. 1 ✓	165,700	0.36	1.05	2.9	4.5
	Brunswick No. 5 ✓	171,100	0.41	1.30	3.2	8.7
	Brunswick No. 6 ✓	5,400	0.77	2.08	2.7	6.6
	Brunswick No. 7 ✓	80,000	0.75	2.37	3.2	6.4
	1900 ✓	32,000	0.48	0.92	1.9	
	1600 ✓	109,000	0.36	1.20	3.3	13.0
	512 ✓	15,000	0.42	1.40	3.3	
	Trail ✓	18,900	0.49	1.26	2.6	1.3 (?)
Massive	Brunswick No. 2 ✓	177,600	0.54	1.30	2.4	4.5
	Brunswick No. 8 ✓	4,100	0.61	1.75	2.9	
	Brunswick No. 9 ✓	2,400	0.52	1.40	2.7	
	Pride of Emory ✓	402,300	0.57	1.49	2.6	6.6
	Total	1,183,500	0.50 + Av.	1.39	2.8	

The ore occurs entirely within the ultrabasics as remarkable steeply-plunging bodies (Figs. 2 and 4), which are divisible into zoned and massive types, now described below.

1. Zoned Orebodies.—The zoned orebodies are mineralized parts of steeply plunging ultrabasic structures of circular or elliptical cross section with mineralization and rock types apparently concentrically distributed and forming somewhat cylindrical shells about the long axes of the structures. Some of these structures reach several hundred feet in diameter. The sulfide zones of several are about 100 feet across and have a plunge length of 5 to 10 times their diameter. The zoning and other characteristics described in the next few paragraphs are generally suggestive of some type of high temperature replacement origin, as discussed later under the hydrothermal theory of genesis of the rocks and ore. Table 2 is a summary of the zonal characteristics of these orebodies:

TABLE 2

Orebody	Zoning from core outward	Sulfide-rich zone	Rock surrounding the structure
Brunswick Nos. 5 and 6 (Fig. 6)	Dunite to olivine pyroxenite to barren bronzitite and bronzitic pyroxenite (bronzite, minor hornblende and augite)	Dunite core	"Common" pyroxenite (bronzite, augite, minor hornblende)
Brunswick No. 1 (Fig. 7)	Dunite to harzburgite to barren bronzitite	Dunite core and harzburgite	"Common" pyroxenite and peridotite
1600	Dunitic ore to barren hornblendic peridotite	Dunitic core	Pyroxenite and diorite
1900 (Fig. 8)	Hornblendic peridotite to bronzitite	Bronzitite ring	Augitic pyroxenite
512 (Fig. 10)	Barren olivine pyroxenite to peridotite to barren hornblendic pyroxenite to diorite	Peridotite ring	Hornblendic pyroxenite

Table 2 shows that the sulfides are, as a rule, concentrated in the olivine-rich parts of the orebodies, the only exception being the 1900 orebody where the peridotite is not as well mineralized as the surrounding bronzitite. Some of the orebodies show concentric distribution of mineralization around a peridotitic core and one, the 512, contains pyroxenite inside the peridotitic zone. The cores of most of these structures consist of dunite or peridotite containing disseminated to massive sulfides which enclose a gangue of corroded or idiomorphic olivine (Fe_{14}). The olivine tends to be coarser where sulfides are most abundant; for example, the dunitic core of the 1600 orebody is coarser grained and higher in grade than that of any of the other orebodies—it contains olivine up to a quarter-inch across and averages 5% Ni and 1.2% Cu. The cores also contain schlieren, patches, or dike-like bodies of more

massive sulfides, and local rounded or irregular pyroxenite inclusions which are rimmed in places by massive sulfides. In these characteristics the fabric of the dunitic ores is strikingly similar to the fabric of some of the hornblendite replacement bodies described earlier; that is, if the olivine is compared to the hornblende and the sulfides are compared to the calcic plagioclase.

With lesser amounts of olivine the dunitic or peridotitic cores grade outward into zones of either harzburgite or olivine pyroxenite and into bronzitite. Contacts between these zones within the ore-bearing structures are generally gradational but in places they are sharp. The outer fringes or rocky sections of the orebodies have a higher proportion of chalcopyrite (lower Ni/Cu ratio) and are more erratically and poorly mineralized, commonly with blebs or irregular patches of sulfides or with veinlets of chalcopyrite. Similar relations have been noted in other nickel deposits (11, p. 619; 14; 31, p. 79; 33, p. 198;

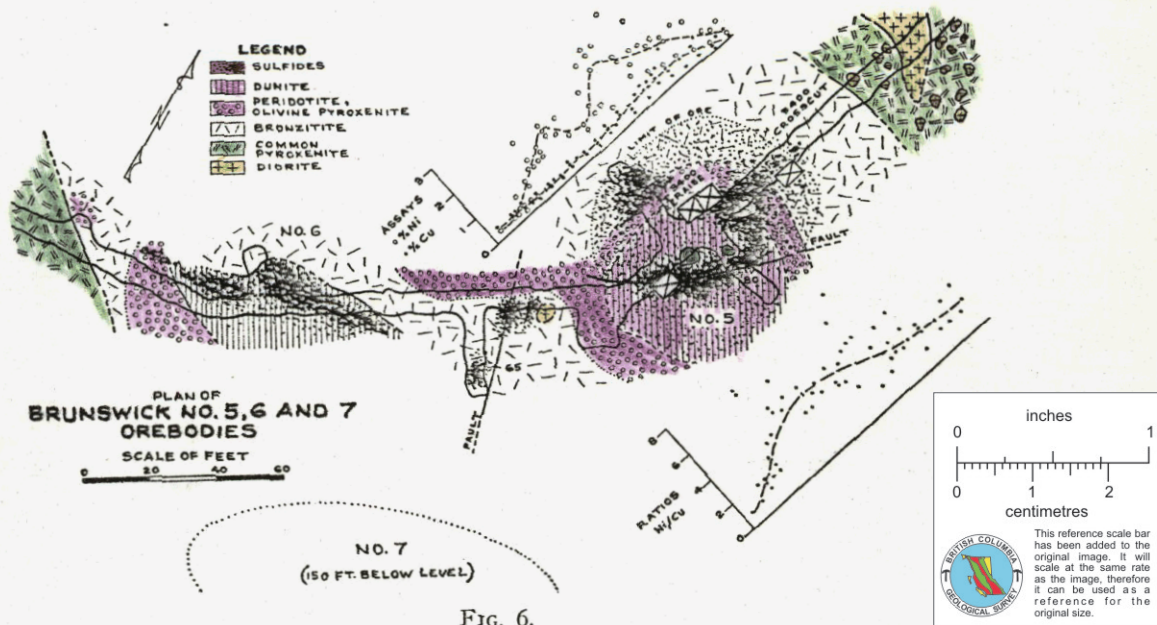


FIG. 6.

37, and others). These accounts describe chalcopyrite as being variable in amount, always associated with the other sulfides, but proportionately more abundant in margins or rocky parts of orebodies, and extending out into the country rocks. The writer has also observed similar relations in several other nickel deposits in Yukon Territory, Canada. As seen from the table of estimated ore, the ratio of nickel to copper averages about 2.8. It and the percentage of nickel in the sulfides are highest in dunite (e.g. in Brunswick No. 5 and No. 6 orebodies) and lowest in erratically mineralized hornblendic rocks (e.g. 1900 orebody). This variation is shown even in individual orebodies, especially Brunswick No. 5 where the Ni/Cu ratio is about 4 in the dunite core and about 2.5 in olivine pyroxenite and bronzitite on the north

Cu DIST.

side of the orebody (Fig. 6). Elsewhere on the property minor mineralization localized near fractures, contacts, or hornblendite bodies was found to have the lowest nickel content. The above distribution of sulfides and textures seems too varied to be entirely magmatic in origin.

Most of the ore-bearing rocks of the zoned structures also differ in composition, texture, and color from the surrounding ultrabasics—they are more magnesian, and contain more olivine and bronzite, and commonly less augite

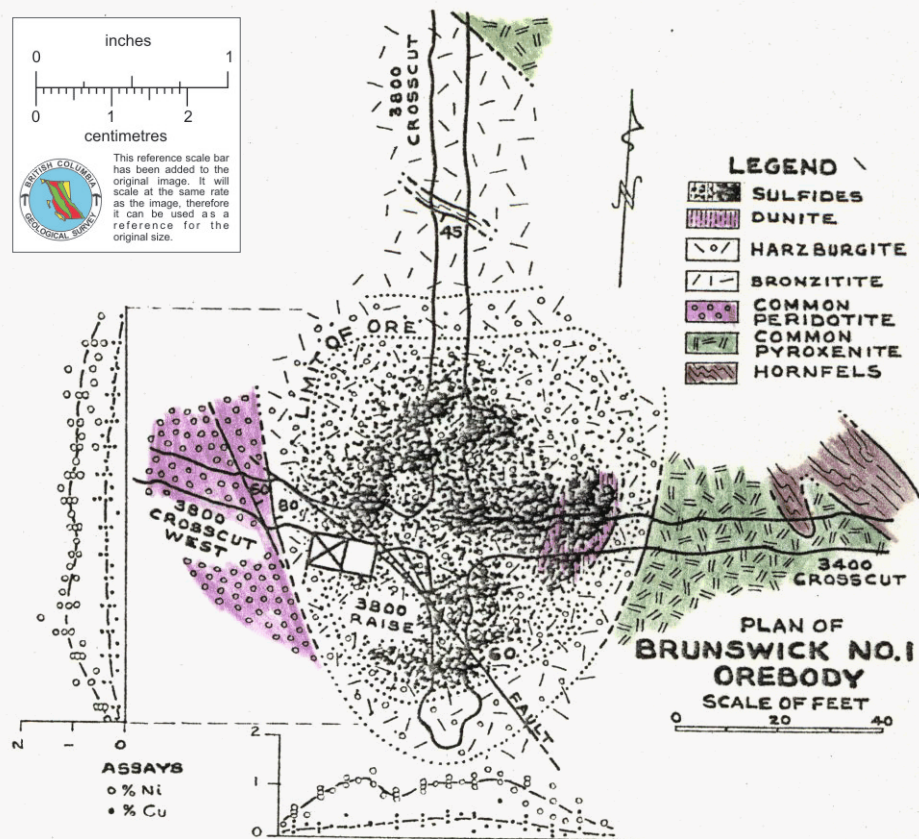


FIG. 7.

or hornblende than the surrounding rocks. For example, augite and hornblende are minor or absent in the Brunswick and Pride of Emory group of orebodies but the wall rocks contain various amounts of these minerals. In the 1900 orebody hornblende is abundant but augite is absent even though the surrounding rock contains 60 percent augite. It might be argued here that these sulfide- and magnesium-rich bodies are early magmatic differentiates injected from depth after segregation and that the zoning resulted from successive injections up the same channelway.

The most complex, zoned structures are illustrated by the 1900 and 512 orebodies, described below in detail:

The 1900 orebody (Fig. 8) has a medium- to coarse-grained hornblende peridotite core consisting of olivine (ca. Fa_{14}), bronzite (Of_{16}), and poikilitic hornblende in nearly equal proportions. Aligned blebs of sulfides (Fig. 15) are disseminated in parts of this core. Surrounding the core is a zone of medium-grained bronzitite (Of_{16}) containing concentrically distributed barren hornblendite schlieren, erratically mineralized bronzitite with interstitial sul-

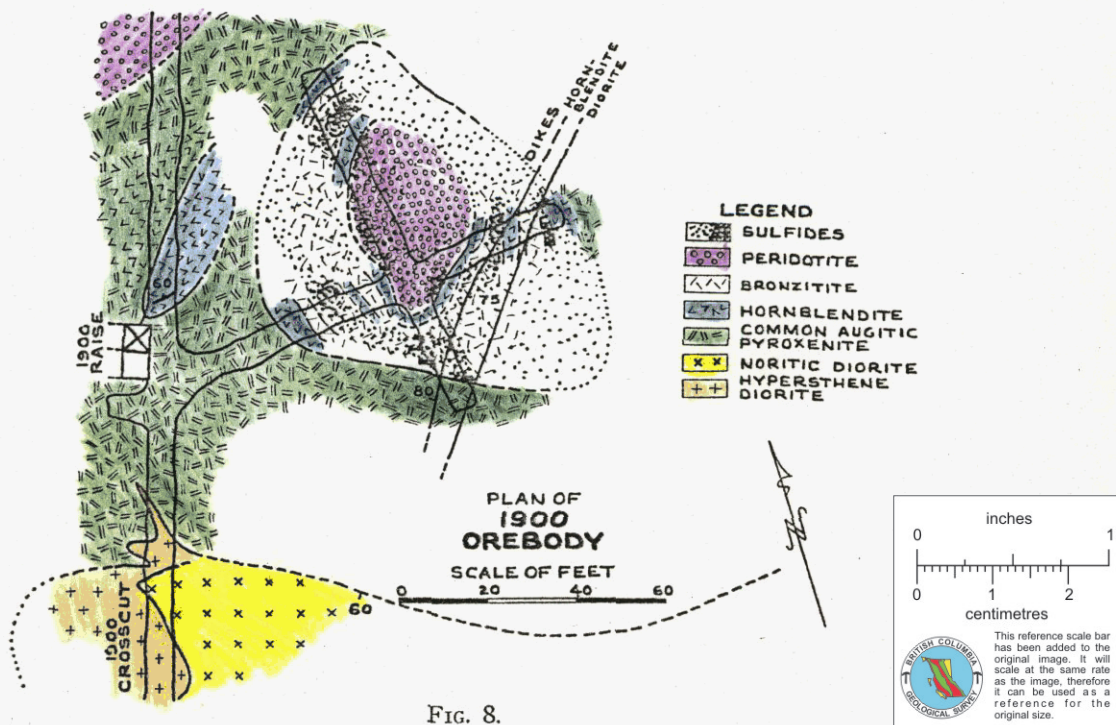


FIG. 8.

fides, and barren porphyritic hornblende bronzitite with hornblende phenocrysts. Interstitial labradorite is locally present in the bronzitite and in the coarser hornblendic schlieren. Some of the ore shows "protoclastic structure" (Fig. 16). Mapping shows a concentric arrangement of mineralization corresponding to the bronzitite zone, and assays (Fig. 9) show this zonal arrangement well. Bronzitite and hornblendite at the outer edge grade within inches into completely barren, surrounding, hornblende-speckled augitic pyroxenite (60% augite (ca. $Wo_{43}En_{44}Fs_{13}$), 25% bronzite (Of_{16}), 15% hornblende). Eight thin sections from various parts of the orebody itself showed no augite. Several hornblendite dikes and dioritic dikes cut the orebody. The 1900 orebody is more complex, lower in grade, lower in ratio of nickel to copper, and more hornblendic than the others, and is more suggestive of replacement origin.

The 512 orebody is a striking example of what appears to be a steeply plunging troughlike body of ore in a westerly plunging zoned structure (Fig. 10). Here, a central body of barren olivine-bearing hornblende pyroxenite is surrounded in turn by an arc of mineralized olivine pyroxenite, a shell of barren hornblende pyroxenite and hornblende, a shell of barren diorite, and finally by barren, enclosing, hornblende or hornblende pyroxenite. The mineralization exposed in the raise and on the surface consists of blebby and interstitial sulfides in the footwall side of the olivine pyroxenite zone. The

ASSAYS OF 1900 OREBODY

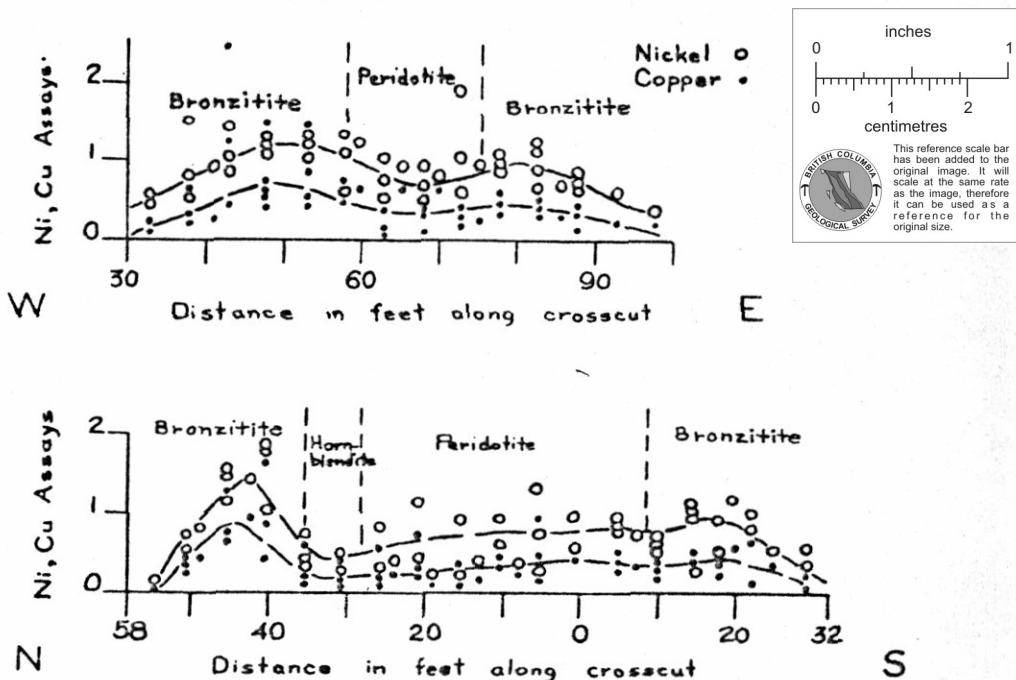
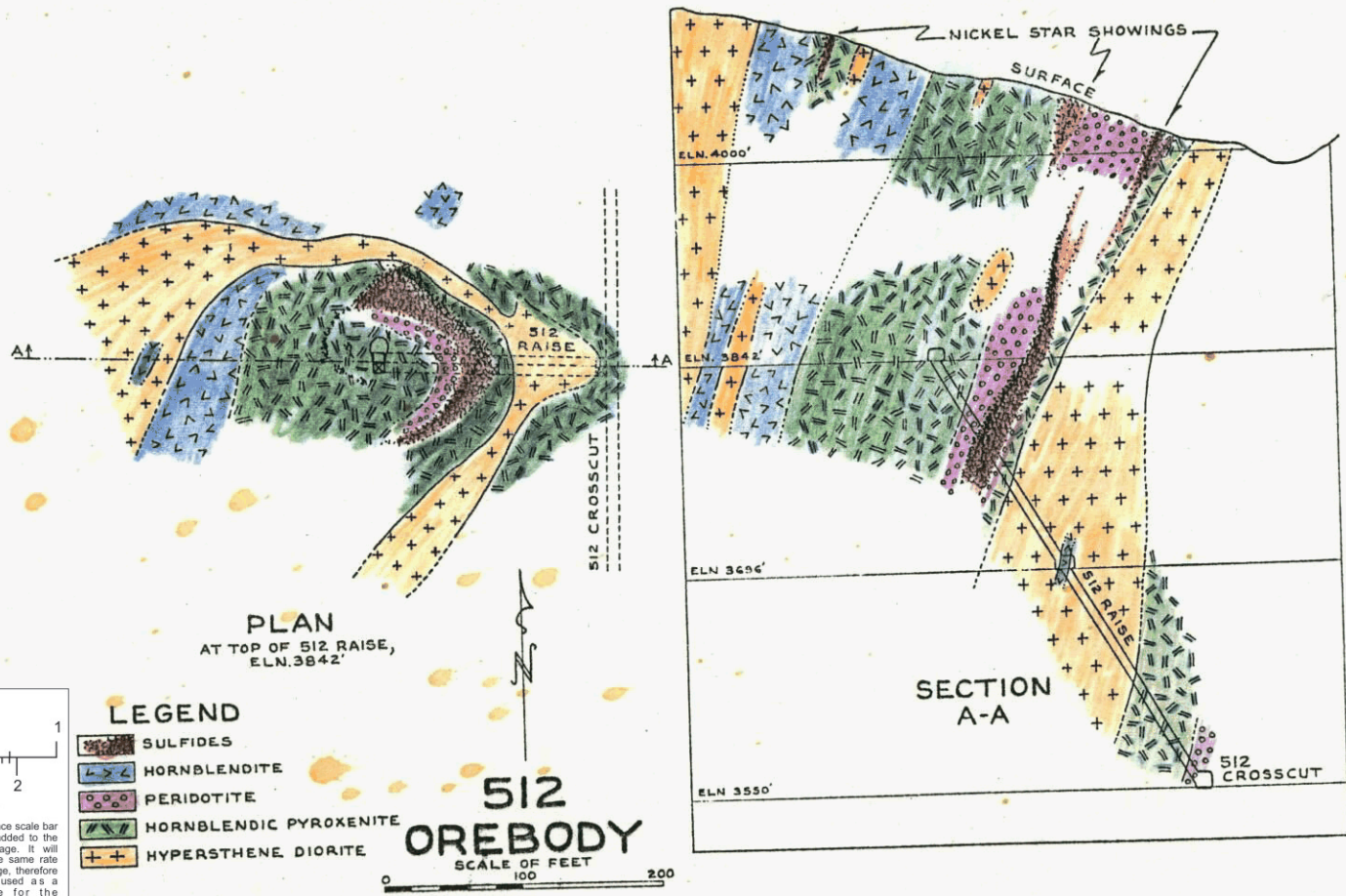


FIG. 9.

ultrabasics appear to cut the diorite in the adjacent 512 crosscut. Although the general characteristics of the other zoned orebodies may suggest some type of replacement origin, this zoning of the 512 orebody seems difficult to explain simply by any theory of origin except perhaps by injection into the diorite shell followed by replacement.

2. Massive Orebodies.⁵—The "massive" orebodies are similar to the zoned type in size, attitude, mineralogy, and many other characteristics but they are much more suggestive of magmatic sulfide injections rather than hydrothermal replacements. They are more irregular in cross section and

⁵ The term "massive" is used here to imply massive structure.



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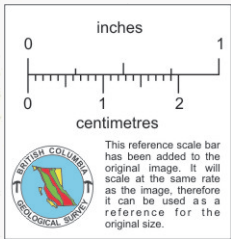
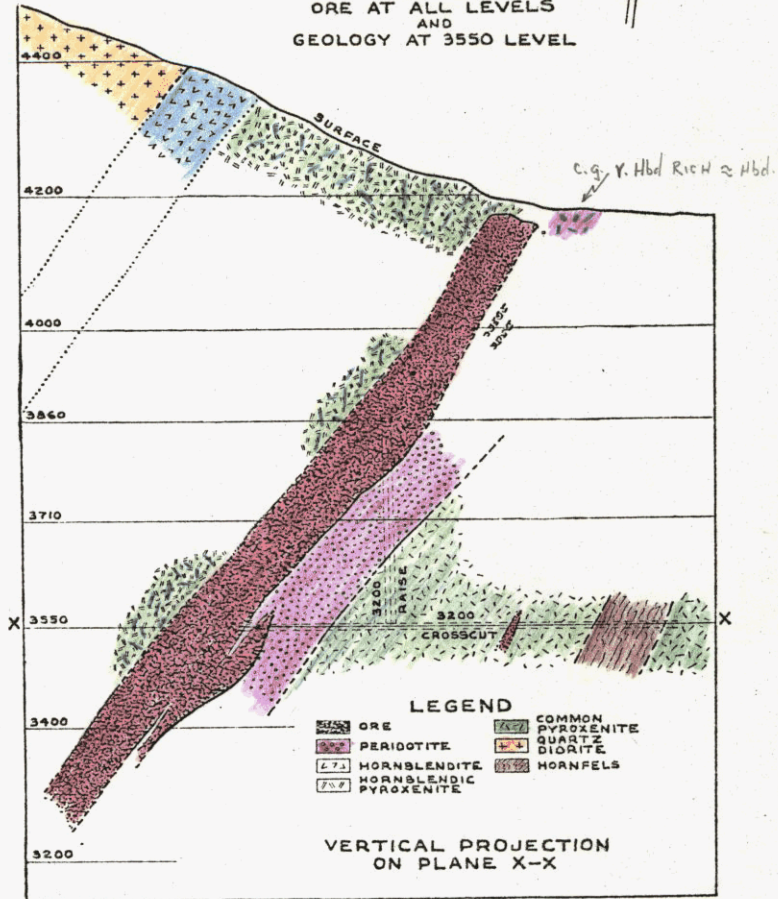
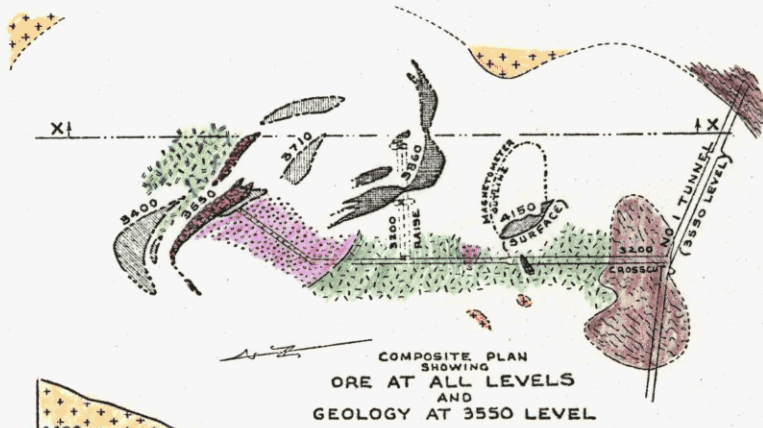
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BRITISH COLUMBIA
GEOLOGICAL SURVEY

- LEGEND**
- SULFIDES
 - HORNBLENDITE
 - PERIDOTITE
 - HORNBLENDIC PYROXENITE
 - HYPERSTHENE DIORITE

FIG. 10.



LEGEND

	ORE		COMMON PYROXENITE
	PERIDOTITE		QUARTZ DIORITE
	HORNBLENDITE		HORNFELS
	HORNBLENDIC PYROXENITE		

PRIDE OF EMORY OREBODY

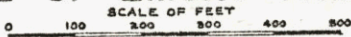
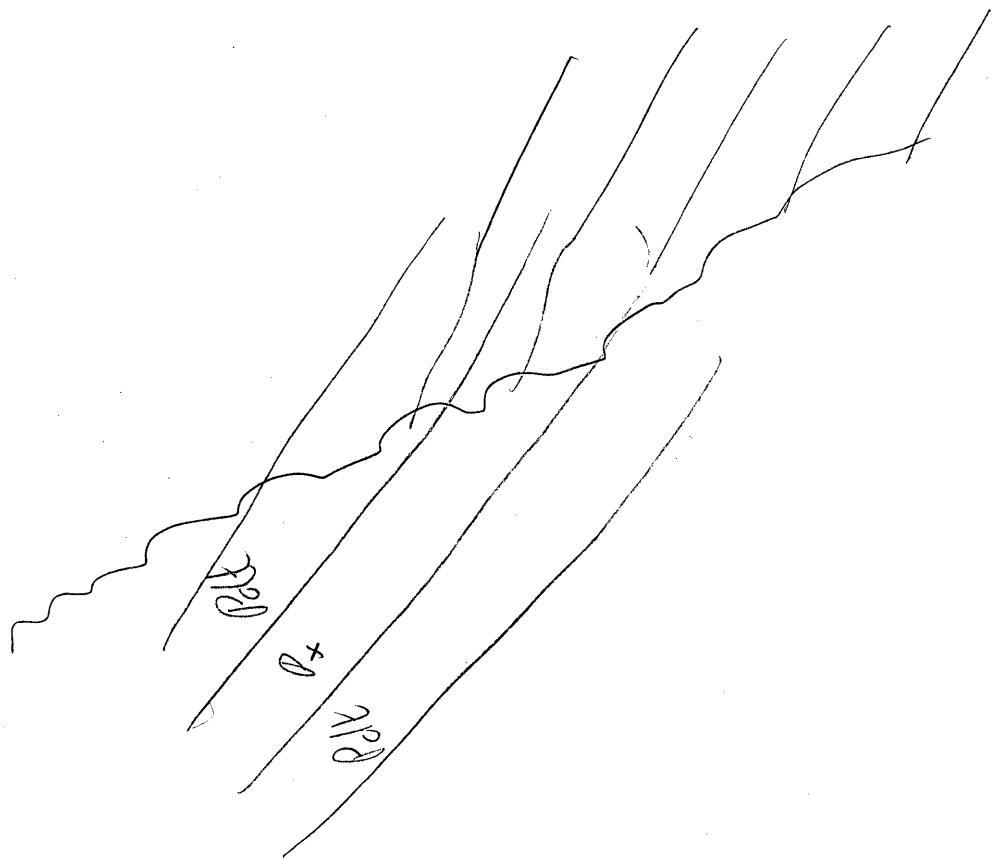


FIG. 11.



consist rather uniformly of a groundmass of sulfides which contains up to 50 percent or more of evenly scattered idiomorphic or corroded crystals of bronzite or olivine or both. The type or relative proportion of these two silicates may vary in the different orebodies and even in the same orebody. Zonal arrangement, if present, was not seen. Locally, inclusions of wall rock, marginal flow lines, banding, and even drag folds (Fig. 17) are present in the "massive" ore, suggesting injection origin. Many of the contacts of the ore are as sharp as a pencil line, some are gradational over a few inches, and some show local hornblendic reaction rims. The wall rocks vary from peridotite to norite and show no apparent zonal relation to the ore. The "massive" type

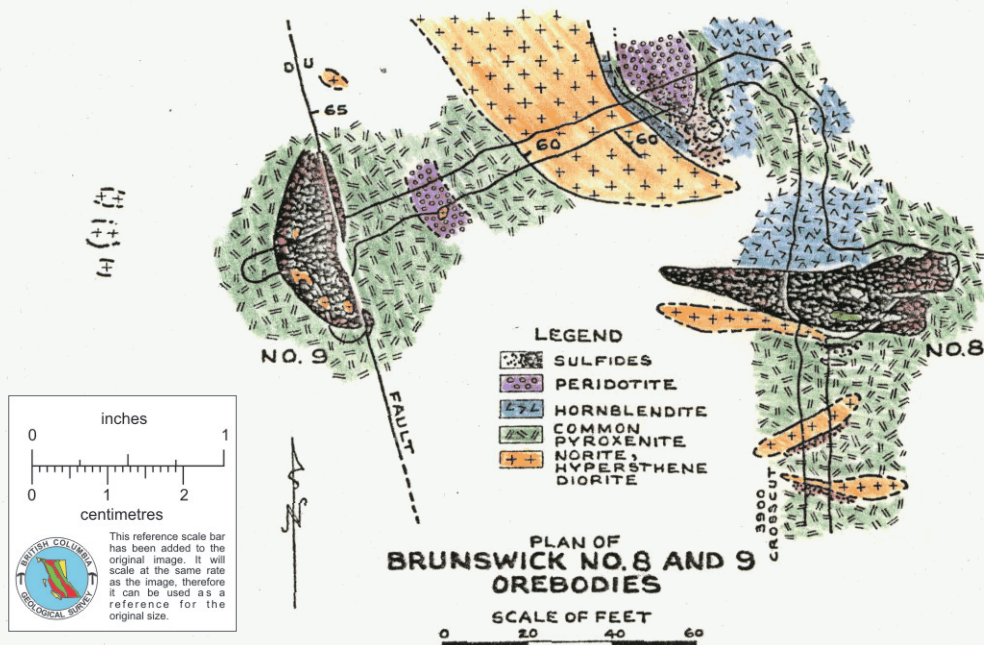


FIG. 12.

of ore, however, is otherwise similar to the zoned type; moreover, it apparently grades into the zoned type in at least two orebodies so any theory of origin must apply to both types. The following examples of the massive orebodies illustrate their general features in more detail:

A small sulfide body about 10 feet across, exposed on a cliff north of the portal of the 2600 level, illustrates admirably on a small scale many of the textures and contact characteristics of the larger massive bodies. It consists of coarse sulfidic harzburgite (Fig. 18) (similar to ore of the zoned Brunswick No. 1 orebody) with sulfidic schlieren, concentrations of olivine, rounded pyroxenite inclusions, and coarse-grained sulfide borders at contacts with surrounding pyroxenite and peridotite, which are largely barren and unaltered except near fractures.

Brunswick No. 2 orebody, although similar in size, attitude, and known extent to the zoned Brunswick No. 1 orebody and associated with a similar mass of bronzitite, is irregular in cross section and has sharp contacts. The ore consists of subhedral bronzite and clots or large crystals of olivine enclosed in a sulfide groundmass. It is separated from surrounding peridotite by a shell of pyroxenite 2 to 4 feet thick. Lenses of bronzitite and harzburgite occur in and near the ore. Silicate clots in the ore are crudely linedated.

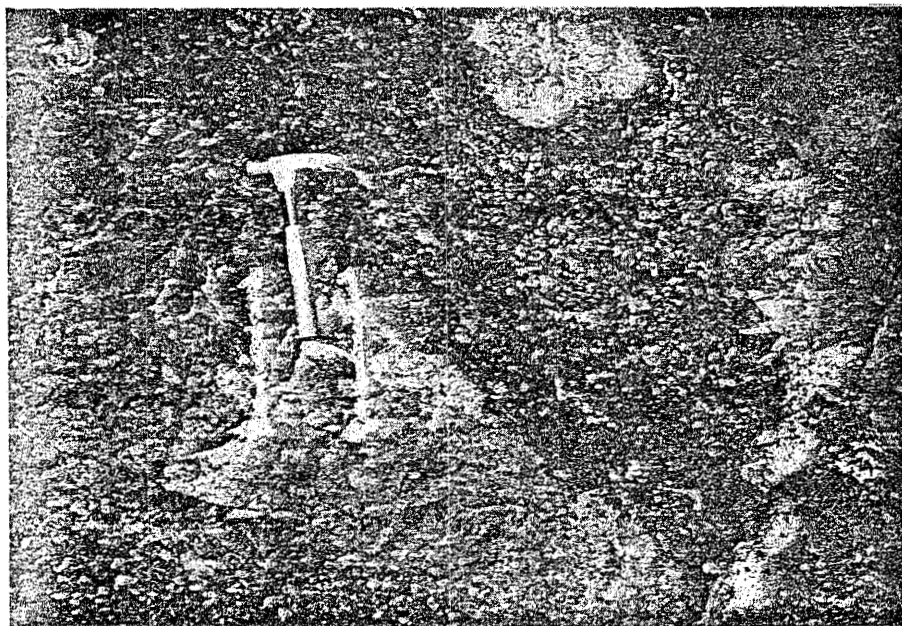


FIG. 13. Hornblendite at 1600 crosscut, 3550 level, showing pyroxenite inclusions and plagioclase-rich "segregations." Inclusions in the top right hand corner are steatitized whereas the large inclusion by the hammer appears unaltered but is partly replaced by hornblendite. Many of the white specks are shining hornblende cleavages, not plagioclase grains.

The Pride of Emory orebody (Fig. 11) consists of several elongate bodies, perhaps anastomosing, which were traced for about 900 feet from the surface with little change in bulk. At the surface and in the 3200 raise the ore forms massive lenses with a fresh medium-grained bronzite (Of_{14}) gangue in a sulfide groundmass. This ore shows sharp contacts and flow lines. On the 3550 level the ore consists largely of medium-grained dunite with interstitial sulfides between fresh subhedral olivine (Fa_{14}), identical to dunite ore of the zoned orebodies. On the west this dunite ore grades into relatively barren peridotite, on the south it grades into a border zone of bronzitite ore, and on the east it is in sharp contact with hornblendic pyroxenite. Small irregular stringers, massive coarse-grained blobs, and disseminated grains and blebs of sulfides extend a couple of feet outward from the sharp eastern contact.

One block of ore, believed to have come from this contact, shows drag-folding of banding parallel to a contact between dunite ore and barren pyroxenite (Fig. 17).

Brunswick No. 8 and No. 9 orebodies (Fig. 12) are identical to one another and consist of fine- to medium-grained, fresh, euhedral bronzite (ca. Of_{18}) in a groundmass of sulfides, parts of which have a delicately interlacing network of thin chalcopyrite stringers. Minor constituents of the ore are hornblende, bytownite (An_{80}) and local alteration products. Both orebodies contain rounded or irregularly shaped anorthositic norite streaks and inclu-



FIG. 14. Hornblende dikes cutting crumbly altered peridotite in 512 crosscut, 3550 level.

sions from an inch to two feet or more across. Some of these inclusions are drawn out into streaks and lenses which, if seen alone or on one surface, might be interpreted as norite cutting ore (see Horwood's statement (20, p. 14) that "... sulfide bodies have been intruded by irregular tongues and bodies of diorite"). In places, sulfide-impregnated reaction rims up to two inches thick, composed of hornblende with minor spinel and sulfides, separate the ore from the barren norite inclusions or from surrounding pyroxenite. The sulfides in most places do not penetrate far into the wall rocks and many of the contacts of these two orebodies are as sharp as a pencil line.

Veinlike Mineralization.—Many beaded stringers or veinlets of sulfides from a fraction of a millimeter to two inches in width occur within or near

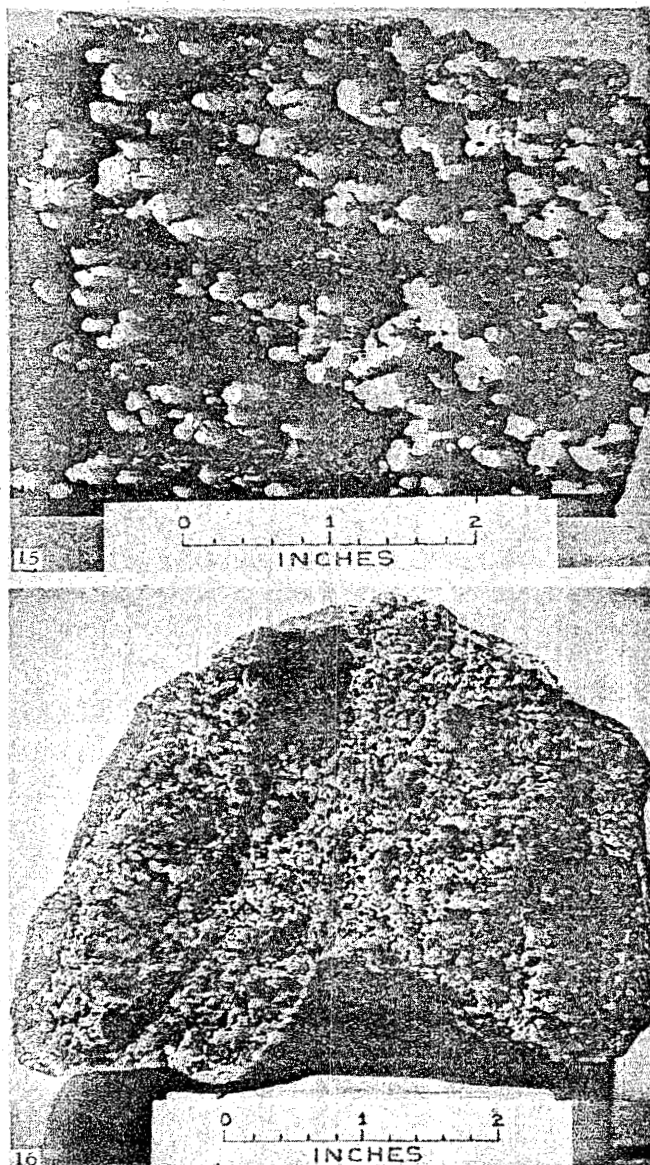


FIG. 15. Typical blebby disseminated ore in hornblende olivine pyroxenite, core of 1900 orebody, showing aligned sulfide blebs (white). The silicates are fresh olivine, bronzite and hornblende in equal amounts and the blebs are chiefly pyrrhotite with minor pentlandite and chalcopyrite. Some of the blebs consist entirely of chalcopyrite.

FIG. 16. "Protoclastic" structure in hornblende bronzite with stringer-like interstitial network of chalcopyrite (white). From 1900 orebody.

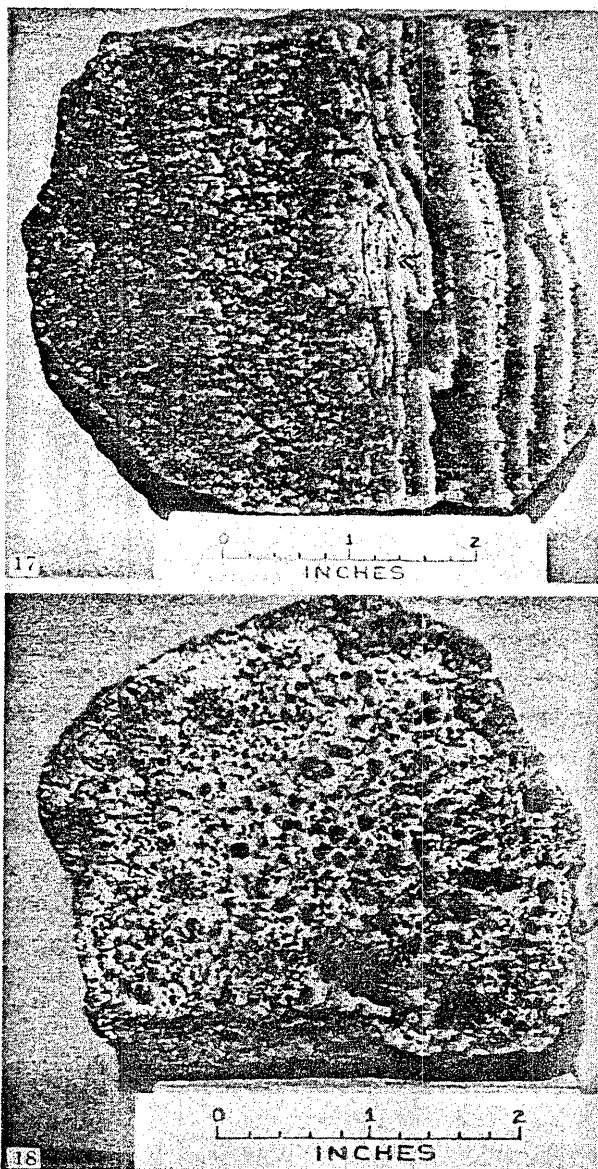


FIG. 17. Lineation and drag-folded marginal sulfide bands at contact between dunite ore (left) and barren pyroxenite (right, broken off). Note the euhedral olivine in the faintly banded dunite ore. The dark bands on the right are pyroxenite with pyroxene lineated parallel to the banding. Probably from northeast contact of Pride of Emory orebody.

FIG. 18. Typical harzburgite ore. The large euhedral crystals are mainly bronzite and the smaller crystals and clots are mainly olivine. The groundmass consists of coarse-grained pyrrhotite with pentlandite (shining cleavages) and minor chalcopyrite. From small massive sulfide body north of portal of 2600 level.

most of the orebodies and to a lesser extent in the surrounding rocks. These veinlets are commonly rich in chalcopyrite but some consist mainly of pyrrhotite which may impregnate the wall rocks up to distances of two inches. In the orebodies most of these veinlets cut the other sulfides but in many places they intermingle and cut only the silicates. They display the same degree of corrosion or replacement as observed in the ore. Some appear to be simple infillings with matching walls. Others show altered walls and from still others irregular patches of sulfides extend into unaltered wall rocks, similar to relations shown by Cameron (6) from Mount Prospect, Connecticut. At Pacific Nickel the lack of such sulfides in most of the later veins and alteration fractures, some of which cut these sulfide veinlets, suggests that the vein-

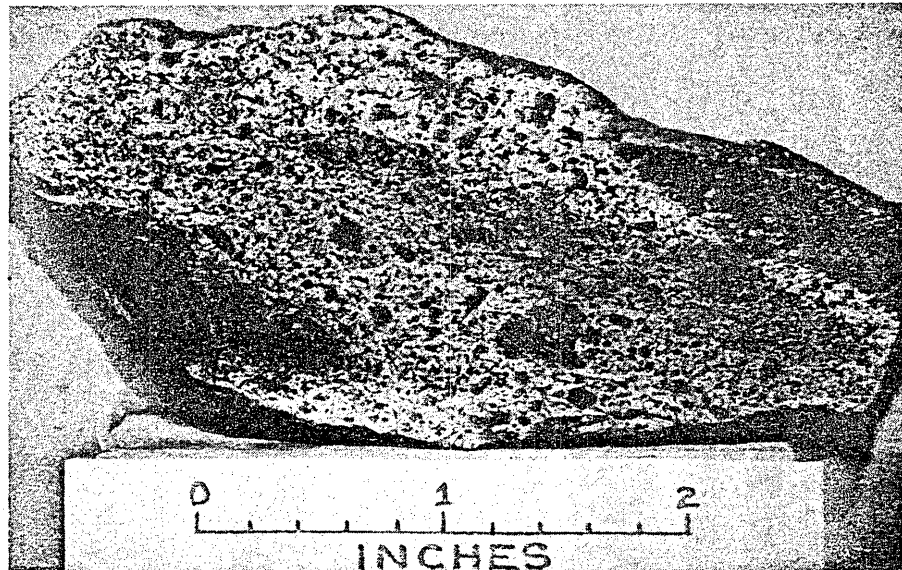


FIG. 19. Section of 2-inch-wide hornblende-pyrrhotite "dike" or "vein" showing euhedral hornblende, an inclusion of pyroxenite altered to actinolite, and hornblenditic margins. The pyrrhotite (light) carries minor chalcopyrite and small exsolution laths of pentlandite. This "dike" cuts olivine pyroxenite and grades visibly into a hornblendite dike. From 1,250 feet within 512 crosscut, 3550 level.

lets are a late dying phase of the main sulfide mineralization whether magmatic or hydrothermal, and not later mineralization "related to the diorite" as believed by Horwood (20, p. 12).

Lenticular, discontinuous, heavily mineralized, medium- to fine-grained pyroxenite and hornblendite "dikes" a few inches to a foot wide cut peridotite 1,300 feet within the 3550 level and 1,250 feet within the 512 crosscut. The pyroxenite dikes locally grade into the hornblendite dikes; sulfides within both are unevenly distributed and tend to be concentrated into massive blobs that extend irregularly like replacements into unaltered wall rocks. These sulfides are chiefly pyrrhotite, with smaller amounts of nickel and copper than sulfides

in the orebodies. In places the "dikes" grade into massive sulfide "veins" or lenses that carry scattered idiomorphic crystals of hornblende (Fig. 19). Flow lineation and altered wall rock inclusions were found in one such "vein." The surrounding pyroxenite and peridotite are mineralized and locally altered, especially along fractures. Bands of sulfides an inch or two wide and similar to the above lenses occur in a few localities in pyroxenite and in hornblendite elsewhere on the property. Although the above tabular sulfide bodies might be attributed to high temperature pneumatolysis, their characteristics seem equally suggestive of injection accompanied by replacement. In either case the relations indicate close contemporaneity of the early pyroxenite-hornblendite dikes and the late stage of mineralization. Hornblendite dikes similar to the sulfidic ones clearly cut some of the ore bodies but these dikes contain only thin stringers and local impregnations of sulfides, which could be explained by reactivation of sulfides by the dikes.

Now that the sulfide bodies and their environment have been described, one is confronted with the problem of genesis. However, since the theories of genesis that are to be presented may apply to other similar nickel deposits as well, the significant genetic characteristics of other deposits in the world are first summarized and compared with those of Pacific Nickel, then the theories of genesis are discussed.

GENESIS OF THE ROCKS AND ORES

Genetic Comparisons

In the layered norite-ultrabasic complexes such as the Bushveld complex of South Africa (40), the complexes of Griqualand and Pondoland (33), the Petsamo complex of Finland (15), and the Stillwater complex of Montana (23), sulfides are generally concentrated in basic or ultrabasic horizons and this concentration may be explained by simple gravity segregation followed in some cases by minor movement which would give rise to cross-cutting relations. Wagner has expressed the view that it is inconceivable that vagrant solutions could have selectively impregnated extensive layers of such lopoliths with sulfides.

Many of the other nickel deposits of the world are found chiefly within or marginal to noritic rocks, notably in the more basic and varied portions or near pendants or inclusions (1, 6, 12, 24, 36, 37, and others). A lesser number, often smaller but richer in nickel, occur within or marginal to ultrabasic bodies (25, 29, 38, and others). A few "offset" deposits occur along tectonic breaks near the parent intrusives (14, 36). Evidence has been cited from some of the above deposits that favors gravity segregation of sulfides with or without subsequent injection. From others (especially some of the complex offset types) much evidence is cited for hydrothermal origin. Most of the deposits, however, are still noted for general lack of hydrothermal alteration associated with the ore. (This is also true for many pyrometamorphic deposits formed above the temperatures of the more common alteration products). No concentric zoning is described even in the ultrabasic deposits, which are otherwise very similar to those at Pacific Nickel.

} Common
Alt. and Form
Lower Temp.

Compared with Pacific Nickel, the Canadian nickel region of Sudbury, Ontario, which has been most extensively studied, has the same petrologic association of feldspathic rocks with ambiguous age relations, the same type of ore and alteration, with the same general evidence of high temperature, lack of widespread alteration, close relation to magmatic activity, "magmatic" textures and mineralogy with minor replacement, high copper at margins of ore, sharp and gradational contacts, "suspended" inclusions, and hornblende reaction rims between massive ore and country rocks. In contrast to Pacific Nickel, the deposits of Sudbury contain micropegmatite or potash feldspar, occur in quartz diorite host rocks, contain no ultrabasics and little or no olivine or pyroxene, are controlled more by tectonic breaks, and apparently show more evidence of hydrothermal action, replacement, reconstitution of rocks, and impregnation by sulfides. The offset deposits, particularly, show greater complexity, richness, concentration of rarer constituents, and more hydrothermal action. Many characteristics of the deposits at Sudbury led Coleman (8) and Howe (22) to suggest sulfide segregation and injection, and Bateman (2) and Collins (9) to suggest injection accompanied by extensive hydrothermal modification and redistribution. Further study, however, has led Davidson (11) and Yates (43) to conclude that the deposits are hydrothermal in origin. The columnar offset orebodies of Sudbury are strikingly similar in size, shape, and attitude to some of the orebodies of Pacific Nickel. Coleman (8, pp. 36-37) reported that "the Copper Cliff deposit was known to go down for 1,000 feet without interruption as a rude oval pipe with diameters varying from 50 to 200 feet, and a dip of $77\frac{1}{2}$ degrees to the northeast." The two orebodies of the Victoria mine are similarly described as ". . . two small cylinders of ore, more than 1,400 feet in length and close together, but never meeting . . ." (compare with Pride of Emory orebody).

A nickel-copper deposit at ~~Foster Bay~~^{Foster Bay},⁶ 18 miles west of Juneau, Alaska, is also somewhat similar to the elongate, steeply plunging orebodies at Pacific Nickel, and probably similar to the small mineralized ultrabasic bodies a mile to the southwest. Surrounded by schist and phyllite, this deposit is an almost cylindrical mineralized gabbro plug or pipe about 100 feet in diameter, which has been followed for 600 feet down a moderate southeast plunge. The best mineralization lies along the lower contact of the plug, near the crest of a complex fold in the adjacent schists and phyllites. This mineralization consists of a massive body of several hundred tons of sulfides assaying up to 4% Ni and 6% Cu. Low-grade mineralization consisting of pyrrhotite, chalcopyrite, and minor pentlandite, is scattered in the gabbro as disseminated interstitial grains, as round or elongate blebs up to an inch across, and as patches and veinlets some of which cut or partly replace acidic dikes in the gabbro. The sulfides also extend a few feet into a 40-foot-wide cordierite hornfels metamorphic aureole which apparently surrounds the gabbro. In some places in the gabbro as well as in the hornfels, the sulfide blebs are generally oriented, commonly with curious chalcopyrite rims that thicken in one particular direction. Carbonate blebs of similar size and shape, with

⁶ Personal communication with J. J. McDougall, St. Eugene Mining Corporation.

rims of talc, are locally associated with these sulfide blebs. The disseminated sulfides were thought to be magmatic in origin whereas the blebs, patches, and veinlets were thought to represent extension of the same mineralization into a hydrothermal phase.

At the south end of Tagish Lake in northern British Columbia, Canada, the writer saw a small gabbro-ultrabasic complex locally mineralized with pyrrhotite and chalcopyrite, especially in its more ultrabasic phases. One partly altered pyroxenitic area contains a sharply bounded, six-foot-diameter sulfide body consisting of about 50 percent of medium to coarse subhedral hornblende in a pyrrhotite matrix, producing a texture similar to that shown in Figure 19. The pyrrhotite contains blebs, stringers, and patches of chalcopyrite and, under the microscope, small exsolution laths of the pale nickeliferous phase of pyrrhotite. The chalcopyrite is erratically distributed and favors margins or rocky parts of the sulfide body. The mineralization averages 0.56% Ni and 0.8% Cu.

In association with peridotite and hornblendic pyroxenite at Bruce Lake, southeast of Ross River Post in Yukon Territory, Canada, the writer saw float of olivine-pyrrhotite rock which carried only traces of copper and nickel but was otherwise identical in appearance to the dunite ore at Pacific Nickel.

In the Kluane Range of Yukon Territory, nickel-copper sulfide mineralization is localized at contacts of gabbro and peridotite bodies; for example, at the Wellgreen property presently being explored by Hudson Bay Exploration and Development Company. On this property lenses of ore are localized where a dioritic phase is found along the contact of a peridotite body. A careful detailed study of this deposit may provide a valuable link between knowledge on deposits such as Sudbury on the one hand and Pacific Nickel on the other.

WELLGREEN PROPERTY

Some zoned cylindrical- and funnel-shaped ultrabasic complexes in southeastern Alaska (26, 27, 42) are very similar in zoning to the stocklike ultrabasic body at Pacific Nickel. These complexes are hundreds or thousands of feet across, and have peridotitic cores surrounded successively by pyroxenitic and gabbroic or hornblenditic rocks. Walton (42) suggests that the zoning originated by gaseous and ionic transfer.

The platiniferous dunite pipes of the Bushveld igneous complex of South Africa (41) show zoning most similar to that of the orebodies at Pacific Nickel. These pipes, up to 200 feet in diameter, have a core of hortonolite dunite surrounded by olivine dunite, wehrilite, and other less olivine-rich rocks, all of which cut across layering of the surrounding complex. They also contain chromitite xenoliths (*ibid.*, p. 68) and "boulder-like inclusions of anorthositic norite" (*ibid.*, p. 72) apparently derived from the surrounding complex and displaced slightly (compare with inclusions in ore at Pacific Nickel). In contrast to the zoned structures at Pacific Nickel these pipes contain a more iron-rich olivine and lack sulfides. They were believed by Wagner to be pneumatolytic although inclusions, sharp contacts, and displacement of the chromitite inclusions also suggest minor movement.

Most strikingly similar in character to the deposits of Pacific Nickel are the sulfidic harzburgite pipes of Vlackfontein, 4,000 feet above the base of the

same Bushveld igneous complex (19, 40). These deposits are equally well developed in bronzitic norite, bronzitite, and harzburgite of the complex and cut across and replace flatly dipping layers of these rocks. The pipelike bodies are gradationally as well as sharply bounded, steeply plunging, and from a few feet to 70 feet across and several hundred feet long; they commonly show disseminated ore toward the periphery and more massive sulfides near the centre. Basic dikes that cut the bronzitite and harzburgite are displaced and partly replaced by the sulfides indicating ". . . that the ore was introduced after the bronzitite and harzburgite had sufficiently cooled and crystallized to permit the dike to intrude them and preserve its identity" (19, pp. 209-210). Hoffman ruled out pneumatolytic origin because of lack of "typical" pneumatolytic minerals, but left the impression that the ore may have formed by some replacement process, perhaps accompanied by some movement. No zoning is described.

The above genetic comparisons show that pipe- or parsnip-like shapes and zonal characteristics occur in other similar rocks and ores in the world and may be much more common than previously recognized. With these occurrences, and their characteristics, similarities, and proposed origins in mind, theories of origin of the ore at Pacific Nickel may now be considered.

The Magmatic Theory

The mineralogy, fabric, and occurrence of the igneous rocks and ore at Pacific Nickel could be explained well by a theory of fractional crystallization and gravitative differentiation followed by injection. During fractional crystallization of a basic parent magma, silicate crystals and immiscible sulfide melt could settle to the bottom of the magma chamber to form sulfidic olivine-rich layers which could then be buried in turn by pyroxenitic, noritic and dioritic layers. Then, beginning with the overlying diorite and followed by ultrabasics and ore, the layered differentiates could have been injected into the roof of the magma chamber to give the present field relations and sequence. Presence of sulfides in the ultrabasics and their scarcity in the norites and diorites would substantiate such a theory of early sulfide segregation from a still fluid magma into a compacted, early-formed ultrabasic crystal mush at the bottom of the magma chamber. Blebs of sulfides are found totally enclosed in bronzite ($Of_{1.3}$) in pyroxenite—this might also indicate immiscible segregation during early stages of fractional crystallization, as suggested by Vogt (36).

The textures, lack of alteration, and gradation of ore into widely disseminated, apparently primary sulfides do suggest magmatic origin of the ore particularly since it occurs in the most magnesian of the ultrabasics. Even the corrosion, replacement, sulfide veinlets, and minor alteration observed in places can be explained by a magmatic theory assuming some redistribution. The steeply plunging orebodies, however, could not be explained by simple magmatic gravity segregation; but segregation followed by injection would account admirably for their attitude and for the signs of movement such as

sharp contacts, flow lines, drag folds in marginal sulfide bands, wall rock inclusions, and dike-like sulfide bodies. Even the zoning might be explained by successive injections. Characteristics suggestive of intrusive origin found in other nickel deposits led Vogt (36), Howe (22), Bateman (2), Collins (9), and others to conclude that such ores were indeed molten sulfide injections. But the sulfides at Pacific Nickel, if injected, could not have been entirely molten; otherwise inclusions and silicates would have floated and schlieren, lineation, and drag folds would have been destroyed. The larger scale "protoclastic" textures of some of the ore are suggestive of movement in a largely solid state but microscopic textural evidence of such is lacking in general, except possibly in the crystallographic fabric orientation of the sulfides. Any textural evidence of such a fabric, if it existed, may have been obliterated by recrystallization, minor hydrothermal redistribution, and exsolution.

Since pyrrhotite begins to crystallize at rather high temperatures, the sulfide bodies, if injected, probably were largely crystalline. Hawley, Colgrove, and Zurbrigg (16) show that in a simple anhydrous Fe-Ni-S melt containing about 6 percent nickel (average for Pacific Nickel), FeS would begin to crystallize at about 1150° C; and at about 870° C these early formed crystals would probably enter into a peritectic reaction with the residual nickel-enriched liquid to give a pyrrhotite solid solution which, upon cooling below 400° C, would exsolve pentlandite. Two or three percent copper would probably lower the initial crystallization temperature of simple pyrrhotite to about 900° C (30). Considering the possible effect of small amounts of water and other constituents in addition to copper and nickel, the crystallization temperature of sulfides such as those at Pacific Nickel might be decreased to as low as 700° or 800° C. In any case a single pyrrhotite phase carrying nickel and some copper in solid solution would crystallize first and, if the amount of copper exceeded 2 percent, a residual copper-rich melt would form. This would crystallize as a separate copper-rich solid solution and then later exsolve as discussed earlier under mineralogy and texture. A residual copper-enriched melt could lubricate the ore during injection, eliminate deformative effects and form the minor cross-cutting veinlets and marginal copper enrichment that are locally common. However, any differential pressure on such a crystal mush might be expected to produce separate nickel- and copper-rich bodies by filter pressing.

Two main lines of objection to the magmatic injection theory are: (a) the zoned orebodies with their gradational contacts and undeformed silicates seem difficult to explain; (b) some of the sulfides must have been transported to produce the sulfide veinlets and impregnations with lower nickel content, the varied ore textures, the erratic copper mineralization at margins of orebodies, and the mineralization at contacts of various rock types. For explanation of these features, we must consider some type of hydrothermal replacement theory of origin as an alternative or addition to magmatic segregation and injection.

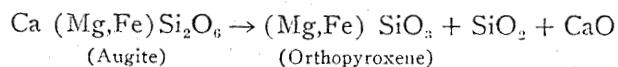
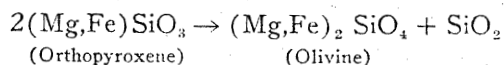
OBJECTIONS

A Hydrothermal Theory

Although most hydrothermal ore-forming fluids cause alteration, and although ultrabasic rocks are especially easily hydrothermally altered, alteration at Pacific Nickel shows little relation to the main ore and is at least partly controlled by post-ore fractures. Most of the ore is fresh and the following evidence points to its origin at temperatures that exceed those of common hydrothermal alteration: (a) The ore was apparently formed before complete crystallization of the hornblende; as shown by textures, derivation of post-ore hornblendite dikes from the adjacent ultrabasics, and hornblendic reaction rims at contacts of the ore. (b) The sulfide exsolution textures indicate formation of the ore above 400° C. (c) Pyroxene hornfels inclusions indicate that temperatures above the 600° C range were attained at some time within the ultrabasics. (d) According to experiments by Bowen and Tuttle (4), water vapor could produce hydrous alteration in peridotite up to 800° C if saturated in silica, but only up to 650° C if lacking in silica. Thus 650° C would appear to be the minimum temperature for hydrothermal deposition of the sulfides in unaltered peridotite. Where alteration does locally accompany weak or dying phases of mineralization the hydrothermal fluid that produced it must have been below 650° C or else saturated in silica. Subsequent fluids in the post-ore stage were saturated in silica since they deposited quartz veinlets in alteration zones.

Bowen and Tuttle (4) also showed that above 650° C water vapor can convert enstatite to forsterite by removing silica and, by adding silica, it might convert forsterite to enstatite. They propose that such conversions could produce veinlike and pipelike bodies of olivine or orthopyroxene rock in ultrabasic complexes. Application of this reasoning to the veinlets and marginal zones of olivine and bronzite rock (locally mineralized) at Pacific Nickel strongly suggests that such vapors did traverse these ultrabasics. Perhaps the sulfide-rich pyroxenite and hornblendite "dikes" or "veins" were also formed by such vapors along fractures. Since some of the vapors formed olivine they were at least partly unsaturated in silica and thus their minimum temperature (without causing alteration) was indeed 650° C.

Now that it appears that such fluids probably were present and did carry some sulfides, the origin of the ore can be considered in this light. High-temperature, sulfide-bearing water vapor poor in silica thus might have formed the zoned pipelike orebodies, the olivine core being formed along a permeable channelway along which the vapor moved, while the orthopyroxene envelope was formed by vapor that had become enriched in silica removed from the core. This replacement-conversion process probably would have occurred in pyroxenitic host rock so lime would also have to be removed to convert any augite to olivine or orthopyroxene. Changing orthopyroxene to olivine or augite to orthopyroxene would increase the silica content of the proposed ore-forming fluid as shown by the following relations:



and other nickeliferous pyrrhotite deposits elsewhere in the world commonly are localized near contacts or pendants. The nickel deposits are even more closely associated both genetically and spatially with the parent intrusive than are other pyrometasmatic deposits, and more commonly occur within it rather than in its wall rocks, perhaps because of higher temperatures and because of physical conditions such as decreasing pressures and fracturing being more favorable in the cooling intrusive than in its wall rocks.

The chief objections to the above replacement-conversion theory of origin of ore at Pacific Nickel are the signs of movement suggestive of injection. These, it should be remembered, are as abundantly present in the hornblendite bodies which present similar problems but show even more evidence of replacement origin. Since the suggested temperatures of ore deposition at Pacific Nickel (mostly above 650° C) border on temperatures of partial melting of such sulfides (700 to 800° C), perhaps it may be possible for some flowage to occur in the most massively replaced localities, resulting in features suggestive of injection. On the other hand, injection of largely crystalline silicates and sulfides as proposed in the magmatic theory, accompanied to varying degrees by the replacement-conversion process, might account for massive and zoned ore almost as well. As seen from the genetic comparisons, many of the other nickeliferous pyrrhotite deposits, pipelike bodies, and zoned ultrabasics of the world are quite similar to those of Pacific Nickel and, although consensus of opinion on their origin tends to favor some type of replacement, evidence of movement or other features suggestive of flowage are left unexplained in some cases. The problems of physical state and of processes involved resemble those met in the origin of granite and pegmatite and the final answer on genesis of such ores may well involve both replacement and flowage. Nickeliferous pyrrhotite deposits should be well suited to further physical-chemical research on this problem of genesis because of their relative mineralogical simplicity and relative freedom from influence of external physical-chemical factors.

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March 12, 1956

REFERENCES

1. Allan, J. D., 1950, *The Lynn Lake nickel area, Manitoba*: Trans. Canadian Inst. Min. & Met., v. 53, p. 343-348.
2. Bateman, Alan M., 1917, *Magmatic ore deposits, Sudbury, Ont.*: ECON. GEOL., v. 12, p. 391-426.
3. Borchert, Hermann, 1934, *Über Entmischungen im System Cu-Fe-S and ihre Bedeutung als "geologische Thermometer"*: Chemie der Erde, v. 9, p. 145-172.
4. Bowen, N. L., and Tuttle, O. F., 1949, *The system MgO-SiO₂-H₂O*: Geol. Soc. America Bull., v. 60, p. 439-450.
- ✓ 5. Cairnes, C. E., 1924, *Nickeliferous mineral deposit, Emory Creek, Yale Mining Division, British Columbia*: Geol. Surv. Canada Summ. Rept., pt. A, p. 100-106.
6. Cameron, E. N., 1943, *Origin of sulphides in the nickel deposits of Mount Prospect, Connecticut*: Bull. Geol. Soc. Amer., v. 54, p. 651-686.
- ✓ 7. Cockfield, W. E., and Walker, J. F., 1933, *The nickel-bearing rocks near Choate, British Columbia*: Geol. Surv. Canada Summ. Rept., pt. A, p. 62-68.
8. Coleman, A. P., 1913, *The nickel industry, with special reference to the Sudbury region*: Canada Dept. of Mines, Mines Branch.
9. Collins, W. H., 1937, *The life history of the Sudbury nickel irruptive; Part IV—Mineralization*: Trans. Royal Soc. Canada, v. 31, sec. IV, p. 15-43.

10. —, and Kindle, E. D., 1936, Life history of the Sudbury nickel irruptive; Part III: Trans. Royal Soc. Canada, v. 30, section IV, p. 29-54.
11. Davidson, Stanley, 1948, Falconbridge mine: Structural Geology of Canadian Ore Deposits, a Symposium, Can. Inst. Min., p. 618-626.
12. Dennen, W. H., 1943, A nickel deposit near Dracut, Mass.: ECON. GEOL., v. 38, p. 25-55.
13. Edwards, A. B., 1947, Textures of the ore minerals: Australasian Inst. Min. & Met.
14. Foslie, S., and Høst, M. J., 1932, Platina I Sulfidisk Nikkelmalm: Norges Geologiske Undersøkelse, Nr.137.
15. Hansen, H., 1926, Über die Präquartäre Geologie des Petsamo-Gebeites am Eismeer: Bull. de la Commission Geologique de Finland, no. 76, p. 55-58.
16. Hawley, J. E., Colgrove, G. L., and Zurbrigg, H. F., 1943, The Fe-Ni-S system: ECON. GEOL., v. 38, p. 335-388.
17. Hess, H. H., 1952, Orthopyroxenes of the Bushveld type, ion substitutions, and changes in unit cell dimensions: Amer. Jour. Sci., Bowen volume, p. 173-187.
18. Hewitt, R. L., 1938, Experiments bearing on the relation of pyrrhotite to other sulfides: ECON. GEOL., v. 33, p. 305-338.
19. Hoffman, R. D., 1931, Vlackfontein nickel deposits, Rustenburg area, Transvaal, South Africa: ECON. GEOL., v. 26, p. 202-214.
- ✓20. HORWOOD, H. C., 1936, Geology and mineral deposits at the mine of B. C. Nickel Mines, Ltd., Yale District, B. C.: Geol. Surv. Canada Memoir 190.
- ✓21. —, 1937, Magmatic segregation and mineralization of the B. C. Nickel Mine, Choate, B. C.: Trans. Royal Soc. Canada, sec. 4, p. 5-14.
22. Howe, Ernest, 1914, Petrographical notes on the Sudbury nickel deposits: ECON. GEOL., v. 9, p. 505-522.
23. Howland, A. L., Peoples, J. W., and Sampson, Edward, 1936, The Stillwater Igneous Complex and associated occurrences of nickel and platinum group metals: Montana Bur. Mines and Geol., Misc. Contr. 7.
24. Hudson, F. S., 1922, Geology of the Cuyamaca region of California with special reference to the origin of the nickeliferous pyrrhotite: Univ. Calif. Pub., Bull. Dept. Geol. Sci., v. 13, p. 175-252.
25. Kemp, J. F., 1894, The nickel mine at Lancaster Gap, Pennsylvania, and the pyrrhotite deposits at Anthony's Nose, on the Hudson: Trans. Am. Inst. Min. & Met. v. 24, p. 620.
- ✓26. Kennedy, G. C., and Walton, M. S., 1946, Nickel investigations in southeastern Alaska: U. S. Geol. Surv. Bull. 947-C.
- ✓27. —, 1946, Geology and associated mineral deposits of some ultrabasic rock bodies in southeastern Alaska: U. S. Geol. Surv. Bull. 947-D.
28. Lindgren, Waldemar, 1933, Mineral Deposits: New York, McGraw-Hill.
29. —, and Davy, W. M., 1924, Nickel ores from the Key West Mine, Nevada: ECON. GEOL., v. 19, p. 309-319.
30. Merwin, H. E., and Lombard, R. H., 1937, The system Cu-Fe-S: ECON. GEOL., v. 37, p. 203-284.
31. Pelzer, E. E., 1950, The Rankin Inlet nickel copper deposit: Can. Min. Jour., Sept., p. 79-83.
32. Poldervaart, Arie, 1950, Correlation of physical properties and chemical composition in the plagioclase, olivine, and orthopyroxene series: Amer. Mineralogist v. 35, p. 1067-1079.
33. Scholtz, D. L., 1936, The magmatic nickeliferous ore deposits of East Griqualand and Pondoland: Trans. Geol. Soc. S. Africa, v. 39, p. 81-210.
34. Turner, F. J., 1947, Determination of plagioclase with the four-axis universal stage: Am. Mineralogist, v. 32, p. 389-410.
35. —, and Verhoogen, Jean, 1951, Igneous and Metamorphic Petrology: New York, McGraw-Hill.
36. Vogt, J. H. L., 1893, Bildung von Erzlagerstätten durch Differentiationsproesse in basischen Eruptivmagmata: Zeits. für Prak. Geol., v. 1, p. 125-143, 257-284.
37. —, 1914, The deposits of the useful minerals and rocks: by Beyschlag, Vogt and Krusch, transl. by S. J. Truscott.
- ✓38. —, 1923, On the content of nickel in igneous rocks: ECON. GEOL., v. 18, p. 307-353.
39. Wager, L. R., and Mitchell, R. L., 1951, The distribution of trace elements during strong fractionation of basic magma—a further study of the Skaergaard intrusion, East Greenland: Geochimica et Cosmochimica acta, v. 1, p. 129-208.
40. Wagner, P. A., 1924, Magmatic nickel deposits of the Bushveld Complex in the Rustenburg district, Transvaal: Geol. Surv. S. Africa Memoir 21.
41. —, 1929, Platinum Deposits and Mines of South Africa: Edinburgh, Oliver and Boyd.
42. Walton, M. S., 1951, The Blaske Island ultrabasic complex: with notes on related areas in southeastern Alaska: Trans. New York Acad. Sci., v. 13, p. 320-323.
43. Yates, A. B., 1948, Properties of International Nickel Company of Canada: Structural Geology of Canadian Ore Deposits, a Symposium, p. 596-617.