

Nickel Deposits of North America

GEOLOGICAL SURVEY BULLETIN 1223



Nickel Deposits of North America

By H. R. CORNWALL

G E O L O G I C A L S U R V E Y B U L L E T I N 1 2 2 3

*Geology, resources, and reserves of
nickel sulfide and nickeliferous
laterite deposits in 7 Provinces of
Canada and 15 States of the
United States*



UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

First printing 1966

Second printing 1967

**For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 25 cents (paper cover)**

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By H. R. CORNWALL

ABSTRACT

Nickel is estimated to be the fifth most abundant element of the earth, having an average bulk percentage of 2.7. The average nickel content of the earth's crust, however, is estimated to be only 0.008 percent. The minimum concentration of nickel in deposits that can be economically mined is about 1.2 percent, or 150 times the content of the crustal rocks in which the deposits occur.

There are two principal types of nickel deposits: (1) sulfide deposits consisting mainly of pyrrhotite and pentlandite, with or without accompanying chalcopyrite, and closely associated with norite and peridotite, and (2) nickeliferous laterite deposits, occurring as weathering mantles that overlie peridotite (the nickel silicate variety) and serpentinite (the nickeliferous iron variety).

The largest nickel sulfide deposits in the world are in Canada—in the Sudbury district, Ontario, and the Thompson district, Manitoba. Smaller deposits of this type are scattered throughout Canada and the United States. Small nickel-cobalt deposits, characterized by sulfides, sulfosalts, and arsenides and related to intermediate or salic igneous intrusives, also occur in Canada and the United States.

Nickeliferous laterite deposits have been explored in parts of the Northwestern and Southeastern United States. Mining of one deposit in Oregon was begun in 1954.

Nickeliferous laterite clearly appears to be the result of weathering under tropical to subtropical conditions, probably mostly in Tertiary time. The sulfide deposits are generally believed to have resulted, in part, from magmatic segregation of immiscible sulfides and concentration by gravity sorting of the lighter and heavier fractions. This theory is contested by some geologists, however, particularly for deposits in several of the larger districts. The most popular alternate theory is that the deposits formed by deposition from hydrothermal solutions that migrated upward from igneous sources at depth along permeable zones of fracturing and faulting. One large recently discovered deposit possibly formed by the leaching effect of sulfur-bearing solutions on peridotite during regional metamorphism.

Resources and reserves in individual deposits are given if the information is available.

INTRODUCTION

Nickel is widespread, in fact, ubiquitous in nature. Estimates of the nickel content of the earth's crust range from 0.008 to 0.02 weight percent (Fleischer, 1953). Ultramafic igneous rocks—dunite, peridotite, and pyroxenite—contain the most nickel, 0.1–0.3 percent. Vino-

gradov (1956) estimated the average nickel content of these rocks to be 0.12 percent. His estimates for other rock types are: mafic igneous rocks (basalt, gabbro, norite, and related rocks) 0.016 percent; neutral igneous rocks (diorite, andesite), 0.0055 percent; silicic igneous rocks (granite, rhyolite, and related rocks), 0.0008 percent; and sedimentary rocks (clay, shale), 0.0095 percent.

A generally accepted theory is that the core of the earth, 4,300 miles in diameter, has a composition similar to that of iron meteorites, most of which are kamacite, native iron, having a nickel content of almost 7 percent. Inasmuch as the margin of the core is 1,800 miles below the earth's surface, this vast amount of nickel will probably never become available to man. The crust of the earth (about 10 miles thick), from which man must obtain the nickel he needs, contains only 0.003 percent of the total nickel in the earth, as computed from data given by Mason (1958, p. 44, 50).

The mantle, lying between the crust and the core of the earth, is nearly 1,800 miles thick and is believed to be peridotitic. These ultramafic rocks, like similar rocks exposed at the surface, may contain 0.1–0.3 percent nickel. And because the mantle makes up more than two-thirds of the total mass of the earth, it probably contains a large quantity of nickel.

The peridotite and related mafic rocks that have intruded the crust of the earth and are in part exposed at the surface probably have been derived largely from the mantle. Furthermore, most of the known nickel ore deposits are closely associated with mafic and ultramafic intrusive rocks, and the nickel in the ore bodies was probably derived either from the intrusives themselves or from similar rocks at depth. Thus the original source of most of the nickel ore bodies found in North America and elsewhere in the world was probably the mantle.

TYPES OF DEPOSITS

All the significant types of nickel ore deposits are represented in North America. Sulfide deposits are by far the most important source of nickel, both quantitatively and numerically. In 1964 two single districts of sulfide deposits in Canada were producing about 80 percent of the free world total; one of these, the Sudbury district, has produced more than half the total world supply since about 1905.

Another type of deposit, in which sulfides (together with arsenides of nickel, cobalt, and copper) occur in hydrothermal veins, has been found in both Canada and the United States, but these deposits are small and unimportant sources of nickel.

Important nickel deposits are found in the lateritic mantles formed by the weathering of peridotite, including dunite, pyroxenite, and

serpentinite, mostly in tropical and subtropical climates. The weathering of fresh peridotite has yielded the nickel silicate laterite in which the hydrosilicate garnierite is the principal nickel mineral. These deposits contain more than 1.5 percent nickel. Large deposits of this type occur in New Caledonia and medium to large deposits occur in Indonesia, Venezuela, Brazil, Oregon (United States), and elsewhere. The weathering of serpentinite (serpentinized peridotite) has also formed nickeliferous iron laterite that averages 0.9–1.4 percent nickel. Large deposits of this type occur in Cuba and the Philippines and medium to large deposits occur in Indonesia, the U.S.S.R., Western United States, Guatemala, and other localities.

SULFIDE DEPOSITS

The nickel-bearing sulfide deposits typically consist predominantly of pyrrhotite (Fe_{1-x}S) and associated pentlandite [$(\text{Fe}, \text{Ni})_9\text{S}_8$] and chalcopyrite (CuFeS_2). Many of the deposits contain minor but recoverable amounts of platinum metals, cobalt, and selenium. These deposits occur in or near peridotite or norite intrusions and are generally considered to be genetically related to them. The sulfides occur as disseminations, massive bodies, or veins and stringers in the igneous rocks. Some of the massive ores contain fragments of the host rock. The individual ore bodies are normally elongate, lenticular, or sheet-like and may extend for hundreds or thousands of feet.

Some deposits are clearly epigenetic and the place of deposition was structurally controlled. Such ore bodies commonly occur along faults or shear zones. Many deposits, however, occur at or near the base of peridotite or norite intrusives and are particularly well formed in local hollows or reentrants along the basal contacts. Many geologists consider deposits of this type to have resulted from segregation of immiscible liquid sulfide droplets from the parent mafic or ultramafic magma at an early stage of crystallization, followed by settling and coalescing of the droplets to form a sulfide zone at the base of the intrusive. In many small deposits associated with relatively small intrusives, the evidence for formation by such a mechanism is strong.

Some of the largest deposits, such as those in the Sudbury district, Ontario, Canada, also occur along the base of a mafic intrusive—at Sudbury a basin-shaped or funnellike norite intrusive—but their origin is disputed. Some geologists favor the theory of magmatic segregation, that is, that the iron-nickel-copper sulfides separated from the norite and settled to form sulfide concentrations along the base. Others support a theory of epigenetic origin, that is, that sulfides were introduced into the norite contact zone by hydrothermal

solutions that migrated from depth. The Sudbury deposits are described in some detail on pages 26-32, and the alternative theories of origin, including one involving the possibility of a meteoritic impact, are discussed.

NICKELIFEROUS LATERITE DEPOSITS

Laterite has formed over large areas during long periods of intensive weathering and erosion, mainly in tropical to subtropical climates, where stable landmasses have gradually been reduced to almost flat, featureless penepains. Such a period of erosion took place in the Tertiary in many parts of the world. Where the rock exposed at the surface was peridotite (composed essentially of olivine and pyroxene), dunite (all olivine), pyroxenite (all pyroxene), or serpentinite (serpentinized peridotite), the laterite that was developed is almost invariably rich in iron and nickel.

The laterite formed from the weathering of serpentinite is richest in iron, generally containing 45-55 percent. The nickel content of this laterite commonly averages about 1 percent, ranging from about 0.9 to 1.3 percent for large volumes of material. These deposits are called nickeliferous iron laterite. The mode of occurrence of the nickel in this laterite is not known; most likely the nickel is included in the goethite, limonite, and serpentine minerals, which are the major constituents. Huge deposits of nickeliferous iron laterite, such as those in Cuba, the Philippines, and Indonesia, have not been mined in North America, but several smaller deposits have been thoroughly explored in California, Oregon, and Washington.

The other type of nickeliferous laterite is known as the nickel silicate type, because a significant part of the nickel occurs either as the hydrosilicate garnierite or as nickel-bearing talc or antigorite. This laterite has formed from the weathering of fresh peridotite, dunite, and, to a lesser degree, pyroxenite. The iron content is less than 30 percent in most laterite of this type; the SiO_2 content, which is very low in the iron laterite, may be as much as 30 percent; and the nickel content exceeds 1.5 percent and averages about 1.6 percent for large tonnages. The largest known deposits of nickel silicate laterite occur in New Caledonia and Indonesia. A moderately large deposit occurs in the United States at Riddle, Oreg.

NICKEL MINERALS

The nickel minerals are listed in table 1. The nickel-iron sulfide pentlandite $[(\text{Fe}, \text{Ni})_9\text{S}_8]$ is the principal economic source of nickel, and garnierite $[(\text{Ni}, \text{Mg}) \text{ hydrosilicate}]$ is next in economic importance. Garnierite—also called nickel gymnite, genthite, noumeite, and nepouite (Pecora and others, 1949, p. 22)—is not a true mineral

but rather a mixture of nickel-serpentine, nickel-talc, and possibly other silicates.

TABLE 1.—*Nickel minerals*

Mineral	Formula	Occurrence
Native nickel-iron	Ni_3Fe	Rare.
Pentlandite	$(\text{Fe}, \text{Ni})_9\text{S}_8$	Common.
Bravoite	$(\text{Fe}, \text{Ni})\text{S}_2$	Minor-secondary.
Violarite	Ni_2FeS_4	Do.
Vaesite	NiS_2	Rare.
Polydymite	Ni_3S_4	Do.
Millerite	NiS	Minor-secondary.
Heazlewoodite	Ni_3S_2	Rare.
Siegenite	$(\text{Ni}, \text{Co})_3\text{S}_4$	Minor.
Linnaeite	$(\text{Co}, \text{Fe}, \text{Ni})_3\text{S}_4$	Do.
Gersdorffite	NiAsS	Do.
Niccolite	NiAs	Do.
Rammelsbergite	NiAs_2	Rare.
Chloanthite	$(\text{Ni}, \text{Co})\text{As}_3$	Do.
Smaltite	$(\text{Co}, \text{Ni})\text{As}_3$	Do.
Skutterudite	$(\text{Co}, \text{Ni})\text{As}_3$	Do.
Maucherite	$\text{Ni}_{11}\text{As}_8$	Do.
Breithauptite	NiSb	Do.
Ullmannite	NiSbS	Do.
Parkerite	$\text{Ni}_3\text{Bi}_2\text{S}_2$	Do.
Annabergite	$\text{Ni}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$	Rare-secondary.
Morenosite	$\text{NiSO}_4 \cdot 7\text{H}_2\text{O}$	Do.
Zaratite	$\text{NiCO}_3 \cdot 2\text{Ni}(\text{OH})_2 \cdot 4\text{H}_2\text{O}$	Do.
Garnierite	(Ni, Mg) hydro-silicate.	Common-second-ary.

Besides the nickel minerals listed in table 1, nickel occurs in minor amounts in pyrrhotite (Fe_{1-x}S) and pyrite (FeS_2), particularly where these sulfides are associated with mafic or ultramafic rocks. In most of these occurrences the total amount of included nickel is less than 1 percent (Fleischer, 1955; Palache and others, 1946). Nickel may replace iron to a considerable extent in these minerals, but substantial amounts may also be present as intergrowths of pentlandite or other nickel sulfides (Fleischer, 1955; Deer and others, 1962b, p. 150). Native terrestrial iron also contains nickel, commonly in amounts ranging from 2 to 7 percent, but such native iron is rare; it occurs in basalts and carbonaceous sediments and with limonite and organic matter in petrified wood (Palache and others, 1946, p. 114–116). The most important occurrence of native terrestrial iron is on Disko Island, Greenland, where it occurs in basalt as particles and in places as masses as large as 20 tons.

New significant data have been published for some minerals, such as the Ni-S system (Kullerud and Yund, 1962), the Fe-Ni-S system (Clark and Kullerud, 1963), and native nickel-iron (Nickel, 1959). These are described in greater detail in the following sections.

NATIVE NICKEL-IRON

Nickel (1959, p. 307) noted that terrestrial nickel-iron has been found in widely scattered areas throughout the world. Most of the native nickel-iron has been found in alluvial gravel deposits, as, for example, along the Gorge River at Awarua Bay, New Zealand; the Fraser River, British Columbia; the Brokovka River in the Urals, U.S.S.R.; and in Josephine and Jackson Counties, Oreg. The native nickel-iron—given various names including awaruite, josephinite, souesite, and brokovkite—all contains 60–75 percent nickel, 25–35 percent iron, and minor amounts of cobalt.

Most of the nickel-iron specimens are not attached to any other material, but a few have adhering serpentine. In a few places native nickel-iron has been found in place in bedrock, but only in serpentine. Ramdohr (1950b) recognized the close association of native nickel-iron with serpentine and suggested a thermal origin for the native metals in the temperature range of talc formation. He also noted the association of these metals with sulfides of nickel and iron and with native copper and copper sulfides. Ramdohr further suggested that native nickel-iron is probably widely distributed in serpentine but in grains so small that they pass unseen, whereas the larger grains and bodies of native nickel-iron are concentrated in the placer deposits and are more easily recognized. Morley (1949) has described josephinite (native nickel-iron) occurrences associated with chromite, magnetite, and platinum in stream gravels in Josephine County, Oreg. For many years mineralogists assumed that the josephinite was derived from serpentine through which Josephine Creek cut its channel, but samples of josephinite with serpentine adhering to it were not described. Of the 75 specimens collected by Morley, several had serpentine adhering to the josephinite. The 75 specimens ranged in largest dimension from 3.2 to 31.4 mm. Morley stated that specimens of considerably larger size have been found, but that they are rare. Nickel (1959) studied the widespread occurrence of native nickel-iron in serpentized dunite and peridotite of the asbestos deposits in the eastern townships of Quebec. He collected specimens in half a dozen different deposits and found microscopically that all the serpentized specimens contained rather uniformly disseminated tiny grains of native nickel-iron. The largest grain observed was one-tenth millimeter in diameter, and many were as small as 10 microns. The chemical analysis of two grains showed a nickel content of about 70 percent, iron content of about 25 percent or slightly more, and the remainder cobalt.

In trying to determine the origin of the native nickel-iron, Nickel (1959, p. 313–316) assayed serpentines containing microscopically visible native nickel-iron and included un-serpentized crystals of olivine and pyroxene. The fresh olivine and pyroxene did not con-

tain microscopically visible grains of native nickel-iron but nevertheless contained about the same percentage of nickel as the serpentine, 0.2 percent. Nickel found that in the serpentinized rock about one-half of the total nickel occurs as visible native nickel-iron; the rest apparently is in the silicate structure of the serpentine. In the fresh olivine and pyroxene, all the nickel appears to be in the silicate. These data, he concluded, indicate that the native nickel-iron formed during serpentinization of the olivine and pyroxene. This conclusion is in general agreement with Ramdohr's theory (1950b).

SULFIDES

Most of the nickel in nickel sulfide deposits occurs as pentlandite, but in nearly all these deposits pyrrhotite is the most abundant sulfide mineral. Two other mixed iron-nickel sulfides that are probably secondary alterations of pentlandite are bravoite and violarite. Nickel and sulfur form a suite of minerals that occur in minor amounts, mostly in association with pyrrhotite and pentlandite. These are, in order of increasing nickel content, vaesite, polydymite, millerite, and heazlewoodite. Cobalt and nickel occur together as siegenite and linnaeite in some copper and lead-zinc sulfide deposits.

Pentlandite.—Natural pentlandite $[(\text{Fe}, \text{Ni})_9\text{S}_8]$ apparently has a constant composition with the Fe:Ni ratio equal to 10:11, but synthetic pentlandite has a wide range in the Fe:Ni ratio, which varies with temperature and sulfur pressure (Hawley and others, 1943, p. 335; Hawley and Haw, 1957; Kullerud, 1956). Hawley and Haw (1957, p. 138) believed that the constant composition of natural pentlandite is explained by exsolution on cooling from an original nickeliferous pyrrhotite $[(\text{Fe}, \text{Ni})_{1-x}\text{S}]$ solid solution that forms at a higher temperature. They further stated that "Natural nickeliferous sulfide ores consist dominantly of pyrrhotite with lesser quantities of pentlandite and chalcopyrite. Average pentlandite in some ores is about 10 percent, and average Ni:Fe is probably less than 10:90. Textural relations of pyrrhotite and pentlandite are intimate and dominantly of an ex-solution type."

Bravoite and violarite.—Bravoite $[(\text{Fe}, \text{Ni})\text{S}_2]$ and violarite $(\text{Ni}_2\text{FeS}_4)$ most commonly are secondary minerals formed from primary sulfides in the weathering zone by circulating ground water (Ramdohr, 1955; Clark and Kullerud, 1963). Clark and Kullerud found experimentally that bravoite must form below $137^\circ \pm 6^\circ\text{C}$; above that temperature the end members pyrite (FeS_2) and vaesite (NiS_2) form a stable mineral assemblage. Violarite may also form by deposition in veins from hydrothermal solutions, together with other complex sulfides of the linnaeite series (Ramdohr, 1955; Palache and others, 1946).

Vaesite.—*Vaesite* (NiS_2) was first described by Kerr (1945) after its discovery in the Kasompi Mine, in what is now the Republic of the Congo, in a disseminated deposit in dolomite together with pyrite, chalcopyrite, and polydymite(?). *Vaesite* has recently been investigated experimentally by Kullerud and Yund (1962). Their data indicate that the Kasompi mine *vaesite* formed at 390°C ; thus it is a hydrothermal mineral, even though microscopic studies (Ramdohr, 1955) indicate that it is a secondary alteration of other nickel sulfides and arsenides.

Millerite.—*Millerite* (NiS) has been found at numerous localities; its mode of occurrence suggests that it is a supergene mineral, formed by the action of ground waters on nickel-bearing sulfides. Laboratory experiments indicate that it may also form under hydrothermal conditions at temperatures above 300°C (Ramdohr, 1955; Kullerud and Yund, 1962).

Heazlewoodite.—*Heazlewoodite* (Ni_3S_2) has been identified at only a few localities; it occurs as tiny crystals disseminated in serpentinized peridotite and associated with pentlandite, native nickel-iron, magnetite, and shandite, a rare nickel mineral having the composition $\text{Ni}_3\text{Pb}_2\text{S}_2$ (Ramdohr, 1950a, 1955). This association indicates that *heazlewoodite*, like native nickel-iron, is formed hydrothermally during serpentinization of peridotite. Kullerud and Yund (1962, p. 170) found that *heazlewoodite* forms together with native nickel at a eutectoid at 533°C by cooling of $\text{Ni}_{3+x}\text{S}_2$ that had deposited earlier in equilibrium with native nickel or nickel-iron.

Linnaeite, polydymite, siegenite, and violarite.—These nickel-bearing minerals of the linnaeite series having the general formula $(\text{Co, Fe, Ni})_3\text{S}_4$ occur in hydrothermal vein and replacement deposits commonly associated with pyrite, chalcopyrite, galena, and sphalerite. *Violarite* also occurs as a supergene weathering product of primary pentlandite and linnaeite.

OTHER MINERALS

The remaining nickel minerals grouped together here are, except for garnierite, unimportant commercially. Included in this group are the arsenides and antimonides and their sulfosalts, plus their alteration products—the arsenates, sulfates, carbonates, and silicates. These minerals characteristically occur in hydrothermal vein deposits primarily important for their cobalt and silver content. Garnierite is most abundant in the lateritic weathering mantles that overlie ultramafic intrusives.

Nickel arsenide, sulfarsenide, antimonide, and other minerals.—The minerals in this group are gersdorffite (NiAsS), niccolite (NiAs),

rammelsbergite (NiAs_2) chloanthite $[(\text{Ni}, \text{Co})\text{As}_{3-x}]$, smaltite $[(\text{Co}, \text{Ni})\text{As}_{3-x}]$, skutterudite $[(\text{Co}, \text{Ni})\text{As}_3]$, maucherite ($\text{Ni}_{11}\text{As}_8$), breihauptite (NiSb), ullmannite (NiSbS), and parkerite ($\text{Ni}_3\text{Bi}_2\text{S}_2$). These minerals occur in and characterize hydrothermal vein deposits that have been called the nickel-cobalt-native silver ore type by Bastin (1939). The deposits are mined for silver and cobalt; the nickel is not economically important. Copper and lead minerals are also present, and native bismuth is characteristic. The most important deposits are in the Erzgebirge of East Germany and Czechoslovakia, and the Cobalt district, Ontario, Canada. Some of these deposits have been enriched by supergene processes. Bastin (1939) believed that the mineralizing solutions were derived from granitic magmas, although the cobalt deposits are associated with diabase. In the major nickel-copper ores of pyrrhotite, pentlandite, and chalcopyrite at Sudbury, niccolite and gersdorffite are locally abundant, but maucherite, smaltite, and parkerite are rare (Hawley, 1962). Because these minerals are intimately intergrown with the other sulfides, particularly chalcopyrite, they are believed to be primary.

Hydrated nickel arsenate, sulfate, and carbonate.—Annabergite $[\text{Ni}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}]$, morenosite ($\text{NiSO}_4 \cdot 7\text{H}_2\text{O}$), and zaratite $[\text{NiCO}_3 \cdot 2\text{Ni}(\text{OH})_2 \cdot 4\text{H}_2\text{O}]$ form in the weathering of primary nickel minerals and are particularly common in the oxidized zone of the nickel-cobalt-native silver deposits. Zaratite has been found associated with chromite in serpentine.

Garnierite.—Garnierite is probably a mixture of two or more nickel-magnesium silicates. Pecora, Hobbs, and Murata (1949) studied eight samples of garnierite from Riddle, Oreg., by various methods, including chemical, X-ray, and differential thermal analyses and microscopic study. They concluded that the garnierite is a mixture of serpentine, deweylite, and saponite. The nickel content of the samples ranged from 2.62 to 37.08 percent. Hotz (1964, p. 382–385), from a recently completed X-ray study of garnierite from Riddle (Nickel Mountain) and from Woodcock Mountain, Oreg., concluded that the garnierite appears to be a mixture of nickel serpentine and nickeliferous talc. Deer, Howie, and Zussman (1962a, p. 175–177) called garnierite “a naturally occurring nickel serpentine.”

NICKEL RESOURCES

The nickel deposits of North America, except for a few small and insignificant ones, are listed in table 2 and located on figure 1.

The nickel resources are summarized in table 3, reserves in individual deposits are listed in table 4, and resources in marginal and sub-marginal deposits are listed in table 5.

NICKEL DEPOSITS OF NORTH AMERICA

TABLE 2.—*Nickel deposits of North America*

[Localities shown by number on fig. 1]

Number	Locality	State or province	Number	Locality	State or province
1	Spirit Mountain.....	Alaska.	28	Webster.....	North Carolina.
2	Brady Glacier.....	Do.	29	Fredericktown.....	Missouri.
3	Funter Bay.....	Do.	30	Saline County.....	Arkansas.
4	Bohemia Basin.....	Do.	31	Boulder County.....	Colorado.
5	Mirror Harbor.....	Do.	32	Mouat.....	Montana.
6	Snipe Bay.....	Do.	33	Jumbo Mountain.....	Washington.
7	Canalask.....	Yukon.	34	Mackinaw.....	Do.
8	Quill Creek.....	Do.	35	Winesap.....	Do.
9	Rankin Inlet.....	Northwest Terri- tories.	36	Blewett.....	Do.
10	Ungava.....	Quebec.	37	Cle Elum.....	Do.
11	Lynn Lake.....	Manitoba.	38	Nickel Mountain.....	Oregon.
12	Thompson.....	Do.		Woodcock Mountain.	Do.
13	Hope.....	British Columbia.		Eight Dollar Mountain.	Do.
14	Trout Lake.....	Ontario.		Red Flats.....	Do.
15	Gordon Lake.....	Do.		Pine Flat.....	California.
16	Populus Lake.....	Do.		Cottonwood Canyon.	Nevada.
17	Shebandowan Lake.	Do.	39	Gibellini.....	Do.
18	Sudbury.....	Do.	40	Bunkerville.....	Do.
19	Timmins.....	Do.	41	Julian.....	California.
20	Alexo.....	Do.	42	Old Ironsides.....	Do.
21	Limerick.....	Do.	43	Little Red Mountain.	Do.
22	Raglan.....	Do.		Montgomery.....	Idaho.
23	Belleterre.....	Quebec.	44	Ely.....	Minnesota.
24	La Motte.....	Do.	45	Hodges.....	Connecticut.
25	St. Stephen.....	New Brunswick.	46	Mount Prospect.....	Do.
26	Knox County.....	Maine.			
27	Gap.....	Pennsylvania.			

TABLE 3.—*Total nickel resources of North America*

	Measured and indicated			Inferred		
	Nickel-bearing material (tons)	Grade, (percent Ni)	Nickel (tons)	Nickel-bearing material (tons)	Grade, (percent Ni)	Nickel (tons)
Reserves:						
Canada, sulfide ore.....	429,856,000	1.46	6,278,500	(¹)	(¹)	(¹)
United States, laterite ore.....	16,200,000	1.50	243,000	-----	-----	-----
Marginal and submarginal resources:						
Canada, sulfide material.....	2,188,000	.75	16,400	-----	-----	-----
United States, sulfide material.....	17,444,500	.42	74,000	25,160,000	0.37	93,400
United States, laterite material.....	54,090,000	.78	421,800	13,630,000	.58	78,600

¹ Data not available; gross tonnage probably large and grade probably comparable to figure given for measured and indicated ore.

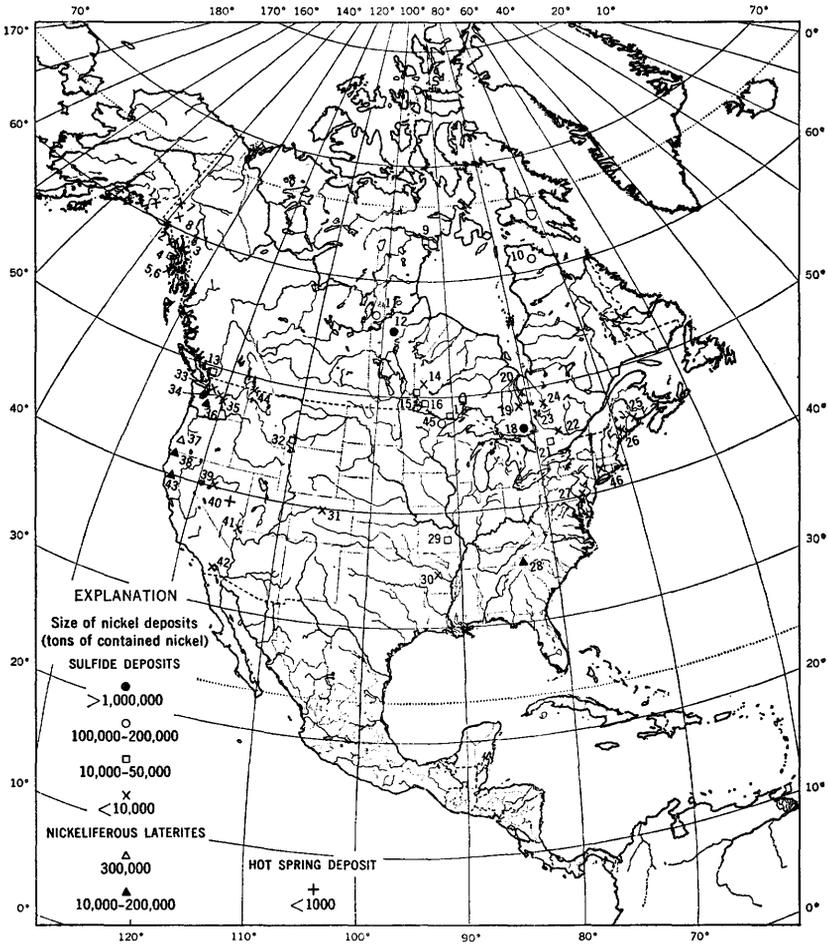


FIGURE 1.—Nickel deposits of North America. Numbered localities identified in table 2.

TABLE 4.—*Nickel reserves of North America*

Location	Measured and indicated			Inferred	Source of data
	Nickel-bearing material (tons)	Grade (percent Ni)	Nickel (tons)	Nickel-bearing material (tons)	
Sulfide deposits in Canada					
British Columbia: Hope, Giant Nickel mine.	1,025,000	0.95	9,700	-----	Stephens (1963).
Manitoba:					
Lynn Lake district.....	11,916,000	.96	114,400	-----	Canadian Mines Handbook (1964).
Thompson-Moak Lake district:					
Thompson mine.....	25,000,000	2.80	700,000	(¹)	Northern Miner (Mar. 30, 1961).
Moak Lake mine.....	50,000,000	.70	350,000	(¹)	Northern Miner (Aug. 17, 1961).
Ontario:					
Kenora district:					
Gordon Lake mine.....	1,100,000	1.62	17,800	-----	Canadian Mines Handbook (1963).
Popul Lake deposit....	3,503,000	1.06	37,200	-----	Northern Miner (Aug. 15, 1957).
Limerick township deposit..	2,000,000	1.0	20,000	-----	Northern Miner (Nov. 15, 1961).
Shebandowan Lake deposit..	1,000,000	1.7	17,000	-----	Thomson and others (1957).
Sudbury district:					
Falconbridge Nickel mines.	48,263,000	1.45	699,800	(¹)	Company annual report (1962).
International Nickel mines.	274,400,000	1.50	4,130,000	(¹)	Company annual report (1962).
Quebec:					
Bellettre deposit.....	550,000	1.0	5,500	-----	Northern Miner (Nov. 21, 1963).
La Motte township district..	143,000	2.28	3,300	-----	Canadian Mines Handbook (1964).
Ungava district:					
Cross Lake deposit.....	10,050,000	1.54	154,800	-----	Do.
Raglan Lake deposit....	356,000	2.74	9,800	-----	Do.
Yukon: Canalask deposit.....	550,000	1.68	9,200	-----	Northern Miner (Sept. 12, 1957).
Total.....	429,856,000	1.46	6,278,500	-----	
Laterite deposits in the United States					
Oregon: Nickel Mountain, Douglas County.	16,200,000	1.50	243,000	-----	F. M. Chace (written commun., August, 1965).

¹ Data not available; gross tonnage probably large and grade probably comparable to figure given for measured and indicated ore.

Nickel resources may be classified into two major categories: (1) reserves, known mineral material that may be quantitatively appraised and is economically exploitable at present, and (2) marginal and submarginal resources, mineral material that must be mined under more favorable economic or technologic conditions. These two classes may be further subdivided according to the accuracy of the appraisal. The subcategories of reserves used in this report are the same as those used by the U.S. Bureau of Mines and the U.S. Geological Survey:

Measured reserves are those for which tonnage is computed from dimensions revealed in outcrops, trenches, workings and drill holes and for which the grade is computed from the results of detailed sampling. The sites for inspection,

TABLE 5.—Marginal and submarginal nickel resources of North America

Location	Measured and indicated			Inferred			Source of data
	Nickel-bearing material (tons)	Grade (percent Ni)	Nickel (tons)	Nickel-bearing material (tons)	Grade (percent Ni)	Nickel (tons)	
Sulfide deposits in Canada							
New Brunswick: St. Stephen deposit.	264,000	0.98	2,600	-----	-----	-----	Northern Miner (Aug. 25, 1960). Thomson and others (1957).
Ontario: Sudbury district: Nickel Rim mine.	1,924,000	.72	13,800	-----	-----	-----	
Total.....	2,188,000	.75	16,400	-----	-----	-----	
Sulfide deposits in the United States							
Alaska:							
Bohemia Basin, Yakobi Island.	10,300,000	0.37	38,000	10,500,000	0.28	29,000	Kennedy and Walton (1946).
Funter Bay, Admiralty Island.	(¹)	1.0	(¹)	(¹)	1.0	(¹)	
Mirror Harbor, Fleming Island.	8,000	1.54	100	-----	-----	-----	Do.
Snipe Bay, Baranof Island.	-----	-----	-----	430,000	.3	1,300	Reed and Gates (1942).
Spirit Mountain, Copper River area.	-----	-----	-----	6,500	.7	-----	Kingston and Miller (1945).
California:							
Julian deposit, San Diego County.	5,000	2.5	100	100,000	1.5	1,500	Creasey (1946).
Old Ironsides, San Diego County.	-----	-----	-----	(¹)	.3	(¹)	
Colorado: Copper King deposit, Boulder County.	22,000	3.0	700	50,000	.5	200	Goddard and Lovering (1942).
Maine: Crawford Pond deposit, Knox County.	(¹)	.6	(¹)	-----	-----	-----	
Missouri: Fredericktown deposits, Madison County.	2,000,000	.46	9,200	(¹)	.45	(¹)	U.S. Bureau of Mines (1952).
Montana: Moutat deposit Stillwater County.	(¹)	.4	(¹)	(¹)	.4	(¹)	
Nevada: Great Eastern deposit, Clark County.	(¹)	.31	-----	-----	-----	-----	
Pennsylvania: Gap mine Lancaster County.	(¹)	.7	(¹)	-----	-----	-----	
Washington:							
Mackinaw deposit, Snohomish County.	(¹)	.9	(¹)	-----	-----	-----	
Winesap deposit, Chelan County.	(¹)	1.12	(¹)	(¹)	.8	(¹)	
Total.....	17,444,500	.42	74,000	25,160,000	.37	93,400	

¹ Unpublished resource data, included in total.

TABLE 5.—*Marginal and submarginal nickel resources of North America—Continued*

Location	Measured and indicated			Inferred			Source of data
	Nickel-bearing material (tons)	Grade (percent Ni)	Nickel (tons)	Nickel-bearing material (tons)	Grade (percent Ni)	Nickel (tons)	
Laterite deposits in the United States							
California: Mendocino and Del Norte Counties.	16,400,000	0.8	131,000	-----	-----	-----	Pawel (1943).
North Carolina: Webster, Jackson County.	-----	-----	-----	1,000,000	1.0	10,000	
Oregon: Josephine and Curry Counties.	30,300,000	.8	242,000	-----	-----	-----	Lamey (1950).
Washington: Blewett deposit, Chelan County.	3,540,000	.47	16,600	10,230,000	.47	48,000	
Cle Elum deposit, Kittitas County.	3,850,000	.84	32,200	2,400,000	.86	20,600	
Total.....	54,090,000	.78	421,800	13,630,000	.68	78,600	Lamey and Hotz (1951).

sampling, and measurement are spaced so closely and the geologic character is so well defined that size, shape, and mineral content are well established. The computed tonnage and grade are judged to be accurate within limits which are stated, and no such limit is judged to be different from the computed tonnage or grade by more than 20 percent.

Indicated reserves are those for which tonnage and grade are computed partly from specific measurements, samples, or production data and partly from projection for a reasonable distance on geologic evidence. The sites available for inspection, measurement, and sampling are too widely or otherwise inappropriately spaced to permit the mineral bodies to be outlined completely or the grade established throughout.

Inferred reserves are those for which quantitative estimates are based largely on broad knowledge of the geologic character of the deposit and for which there are few, if any, samples or measurements. The estimates are based on an assumed continuity or repetition, of which there is geologic evidence; this evidence may include comparison with deposits of similar type. Bodies that are completely concealed may be included if there is specific geologic evidence of their presence. Estimates of inferred reserves should include a statement of the specific limits within which the inferred material may lie.

In this report, estimates of reserves and of marginal and submarginal resources are classified as combined measured and indicated or inferred, according to the accuracy of the appraisal. For most of the deposits, the estimates given are those released by the companies holding the properties, but for some deposits the estimates are based on investigations and explorations of the Canadian and U.S. Governments. The estimates given in tables 3-5 are probably conservative.

The estimates given for the total nickel resources in table 3 show that Canada is dominant in North America, having a total of 430 million tons of measured and indicated sulfide ore averaging 1.46 percent nickel. No estimate has been made of inferred ore in the Sudbury and Thompson-Moak Lake districts, but the amount of ore averaging more than 1 percent nickel is probably large. Canada also has the largest resources of minable sulfide reserves in the world, but there are very large tonnages of nickeliferous laterite, including large amounts of economically minable ore, in Cuba, New Caledonia, Indonesia, Venezuela, Guatemala, and the Philippines. These vast nickel resources include 4-5 billion tons of nickeliferous iron laterite, averaging 0.8-1 percent nickel, and nearly 1 billion tons of nickel silicate laterite, averaging 1.5-2 percent nickel.

The United States has only one nickel reserve that is being mined at the present time, the nickel silicate laterite at Nickel Mountain, Oreg. The deposit averages somewhat more than 1.5 percent nickel (Hotz, 1964) and has reserves of at least 16,200,000 tons of ore (F. M. Chace, written commun., August 1965). Production records for the first 10 years of operation, plus consideration of present capacity and minimal requirements for profitable exploitation of a metal deposit, indicate that the deposit is large enough to support a production rate of 24 million pounds of nickel per year for a minimum of 30 years.

Disseminated nickel-copper sulfides in the Duluth Gabbro in Minnesota are a promising potential source of nickel. Deposits containing several hundred million tons of material averaging 0.25 percent nickel and 0.75 percent copper are reported to occur there. In addition, approximately 100 million tons of material containing 0.4-0.8 percent nickel are scattered around the United States in a variety of marginal to submarginal deposits.

NICKEL DEPOSITS OF CANADA

The Canadian nickel deposits are discussed in the following pages in alphabetical order by province and by district or individual deposit. Locations of the deposits are shown on figure 1. The amount of detail given for the individual districts or deposits depends partly on their respective importance and partly on the information available.

The Sudbury district, Ontario, is, and has been for many years, the outstanding district of the world, both in nickel production and in size of deposits of sulfide ore. The Thompson and Lynn Lake districts, Manitoba, rank second and third in Canada, and probably also in the world, although the Petsamo deposit, U.S.S.R., may be larger than Lynn Lake. Recent intensive exploration in Ungava, in northern Quebec, has revealed significant reserves of nickel-copper sulfides

there. Other smaller nickel deposits were being mined in 1965 in British Columbia, Ontario, and Quebec.

BRITISH COLUMBIA

HOPE

A deposit of nickel-copper sulfides is mined near Hope, British Columbia, by the Giant Mascot Mines, Ltd. Ore reserves on September 30, 1962, were estimated by the company to be 1,066,000 tons containing 1.03 percent nickel and 0.35 percent copper (Stephens, 1963, p. 34). During 1963, continued exploration outlined another 75,000 tons of ore containing 1.30 percent nickel and 0.40 percent copper, but production during this period reduced net reserves to 1,025,000 tons that average 0.95 percent nickel and 0.35 percent copper. A nickel-copper concentrate was shipped from the mine to Japan.

The nickel-copper deposit near Hope was first discovered in 1927. Between 1930 and 1937 much diamond drilling and underground development was done by the British Columbia Nickel Co., Ltd., later British Columbia Nickel Mines, Ltd. By 1938, when the mine was taken over by the newly organized Pacific Nickel Mines, Ltd., a reserve of approximately 1 million tons of ore had been developed. Difficulty in obtaining a market for the nickel concentrates prevented the company from going into production, and in 1952 the Pacific Nickel Mines, Ltd., joined with Newmont Mining Corp. of Canada to form a new company called Western Nickel Mines, Ltd. Considerable new development work was done between 1952 and 1959, and the first ore was produced in 1958. In 1959, Newmont's interest in the property was acquired by Giant Mascot Mines, Ltd., and the present company, the Giant Nickel Mines, Ltd., was formed and has been operating profitably since that time. This is the first successful nickel-mining operation in western Canada.

A number of separate nickel-copper ore bodies occur in an irregular stocklike ultramafic intrusive (Aho, 1956, 1957; James, 1962; Stephens, 1963). The ultramafic mass, late Mesozoic in age and 1½ miles in diameter, consists of peridotite, pyroxenite, and hornblendic pyroxenite having marginal zones of hornblendite. It is bordered by a larger batholithic mass of genetically related diorite and minor norite. The southwest half of the ultramafic mass contains all the ore bodies and is characterized by hornblendic variations of the various rock types; the barren northeast half contains little hornblende except along the margins.

The sulfide ore bodies are steeply dipping, mostly pipe- or parsnip-shaped deposits. In some of the ore bodies the ultramafic rocks are zoned, commonly with olivine-rich (dunite or harzburgite) cores and

pyroxene-rich (bronzitite or peridotite) outer rings (Aho, 1956, p. 459-473). Sulfides are concentrated in the cores in some deposits and in the outer rings in others. In other ore bodies, including the important Pride of Emory deposit, there is no apparent zoning of the ultramafic rocks.

The sulfides, consisting of pyrrhotite, pentlandite, and chalcopyrite, occur both disseminated and in massive bodies, but even in the massive bodies, silicates commonly make up 50 percent or more of the rock. Everywhere the sulfides are interstitial to the silicates (olivine, pyroxene, and hornblende).

The origin of the deposits is uncertain. A magmatic origin is suggested by textures, lack of alteration, location of deposits in or marginal to the most ultramafic facies, and gradation of ore into sparsely disseminated probable primary sulfides. The steeply dipping pipelike ore bodies, cannot be explained by simple magmatic segregation, but could have resulted from segregation followed by injection into their present positions, and some ore bodies do show signs of such movement. Aho (1956, p. 476-480) and Stephens (1963, p. 36) both state that a good case can be presented for an origin due to magmatic segregation followed by injection, but they also suggested that the pipelike bodies having zoning of olivine and bronzite could have resulted from high-temperature (greater than 650°C) alteration by ascending water vapor that deposited the sulfides.

MANITOBA

LYNN LAKE DISTRICT

A small outcrop of nickel-copper-bearing sulfides was discovered near Lynn Lake in 1941, but active prospecting of the area was delayed by World War II. During the period 1945-48, intensive geophysical surveys using magnetometer and electromagnetic methods, accompanied by 200,000 feet of diamond drilling, resulted in the location of five ore bodies, including the high-grade EL ore body. Subsequent exploration located two additional ore bodies, and when the mine went into active production in 1954, the proven ore reserves amounted to more than 14 million tons containing 1.22 percent nickel and 0.62 percent copper, distributed in separate ore bodies as shown in table 6 (Waldron, 1951, p. 73). At the end of 1963, after 10 years of continuous production at the rate of 24 million pounds of nickel per year, Sherritt Gordon Mines, Ltd., reported a proven reserve of 11,916,000 tons having an average grade of 0.96 percent nickel and 0.58 percent copper (Canadian Mines Handbook, 1964, p. 277). In the early years of its production, the Lynn Lake mine was second only to the Sudbury district as a producer of nickel from sulfide ore in

Canada and, in fact, in the whole free world. Since then it has been superseded in size and rate of production by the Thompson mine, 140 miles southeast of Lynn Lake.

TABLE 6.—*Nickel-copper reserves of Lynn Lake, 1951*

[Waldron, 1951, p. 73]

Ore body	Short tons	Nickel (percent)	Copper (percent)
A:			
Upper-----	590,000	1.083	0.535
Lower-----	4,200,000	1.257	.664
Footwall-----	185,000	.867	.467
B:			
Upper-----	1,570,000	.874	.555
Lower-----	2,705,000	.660	.467
C:			
Upper-----	100,000	1.135	.514
Lower-----	660,000	.712	.500
E-----	755,000	1.020	.471
F-----	700,000	.560	.428
G-----	145,000	.663	.275
EL-----	2,445,000	2.500	.933
Total-----	14,055,000	1.223	.618

GEOLOGY

The Lynn Lake nickel-copper deposits, as described by Ruttan (1957), occur in two mafic intrusive bodies that intrude a series of volcanic and sedimentary rocks. All these rocks are Precambrian in age. The mafic intrusives consist predominantly of diorite and gabbro, but the most common rocks in the vicinity of the ore bodies are amphibolite, norite, and peridotite. Six of the ore bodies occur in one mafic intrusive that is 12,000 feet long and 5,000 feet wide. The seventh ore body, the high-grade EL deposit, occurs in a small circular mafic plug 1,200 feet in diameter.

ORE DEPOSITS

The nickel-copper ore bodies occur as massive sulfides, disseminated sulfides, and stockworks of sulfide stringers. Each individual ore body is mainly of one type, although combinations of two or more types may be present, depending on the physical character of the rock in which they occur. The sulfide minerals consist of, in relative order of abundance, pyrrhotite, pentlandite, chalcopyrite, and pyrite. Minor amounts of cobalt, zinc, and gold are present.

The two most important ore bodies are the high-grade EL ore body and the A ore body. The EL ore body contained a total of 2½ million tons, averaging 2.5 percent nickel and 0.93 percent copper. In the EL deposit, ore occurs as massive sulfides containing a variable quantity

of unmineralized rock fragments and as disseminated sulfides in amphibolite, norite, peridotite, and diorite, adjacent to, but separate from, the massive body. The largest single ore body, the A, contained 5 million tons averaging 1.22 percent nickel and 0.64 percent copper. The A ore body is irregular in outline, about equal in length and width, and consists mainly of disseminated sulfides in amphibolite, norite, and peridotite. Both the A and the EL ore bodies contain small variable amounts of cobalt. Four of the other five ore bodies consist of disseminated sulfides and are similar to the A ore body in the mafic host rock. The seventh ore body, the C, is primarily a stockwork of irregular sulfide stringers in a rather hard, more feldspathic variety of the mafic intrusive; these stringers follow a coarse fracture pattern.

The mafic intrusive host rocks are generally highly altered in the vicinity of the ore bodies, but ore mineralization also occurs in relatively fresh rocks. Ruttan (1957, p. 281-282) stated that the rock where the ore mineralization has occurred is generally intensely fractured and that this fact is significant in connection with the origin of the deposits: the fractured rocks were permeable and served as channels for hydrothermal ore solutions.

ORIGIN OF THE DEPOSITS

The nickel-copper deposits at Lynn Lake may be genetically related to comparatively small copper-zinc-gold deposits associated with pyrrhotite and pyrite present in the area. Several of these deposits occur in sedimentary deposits or volcanic rocks, and one occurs at the contact between granite and volcanic rocks. According to Ruttan (1957, p. 282-283), chief geologist of Sherritt Gordon Mines, Ltd., which operates the Lynn Lake mine, the nickel-copper deposits and the copper-zinc-gold deposits have a similar origin; that is, they must have been deposited by hydrothermal solutions that came from, or were genetically related to, one of two types of intrusives: either the granitic intrusives or the mafic intrusives. Ruttan thought that the ore-bearing hydrothermal solutions were more likely related to the granitic bodies. The nickel-copper-cobalt sulfides occur only in the mafic intrusives because the environment there was neutral to alkaline and the rock was therefore chemically favorable for the deposition of those metals, whereas the more acid environment of the granites and sedimentary rocks was favorable for deposition of the copper-zinc-gold minerals.

Other geologists, however, believe that the close association of the nickel-copper deposit with the mafic intrusives is due to factors more fundamental than simply a favorable chemical environment. One possibility, also considered in relation to the Sudbury deposits, is that the nickel-copper-iron sulfides formed an immiscible sulfide phase

at the time the silicate magma was crystallizing and part of this sulfide phase became segregated into separate masses, which later crystallized to form massive ore bodies, the rest remaining as droplets to form disseminated ores in the host rock.

THOMPSON-MOAK LAKE DISTRICT

The Thompson and Moak Lake nickel sulfide deposits of the International Nickel Co. of Canada, Ltd. (Inco), represent a major part of the world's sources of nickel. The rich Thompson ore body was found in 1956 and the lower grade Moak Lake deposit somewhat earlier as a result of extensive geophysical and geologic investigations by Inco. The district is about 400 miles north of Winnipeg and 200 miles southwest of Hudson Bay.

REGIONAL GEOLOGIC SETTING OF THE DEPOSITS

The nickel ores of the Thompson-Moak Lake belt occur as nickeliferous sulfides disseminated in serpentinized peridotite and as massive bodies and stringers of sulfide minerals in gneiss near serpentinized peridotite. On the basis of geologic mapping and gravity and airborne magnetometer surveys, Wilson and Brisbin (1961) hypothesized that the nickel belt lies along the axis of a Precambrian mountain range of the island-arc or alpine type and that this belt coincides with the northeast-trending boundary between the Superior and Churchill blocks of the Precambrian shield. The nickeliferous peridotite and nickel ores occur along a strip of negative gravity anomalies that coincides with a zone of strong thrust faulting and intense deformation of the ancient mountain range.

The Thompson mine and other nickel occurrences held by Inco in the nickel belt, which is roughly 85 miles long and 15 miles wide, have been described by Zurbrigg (1963). He designated nine nickel deposits and occurrences on his map (p. 453) of the belt, the principal ones being the Thompson, Moak Lake, Mystery Lake, Birchtree, and Pipe deposits. Most of the area is underlain by biotite gneiss, dark hornblende-plagioclase gneiss, or amphibolite, although the latter two types of rock are much less abundant. According to Zurbrigg (1963, p. 452), virtually all the peridotite found in the area is spatially associated with linear zones of metasediments and metavolcanics. In some localities, the metasedimentary beds appear to have been intensely deformed into isoclinal folds and domal structures or into doubly plunging folds, several of which, including the Thompson, have been mapped in the vicinity of nickel deposits.

GEOLOGY OF THE THOMPSON MINE

The major structure that controls the distribution of ore at Thompson is an anticlinal fold striking northeast and plunging steeply to the

southwest. The ore is in a schist zone which extends the length of the structure and conforms with overlying and underlying formations. According to Zurbrigg (1963, p. 452), the ore zone has an overall length of $3\frac{1}{2}$ miles and the main concentration of ore occurs along the southern part of the east limb of the fold, around the nose of the fold, and within associated minor crenulations and drags.

The rocks in the Thompson area consist of conformable gneisses, metamorphosed sediments, pegmatite, and peridotite; no evidence is apparent of an unconformity between the gneisses and the metamorphosed sediments. The oldest rock in the sequence appears to be a metamorphosed quartzite; other metamorphosed sediments are skarn, iron-formation, and the ore-bearing biotite schist. The nickel deposits are closely associated with serpentinized and sheared peridotite.

MINERALIZATION

The nickel ore consists of pyrrhotite, pentlandite, pyrite, minor chalcopyrite and marcasite, and trace amounts of nickel arsenides. The paragenetic relations indicate an early formation of the pyrite, followed by deposition of pyrrhotite and the nickel-bearing minerals. Later the marcasite was deposited in carbonate veinlets. Near the surface some of the pyrrhotite has been altered to pyrite and magnetite and some of the pentlandite to violarite and magnetite. The sulfides occur as fine-grained masses, lenses, and veinlets in the schist and as coarse-grained masses and stringers where the host rock is less schistose. Both the coarse- and fine-grained sulfide masses are termed breccia sulfide because of numerous rock inclusions (Zurbrigg, 1963, p. 459-460).

ORIGIN OF THE DEPOSITS

Zurbrigg (1963, p. 460) had the following to say about the origin of the Thompson deposit:

Although some mineral and ore-rock relationships can be accepted with little reserve, it is premature to suggest a comprehensive history of ore deposition with any assurance that it would prove to be durable. The deposit has features that could be accounted for by more than one combination of events and the combination that most logically explains the end result remains to be determined.

The genesis of the Thompson-Moak Lake deposits has been briefly considered by several other leading Canadian geologists. Michener (1957), in discussing the basic problem of the nature of the ore-forming process, apparently had the Thompson-Moak Lake deposits in mind when he described one process of ore formation as:

Sulfur leaching, a process whereby original olivine-bearing peridotites which contain nickel in the silicate form are subject to regional and thermal metamorphism, including sulfur in gaseous or liquid form, resulting in the removal of silicate nickel and its combination with sulfur to produce sulfide deposits

associated with, and disseminated in, peridotite masses. This type of deposit contains practically no copper.

Gunning (1959), in discussing the origin of massive sulfide deposits, made the following comment on Michener's statement:

I believe that Michener's suggestion of sulfur leaching of nickel-rich silicates is a good one. * * * It is to be hoped that by extensive analytical work in some of the new Manitoba deposits he may be able to prove or disprove that nickel leaching of this kind, and subsequent deposition of the sulfides to form ore bodies, actually has taken place. As far as I know no one has as yet proven any such process for this type of deposit. It is a kind of lateral secretion.

Wilson and Brisbin (1961, p. 821), in considering the origin of the Thompson-Moak Lake deposits, stated:

The origin of the ore deposits is speculative at this stage of their development. The principle of multiple hypotheses seems to be the best approach. * * * An igneous origin of the ore is an obvious possibility. Solidification of peridotite intrusions containing a high sulphur content may have resulted in low-grade disseminated ores, a sulphide liquid segregated from a peridotite liquid may have been injected into the gneiss to produce the massive and stringer ore.

* * * * *

A metamorphic origin of the ore must be considered where metamorphism is so prominent. The extensive metamorphism of siliceous iron formation in this region gives a clue to a possible origin of the nickel deposits. Much of the iron formation is metamorphosed to medium-grained banded mixtures of quartz, grunerite, and magnetite. In many places more than half of the magnetite has been converted to pyrrhotite. * * * The disseminated nickel-iron sulphides in the peridotite and the pyrrhotite in the iron formation may have a similar origin. This origin is suggested by laboratory experiments in which the presence of hydrogen sulphide will form nickeliferous pyrrhotite in peridotite and will convert magnetite to pyrrhotite in the temperature range between 400°C and 650°C at standard pressures. Such an origin might explain the presence of sulphide in the Manitoba peridotites and its absence in recent island arcs where metamorphism is lower grade.

* * * * *

Hydrothermal solutions may also be invoked as playing a part in the origin of the ore. Water must be present at some stage because the peridotites are serpentized, although the age of the serpentization has not been determined.

* * * * *

The lack of copper in all the nickel deposits of the belt is an important field fact. It appears to rule out separation of the ore by differentiation from a basaltic melt.

ORE RESERVES

Zurbrigg (1963, p. 451) stated that "At the close of 1960, with production about to begin, the ore reserves at the Thompson mine amounted to 25 million tons, containing 2.97 percent nickel-copper." The 1960 annual report of Inco stated that this reserve estimate includes only proven ores. According to statements made by Inco geologists and others, it would appear that nickel greatly predominates over copper.

The Northern Miner (Mar. 30, 1961) reported:

The Thompson ore deposit has been estimated at 25 million tons. Grade is close to 3 percent combined nickel and copper, but this is practically all nickel since the copper content is only one-fifteenth that of the nickel. That suggests an approximate grade of 2.8 percent nickel and 0.2 percent copper. * * * Cobalt is also recoverable from the Thompson ore. It occurs in smaller proportion than at Sudbury. * * * Platinum, palladium, gold and silver are also present. More information is necessary to determine the actual content, but it appears that palladium approaches the general run of the Sudbury ores, while the others are much lower.

Davies (1960, p. 103), in discussing the ore deposits and reserves at Moak Lake and Mystery Lake, stated:

The deposits at Mystery Lake and Moak Lake occur in serpentinite, and, although large, contain mainly disseminated nickel-bearing sulphides; the grades are about 0.5 and 0.75 percent nickel respectively. The sulphides in these low-grade occurrences form an integral part of the rock and appear to have crystallized along with the silicates.

The Northern Miner (Aug. 17, 1961) estimated that the Moak Lake deposit probably totals 50 million tons averaging 0.7 percent nickel.

The success of Inco in finding nickel ore bodies along the Thompson-Moak Lake nickel belt has spurred intensive exploration by other mining companies. In 1963, Falconbridge Nickel Mines, Ltd., was exploring a property at the south end of the zone prospected by Inco, near Wabowden. Earlier work on this property by another company outlined an ore body of 5 million tons containing approximately 1 percent nickel. Another group, the Nickel Belt Extension Syndicate, has a 70,000-acre concession adjoining the Falconbridge holding, which they were actively prospecting in 1963.

NEW BRUNSWICK

ST. STEPHEN

Relatively small lenses of nickel- and copper-bearing sulfides have been intermittently explored for many years at St. Stephen in southwestern New Brunswick. These deposits are associated with a differentiated gabbro-anorthosite-peridotite intrusive. The sulfides, consisting of pyrrhotite, pentlandite, and chalcopyrite, occur mainly in the gabbro as disseminations or as irregular, lens-shaped masses related, in part at least, to shear zones (McAllister, 1960, p. 50). According to McAllister, the most recent reports of St. Stephen Nickel Mines, Ltd., suggest a reserve of 350,000 tons of sulfide-bearing rock containing 0.97 percent nickel and 0.52 percent copper. In contrast, an article in the Northern Miner (Aug. 25, 1960) gives for the deposit a more conservative reserve estimate of 264,000 tons containing 0.98 percent nickel and 0.52 percent copper, a reserve inadequate to sustain a profitable mining operation.

NORTHWEST TERRITORIES

RANKIN INLET

In 1928 R. G. O. Johnston discovered a nickel sulfide deposit on the north shore of Rankin Inlet, west coast of Hudson Bay, about 900 miles north of Winnipeg. It was drilled between 1930 and 1937, and in 1951 the North Rankin Nickel Mines, Ltd., was organized to mine the deposit. Mining started in 1957 and was completed in 1962. The deposit contained 460,000 tons of nickel-copper sulfide ore containing 3.3 percent nickel, 0.8 percent copper, 0.2 percent cobalt, 0.03 ounces platinum per ton, and 0.06 ounces palladium per ton. This operation is one of the few that have been attempted in the subarctic region of Canada.

The deposit was in the basal part of a serpentinized pyroxenite sill that intrudes Proterozoic rocks of the Precambrian shield. The sill was emplaced along a contact between quartzite and younger volcanic rocks of andesitic to dacitic composition in a syncline that plunges gently to the east. The sill follows the north limb of the syncline over a strike length of about 6,000 feet; it is 200–300 feet thick and dips about 50°. Sulfide ore occurred where the basal contact of the sill makes a troughlike reentrant into the footwall. The main lens of ore had a thickness of about 8 feet of massive sulfides and 18 feet of disseminated sulfides. A second zone consisting largely of disseminated sulfides occurs above the main zone.

Pyrrhotite was the main sulfide mineral, but the ore also contained nickel-bearing pentlandite and copper-bearing chalcopyrite. Minor magnetite and pyrite were also found in the ore; violarite and marcasite were locally found near the surface as supergene alteration products. The platinum metals palladium and platinum occurred in amounts similar to those found in the Sudbury ores.

The genesis of this deposit has been debated by various geologists. Probably the most widely accepted hypothesis is that of Weber and Teal (1959), who suggested that the ore body is the result of sulfide segregation from the pyroxenite sill, the sulfide minerals settling into the troughlike depression at the base of the sill, which was later folded. Supporting this hypothesis are the textural relations of the sulfide minerals with the silicate host rock. Reportedly (Precambrian, 1961, p. 16), in the disseminated ore, some sulfide grains are enclosed in silicate crystals, and some silicate crystals are enclosed in sulfide patches; this fact suggests the coexistence of immiscible silicate and sulfide phases of the magma during consolidation. Another hypothesis is that the deposit originated in a chemically favorable pyroxenite host by deposition of copper-nickel-iron sulfides from ascending hydrothermal solutions trapped in a folded synclinal structure.

ONTARIO

ALEXO NICKEL MINE

The Alexo Nickel mine, held by Noranda Mines, Ltd., in Donald township, northeastern Ontario, developed an ore body along the contact between peridotite and pillow lavas of the Keewatin Series (Thomson and others, 1957, p. 32). The main ore shoot, 700 feet long and 3-40 feet thick, consisted of massive and disseminated pyrrhotite, pentlandite, and small amounts of chalcopyrite and pyrite; 50,800 tons mined by 1957 averaged 4.2 percent nickel and 0.5 percent copper.

KENORA DISTRICT

Numerous nickel-copper prospects are associated with mafic intrusives in the Kenora district of northwestern Ontario. Most are too small or too low in grade to be economically mined. The property of Metal Mines, Ltd., at Gordon Lake was being mined in 1963, and the Kenbridge deposit at Populus Lake is almost of minable grade.

GORDON LAKE

The Metal Mines, Ltd., deposit at Gordon Lake, 55 miles northwest of Kenora, northwestern Ontario, contains four ore bodies—A, B, F, and G—having a total reserve of about 1.1 million tons averaging 1.62 percent nickel and 0.68 percent copper, plus minor amounts of platinum metals (Canadian Mines Handbook, 1963, p. 209). The ore occurs as disseminated and massive bodies of pyrrhotite, pentlandite, and chalcopyrite in, and adjacent to, lenticular bodies of peridotite along a major east-west steeply dipping fault zone that separates gneisses on the north from massive granites on the south.

The Northern Miner (June 13, 1963) reported that concentrates produced at the mine were being shipped to the International Nickel Co. smelter. Intensive exploration has been and was being done by geophysical surveys, diamond drilling, and underground development.

POPULUS LAKE

The Kenbridge Nickel Mines, Ltd., a subsidiary of Falconbridge Nickel Mines, Ltd., has a property at Populus Lake, 43 miles southeast of Kenora in northwest Ontario. Exploration, including geological mapping, geophysical surveys, and 70,000 feet of diamond drilling, together with underground development, had outlined reserves that amounted to 794,960 tons, averaging 1.14 percent nickel and 0.53 percent copper, and 2,707,780 tons of indicated ore, containing 1.04 percent nickel and 0.54 percent copper (Northern Miner, Aug. 15, 1957).

The ore occurs as disseminated and massive pyrrhotite, chalcopyrite, pentlandite, and pyrite in flat, layered lenses, mostly small, plunging

55° NE (Thomson and others, 1957, p. 17-18). The host rock is a mafic intrusive that ranges in composition from gabbro to peridotite and intrudes greenstone. The intrusion, 2,500 feet long and 200 feet wide, occurs near a major northeast-trending fault zone.

LIMERICK TOWNSHIP

The Bicroft Uranium Mines, Ltd., has found a nickel-copper deposit in the Limerick township, 14 miles south of Bancroft, eastern Ontario (Northern Miner, Nov. 16, 1961). The deposit was discovered by geophysical survey; diamond drilling has indicated 2 million tons of ore containing 1.0 percent nickel and 0.25 percent copper. The deposit is in an l-shaped zone on the edge of a gabbro intrusion; it dips 80° NW.

RAGLAN TOWNSHIP

The Raglan Nickel Mines, Ltd., has a deposit of disseminated pyrrhotite, pentlandite, and chalcopyrite in metagabbro in Raglan township, eastern Ontario (Thomson and others, 1957, p. 8). Two small flat lenses found there are said to be low in grade.

SHEBANDOWAN LAKE

The International Nickel Co., Ltd., has thoroughly explored a nickel-copper deposit on lower Shebandowan Lake, 60 miles west of Port Arthur, western Ontario. An ore zone of approximately 1 million tons containing somewhat less than 2 percent nickel and smaller, but recoverable, amounts of copper and platinum metals has been outlined. The deposit consists of narrow lenses 800-1,600 feet long, as much as 100 feet wide, and 5-10 feet thick, of pyrrhotite, chalcopyrite, pyrite, and polydymite, both massive and disseminated, in sheared peridotite (Thomson and others, 1957, p. 51). The entire zone is under the lake, which is 140-150 feet deep.

SUDBURY DISTRICT

The largest known nickel sulfide deposits in the world are in the Sudbury district of Ontario along the outer margin of a norite-granophyre complex—the Sudbury irruptive—that rims the Sudbury basin, which is 37 miles long and 16 miles wide. Since the original discovery of sulfide ore in 1883, many geologists have studied the ore deposits, the Sudbury irruptive, and the regional geologic setting, yet considerable doubt remains as to the correct interpretation of many aspects of the overall geologic picture. Although the complex geology of the district cannot be adequately described in a paper of this scope, the present status of geologic opinion concerning this, one of the foremost mining districts in the world, is summarized in the following pages.

GENERAL GEOLOGIC SETTING

The Sudbury basin trends slightly north of east. According to mapping by Thomson (1956), the rocks outside the basin on the south are a series of steeply dipping rhyolite, andesite, and basalt flows, tuffs, and intrusives, overlain southward by graywackes, quartzites, and conglomerates. This assemblage is moderately to intensely metamorphosed. Gneissic granite covers the area north of the Sudbury irruptive for about 10 miles and is overlain to the north by north-dipping sedimentary rocks that correlate with those south of the basin (Speers, 1957, p. 498-499). According to Speers, these sedimentary rocks also crop out discontinuously east of the basin, and the basin therefore occupies the center of a large domal structure.

The Sudbury basin proper is rimmed by the irruptive complex, which is roughly 1-3 miles thick and consists of a basal norite zone and an upper granophyre (commonly called micropegmatite) zone separated by a transitional zone. The basal contact of the irruptive dips inward 35° - 50° for the most part, but locally at the southwest and northeast corners the dips are steep or even overturned. The irruptive is overlain by 3,000-5,000 feet of tuffs and welded tuffs, which, in turn, are overlain by several thousand feet of shale and sandstone. These rocks, except locally along folds and faults, dip gently to moderately inward toward the center of the basin.

The Sudbury basin is traversed from east to west, approximately parallel to its long axis, by steeply dipping faults, some of which have substantial vertical displacements. About 10 miles south of the basin is a zone of major thrust faulting toward the northwest, along the Grenville front, but it has not been determined whether this deformation has markedly affected the structure of the basin.

Some geologists who have studied the district (Coleman, 1905; Walker, 1897; Collins, 1934) believed that the unmetamorphosed rocks inside the basin are unconformable over the metamorphosed rocks outside the basin and that the irruptive was intruded as a flat sheet along the unconformity and then folded. Age determinations (Fairbairn and others, 1960) have ranged from 1.5 to 1.7 billion years for rocks both inside and outside the basin, as well as for the irruptive itself. These dates probably indicate the latest orogeny to which the rocks have been subjected and that the irruptive is probably not much younger, and thus not possibly of Keweenaw age. Thomson (1956) has indicated, on the basis of new mapping, that the tuffs and welded tuffs inside the basin correlate with similar rocks to the south outside the basin.

Thomson (1956) and Williams (1956) concurrently proposed, with supporting evidence, that the Sudbury basin is a caldera, relatively

steep-walled at depth, that formed by subsidence into a void left in an underlying magma chamber by the catastrophic eruption of more than 300 cubic miles of tuffs and welded tuffs, now both inside and outside the basin. They believed that the norite and granophyre were later intruded separately, but closely spaced in time, along ring fractures that rim the basin.

Wilson (1956) proposed that the Sudbury irruptive, like some other lopoliths, may be funnel shaped; he observed that layering in the irruptive is gentler than the footwall contact. The irruptive could have been intruded virtually in its present form as a single body of magma that crystallized and differentiated in place to develop a lower norite zone and upper granophyre separated by a mixed or transitional zone. This concept is popular with many geologists (Hawley, 1962) who have studied the district for many years. Along the margins of the irruptive and in reentrants into the footwall or in offset dikes, the rock has the composition of quartz diorite rather than norite; Hawley (1962, p. 25), quoting Collins (1934), stressed that the combined bulk composition of granophyre plus norite for the whole exposed irruptive is roughly equivalent to that of the marginal quartz diorite, which might be a chilled phase of the original magma. The ratio of granophyre to norite as exposed on the south side is 1:1 and on the north side 3:1; this amount of granophyre is too great to have been developed in place from magma comparable to the norite in composition, but it could have developed from a magma having the composition of the marginal quartz diorite. Another possibility suggested by Wilson (1956) and Hawley (1962) is that, if the intrusion is funnel shaped, there must be at depth a large body of norite and more mafic rocks from which granophyre could have differentiated.

Another unexplained feature of the district is the breccia in the rocks outside the Sudbury basin, particularly at or near the footwall of the basal norite. Speers (1957), in a recent study of the breccia, concluded that it predates the irruptive, is not tectonic, and probably formed during the explosive eruptions of tuffs and welded tuffs that resulted in the formation of a caldera (similar to the concept of Thomson, 1956, and Williams, 1956).

An impact-crater origin has been proposed by Dietz (1962) :

The Sudbury structure in Ontario, Canada, is interpreted as a 1.7-billion-year-old asteroid impact structure or "astrobleme" created by a 3×10^{26} erg event. A crater was formed 30 miles across and 3 miles deep. Although converted to sulfides, the bolide, a copper-rich nickel-iron meteorite, is still partially preserved, as marginal sheets along the crater wall and as injections into radial tension cracks. Shock brecciation and shatter coning were extensively developed. A thick collar of rock was heaved up, forming the crater wall. * * * Because of its great magnitude, the Sudbury event triggered magmatism by off-

loading the lower crust and mantle and by adding shock heat. This resulted in partial fusion of rock which was already critically hot. An *extrusive* lopolith, a saucer-shaped pool of magma, formed and differentiated in the crater bottom. The magma also laid down a thick cap of welded or Onaping tuffs.

Dietz believed that the present oval shape of the basin is due to later deformation from the south along the Grenville thrust zone.

Dietz' impact-crater hypothesis seems to have grave weaknesses. The bolide itself must have been very abnormal with such a high copper content. A mechanism by which copper, nickel, and iron metals could be splashed against the walls of the crater and there completely transformed to sulfides seems most unlikely. Dietz later proposed, in an alternative hypothesis (1964, p. 422-423), that the metals may have occurred in the meteorite as sulfides. The idea of tuffs and welded tuffs extruding from the molten norite-granophyre pool and forming a crust under which the magma slowly crystallized seems quite implausible. The impact-crater hypothesis does offer an explanation for the domal structure of the rocks surrounding the basin and having steep to overturned attitudes on the south side. But the presence of welded tuffs in the steeply dipping rocks outside the basin coeval with those inside, as is indicated by Thomson (1956) and Williams (1956), cannot be explained by Dietz' hypothesis.

The attitudes of the rocks outside the basin cannot be explained by the Williams-Thomson caldera hypothesis. Younger well-exposed calderas do not exhibit such deformation of the surrounding rocks. Northward thrusting, at a later date along the Grenville thrust south of Sudbury basin, could have developed folds such as those found in the basin, but the net effect of such deformation outside the basin should have been to flatten rather than steepen the dips of the beds.

ORE DEPOSITS

Most of the sulfide deposits are either along the footwall contact of the Sudbury irruptive in the norite or marginal quartz diorite or in the wall rocks of the irruptive. Along the south margin of the irruptive, more or less from west to east, are the Crean Hill, Gertrude, Ellen, Creighton, North Star, Clara Belle, Murray, Blezard, Sheppard, Kirkwood, and Garson mines of the International Nickel Co. of Canada, Ltd. (Inco), and the McKim, Mount Nickel, Falconbridge, and East mines of Falconbridge Nickel Mines, Ltd. On the north margin are the Levack and Big Levack mines of Inco and the Hardy, Onaping, Fecunis Lake, Strathcona, and Longvack mines of Falconbridge. The Nickel Rim and Emtwo mines are on the east margin.

Several deposits occur along dikes or so-called "offsets" of quartz diorite that occur near the margins of the main irruptive and in general extend outward from it. The largest and richest individual ore

bodies, the Frood-Stobie deposits of Inco, occur in the Frood-Stobie offset near the south rim. Also near the south rim are the Copper Cliff and Evans deposits in the Copper Cliff offset and the Arcadia deposit in the Worthington offset. Offsets near the north rim contain the Milnet and Nickel Offsets deposits.

The individual ore bodies generally are moderately dipping, elongate, lenticular, or sheetlike bodies of disseminated, massive, or breccia ore or sulfide stringer zones. Some are arranged en echelon both laterally and downdip. In general the ore bodies grade from massive sulfides at the basal contact of the irruptive upward into progressively leaner disseminated ores. Ores are also concentrated in embayments of the irruptive into the footwall, as is well shown in the Creighton and Garson embayments.

Some ore bodies coincide with steep faults along the norite contact; the Falconbridge ore body is a fine example (Lochhead, 1955). It is mineralized for 1 mile horizontally and at least 5,600 feet vertically along a vertical fault, where the fault follows the contact between norite and greenstone wall rock. At both ends the fault branches off from the contact and becomes barren, either abruptly or within a short distance.

The largest ore bodies in the district occur in the steeply dipping keel-shaped Frood-Stobie quartz diorite offset (Zurbrigg and others, 1957). This offset contains disseminated sulfides for a strike length of 2 miles, to depths ranging from 1,400 to 4,000 feet, and across widths ranging from 250 to 400 feet. More than 120 million tons of ore has been mined. Rich massive sulfide ore bodies occur at the base of the keel-shaped quartz diorite intrusive at its north and south ends. These bodies grade upward into disseminated ore. Only part of the disseminated sulfides in quartz diorite is of commercial grade.

TYPES OF ORE

The ore can be classed as massive, breccia, disseminated, or stringers. The normal mineral assemblage in all types is pyrrhotite, chalcopyrite, and pentlandite, the pyrrhotite (Fe_{1-x}S) making up 70–80 percent of the total. Chalcopyrite (CuFeS_2) is second in abundance, and pentlandite [$(\text{Fe}, \text{Ni})_9\text{S}_8$] is least abundant. Cubanite (CuFe_2S_3) is locally abundant and constitutes roughly 15 percent of the copper in the ore. Nickel is present predominantly as pentlandite, but some is present in the pyrrhotite either in its crystal lattice or as very fine disseminations.

Platinum metals, mainly platinum and palladium, are economically important minor constituents in the Sudbury ores, averaging about 0.025 ounces per ton (Allen, 1960, p. 9). Platinum occurs as sperry-

lite (PtAs_2), and palladium as michnerite (PdBi_2) and froodite (PdBi_3 or PdBi_x). Part of the platinum metals probably are disseminated in the sulfide minerals. The Frood ore body is considerably richer in platinum metals than the other deposits.

The massive sulfides range in grain size from less than 1 to 50 mm. They pass either gradually or abruptly into disseminated or breccia ores, which are quantitatively important. For example, Davidson (1946) estimated that 80 percent of the ore at Falconbridge is the breccia type. Fragments of the footwall rock below the norite intrusive are most common; norite and quartz diorite fragments are also present but usually are sparse.

Hawley (1962, p. 34) reported an unusual but significant type of ore in the Frood deposit that suggests the coexistence of immiscible sulfide and silicate liquids. This ore has a dominant sulfide matrix that contains rounded to club-shaped and some large irregular inclusions of quartz diorite. The silicate inclusions themselves contain fine droplets of sulfides, which, Hawley believed, indicate further unmixing during crystallization of the sulfide-saturated immiscible silicate ovoids.

The disseminated ore is mostly associated with the quartz diorite phase in the lower margin of the norite zone, or in the offset dikes, and it commonly passes abruptly downward into massive or breccia ore. Hawley (1962, p. 32) stated that the disseminated ore apparently is of two types: one clearly represents immiscible sulfide droplets trapped in the crystallized quartz diorite or norite, and the other was formed by sulfide impregnation of wall rocks or breccia fragments near massive ore in fractures or faults. The best examples of the disseminated ore are in the Creighton and Frood deposits.

The vein and stringer ores, according to Hawley (1962, p. 37), are chiefly massive sulfide bodies in fractures of varying widths; they often occur below or at the ends of larger disseminated bodies, parallel to their major trends or to faults within them. Chalcopyrite is commonly the predominant sulfide in the vein ore.

ORIGIN OF THE DEPOSITS

The Sudbury ore deposits are generally considered to be related to the Sudbury irruptive or its parent magma; they have been classified chiefly, as either (1) magmatic sulfides that segregated as immiscible droplets from the silicate magma and settled to the base of the intrusive, where they either crystallized in place or were injected into wall rocks, or (2) hydrothermal replacements (Hawley, 1962, p. 38). Sullivan (1954, p. 572) has suggested that the Creighton ore body, at least, may have resulted from the heat of molten granite which intruded adjacent to the irruptive and caused the migration

of nickel and copper from the norite into quartz diorite, the quartz diorite being a transitional facies produced by the assimilation of norite by the granite magma. Sullivan's theory is probably not valid because most of the granite in question is now considered to be prenorite.

Walker (1897), Barlow (1907), and Coleman (1913) concluded that the ore bodies formed by gravitative segregation of molten sulfides in place from the noritic magma. This explanation has been strongly supported by the painstaking studies of Hawley (1962) and his associates. If the explanation is valid, the magma must have been saturated with sulfur early in the process of crystallization because the sulfides must have segregated and settled early to have accumulated in such quantity in the basal chill zone of the irruptive. According to this theory, the sulfide segregations tended to collect in hollows at the base of the irruptive, and this process explains the rich deposits at Creighton and Garson. Some sulfides were injected, while still molten, into openings in the footwall that developed by tectonic or other activity. Disseminated sulfides remained trapped in the norite and quartz diorite when the rock crystallized.

Some investigators, although acknowledging a genetic relationship of the sulfide ores to the Sudbury irruptive or its parent magma at depth, believe that the ore minerals were deposited from hydrothermal solutions by replacement of the rocks in which the minerals occur. Knight (in Knight and Miller, 1917), Phemister (1926), and Yates (1948) favored such an origin. Lochhead (1955, p. 50) also seems to favor a hydrothermal origin for the Falconbridge deposit, for he concluded:

1. The ore deposit was emplaced after the arrival and partial cooling of the norite.
2. The ores reached their present position by travelling upwards from the source in an extremely mobile state.
3. Postbasin faulting along the norite-greenstone contact provided the ore channels.

ORE RESERVES

Published estimates of ore reserves in the Sudbury district are given in table 7. The data for the Inco deposits include only proven ore reported by the company; they indicate reserves sufficient for about 20 years' operation at the current rate of production. The data for the other companies include proven and indicated reserves.

TIMMINS

The Fatima Mining Co. drilled 18 holes on a property near Timmins, northern Ontario. Nickel mineralization was found in several locations, and four areas were recommended for further drilling (Northern Miner, Aug. 28, 1958).

TABLE 7.—Ore reserves in the Sudbury district

Mine	Ore (short tons)	Contained nickel (short tons)	Ni (percent)	Cu (percent)
International Nickel Co. mines ¹	274, 400, 000	4, 130, 000	1. 50	-----
Falconbridge Nickel mines: ²				
Developed ore.....	21, 096, 850	} 699, 800	{ 1. 62	0. 84
Indicated ore.....	27, 166, 150			
Total or average.....	48, 263, 000	699, 800	1. 45	. 80
Arcadia Nickel Corp.: ³ Indicated ore.....	⁴ (2, 500, 000)			
Emtwo mine ⁵	⁴ (300, 000)	⁴ (4, 000)	1. 40	. 60
Milnet mine ⁶	(?)	⁴ (2, 362)		
Nickel Offsets mine ⁶	41, 365		. 92	. 59
Nickel Rim mine ⁶	1, 924, 216	13, 800	. 72	. 28
Grand total.....	324, 600, 000	4, 844, 000	-----	-----

¹ Estimate based on International Nickel Co. of Canada, Ltd., 1962 annual report, after subtraction of Inco's estimated reserve (25,000,000 tons containing 2.97 percent Ni+Cu) at Thompson, Manitoba, when mining began there in 1961 (Zurbrigg, 1963, p. 451). The combined nickel-copper content of the ore is 8,263,000 tons; on the basis of production records over a period of years, half of this is estimated to be nickel.

² Falconbridge Nickel Mines, Ltd. 1962 annual report.
³ Thomson and others (1957, p. 84). This estimate from company annual report for 1956, to 1,000-foot level; no grades given.

⁴ Numbers in parentheses not included in total.

⁵ Thomson and others (1957, p. 88). Falconbridge 1962 annual report stated that all the ore was mined out by the end of 1962.

⁶ Thomson and others (1957, p. 94-95). Two ore bodies, which yielded a total of 4,724,427 pounds nickel and 4,861,458 pounds copper, have been mined out.

⁷ Mined out.

⁸ Thomson and others (1957, p. 96-97).

⁹ Thomson and others (1957, p. 97).

In 1965 Texmont Mines, Ltd., was exploring a nickel deposit in the Timmins area that is estimated to contain 2 million tons of material averaging 1.07 percent nickel (Northern Miner, Mar. 4, 1965).

TROUT LAKE

Pochenour Willans Gold Mines has a nickel-copper-zinc prospect at Trout Lake, 26 miles west of Red Lake in northwest Ontario. The Northern Miner (Aug. 10, 1961) reported that exploration revealed unusual nickel-copper values over good widths. The sulfides occur in serpentized sediment "butting against an iron formation." For nearly 2 miles the average width is 50 feet. Generally the values have been below ore grade, but grab samples have run as high as 6 percent nickel and many contain 1 percent nickel. The ratio of nickel to copper is 2½:1. Falconbridge Nickel Mines, Ltd., is reported to have taken an option to explore the property.

QUEBEC

BELLETERRE

According to the Northern Miner (Nov. 21, 1963), the property of Lorraine Mining Co., Ltd., controlled by McIntyre Porcupine Mines, Ltd., may become Quebec's second nickel-copper producer. Reserves, on the basis of drilling, amount to 550,000 tons averaging 2.1 percent

combined nickel-copper. It was planned to start production in late 1964 at an initial rate of 400 tons of ore per day.

LA MOTTE TOWNSHIP

Marbridge Mines, Ltd., jointly owned by Falconbridge Nickel Mines, Ltd., and Marchant Mining Co., Ltd., started mining nickel sulfide ore in March 1962 from a small deposit in La Motte township, northwestern Quebec. This deposit is the first nickel producer in Quebec. Mineralization consists of pentlandite and pyrrhotite along the margin of peridotite (Northern Miner, Dec. 19, 1963).

On December 31, 1963, ore reserves were estimated at 143,330 tons averaging 2.28 percent nickel to a depth of 900 feet; more ore was being developed at greater depth and in two then newly discovered ore shoots (Canadian Mines Handb. 1964, p. 190). The copper content of the ore is very low, about 0.10 percent. One of the newer ore shoots, located 3,000 feet away from the original main deposit, was being intensively drilled in 1964; it appeared to be of a higher grade and to be wider (Northern Miner, July 16, 1964) than the deposit being mined.

UNGAVA DISTRICT

During the summer season of 1957, several companies intensively explored the Ungava nickel belt, which extends eastward across the northern Ungava Peninsula from Cape Smith on Hudson Bay to Wakeham Bay on Hudson Strait. By the end of that season, promising results from diamond drilling were reported by Asarco Nickel Co., Ltd., a subsidiary of the American Smelting and Refining Co., and by Raglan Nickel Mines, Ltd. During the following years, exploration was intermittent. By the end of the 1962 season, Raglan Nickel Mines, Ltd., had outlined reserves totaling 8,130,000 tons containing 1.54 percent nickel and 0.78 percent copper: the large Cross Lake deposit at Cross Lake Tract, which contains 5,596,000 tons, and two smaller, higher grade bodies, the C-1 and C-2, about 2 miles east of the Cross Lake deposit, which contain a total of 2,534,000 tons (Northern Miner, May 9, 1963).

Exploration during 1963 by Raglan Nickel Mines, Ltd., increased ore reserves at the Cross Lake Tract to 10,050,000 tons averaging 1.54 percent nickel and 0.78 percent copper, or 7,982,000 tons averaging 1.70 percent nickel and 0.87 percent copper, whereas at Raglan Lake reserves totaled 356,000 tons averaging 2.74 percent nickel and 0.48 percent copper (Northern Miner, Apr. 9, 1964; Canadian Mines Handb., 1964, p. 261). Four diamond drills worked at Raglan Lake in 1964; one of these intersected 136 feet of material that averaged 2.83 percent nickel, and the estimate of Raglan Lake reserves has been

increased to 1,074,000 tons of material containing 2.62 percent nickel and 0.48 percent copper (Northern Miner, May 13, 1965).

The nickel and copper minerals are along the margins of gabbro sills (Northern Miner, Aug. 15, 1957) as pentlandite and chalcopyrite associated with pyrrhotite. The gabbro is in contact with slates at most mineralized areas, but in one area high-grade sulfide mineralization was noted in the gabbro where it is in contact with diorite. The gabbro intrusive, or intrusives, containing nickel-copper sulfides extends east along the Ungava nickel belt for a distance of at least 70 miles from the Cross Lake deposit, and a strong possibility exists that new ore bodies will be discovered as exploration continues.

YUKON

CANALASK (WHITE RIVER)

The Canalask nickel deposit is on the White River 2 miles south of the Alaska Highway and about 200 miles north of Whitehorse. The deposit consists of nickel-bearing sulfides, mainly pyrrhotite, in altered volcanic rocks near intrusive serpentized peridotite (Campbell, 1960, p. 666). In 1957 diamond drilling by the Canalask Nickel Mines., Ltd., indicated a reserve of 550,000 tons averaging 1.68 percent nickel (Northern Miner, Sept. 12, 1957).

QUILL CREEK (KLUANE LAKE)

Nickel and copper sulfides were discovered about 1952, on Quill Creek, about 9 miles from the Alaska Highway near Kluane Lake, Yukon. The deposit was explored by the Hudson Bay Mining and Smelting Co., Ltd., during the period 1952-56. The sulfide bodies consist of pyrrhotite, pentlandite, and chalcopyrite in sheared and altered chert and diorite near the contact of intrusive serpentized peridotite (Campbell, 1960, p. 666-667). The serpentized peridotite and associated gabbro contain some sulfides near the contact but not in commercial amounts. Although the size and grade of the ore body were not known, Campbell (1960, p. 663) stated that available data indicate that more sulfide mineralization is associated with the Quill Creek peridotite intrusive than with the smaller intrusive at the Canalask deposit at White River.

Campbell (1960, p. 668) suggested that the peridotite and sulfides of the Canalask and Quill Creek deposits were of comagmatic origin, but that the sulfide fractions separated from the parent magmas at depth and were later injected upward along shear zones.

NICKEL DEPOSITS OF THE UNITED STATES

Most of the nickel deposits of the United States are too small or of too low a grade for commercial exploitation. In fact, significant production has come from only one deposit, that at Nickel Mountain, Riddle, Oreg.; the deposit is a nickel silicate laterite similar to the large deposits in New Caledonia.

There are several kinds of nickel deposits in the United States. Many consist of pyrrhotite, pentlandite, and chalcopyrite associated with mafic rocks, such as gabbro, norite, or peridotite. These mafic rocks occur in southeastern Alaska, California, Connecticut, Idaho, Montana, Pennsylvania, and Washington. Several deposits of the nickel-cobalt-native silver ore type have been described by Bastin (1939). Two deposits, one in Washington and one in Nevada, have a unique mineralogy.

The U.S. deposits are described in the following pages in alphabetical order by States. Locations of the deposits are shown on figure 1.

ALASKA

BOHEMIA BASIN, YAKOBI ISLAND

There are at least six known nickel-copper sulfide deposits in southeastern Alaska; the largest is in the Bohemia Basin on Yakobi Island, approximately 80 miles west of Juneau. These deposits were studied and mapped by Reed and Dorr (1942) and later explored by diamond drilling by the U.S. Bureau of Mines in cooperation with the U.S. Geological Survey (Kennedy and Walton, 1946). The nickel and copper sulfides occur as disseminations of pentlandite and chalcopyrite associated with pyrrhotite in the basal part of a basin-shaped intrusive of norite that overlies amphibole schist and gabbro. These low-grade disseminated sulfide ore bodies are believed to have formed by the settling of immiscible droplets of sulfides into the lower part of the norite body during its crystallization.

The estimated tonnages of submarginal resources are summarized from the report of Kennedy and Walton (1946, p. 50-56). The East and West Tripod deposits are estimated to contain 4,400,000 tons of measured and indicated material averaging 0.38 percent nickel and 0.19 percent copper. The Tunnel deposit is estimated to contain 5,900,000 tons of measured and indicated material averaging 0.37 percent nickel and 0.2 percent copper. The Takanis deposit has an estimated inferred tonnage of 2,400,000 tons averaging 0.31 percent nickel and the Muskeg and Side Hill deposits, 8,100,000 tons averaging 0.27 percent nickel. The total estimated submarginal resources of the Yakobi Island deposits are 10,300,000 tons of measured and indicated

material averaging 0.37 percent nickel and 10,500,000 tons of inferred material averaging 0.28 percent nickel.

BRADY GLACIER

The Brady Glacier deposit is about 25 miles north of Yakobi Island and 85 miles west of Juneau. It is held by the Fremont Mining Co. and consists of nickel-bearing gabbro and peridotite, parts of which crop out in nunataks that rise above the Brady Glacier. Sulfide minerals in the deposit include pyrrhotite, pentlandite, and chalcopyrite. Samples collected from the nunataks contained more than 1 percent nickel and about 0.5 percent copper. For several years prior to 1962, the deposit was explored by diamond drilling through the glacier, which is as much as 800 feet thick. The gabbro and peridotite underlying the glacier are said to form a flat trough-shaped body as much as 1,500 feet thick, and the drilling was intended to explore lower parts of the trough where sulfides might be concentrated. The exploration did not disclose mineralized bodies of sufficient size and grade to be of commercial interest. This mafic body is a salient of the much larger Mount Crillon layered gabbro massif that extends to the northwest along the Pacific Coast.

FUNTER BAY, ADMIRALTY ISLAND

A nickel-copper sulfide deposit near the north end of Admiralty Island, about 18 miles west of Juneau, was found and first mapped in 1919 by John Mertie of the U.S. Geological Survey. It was later mapped and described by Reed (1942), who described the sulfide mineralization as occurring in a mafic sill that averages 100 feet in thickness and dips steeply eastward. He estimated that the deposit contains 560,000 tons of material averaging roughly 0.3 percent nickel and 0.35 percent copper. In the 1950's, exploration was supported by assistance from DMEA (Defense Minerals Exploration Administration); a second adit was driven and quite a number of diamond-drill holes were sunk. This exploration revealed that the mafic intrusive is pipelike in form and consists of both gabbro and norite containing disseminated and massive pyrrhotite, chalcopyrite, and pentlandite. The pipe plunges approximately 30° E. along a contact between quartz-sericite schist and overlying graphitic phyllite. It has a maximum diameter of 60–200 feet and has been explored for 900 feet downdip.

The mafic pipe, as described by Fred Barker (written commun., 1956), contains sulfide-rich norite and gabbro in its lower part, whereas the middle and upper parts of the pipe are sulfide-poor gabbro. In the sulfide-rich norite-gabbro, pyrrhotite, pentlandite, and chalcopy-

rite are disseminated through the rock and also form massive pods a few inches to several feet thick. The norite-gabbro is dark gray, fine to medium grained, and hypidiomorphic; it consists of olivine, hypersthene, augite, hornblende, plagioclase, sulfides, and minor magnetite, biotite, chlorite, sericite, serpentine, anthophyllite, talc, and calcite. Most of the olivine is fresh; the plagioclase is labradorite and has been partly sericitized. The sulfides embay the silicates, and no alteration is found at contacts. A typical specimen was found to contain 33 percent sulfides (mostly pyrrhotite), 27 percent olivine, 20 percent plagioclase, 10 percent hornblende, and minor amounts of the remaining minerals.

The sulfide-poor gabbro making up the main bulk of the pipe is light to dark green, medium grained, and hypidiomorphic. A typical specimen contains 55 percent plagioclase, 30 percent augite, 5 percent hornblende, 4 percent magnetite-ilmenite, 3 percent biotite, 2 percent chlorite, and 1 percent sulfides. The plagioclase ranges from labradorite (An_{54}) to andesine (An_{38}).

The sulfides probably segregated as immiscible droplets from the mafic magma of the pipe as it crystallized and settled downward together with other heavier constituents, mainly olivine, to form concentrations in the lower part. The sulfide-rich part of the pipe is estimated, as a result of the exploration under DMEA contract, to contain a small to moderate tonnage of material averaging 1 percent nickel and 1 percent copper.

MIRROR HARBOR, FLEMING ISLAND

Several nickel-copper deposits on Fleming, Chichagof, and Baranof Islands, immediately southeast of Yakobi Island have been described by Pecora (1942) and by Kennedy and Walton (1946). All the deposits, except the one at Mirror Harbor on Fleming Island, are either too low in grade or too small to be considered as potential commercial deposits. All the nickel-bearing deposits occur in norite. The deposit at Mirror Harbor is characterized by small podlike masses of sulfides consisting of pyrrhotite, chalcopyrite, and pentlandite. The largest pod seen measures 4 by 4 by 8 inches. The sulfide minerals are commonly coarse grained, and they enclose crystals of pyroxene and plagioclase. The individual pods contain an average of 3 percent nickel and 2 percent copper, whereas the enclosing norite usually contains less than 0.10 percent sparsely disseminated nickel. The deposit has outcrop dimensions of 30 by 40 feet, and it plunges about 75° SE. It has been explored by a shaft reported to be 180 feet deep and by five diamond-drill holes sunk by the U.S. Bureau of Mines. The deposit is estimated to contain 8,000 tons of material averaging 1.54 percent nickel and 0.7 percent copper.

SNIPE BAY, BARANOF ISLAND

A low-grade nickel-copper deposit at Snipe Bay on the southern tip of Baranof Island that has been described by Reed and Gates (1942) is similar to other nickel-bearing sulfide deposits farther north on Chicagof, Fleming, and Yakobi Islands. The mineralization consists of disseminations and small masses of pyrrhotite, chalcopyrite, and pentlandite in an amphibole-bearing norite or gabbro. Pyroxene of the intrusive host rock has been altered to amphibole, and the calcic plagioclase to albite or albite-oligoclase. Because of poor exposures and limited development, Reed and Gates (1942) estimated an inferred tonnage of only 430,000 tons of material containing 0.3 percent nickel and 0.3 percent copper.

SPIRIT MOUNTAIN, COPPER RIVER AREA

A small nickel-copper deposit was discovered about 1907 in the Copper River region, about 15 miles southeast of Chitina. During World War II the deposit was studied and mapped by Kingston and Miller (1945). It occurs in two small, highly altered ultramafic masses, intrusive into Mississippian metamorphic rocks that crop out on the glacier-steepened wall of Canyon Creek Valley. Primary peridotite has been completely altered to antigorite, tremolite, hornblende, and talc. Mineralized parts of the deposit consist of disseminations and massive pods of pyrrhotite, chalcopyrite, and bravoite. The bravoite was first identified by Buddington (1924). The deposit also contains small amounts of pyrite and pentlandite. Small veins of sphalerite cut the other earlier sulfide minerals. The pods of massive sulfides occur near the base of the larger of the two intrusives. Kingston and Miller (1945, p. 55) considered the deposit to be of magmatic origin. They believed that liquid sulfides segregated from the silicate-magma during its crystallization. Part of the liquid sulfide droplets settled by gravity to form massive sulfide in the lower part of the intrusive, and part remained disseminated through the intrusive. The inferred tonnage of the deposit is 6,500 tons averaging 0.7 percent nickel and 0.5 percent copper.

ARKANSAS**SALINE COUNTY**

Sterling and Stone (1961) have described nickel occurrences in soapstone deposits in Saline County, Ark. An irregular serpentinite intrusion in Ordovician shales has marginal lenticular bodies of talc and soapstone. The soapstone and associated serpentinite contain small erratic concentrations of nickel. Some of the nickel is in seams and disseminations of pyrrhotite or pyrite, but most of the nickel concen-

trations are probably due to secondary enrichment during weathering of the serpentinite and soapstone. Nickel values in the enriched rock range from about 0.5 to 3.0 percent. One selected sample of nickeliferous manganese oxide assayed 15.0 percent nickel. The nickel occurrences are too small and spotty to be of commercial importance.

CALIFORNIA

JULIAN

A small nickel-copper sulfide deposit, known as the Friday mine, is located 3 miles south of Julian, San Diego County, Calif. The sulfide deposit is associated with a sizable gabbro-peridotite intrusive complex and occurs in gabbro at the margin of a peridotite body. The gabbro and peridotite have been uralitized in the area where the deposit occurs. The mineralized zone in the Friday mine is an irregular body that strikes N. 75° E. and dips steeply northward. It has a strike length of 35–55 feet and is wedge-shaped in vertical section, decreasing in width from 25 feet on the 132-foot level to 8 feet on the 180-foot level.

The sulfides occur as disseminations and in small massive bodies and have been identified as pyrrhotite, pentlandite, violarite, pyrite, and chalcopyrite. Pyrrhotite is the most abundant mineral and occurs as large crystals poikilitically enclosing the other minerals. Sulfides in the mine workings have been oxidized down to the 132-foot level but are relatively fresh below that to the lowest workings at the 180-foot level.

Creasey (1946, p. 25) believed that the deposit was formed by replacement of the gabbro along fractures. He reported evidence of moderate hydrothermal activity and apparently believed that the sulfides were deposited from solution. He did not, however, consider them to be typical hydrothermal solutions, because of the absence of substantial hydrothermal alteration and of typical hydrothermal gangue minerals. Creasey stated that the solutions apparently were high in sulfides and comparatively low in water, but he did not state whether he considered them to have been derived by segregation during the crystallization of the mafic and ultramafic rocks or introduced from an unknown source at depth.

Creasey (1946) estimated that the rich part of the deposit, totaling 5,000 tons, probably averages about 2.5 percent nickel and 0.75 percent copper. He estimated an inferred reserve of 100,000 tons averaging 1.5 percent nickel and 0.75 percent copper.

OLD IRONSIDES

The Old Ironsides deposit is in San Diego County 49 miles northeast of San Diego and 17 miles northwest of the Julian deposit. This nickel-copper deposit occurs near the middle of a small gabbro intrusive that is probably related to the mafic rocks at the Julian deposit. The gabbro, which is intruded into a larger quartz diorite body, is dark greenish gray and coarse grained; it consists of plagioclase, hornblende, olivine, and a little pyrite and pyrrhotite. The sulfide deposit is overlain by a gossan that covers 25,000 square feet. Oxidation is complete to a depth of 60 feet; below that, primary pyrrhotite, pentlandite, and chalcopyrite occur as disseminations in the gabbro.

The deposit probably formed by the segregation of sulfides from the gabbro during its crystallization. In 1954 the deposit was explored under a DMEA contract by two diamond-drill holes, each 300 feet deep. A small tonnage of material averaging 0.35 percent nickel and 0.7 percent copper is inferred to be present in the deposit to a depth of 100 feet.

COLORADO**BOULDER COUNTY**

An unusual type of nickel deposit, described by Goddard and Lovering (1942), occurs at the Copper King mine near Gold Hill, 32 miles northwest of Denver, Colo. The deposit occurs in a lenticular body of amphibolite that appears in places to grade downward into hornblende-quartz gabbro. These rocks are surrounded by Precambrian schists and granitic intrusives. The amphibolite and gabbro, as well as the deposit itself, are Precambrian in age. The deposit consists of disseminated intergrowths of pyrite, pyrrhotite, chalcopyrite, and polydymite. Small amounts of several other nickel minerals have been identified, namely bravoite, violarite, niccolite, pentlandite, and possibly millerite. Polydymite seems to be the chief primary nickel mineral; the other nickel minerals, except for pentlandite, appear to be of supergene origin. The upper part of the deposit is partly to completely oxidized, and the chief constituents are garnierite, chrysocolla, and serpentine.

The sulfides occur in the coarser grained facies of the amphibolite in layers commonly 5–20 feet in maximum thickness, but locally as much as 50 feet thick. The sulfide minerals are irregularly disseminated or form a network and replace various silicate minerals of the amphibolite.

The mineralized zones are irregular and discontinuous. They have been cut by dikes and veinlets of pegmatite, gabbro, aplite, and diabase. The deposit contains an estimated 21,600 tons of indicated material

containing 3.0 percent nickel and 50,000 tons of inferred material containing 0.5 percent nickel. Cobaltite (CoAsS) is also present in the deposit; analyzed samples contain from 0 to 0.6 percent cobalt. Small percentages of copper are present in the unoxidized ore. Samples of the oxidized ore, which has a small volume, contain 1.3–13.0 percent nickel, 0.2–6.2 percent cobalt, and 0.05–31.6 percent copper.

CONNECTICUT

MOUNT PROSPECT

Mount Prospect, Litchfield County, northwestern Connecticut, is underlain by a Precambrian or early Paleozoic intrusive complex made up of olivine norite, quartz norite, and hypersthene pyroxenite. These rocks, covering an area of 12 square miles, contain six small deposits of pyrrhotite, pentlandite, chalcopyrite, and minor pyrite. The deposits have been worked intermittently since 1835 but are too small and too low a grade to be commercially exploitable.

Cameron (1943) believed that the sulfides, though genetically related to the mafic rocks, were introduced by hydrothermal emanations from a deeper seated parent magma. Others who have studied the deposits believed that the sulfides were derived from the rocks in which they occur and were crystallized during a late deuteritic stage. Small amounts of supergene marcasite and violarite or bravoite formed by the action of circulating ground water on the primary sulfides.

HODGES

The Hodges nickel prospect near Torrington, Litchfield County, and 17 miles northeast of Mount Prospect, is similar to the deposits at Mount Prospect. A small peridotite intrusive, 140 feet long and 5–20 feet wide as exposed on the surface, contains disseminations, small masses, and veinlets of pyrrhotite, pentlandite, and chalcopyrite. Four shallow diamond-drill holes across the peridotite showed 15 feet in one hole that contains 1.31 percent nickel and 1.24 percent copper, and 15 feet in another that contains 0.77 percent nickel and 0.82 percent copper; two holes were barren.

IDAHO

MONTGOMERY

The Montgomery deposit consists of disseminated sulfides in one of the mafic sills of the Purcell Basalt in Boundary County, Idaho (Kiilsgaard, 1951). The sill, 250 feet thick and composed of hypersthene gabbro and uralitized diorite, contains disseminations of pyrrhotite and minor pentlandite and chalcopyrite in its lower 80 feet. The deposit quite clearly resulted from the separation of sulfide drop-

lets during crystallization of the magma and their subsequent differential settling to the lower part of the sill. The amount of sulfide-bearing rock is large, but the tenor of nickel and copper is too low to be of economic interest.

MAINE

KNOX COUNTY

Nickeliferous pyrrhotite in peridotite, known as the Crawford Pond nickel deposit, occurs at East Union, Knox County, Maine. This deposit was first described by Bastin (1908) as a small outcrop of the peridotite, mostly covered by drift, which contains 60 percent olivine, 22 percent pyrrhotite, 1 percent chalcopyrite, and small to moderate amounts of hornblende, andesine-labradorite, magnetite, biotite, spinel, and pyrite. A sample assayed 0.94 percent nickel sulfide. The constituents are intergrown in a manner that indicates simultaneous crystallization; the sulfides corrode the silicates. The deposit was considered by Bastin as a convincing example of a sulfide body that segregated from a molten magma.

The Crawford Pond deposit has been thoroughly explored geophysically and by diamond drilling by Roland F. Beers, Inc., under contract with the DMEA (Beers and others, 1962). Petrographic studies by these investigators indicate that the peridotite is biotite lherzolite (olivine plus orthopyroxene and clinopyroxene) associated with biotite gabbro and biotite-hornblende diorite.

DMEA exploration, completed in 1960, indicated that the Crawford Pond deposit contains a moderate tonnage of material averaging 0.596 percent nickel, 0.282 percent copper, and 0.096 percent cobalt.

MINNESOTA

ELY

A nickel-copper deposit was discovered in 1948 near the base of the Duluth Gabbro in Lake County, 10 miles southeast of Ely, Minn. (Schwartz and Davidson, 1952). The Duluth Gabbro Complex, a huge lopolithic stratiform intrusive, extends for 150 miles northeast from Duluth and has a maximum thickness of 50,000 feet. Gabbro, anorthosite, and granophyre are the main rock types in this highly differentiated layered pluton, but peridotite and norite layers are present in the lower part.

Chalcopyrite, cubanite, pyrrhotite, pentlandite, and bornite are disseminated in layers and lenses in medium- to coarse-grained gabbro for 5 miles along the base of the lopolith where it is thickest southeast of Ely. The base of the lopolith dips 20°-25° SE. in the mineralized area. Layers of gabbro and gabbroic anorthosite dip more or less

parallel to the basal contact. The sulfide lenses appear to be elongate parallel to the layering. Samples from a 188-foot diamond-drill hole at the discovery site averaged 0.36 percent copper and 0.13 percent nickel in its upper 104 feet. Samples of sulfide-bearing gabbro and gabbroic anorthosite at seven points along the strike in the 5-mile zone contained 0.32–1.12 percent copper and 0.07–0.38 percent nickel.

The sulfides are interstitial to the silicates olivine, pyroxene (augite and hypersthene), and plagioclase that make up the rock and also occur as fine blebs in the pyroxene and plagioclase. Schwartz and Davidson (1952, p. 702) believed that the sulfides are primary constituents of the gabbro and concluded: "Strong evidence of the syngenetic origin of the sulphides and the considerable length over which they occur also indicate that there is an excellent geological probability of finding a commercial deposit."

Other mineralized bodies near the base of the Duluth Gabbro have been explored northeast of the area described above. Two large deposits, totaling several hundred million tons of material, are reported to average 0.75 percent copper and 0.25 percent nickel.

MISSOURI

FREDERICKTOWN

Complex lead-zinc-copper-nickel-cobalt deposits occur at Fredericktown, Madison County, in the southeastern Missouri lead district. The majority of the ore bodies in this district contain mainly lead and only minor amounts of zinc, copper, nickel, and cobalt, but some deposits or parts of deposits contain significant amounts of copper, nickel, and cobalt.

In the area around Fredericktown, Precambrian granite and rhyolite porphyry crop out as peaks and ridges protruding through Upper Cambrian sedimentary rocks that have been deposited unconformably around them. Geological and geophysical data indicate that the unconformity above the Precambrian basement represents an erosional surface of high relief, including numerous hills that are completely covered by the Cambrian rocks. The oldest Cambrian unit, the Lamotte Sandstone, occupies depressions in the erosion surface and pinches out against peaks and ridges of the Precambrian basement. The overlying Bonneterre Dolomite consists of interbedded sandstone, shale, and dolomite at the base, a lower member of dark-gray dolomite, and an upper member of light-gray dolomite. Several other Upper Cambrian dolomite formations, containing some shaly, silty, and sandy units, complete the sequence of rocks in this area. The Bonneterre Dolomite and younger formations also pinch out against the higher Precambrian peaks and ridges, and everywhere there is a basal conglomerate immediately above the unconformity.

The regional dip of the Cambrian rocks is gently eastward, but locally these rocks dip peripherally away from the Precambrian peaks, probably because of differential compaction of the sedimentary rocks.

The ore deposits occur as disseminated replacements of galena, sphalerite, siegenite, chalcopyrite, and marcasite in the lower part of the Bonneterre Dolomite and locally in the top of the Lamotte Sandstone. The distribution of the ore minerals between ore bodies, and even within individual bodies, is erratic. A crude vertical zoning is apparent in some ore bodies, significant amounts of copper, nickel, and cobalt minerals being concentrated in the lower parts, and in some bodies the combined metal content and quantity of each metal also varies markedly within short lateral distances.

Quite a few deposits, including those with significant amounts of copper, nickel, and cobalt minerals, occur where the Lamotte Sandstone pinches out against the Precambrian peaks. These deposits are sinuous lenses, 0-40 feet thick, 50-250 feet wide, several hundred feet long, and comparatively flat at depths of 250-400 feet below the surface.

The deposits that contain mostly galena and sphalerite have been and are being mined at a profit, but attempts to recover copper, nickel, and cobalt from deposits with significant amounts of these metals—that is, those with chalcopyrite and siegenite—have failed because of metallurgical problems in separating the metals. Published data (U.S. Bur. Mines, 1952) indicate that measured and indicated marginal resources of material rich in copper, nickel, and cobalt amount to nearly 2 million tons containing 2.3 percent lead, 1.4 percent copper, 0.46 percent nickel, and 0.28 percent cobalt. Inferred marginal resources are probably several times larger than the measured and indicated estimate.

MONTANA

MOUAT

The Stillwater Complex—a Precambrian stratiform intrusion, 18,000 feet thick, of layered peridotite overlain by norite and anorthosite—extends 30 miles along the Beartooth Plateau in Stillwater County. Extensive stratiform deposits of chromite occur at several horizons in the peridotite zone. Copper, nickel, and iron sulfides occur at quite a few places in metamorphic rocks immediately below the Stillwater Complex but are sparse within it. The occurrences are small except for the Mount nickel deposit near the Stillwater River. This deposit, described by A. L. Howland (written commun., 1943-44), was explored by the Anaconda Co. in 1937 and by the U.S. Geological Survey and the U.S. Bureau of Mines in 1940-41. Nineteen holes

were drilled for a total length of 12,500 feet; prior to these explorations 1,700 feet of tunnels had been driven.

The deposit probably contains several million tons, possibly more, of mineralized rock that averages 0.4 percent nickel and 0.35 percent copper. Pyrrhotite, pentlandite, and chalcopyrite occur as pods, lenses, and sill-like bodies, both disseminated and massive, in fine-grained norite sills and adjacent hornfels. The norite sills dip 30°–40° W., parallel to the base of the main igneous complex, to which they are genetically related. The mineralized area is roughly 1,200 feet in diameter. Individual masses and disseminated bodies measure as much as 100 by 30 feet on exposed surfaces and are grouped together in many places to make larger irregular bodies that are more or less parallel to the norite sills. Sulfides are most abundant in the hornfels, which is a banded, metamorphosed fine granular rock composed of cordierite, quartz, biotite, and hypersthene.

Pyrrhotite is the most abundant sulfide. The distribution of pentlandite and chalcopyrite associated with the pyrrhotite is so erratic that the nickel and copper contents of sulfide-bearing rock cannot be estimated by inspection. The highest values obtained in many 5-foot sample were 1.07 percent nickel and 0.83 percent copper; the highest for any greater length of core were 0.81 percent nickel and 0.60 percent copper for a length of 55 feet.

NEVADA

BUNKERVILLE DISTRICT

The Great Eastern and Key West nickel deposits are in the Virgin Mountains in the Bunkerville or Copper King district, southeastern Clark County, Nev. The district has been described by Needham and others (1950) as the result of an exploration program carried out by the U.S. Bureau of Mines during the period 1939–41. More recently the district was explored under a DMEA contract, but the results of this exploration have not been published. The sulfide-bearing material in the great eastern deposit averages 0.3 percent nickel. No significant tonnage has been discovered in the Key West deposit.

The deposits consist of pyrrhotite, pyrite, chalcopyrite, pentlandite, violarite, and possibly polydymite. These sulfides occur as disseminations, pods, and lenticular masses in two dikes of hornblendite and peridotite that intrude Precambrian granitic gneisses. The dikes strike about N. 70° E. and are nearly vertical. The deposits were first described by Bancroft (1910). At that time, interest was centered on the occurrence of minor amounts of platinum in the sulfides. Lincoln (1923, p. 18) described the deposits and gave the following assay of a carload of ore from the Key West deposits: 2.30 percent

copper, 1.79 percent nickel, 0.08 percent cobalt, 0.13 ounces per ton platinum, and traces of gold and silver. Lindgren and Davy (1924) described the mineralogy of the deposits in some detail, as did Budington (1924). They were interested particularly in the mineral violarite, which was first identified at that time, and in its origin. The sulfide minerals are in part interstitial to the silicates in the mafic dikes, and the deposits probably are late magmatic differentiates altered by hydrothermal solutions.

COTTONWOOD CANYON

Small but unusual nickel and cobalt sulfide and arsenide deposits occur in Cottonwood Canyon at the north end of the Stillwater Range, Churchill County, Nev. According to Lincoln (1923, p. 11-12), the nickel and cobalt deposits of Cottonwood Canyon were discovered by George Lovelock and Charles Bell about 1882. The Nickel mine was worked until 1890, reopened in 1904, and again closed in 1908. A second mine, the Lovelock mine, shipped 500 tons of high-grade nickel-cobalt ore to England in the early days. The deposits have been studied more recently by Ferguson (1939), who described the nickel and nickel-cobalt ores in the two mines as small discontinuous stringers that cut the rocks immediately adjacent to an intrusive diorite. The host rocks for the ores are highly altered and probably are andesitic volcanics and aplitic dikes. At the Nickel mine the nickel minerals are oxidized to annabergite $[\text{Ni}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}]$, morenosite $(\text{NiSO}_4 \cdot 7\text{H}_2\text{O})$, and possibly garnierite (Ni, Mg hydro-silicate), according to Ferguson (1939, p. 13). Niccolite (NiAs) was also identified in the ore. At the Lovelock mine, the metallic minerals recognized were tetrahedrite $[(\text{Cu}, \text{Fe})_{12}\text{Sb}_4\text{S}_{13}]$, erythrite $(\text{Co}_3\text{As}_2\text{O}_8 \cdot 8\text{H}_2\text{O})$, and azurite $[\text{Cu}(\text{OH})_2 \cdot 2\text{CuCO}_3]$, and possibly a mixture of annabergite and brochantite $(4\text{CuO} \cdot \text{SO}_3 \cdot 3\text{H}_2\text{O})$.

Ferguson (1939) stated:

In the Nickel mine the principal stopes are along a flat fissure with a dip of about 20 degrees to the southwest. This has been followed along the strike for about 100 feet and stoped over about one-half this distance. Probably this stringer yielded a relatively large amount of nickel, in spite of its small length, for the sample taken from a four-inch vein of green material left at the end of the stope assayed 23.3 percent nickel. Nearby in the same tunnel a stringer with a northerly trend and a westerly dip of 60 to 70 degrees has been followed for about 80 feet, has been stoped for about 30 feet.

The workings of the Lovelock mine were inaccessible at the time of Ferguson's visit.

Ferguson (1939, p. 19-21) believed that the nickel and cobalt deposits of Cottonwood Canyon are related to nearby gold and titanium deposits and to the intrusive body of diorite, and that in the final

stage of mineralization by magmatic solutions, sulfides and arsenides of nickel, cobalt, and copper were introduced along small fissures in the already altered country rock:

At the Nickel mine, at least, this was not a simple process, for the sulfide millerite appears to have been first formed, followed by its almost complete replacement by the arsenide niccolite. The paragenesis of the even more complex ores of the Lovelock mine is unknown, nor can any explanation be offered as to why only nickel minerals are found at the Nickel mine, whereas the similar fissures of the nearby Lovelock mine contain a greater variety of metals.

GIBELLINI DEPOSIT

A very unusual deposit of manganese oxides, containing large amounts of nickel, zinc, and vanadium, occurs about 30 miles south of Eureka in Eureka County, Nev. This deposit was diamond drilled by the U.S. Bureau of Mines in 1946 (Binyon, 1948), and later was explored under a DMEA contract. The manganese oxides occur in limestone of Devonian age, adjacent to vanadiferous shale. They occur in several small bodies near the surface, which in cross section are more or less funnel-shaped. According to Binyon (1948, p. 8), the principal minerals are the manganese oxides psilomelane and pyrolusite, which contain substantial amounts of nickel and zinc and lesser amounts of vanadium; no other metallic minerals have been identified. An analysis of representative material (Binyon, 1948, p. 8) contains 18.5 percent manganese, 3.0 percent iron, 1.7 percent nickel, 0.3 percent cobalt, 3.2 percent zinc, 0.12 percent copper, 0.11 percent molybdenum, 0.88 percent vanadium oxide, 3.7 percent barium, 2.3 percent calcium oxide, 0.2 percent sulfur, and 6.0 percent alumina.

The origin of these deposits is puzzling, but the shape of the ore bodies and the presence of elements suggestive of a hydrothermal origin (D. F. Hewett, oral commun., 1963) indicate that the metallic minerals may have been deposited in a hydrothermal hot spring.

NORTH CAROLINA

WEBSTER

Near Webster, Jackson County, N.C., nickeliferous laterites, formed from the weathering of relatively fresh dunite, have been studied and explored by geologists and engineers for many years (Pawel, 1939, 1943; Ross and others, 1928; Worthington, 1964). The dunite occurs as an elliptical dike that has intruded gneisses and schists. The laterites, which are small and discontinuous, are the silicate variety; nickel occurs as garnierite both in the lateritic soil and in the underlying weathered dunite. The nickel content ranges from 0.5 to 1.9 percent according to published analyses of the residual soil and the weathered dunite. Pawel (1943, p. 278) estimated that the laterites

contain 1 million tons of material averaging 1 percent nickel. One deposit, the Nickel Plant Tract, was explored in 1951-52 by the Olivine Products Corp. under a DMEA contract.

OREGON AND CALIFORNIA

NICKELIFEROUS LATERITES

Nickel-bearing ferruginous laterites that overlie ultramafic rocks have been described by Hotz (1964) at localities in southwestern Oregon and northwestern California. Most of the deposits have been derived from fresh peridotite, but at least one deposit was formed over serpentinite. The laterites occur on flat-lying to gently sloping erosion surfaces, including broad plateaulike summits, saddles, and terraces. The highest concordant erosion surfaces form the mountain tops and represent the oldest peneplains, probably middle Tertiary in age. The surfaces on the flanks of the mountains and on lower terraces of the mountains are, for the most part, younger erosion surfaces, but at a few places the terraces represent older, higher erosion surfaces that have been downfaulted by gravitational slumping.

The principal nickeliferous laterite deposit is at Nickel Mountain near Riddle, Douglas County, Oreg. This laterite, a nickel silicate laterite containing garnierite, has been mined by the M. A. Hanna Co. since 1954. Production capacity there was increased in 1964 from 22 to 28 million pounds of nickel per year. Nickeliferous laterite deposits large enough to be explored commercially also occur at Eight Dollar Mountain, Woodcock Mountain, and Josephine Creek near Cave Junction, Oreg.; at Red Flats, east of Gold Beach, Oreg.; at Pine Flat Mountain, Gasquet, and Little Rattlesnake Mountain, Del Norte County, Calif.; at Trinity Alps, north of Weaverville, Calif.; and at Dunsmuir, Siskiyou County, and Little Red Mountain, Mendocino County, Calif.

The laterite at Nickel Mountain near Riddle, Oreg., is estimated to total 16.2 million tons of nickel silicate ore that contains 1.5 percent nickel (F. M. Chace, written commun., August 1965). Production records for the first 10 years of operation, plus consideration of present capacity and minimal requirements for profitable exploitation of a metal deposit, indicate that the deposit is large enough to support a production rate of 24 million pounds of nickel per year for a minimum of 30 years. Several other deposits, including Eight Dollar Mountain, Woodcock Mountain, Red Flats, Pine Flat Mountain, and Little Red Mountain, are estimated to contain a total of nearly 50 million tons of lateritic material (table 5), but the nickel content in all these deposits is less than 1 percent.

All the deposits, except the Red Flats, are weathering mantles that overlie relatively fresh peridotite, which is mainly saxonite (olivine plus enstatite) but includes some dunite (all olivine). The Red Flats laterite overlies serpentinite. The Nickel Mountain laterite contains garnierite and is thus the nickel silicate type, similar to the rich New Caledonian laterites. The other laterites, like the nickeliferous iron laterites of Cuba and the Philippines, contain little or no garnierite and more iron.

The nickeliferous laterite deposits of California and Oregon are, in general, similar lithologically. A typical lateritic profile from top to bottom, according to Hotz (1964, p. 367), consists of: (1) reddish-brown soil containing varying amounts of iron oxide pellets; (2) yellowish-orange soil, with or without fragments of soft, decomposed peridotite; (3) yellowish-brown saprolite (intensely weathered peridotite); (4) weathered peridotite; and (5) fresh peridotite (bedrock). The lateritic soil commonly contains blocks and boulders of peridotite having thin weathered crusts and hard fresh cores.

The lateritic soils have been studied by Hotz (1964, p. 368-375), both by microscopic and X-ray diffractometer techniques. The soils contain a mixture of residual minerals from the disintegration of the peridotite by weathering and secondary minerals formed by recombination of some constituents released during weathering. The residual minerals of weathered peridotite are enstatite, olivine, chromite, and serpentine. Iron oxides, which lend a yellow, brown, or reddish tone to the laterite, are most prominent among the secondary minerals that formed in the weathering zone. The iron oxides are mostly amorphous hydrates that can be classed as limonite, but X-ray patterns also indicate goethite and maghemite. The soft soillike laterite commonly contains shotlike granules of iron oxides, which have been identified as maghemite and lesser amounts of goethite.

Veinlets of microcrystalline quartz-garnierite also have formed in fractures and joints of the weathered peridotite immediately beneath the lateritic soil zone. The lateritic soils contain microcrystalline quartz fragments which probably were derived from the veinlets as weathering became progressively lower in the profile.

X-ray diffraction patterns of clay fractions of the laterite samples studied by Hotz (1964, p. 369-371) indicated the presence of montmorillonite, chlorite, and talc. The laterite samples contained as much as 1.8 percent nickel and 0.11 percent cobalt, but no specific minerals of these elements were identified in the clay fractions. Garnierite, the hydrous silicate of nickel, has been identified only in veinlets where it is associated with quartz in boxwork in weathered and fresh peridotite, and as residual veinlets in the soil. Possibly the

nickel occurs as a substitute for magnesium in the montmorillonite, talc, and chlorite of the clay fraction.

Nickel has also been found in significant amounts in serpentine minerals and goethite. Montoya and Baur (1963, p. 1228-1230) reported that lizardite, the major serpentine mineral in laterites of northern California and New Caledonia, contains 2.0 and 4.3 percent NiO, respectively. Fisher and Dressel (1959, p. 2), in a study of the Nicaro, Cuba, lateritic ores, concluded that most of the nickel appears to be in the lattices of serpentine minerals and goethite. Cobalt, like nickel, may also substitute in the clay minerals to a limited extent, but more probably it is associated with manganese; although no manganese minerals are recognized by Hotz, X-ray analyses indicate its presence.

Chemical changes during weathering of the peridotite have been described by Hotz (1964, p. 366-381) and are well illustrated by analyses of the peridotite and overlying laterite at Nickel Mountain, Oreg. The most significant changes during weathering from peridotite to laterite are the leaching of MgO from 45.7 percent to a minimum of 2.1 percent and of SiO₂ from 42.8 percent to 26.2 percent. The other most significant changes are the enrichment of the residual laterite in Fe₂O₃ from 0.8 percent (plus 6.8 percent FeO) in the peridotite to a maximum of 46.8 percent (plus 0.29 percent FeO) in the laterite; in Al₂O₃ from 1.1 percent in the peridotite to 8.4 percent in the laterite; and in nickel from 0.28 percent in the peridotite to a maximum of 1.8 percent in the laterite. Cobalt has increased from 0.01 percent to 0.06 percent. Similar changes are indicated by Hotz' analyses of peridotite and laterite at Eight Dollar Mountain, Oreg., but there the leaching of SiO₂ was more complete, from 43.0 percent in the peridotite to a minimum of 15.6 percent in the laterite, and the enrichment in iron was greater, a maximum of 56.1 percent in the laterite. Nickel enrichment was from 0.29 percent in the peridotite to a maximum of 1.7 percent in the laterite.

NICKEL MOUNTAIN

The laterite that mantles Nickel Mountain near Riddle, Oreg., contains the largest known reserve of nickel ore in the United States and the only one that was being mined in 1964. The laterite occurs in two areas: the largest area covers the top of the mountain and is the one that has been mined; a second deposit, considerably smaller, occurs on a bench on the southeastern slope of the mountain. Both deposits overlie fresh peridotite and have a well-developed quartz-garnierite boxwork zone. These deposits, as described by Pecora, Hobbs, and Murata (1949) and by Hotz (1964), are commonly from 5 to 30 feet thick, but the larger deposit has a maximum thickness of approxi-

mately 220 feet along a shear zone in the underlying peridotite, which has been more deeply weathered. According to Hotz, they have, like other laterite deposits, a superficial layer of reddish-brown soil at the top, 2-3 feet thick, which contains pellets of brown iron oxide and, locally, fragments of microcrystalline quartz. Below the surficial layer of red soil is a zone of yellowish-orange soil, which contains a ramifying network of residual quartz-garnierite veinlets, plus box-work. This zone, which is commonly 5-10 feet thick, is the main nickel-bearing layer of the laterite. It grades downward into a thinner zone of altered peridotite that also contains abundant nickel but is thinner than the overlying yellowish-orange soil zone. The weathered peridotite in turn grades downward into fresh peridotite. The laterite at Nickel Mountain, like laterite elsewhere, has a highly irregular lower surface; pinnacles of unweathered peridotite project up into the lateritic soil, and the soil contains blocks and boulders of fresh to partly weathered peridotite. In places these peridotite inclusions are abundant; elsewhere they are sparse.

PENNSYLVANIA

GAP NICKEL MINE

The Gap Nickel mine, Lancaster County, Pa., was discovered in 1718, and unsuccessful attempts were made intermittently to mine copper from the mineralized rock. In 1852 a Cornish miner discovered that pyrrhotite, thrown on the dumps as worthless, contained more than 1 percent nickel. From 1853 to 1893, when the mine closed because of competition from richer and larger deposits in Canada and New Caledonia, the Gap mine was the principal nickel producer in North America having a total production of about 5 million pounds. In 1876 the Gap Nickel mine's output of 200,000 pounds represented one-sixth that of the world. The grade of the ore, as mined, ranged from 1 to 3 percent nickel and 0.4 to 0.9 percent copper. Exploration in 1942 indicated a moderate tonnage of material containing 0.7 percent nickel and 0.4 percent copper. The deposit and its history have been described by Kemp (1895), Knopf and Jonas (1929), and Moyd (1942).

The Gap deposit consists of lenses of massive sulfides surrounded by zones of disseminated sulfides near the base of a trough-shaped intrusion of norite or gabbro, 2,000 feet long and as much as 800 feet wide, that has been metamorphosed to amphibolite. Pyrrhotite and closely associated pentlandite are the most abundant sulfides, but chalcopyrite and pyrite are present in lesser amounts.

The origin of the Gap nickel-copper sulfide deposit has been debated by the authors given above, and also by others. The most favored

theory is that the sulfides segregated as immiscible liquid from the mafic magma during its crystallization and settled to the base of the intrusion. Tectonic activity probably caused the sulfides to be moderately remobilized before they completely crystallized. This theory of origin is strongly supported by the most recent investigation, that of Moyd (1942).

WASHINGTON

BLEWETT DEPOSIT

The Blewett nickeliferous iron deposit is in Chelan County, Wash., about 80 miles east of Seattle, Wash., and 25 miles east of the Cle Elum iron deposit. This deposit, near the crest of a steep ridge at altitudes ranging from 2,900 to 3,700 feet, has been described by Broughton (1943, 1944), Lupher (1944), and Lamey (1950). It was explored by diamond drilling by the U.S. Bureau of Mines during 1943-44 and was mapped by Lamey in 1943. The iron deposit is considered to be an eastward extension of the same iron formation that occurs at Cle Elum, and is an iron-rich conglomerate, which, like that at Cle Elum, overlies serpentine and underlies the Swauk Formation. It is of Tertiary age, probably Eocene.

The deposit consists of a peridotite conglomerate composed of sub-angular to well-rounded pebbles, cobbles, and boulders of serpentinitized peridotite embedded in a ferruginous and serpentinuous matrix, plus scattered iron-rich lenses of finer nonconglomeratic material. The fine-grained lenses and matrix of the conglomerate consist of particles of magnetite, hematite, and serpentine plus spinel and chromite. The fine-grained iron-rich lenses resemble the matrix but are finer grained and contain much more magnetite and hematite. The principal iron-rich lens in the explored area is about 450 feet long, 35 feet wide, and extends downward for 450 feet. The iron-nickel deposit and other rocks of the area are locally cut by younger diabase dikes.

Lamey (1950) believed that the Blewett iron-nickel deposit resulted from residual weathering of the underlying serpentinite, as in the Cle Elum deposit, 25 miles to the west. At the Blewett deposit, however, there must have been more relief to cause the development of conglomerate on the erosion surface.

Lamey (1950) estimated resources of the Blewett iron-nickel deposit at 3,540,000 tons of measured and indicated material averaging 0.47 percent nickel and 10,230,000 tons of inferred material averaging 0.47 percent nickel. The principal iron-rich lens has an average composition of 32.65 percent iron, 0.90 percent nickel, and 1.66 percent chromium. The matrix of the conglomerate, on the other hand, has an average content of 18.11 percent iron, 0.52 percent nickel, and 0.88 percent chromium. The entire conglomerate, including all iron-rich

lenses, averages 13.34 percent iron, 0.47 percent nickel, and 0.64 percent chromium. The average silica content of several composite samples of the entire conglomerate is 34.4 percent.

CLE ELUM

Nickeliferous iron deposits in Kittitas County, Wash., about 60 miles east of Seattle, are exposed along the valley of the Cle Elum River at altitudes ranging from 2,700 to 3,500 feet. The deposits form an iron-rich stratigraphic unit overlying serpentinized peridotite and underlying terrestrial sandstone and conglomerate, the Swauk Formation of Eocene age. These units have been folded into an asymmetric anticline which plunges to the southwest. The iron deposits occur mainly on the west flank of the anticline, and their average dip is 32°. The principal investigations of these deposits since 1906 have been made by geologists of the Northern Pacific Railway. Other investigations have been carried on by the Washington Geological Survey (Broughton, 1944; Luper, 1944). In 1943 and 1944 the U.S. Bureau of Mines explored the deposits by 57 vertical diamond-drill holes totaling 11,205 feet in length. The following description is based mainly on a report of Lamey and Hotz (1951), of the U.S. Geological Survey.

According to Lamey and Hotz (1951), the nickeliferous iron formation occurs as a discontinuous bed overlying the serpentine. The main body of iron formation is on the west flank of the anticlinal structure described above. In the area of drilling, the average thickness of the iron formation is 15 feet, although it ranges from 0 to 48 feet. The nickeliferous iron deposits are composed of fine-grained magnetite and hydrous aluminum oxides plus inclusions of serpentine. Magnetite is the most abundant mineral; chrome-spinel [(Fe, Mg) (Al, Cr)₂O₄], cliachite [Al₂O₂·(H₂O)₂] and diaspore (Al₂O₃·H₂O) are also abundant. Hematite is scarce, as are boehmite (Al₂O₃·H₂O) and gibbsite [Al(OH)₃]. The iron formation is divisible, from the base upward, into the following units: (1) laminated, (2) massive, (3) pebbly, and (4) concretionary.

The laminated unit is distinctly schistose; some of it is contorted, and it is composed chiefly of magnetite, cliachite, serpentine, and chrome-spinel. Reddish hematite appears to be present, but it is not abundant when examined microscopically. The massive unit is also schistose and also is predominantly magnetite. The pebbly unit contains irregular to rounded pebbles or grains of cliachite and a combination of cliachite and diaspore. The concretionary unit consists of many closely spaced concretions, 1-2 mm in diameter, of magnetite and of a mixture of magnetite, cliachite, and diaspore. Despite the fact that the iron deposits contain 0.8 to more than 1 percent nickel,

no nickel-bearing mineral was recognized by Lamey and Hotz, except for small amounts of secondary millerite (NiS) found in fracture fillings of a few drill cores.

The average chemical composition of the nickeliferous iron deposits includes 40.86 percent iron, 0.84 percent nickel, and 1.64 percent chromium. The average alumina content, based on incomplete data, probably is near 25 percent. Nickel and chromium vary directly and alumina and silica inversely with the iron content of the deposits. Iron, nickel, and chromium increase from the top to the bottom of the iron formation, whereas alumina and silica decrease. The serpentine immediately below the iron formation contains an average of 0.6 percent nickel ranging from a trace to 1.9 percent.

The resources of the iron deposits in the area drilled, as calculated by Lamey and Hotz (1951, p. 60), amount to about 6,000,000 tons. Classification data are given in table 8.

TABLE 8.—*Nickel-iron resources at Cle Elum, Wash.*

Class of material	Short tons	Average composition (percent)		
		Iron (Fe)	Nickel (Ni)	Cr ₂ O ₃
Measured.....	3,200,000	40.75	0.82	2.39
Indicated.....	650,000	42.12	.91	2.47
Inferred.....	2,400,000	41.01	.86	2.41
Total.....	6,250,000	40.86	.84	2.40

The Cle Elum deposits resemble, chemically and in other characteristics, the nickeliferous iron laterites that overlie large areas of serpentine in Cuba, the Philippines, and Indonesia. Lamey and Hotz (1951, p. 53-59) favored the hypothesis that the Cle Elum deposits are indeed lateritic mantles that were later covered by terrestrial sediments, deformed, and moderately metamorphosed. The pebbly nature of a part of the deposits indicates that they may have been reworked and removed somewhat from the original site of formation, but because the pebbly unit is not widespread, the amount of reworking was probably small.

In the typical laterite deposits such as those of Cuba and the Philippines, the iron occurs as limonite, goethite, and hematite, but in the Cle Elum deposits, metamorphism has reconstituted the iron oxides to magnetite. The alumina has probably been altered, in part, from bauxite and gibbsite to diaspore and cliachite.

JUMBO MOUNTAIN

Pyrrhotite and pentlandite containing minor chalcopyrite have been found as disseminations in three dunite dikes on Jumbo Mountain in

the rugged Cascade Range, Snohomish County, Wash. (Mills, 1960). Concentrations of nickeliferous sulfides occur along the sheared margins of two of the dunite dikes. Assays run as high as 3 percent nickel, but apparently no sizable bodies have been found.

The dunite, largely unaltered but locally serpentized, intrudes quartzite and argillite. Gabbro and quartz diorite intrusions occur in the same area, but apparently they are not genetically related to the dunite, which is older. Despite the fact that the nickeliferous sulfides occur in the dunite dikes both as disseminations and as concentrations along sheared walls, Mills favored the younger gabbro body as the source of the mineralizing solutions.

MACKINAW

The Mackinaw mine is in a glacial valley in Snohomish County, Wash., 40 miles east of Everett. The deposit was discovered in 1900 and has been worked intermittently since then, particularly during World War II, by the Utility Mining Co. of Everett, Wash. The property was examined in 1943 by the U.S. Bureau of Mines and also by J. J. Collins and S. C. Creasey of the U.S. Geological Survey (written commun., 1944). The U.S. Bureau of Mines report (written commun., 1944) stated:

The ore deposits are in a peridotite dike or intrusive that appears to be an apophysis of the large intrusive of reddish-brown peridotite that comprises the mountain that rises southeast of the ore deposits.

The peridotite is interspersed with small blebs and seams of serpentine, actinolite, and tremolite. At several places in the mass, small deposits of sulfide, which contain copper and nickel minerals, were observed.

The peridotite, in which the principal ore deposits occur, is a dense, dark-colored fine-grained rock that has been partly serpentized.

Collins and Creasey stated:

The sulfide minerals occur as disseminated grains and blebs in the serpentine and may total as much as 20 percent of the rock in some spots. No concentration of sulfide minerals was noted on the numerous fractures in the serpentine, but the supergene oxide minerals, on the other hand, are concentrated on fault and fracture surfaces. The commonest of these minerals are probably malachite and garnierite, or annabergite, but erythrite is also much in evidence.

They estimated (written commun., 1944) that the deposit contains a small tonnage of measured and indicated material containing 0.9 percent nickel, 1.7 percent copper, and 0.14 ounces gold.

The mineralogy of the Mackinaw mine deposit has been studied in detail by Charles Milton and D. F. Milton (1958), who stated:

The Mackinaw mine ore is of an unusual or unique type consisting chiefly of niccolite, maucherite, pentlandite, chalcopyrite, cubanite, and magnetite in an altered peridotite. Vallerite, gold, and sphalerite are minor primary minerals; chalcocite and violarite or bravoite are supergene minerals. Pyrrhotite and

pyrite are absent. From the textural relations it is inferred that a complex copper-nickel-iron sulfide was deposited early. On cooling, the sulfide unmixed into two different complex sulfides, one of which in turn unmixed into chalcopyrite and cubanite, the other into chalcopyrite and pentlandite. The latter exsolution relationship has not been previously reported. Vallerite either exsolved from, or replaced, chalcopyrite. Late solutions altered the niccolite to maucherite and introduced gold and magnetite. The gold is almost always with maucherite.

The occurrence of pentlandite without accompanying pyrrhotite is unusual, if not unique, among nickel-sulfide ore deposits. Milton and Milton (1958, p. 436) believed that this unusual mineral assemblage resulted from exceptionally high Ni:Fe and Cu:Fe ratios in the Mackinaw ore-forming solutions, that is, that there was not sufficient iron present to form the iron sulfide pyrrhotite, and that it was all combined with nickel and copper. Another mineralogical feature discovered by the Miltons is that gold in this deposit occurs in considerable quantity in cracks or openings in maucherite, rarely in niccolite and cubanite. The niccolite was altered to maucherite at a late stage, and they believed that the gold was introduced at this time and is thus closely associated with the maucherite.

WINESAP

The Winesap nickel deposit is 1 mile northwest of Winesap and 12 miles southeast of Chelan, Chelan County, Wash. The deposit consists of disseminated pyrrhotite, chalcopyrite, and pentlandite in a low-dipping lenticular body of peridotite intrusive into granite gneiss. Oxidation of these minerals near the surface has produced soluble sulfates rich in copper and nickel. The primary sulfides are unevenly distributed through the peridotite, which is considerably altered.

The Winesap nickel deposit was discovered in 1898 and was explored intermittently for many years. Most of the present underground workings, consisting of four adits and a small shaft, were driven about 1942. In 1944 the U.S. Bureau of Mines explored the deposit by drilling seven diamond-drill holes for a total length of 1,016 feet. P. J. Shenon and S. C. Creasey, of the U.S. Geological Survey, mapped and studied the deposit. This drilling and sampling of the adits outlined a small tonnage of mineralized material, part of which contains 1.00-1.70 percent nickel and 0.50-0.70 percent copper, and part contains 0.90-1.23 percent nickel and 0.15-0.40 percent copper.

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