Genetic Study of Some Pyrrhotite Deposits of Maine and New Brunswick

by

Robert S. Houston

Bulletin
Maine Geological Survey
Joseph M. Trefethen, State Geologist

Dept. of Development of Industry and Commerce
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ILLUSTRATIONS

PLATE 1

Sketch showing oval shaped ring of hills underlain by the resistant hornfels which surrounds the Onawa granite. The view is a perspective looking southwesterly from the Katahdin pyrrhotite deposit. The bare areas in the left foreground are part of the mineralized area and places where sulfate waters from the deposit have killed the vegetation. Piscataquis County, Maine.

GENETIC STUDY OF SOME PYRRHOTITE DEPOSITS OF MAINE AND NEW BRUNSWICK

by

ROBERT STROUD HOUSTON

ABSTRACT

This report describes the major pyrrhotite deposits of Maine and New Brunswick and includes a compilation of field and laboratory evidence which might aid in establishing magmatic or hydrothermal origin for the ore.

Four of the more important deposits, Union, Black Narrows, Drew Hill, and Katahdin, are in Maine and two others, Rodgers and Hall-Carroll, are in New Brunswick. With the exception of Drew Hill, a hydrothermal replacement in marble, all these deposits are in mafic igneous rocks. The Union and Black Narrows deposits are in peridotite and the Katahdin, Rodgers, and Hall-Carroll are in norite.

The deposits in mafic rocks are, in general, irregular mineralized zones, but at Rodgers and Hall-Carroll the mineralization is controlled by northeast trending fractures. Mineralized felsic dikes and mineralized inclusions of country rock are present at Katahdin and St. Stephen. The Rodgers and Hall-Carroll mines are surrounded by alteration halos, but the other deposits have no more hydrous minerals than are present in unmineralized portions of the host rocks.

Pyrrhotite is by far the dominant constituent of all deposits, and pentlandite and chalcopyrite are the most common accessory sulphides. The only significant variation in mineralization in the deposits in mafic rocks is that the content of pentlandite is higher in the ores which occur in peridotite. The sulphides are found as globular masses, in veinlets, and in interstitial masses between

orthotectic silicates. The dominant texture at Katahdin, Union, and Black Narrows is the interstitial sulphide type, but at Rodgers and Hall-Carroll replacement textures are common. Actually replacement textures can be found in all deposits, but a comparison of the textures with those in slag indicate that replacement textures are present in both slag and ore.

Hydrous minerals, except biotite and hornblende, follow the mineralization in all deposits except at St. Stephen where the sulphide mineralization is last. Cobalt, nickel, and chromite are common trace elements in pyrrhotite from the deposits in mafic igneous rocks, but are not common in known hydrothermal deposits.

An evaluation of genetic evidence suggests that much of it may be interpreted as favoring either hydrothermal or magmatic origin for the ores, but it is the writer's opinion that the occurrence of the ores in mafic rocks would indicate that such rocks were the parent source of the mineralizing solution. A possible theory to account for the varying characteristics of the deposits might be that the ores formed as immiscible segregates from the original magma, and that they segregated early or late depending on the original sulphur content of the magma. A high sulphur concentration would imply an early segregation and a sulphide phase with low volatile and high nickel content, whereas a low sulphur concentration would mean a late segregation of sulphides and therefore a sulphide phase, rich in volatiles and low in nickel, which might resemble a hydrothermal solution.

INTRODUCTION

SCOPE AND OBJECT OF REPORT

The purpose of this work was to make a field and laboratory study of all known pyrrhotite deposits in Maine and New Brunswick, in order to determine the genesis of each, to compare it with that of other similar deposits, and to develop a general hypothesis that might account for all the deposits and relate them to each other. For comparison, the nearby deposits in parts of New Brunswick were included. Field work was confined chiefly to pyrrhotite deposits associated with mafic rocks, but a serious effort was made to compare these deposits with deposits of other types. Special efforts were made to determine the relationship of the mineralization to dikes and other features of the ore bodies, which might aid in deciding whether the deposits are of magmatic or hydrothermal origin. Petrographic and polished section studies were made with the particular object in mind of evaluating the significance of the evidence gained from such studies.

ACKNOWLEDGMENTS

The writer is especially indebted to Messrs. Forbes Wilson and John Bowenkamp of the Freeport Sulphur Company who were particularly helpful and cooperative during the progress of the work. Prof. R. J. Holmes of Columbia University was in charge of the general exploration program in the area covered. His assistance and guidance in the field were of invaluable aid to the writer. Part of the field work was done with the aid of Mr. Oscar Strongin and Mr. Noel Ravneberg. Mr. C. S. Clements and Dr. G. S. McKenzie of the New Brunswick Department of Lands and Mines gave freely of their time and assistance during the work in New Brunswick. Mr. Karl Turekian made the spectrographic analyses and aided the writer in their interpretation. Prof. C. H. Behre, Jr., who gave his advice and assistance

throughout the program and who read and criticized the manuscript was the principal sponsor of the work. Prof. Arie Poldervaart of Columbia University also read and criticized the manuscript, and gave the writer much valuable advice during the latter part of the work. The sketch of the Katahdin Iron Works and the drafting were done by Miss Shirley Harbison. The writer is also grateful to numerous citizens of Maine and New Brunswick who showed a southerner that the hospitality of the north is at least equal to that of the south.

FIELD AND LABORATORY STUDY

The field work was done in the summers of 1951 and 1952. A total of seven months was spent in the field, part of the time in assisting in an exploration program for new sulphide deposits and the rest in mapping mafic igneous bodies and adjoining rocks, as well as the associated ore deposits. Most of the mapping was done either by Brunton compass and pacing or by plane table methods. Of the numerous deposits examined, the following five were selected for detailed study: Katahdin Iron Works, Union, Black Narrows, Drew Hill, all in Maine, and the ore bodies at St. Stephen in New Brunswick. A total of 267 thin sections and 97 polished sections was prepared from samples of the ore and associated igneous rocks. The polished section and petrographic studies were made at Columbia University during the winter of 1952 and 1953.

REGIONAL GEOGRAPHY

TOPOGRAPHY

The major topographic feature of Maine is the older Appalachian Mountain belt. This group of subdued mountains covers the greater part of southern and southwestern Maine. The mountains are poorly defined groups. Isolated monadnocks occur on the eastern fringe of the highland. Mt. Katahdin in north central Maine is a classic example.

The Piedmont Province to the north and east of the Highlands consists of rolling hills with some extensive plains such as the Aroostook plain in northeastern Maine and southeastern New Brunswick.

This whole region has been described by Atwood (1940, pp. 65-101) as an unwarped peneplain surface which has been elevated to its greatest heights in western New England.

Three of the pyrrhotite deposits—Katahdin Iron Works, Drew Hill, and Black Narrows—occur along the border of the highlands between the Piedmont and the Older Appalachian Mountain belt. The other deposits at St. Stephen, N. B., and Union, Maine, are in the Piedmont Province near the Atlantic Coast (Plate 16).

CLIMATE AND VEGETATION

Both Maine and New Brunswick are regions of abundant precipitation in which the summers are mild and warm but the winters are often severe and marked by considerable snowfall.

The forests are extensive, particularly in northern and western Maine. They are, for the most part, second growth and much of the area is covered by newly cut-over second-growth forest. In eastern and southern Maine and southeastern New Brunswick

where farming is more widespread much of the land is cleared but even here large areas of woodland still exist and there are very few patches of earth not covered by some timber or shrubs.

TRANSPORTATION AND INDUSTRY

Maine has 847,226 inhabitants and an area of 33,215 square miles. The population chiefly lives near the coast and is engaged in industries of various types, notably textiles and fishing. In the western and northern parts of the state much of the population is dependent on the pulpwood industry, at present the chief economic enterprise in the state. Farming is carried on throughout the state. The most important farming district is in Aroostook County where a large part of the nation's potato crop is produced.

The eastern and southern sections of Maine and the adjacent coastal part of New Brunswick are covered by adequate road and rail systems and much of the northwestern and western section is accessible because of an extensive system of private logging roads which for the most part are passable. Large areas still remain, however, accessible only by foot or airplane.

GLACIATION

All of Maine and New Brunswick were covered by continental ice sheets during the Pleistocene epoch. Glaciation has therefore left a distinct mark on the topographic features of the area here described. Much of the surface, particularly in the northern and central part of the area, is covered by glacial drift. The mountains contain a considerable thickness of glacial drift, as well as cirques, steep walled valleys, and bald rocky domes.

In the area studied outcrops are usually confined to hilltops, stream beds, and lake shores. In the Katahdin district, particularly near White Cap Mountain, bedrock exposures are very scarce. It is common to walk half a day without seeing a single outcrop definitely in place.

The Piedmont is also covered with drift but here the mantle is not so thick and outcrops are seen in many places on low hilltops

or in plowed fields. Among the most prominent glacial features here are the eskers, long continuous ridges as much as 20 miles in length. These generally trend north-south, corresponding to the direction of glacial movement.

REGIONAL GEOLOGY

STRATIGRAPHY AND GEOLOGIC HISTORY

Maine and southeastern New Brunswick are underlain principally by Lower Paleozoic sediments and volcanics. The entire province is within the Atlantic eugeosynclinal or Magog belt of Kay (1947, pp. 1289-1293).

Some of the metamorphic rocks along the Maine coast and in the southwestern part of the state have been classed as Pre-Cambrian (Smith, Bastin, and Brown, 1907, Keith, 1933), but it is possible that much outlined as Pre-Cambrian on Keith's map is actually metamorphosed Paleozoic (Knopf, 1944).

The Cambro-Ordovician stratigraphy is very little understood. A north-east trending belt of shales and sandstones in the south-central part of Maine and small areas along the coast have been classed as Cambro-Ordovician but the divisions were based chiefly on lithology (Keith, 1933, Smith, 1907, and Bastin, 1908). The Silurian and Devonian stratigraphy has been studied in more detail and the areas of deposition appear to contrast considerably in lithology. In northwestern Maine the area from Chesuncook Lake southwest to Jim Pond is a broad northeast trending asymmetrical synclinorium of Silurian and Devonian sediments. The rocks are chiefly slates and sandstones with interbedded tuffs and flows (Boucot, Arthur, personal communication, 1952). Northeast of this synclinorium, in Aroostook County, Maine, another area of Silurian and Devonian sediments occurs which contains a great series of limestones and extensive but low grade manganese-bearing shales. In the Eastport area 17,000 feet of Silurian shales with interbedded volcanic rocks are unconformably overlain by Devonian continental conglomerates (Bastin and Williams, 1914). As pointed out by King (1951, p. 97), much of the contrast in the lithology of the Silurian and Devonian may be due to the crustal mobility caused by the Taconian and Acadian orogenies and the resulting complexities of sedimentation.

Evidence of post-Devonian sedimentation has not been found in Maine, but to the northeast in New Brunswick and to the southwest in Massachusetts troughs developed in which a great thickness of late Paleozoic sediments accumulated. It is doubtful if this region was a homogeneous mobile belt even in Silurian and Devonian times, but whatever its earlier history, it is clear that in late Paleozoic time it had changed into a heterogeneous mobile belt and it seems probable that the greater part of Maine was a positive belt during that time.

Downdropped areas containing continental Triassic sediments are known to the southwest in Connecticut and to the northeast in Nova Scotia but none are present within the area studied. Direct evidence of the later geologic history of this area is not present but it is probable that it comprised stages of peneplanation and uplift as did the southeastern Appalachian Mountain and Piedmont belts.

STRUCTURE AND METAMORPHISM

The only major structural feature of Maine that has been definitely established is the Moose River Synclinorium. This asymmetrical synclinorium may extend across the entire northwestern border of the state (Keith, 1933). Like most of the structural features of the rocks in this area the synclinorium trends in a northeasterly direction. Hurley and Thompson (1950, p. 838) have postulated a major thrust fault on the eastern flank of this synclinorium.

According to McKenzie (1952, pp. 3-4) the Cambrian and Ordovician rocks in New Brunswick are more highly metamorphosed than the Silurian and Devonian. This may also be true in Maine but the increase in metamorphic rank of the rocks is a regional as well as a time feature. In northeastern Maine near Presque Isle the Silurian rocks are folded into broad open synclines and anticlines but farther south the intensity of deformation and metamorphism in the same formations shows a marked increase. At Houlton the Silurian is isoclinally folded and complexly faulted and the shales have been raised to a higher metamorphic rank than at Presque Isle (Miller, 1947). There is also

a general increase in metamorphic rank in southwestern and southeastern Maine, where the rocks have been converted into high rank gneisses and schists and are cut by numerous granite pegmatites. Keith has classed most of these higher rank metamorphic rocks as pre-Cambrian, but the stratigraphy is not well enough known to be certain that they are not instead lower Paleozoic.

In general, it can be said that considerable variation in the structure and the degree of metamorphism characterize the rocks of this area but the complexity of structure and rank of metamorphism both increase towards the southwest.

INTRUSIVE IGNEOUS ROCKS

Distribution and Age

Igneous intrusions are exposed over large areas in Maine but very little detailed work has been done on them. The exact outline of most of the intrusions is not known but they are generally concordant with the regional structure. Some reach batholithic proportions. The granitic pluton part of which forms the floor of Mt. Katahdin in central Maine is approximately 45 miles long and 20 miles wide.

Most of these intrusions are believed to be earlier than Upper Devonian and later than Upper Silurian in age (Bastin and Williams, 1914), but a highly altered granite near the southwestern end of the Moose River synclinorium is overlain unconformably by Silurian sediments (Arthur Boucot, personal communication, 1952). This granite may correspond to the Highlandcroft series of New Hampshire (Billings, 1945) and could be related to the Taconic orogeny, but there are no data on the age of the rocks it intrudes. The later granite series may correspond to the Oliverian and New Hampshire magma series of New Hampshire (Billings, 1945) and are probably related to the Acadian orogeny.

Lithology

The intrusions vary considerably in lithology. In the Columbia Falls region Terzaghi (1946) has mapped an area of intrusive

rocks which include an older granite series, probably intrusive into Silurian rocks, and a younger intrusive series which contains diorite-gabbro granodiorite, quartz-diorite and granite in order of decreasing age. The igneous pluton south of Calais, Maine, has similar lithologic variations. Some of the smaller granitic intrusions, such as the Onawa pluton (Philbrick, 1936), Penobscot Bay pluton (Smith, Bastin, and Brown, 1908) and the Drew Hill pluton, have mafic borders, varying in composition from quartz diorite to norite. Both Smith and Philbrick attribute these variations to magmatic differentiation but it seems probable that part of the compositional variations may be due to interaction with adjacent sediments. At Drew Hill, for example, the granite becomes syenitic in composition where it is in contact with limestones and the border zone near slate contacts is a norite or quartz diorite.

Contact Metamorphism

Many of the smaller instrusive bodies have contact aureoles surrounding them, particularly where they are in contact with slates. This seems to be a distinctive feature of the younger granite intrusions. The first description of one of these aureoles was made by Philbrick (1936) who described the contact aureole around the Onawa pluton near Brownville Junction, Maine. This contact aureole grades from the intrusion outward through injection hornfels, hornfels, andalusite schist and slate. Similar aureoles surround granitic intrusions at Drew Hill, Jackman, Greenville, Pierce Pond, and Skowhegan, Maine, and it is probable that the Katahdin batholith has also extensively altered the surrounding country rocks (Philbrick, 1940). One of the most striking aspects of these aureoles is their resistance to erosion. Commonly, the contact aureoles stand out as a resistant ring of hills around the level plutons (Plate 1).

Mafic and Ultramafic Rocks

In this area aside from the mafic rocks which are probably phases of the granitic intrusions, a number of ultramafic and mafic plutons occur which are apparently separate intrusions. Lenticular serpentized ultramafic intrusions (some containing

asbestos) are known in northwestern Maine, but the most important group of mafic rocks, as far as this discussion is concerned, are mineralized peridotite and norite bodies which occur in central Maine and along the coast of Maine and southeastern New Brunswick. As far as the writer could determine these mineralized intrusions are not connected with the larger granitic bodies. They are all near the granite plutons but where the granite comes against the mafic rocks the contact is clearly intrusive and the granite is later.

If there was once some connection between these rocks and the granite it must have been in a magmatic chamber at depth.

The distribution of the mineralized mafic rocks is shown in plate 16. No structural localization is indicated. The ages of the mafic rocks are not as well known as those of the granitic plutons. Both the Katahdin and the Black Narrows mafic intrusions cut Silurian sediments and the Union peridotite is intrusive into metasediments classed as Cambrian (?) (Bastin, 1908, p. 9) but there is no indication of an upper age limit. According to McKenzie the St. Stephen mafic complex is intrusive into rocks classed as "pre-Silurian." McKenzie assumes that the mafic complex is related to other igneous rocks in the area which are overlain by Devonian rocks and are believed "to have originated during a major period of igneous invasion accompanying the Acadian disturbance."

PYRRHOTITE DEPOSITS

The following chapters are devoted to presentation and evaluation of evidence bearing on the origin of the pyrrhotite deposits. The major purpose of the discussion is to determine whether the evidence is sufficient to classify the pyrrhotite deposits occurring in mafic rocks as hydrothermal or magmatic in origin.

For details of previous work and development of the deposits the reader is referred to the chapters at the end of the paper. There each deposit is discussed fully, but a brief description of each deposit associated with mafic rocks is given in the following paragraphs for a better understanding of the chapters that follow. It will be noted that the Drew Hill deposit is not included in the genetic discussion since it is clearly a hydrothermal replacement in marble.

BRIEF DESCRIPTION OF DEPOSITS

Katahdin Deposit

The Katahdin deposit, the largest metallic mineral deposit in Maine, is in the center of the state near the town of Brownville Junction (Plate 16). A roughly rectangular mineralized zone approximately 400 feet wide and 2,000 feet long, it is composed almost entirely of pyrrhotite and associated silicate minerals. It occupies a mafic portion of a large norite intrusion which, with the exception of a concentration of olivine in the mineralized zone, is practically structureless and homogeneous (Plate 18). The ore body is likewise essentially structureless and consists of a mixture of the sulphide and silicate minerals. The more massive ore contains about 75% sulphides. This grades toward the outer border of the deposit where the normal norite contains less than 5% sulphides.

St. Stephen Deposits

The St. Stephen deposits are located in a differentiated intrusion the outcrop of which encircles the town of St. Stephen, N. B.,

as a sort of half halo to the north, east, and west. A small part of the intrusion extends across the border into Calais, Maine (Plate 17). The mafic pluton is composed of peridotite, anorthositic norite, and norite. The northeastern part of the pluton is peridotite, which grades into banded anorthositic norite and more or less massive norite. The most important ore deposits occur along the northern rim in norite (Plate 7).

The four important pyrrhotite bodies in the St. Stephen pluton are designated the Rodgers, Hall-Carroll, Exhibition Grounds, and Union Bridge deposits. The peridotite also contains disseminated sulphides but in relatively small quantities. In both the Exhibition Grounds noritic deposit and the deposits in peridotite, the mineralization is of a disseminated type. The Rodgers and Hall-Carroll deposits are veinlike pyrrhotite zones in fractured norite. These deposits are cut by both biotite-spessartite and felsic dikes, themselves mineralized.

Union Deposit

The Union deposit, located near the town of East Union, Maine, consists of two mineralized zones in a small lenticular intrusion which has a peridotite core and highly altered border phase (Plate 20). In two areas the peridotitic core is mineralized, bearing bodies of approximately 25-30% nickeliferous pyrrhotite in a matrix of peridotite. As in the Katahdin deposit, these mineralized zones are structureless.

Black Narrows Deposit

The Black Narrows deposit is located at a point of that name on the shore of Moxie Lake, Somerset County, Maine. It is similar to the Union deposit in almost every respect. It occurs in a northeast trending mafic intrusion which cuts Silurian quartzites. The intrusion grades from peridotite where it is in contact with metasediments on its southeastern side to a highly altered rock which is probably norite (Plate 19). However, the deposit is poorly exposed and its exact extent is unknown. The mineralization is disseminated pyrrhotite, confined chiefly to the peridotite.

FIELD EVIDENCE

Distribution in Host Rocks

In the Katahdin deposit the mineralized zone is located near the western border of the norite intrusion (Plate 18), but it is not at the contact nor is any structural control indicated by the position of the ore body. At St. Stephen, the ore bodies are roughly distributed about the margin of the intrusion (Plate 17). However, the mineralized zones are not parallel with the margins, nor are at the contact with metasediments. In every case the mineralization is entirely within the mafic host rock. In both the Black Narrows and Union deposits the pyrrhotite-rich zones are localized in the peridotitic phase of the intrusion, which is at the center of the Union intrusion and along the southeastern border below the noritic phase of the Black Narrows intrusion (Plates 19 and 20).

Control by Tectonic Features

The two largest deposits at St. Stephen, the Rodgers and the Hall-Carroll, are definitely localized by fractures in the norite. The fracturing is not on a large scale and much of it is obscured by the mineralization but it can at least be detected under the microscope. The veinlike nature of the ore bodies, particularly in the Hall-Carroll prospect, is also strong evidence of localization by shear zones. Further evidence of structural control is found in other parts of the norite where small veinlets of sulphide occur in fractured norite and trend roughly parallel to the larger ore bodies.

Relation to Dikes

Dikes cutting the ore bodies are found in two deposits, the Katahdin ore body and the Rodgers mine at St. Stephen. At Katahdin, an unmineralized mafic dike cuts the ore body in the northwest corner of the deposit and a small felsic dike was noted near the northeastern border. Since no mineralization could be found in the mafic dike, it is apparently later in origin than the ore deposit, but the felsic dike contains numerous small blebs of early (?) sulphide (Plate 6, D). The sulphides in this dike are pyrrhotite and chalcopyrite in about the same proportions as in the ore body.

At the Rodgers mine, two north-south trending mafic dikes cut the ore deposit (Fig. 2). These dikes were first noted by Low (1930, p. 116) and later described by Dunham (1950, p. 725) who classified them as biotite-spessartite. They are poorly exposed at present but a fragment of the western dike was found to contain small felsic dikes which represent a second and later type of intrusion. Both biotite-spessartite and felsic dikes are cut by chalcopyrite veinlets from the ore body and pyrrhotite replaces the biotite-spessartite where it is in contact with the ore bodies (Plate 2). The trend of veinlets of ore in the dikes is parallel to the trend of the mineralized zones at the Rodgers mine.

Relations to Inclusions

Inclusions of various kinds are present in the Katahdin and St. Stephen deposits. In both cases the included material is mineralized.

Exposed ore bodies do not have inclusions at St. Stephen but drill holes in both the Rodgers and Hall-Carroll properties have penetrated quartzite xenoliths in the ore body. One or two of the cores still remaining on the Rodgers property were highly altered quartzite. Both of these cores had numerous scattered grains of sulphides disseminated through the rock.

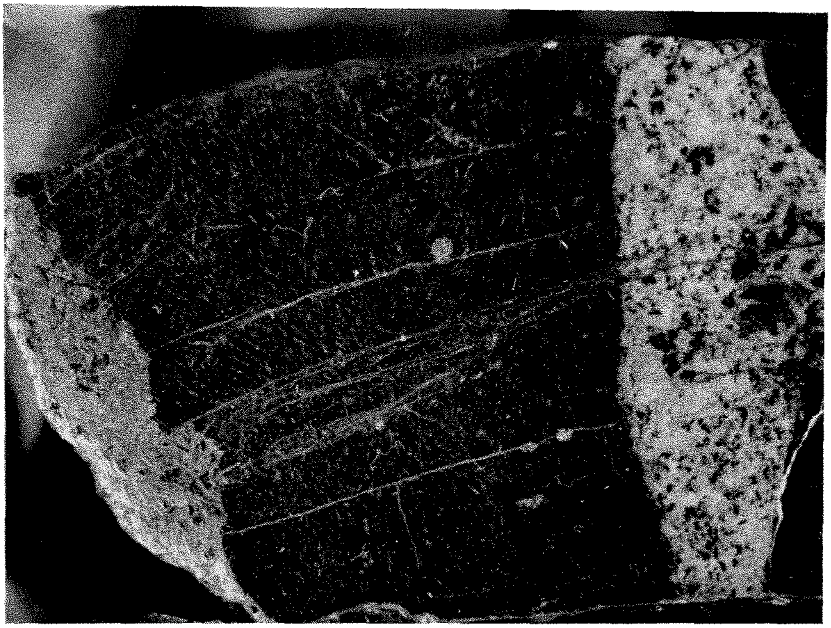
Along the southwest border of the ore body at Katahdin are many subrounded inclusions of quartzitic material, not over 6 inches in diameter, and composed of coarsely crystalline quartz, clinopyroxene, plagioclase (An_{55}), biotite, carbonate, and chlorite. The borders of these inclusions show signs of recrystallization such as the development of myrmekite. They contain small amounts of disseminated sulphide and are cut by microscopic veinlets at their contact with the mineralized norite.

LABORATORY EVIDENCE

Mineralogical Evidence

The mineralogy of the ore bodies is simple. The sulphide minerals consist principally of pyrrhotite, pentlandite, and chalcopy-

PLATE II



Sulphide (extreme left) replacing biotite spessartite dike. At right is a felsic veinlet cutting the mafic dike and near the center of the photograph are parallel veinlets of chalcopyrite cutting both dikes. Rodgers mine X 3. 1.

rite. Secondary minerals include marcasite and hematite, which occur as alteration products of the pyrrhotite, and violarite, which invariably replaces pentlandite.

The sulphides are closely associated with the oxide and silicate minerals of the host rocks. These minerals may be divided broadly into anhydrous and hydrous groups. The anhydrous group includes olivine, orthorhombic pyroxene, monoclinic pyroxene, plagioclase, carbonate, and quartz. The hydrous minerals are amphiboles, micas, chlorite, and serpentine. The latter two groups will be briefly discussed in order to show their relationship to the sulphides and establish a general sequence of crystallization for the silicate and sulphide minerals.

Anhydrous Minerals

Olivine. Olivine (Fe_{75} + —) is present in varying amounts in all of the mineralized zones. Most of the olivine crystals are euhedral. The well developed crystal form and the fact that the other silicates occur interstitially between the olivine grains suggest that the olivine was the first mineral to crystallize from the mafic magma. A typical example of the textural relationship between olivine and other orthotectic silicates is shown in Plate 5, D.

Orthorhombic Pyroxene. Orthorhombic pyroxene, chiefly bronzite, occurs in several different ways in the mafic rocks. In certain phases of the norite at Katahdin large crystals of orthorhombic pyroxene up to 2 mm. in diameter are noted which contain inclusions of euhedral olivine and plagioclase. The texture is typically poikilitic. In other phases of the norite, orthorhombic pyroxene occurs as euhedral crystals in much the same way as olivine. The orthorhombic pyroxene crystals lie in a matrix of plagioclase crystals which appears to have developed around the euhedral pyroxene. The shape of the plagioclase crystals conforms to that of the orthorhombic pyroxene. In the peridotite, where olivine is the dominant mineral, the orthopyroxene usually occurs as anhedral interstitial masses which conform to the olivine crystal outlines.

Monoclinic Pyroxene. The monoclinic pyroxenes are not important in the peridotites but in the norites the occurrence of augite is very similar to that of the orthorhombic forms.

Plagioclase. The most characteristic occurrence for plagioclase is as interstitial aggregates between the pyroxenes and olivine. In places the plagioclase crystals partially penetrate early olivine and pyroxene along fractures or cleavage. None of the textures suggest replacement, however (Plate 5, D).

In general, the textural relationship between these silicates varies with composition. Olivine is early in all cases but the textures of the plagioclase and pyroxenes depend largely on the percentages of these minerals in the rocks. In some of the anorthositic bands in the St. Stephen intrusion, for example, the rock is made up principally of labradorite with minor amounts of olivine and orthopyroxene. The olivine in these rocks occurs as euhedral crystals, partially penetrated by later plagioclase. The orthorhombic pyroxenes appear as narrow interstitial masses between crystals of plagioclase and olivine and apparently crystallized after the solidification of the other two minerals. In norites made up chiefly of pyroxene and olivine, the plagioclase occurs as late intergranular masses. Where the percentages are approximately equal, mutual intergrowths of the minerals are common and it appears that they crystallized at approximately the same time. Wells (1952, pp. 913-914) describes similar textures in some Bushveldt norites. Wells states, "As bytownite and bronzite are members of an isomorphous series, a cotetic relationship must hold; and whichever of the two is in local excess of cotetic ratio will crystallize first." Although olivine must have crystallized first, regardless of the percentage of this mineral present, Wells' cotetic relationship may account for the major relations between pyroxenes and plagioclase. It is also important to emphasize that there is no evidence that replacement played an important role in the origin of these minerals. All minerals are thought to have formed during the orthotectic stage of crystallization of the magma. Comparison of the textures of these and the sulphide minerals will be made in a later chapter.

Quartz. Quartz occurs in certain more felsic phases of the intrusions, such as a small zone near the southwestern corner of

the Katahdin pluton but it is also a by-product of the breakdown of some of the orthotectic minerals, where alteration is extensive. In the Rodgers and Hall-Carroll deposits, quartz is present in zones where most of the orthotectic minerals have been changed into amphiboles, chlorite and serpentine. This quartz is clearly secondary and probably formed as a result of the uralitization of the pyroxenes. Here it was not possible to determine the relationship between the quartz and the sulphide mineralization.

Carbonate. In highly altered areas of the mafic intrusions, a carbonate commonly veins and replaces the other minerals, especially plagioclase. The carbonate is not particularly confined to mineralized areas and is probably the result of post-mineral, near surface deposition.

Hydrous Minerals

In the St. Stephen deposits, in particular, the presence of hydrous minerals is clearly related to the mineralization. Their origin and relationship to the sulphide mineralization is therefore of considerable importance in understanding the origin of the ores. In the following paragraphs, the important hydrous minerals and their relationship to the orthotectic minerals will be discussed. The relationship between the hydrous minerals and the sulphides will be described later.

Amphiboles. The most common amphiboles in these rocks are brown hornblende and colorless to light green tremolite-actinolite. The brown hornblende characteristically replaces the pyroxenes but it also occurs in other ways. Hornblende replaces the pyroxenes along cleavage cracks or other fractures in the minerals. The contacts between the pyroxenes and the replacing hornblende are irregular and in certain instances partially replaced "islands" of pyroxenes remain in the hornblende mass. In some cases, large orthorhombic pyroxenes may contain numerous disconnected irregular areas of hornblende aligned parallel to the pyroxene cleavage. Locally the bands coalesce into complete pseudomorphs of the original mineral. The relationship between hornblende and pyroxene contrasts with rounded contacts between the orthotectic minerals. The hornblende not only replaces the pyroxenes but may replace adjacent plagioclase crys-

tals. Hornblende occurs as reaction rims between feldspar and olivine, a relationship characteristic of the peridotite at Union, Maine (Bastin, 1908). Hornblende also forms subhedral crystals in the mafic rocks.

The tremolite-actinolite characteristically forms veinlets cutting all minerals in the mafic rocks.

It should be noted that in the more felsic phases of the mafic rocks, hornblende may be a primary constituent of the rock, taking the place of pyroxene and in relatively unaltered zones, hornblende constitutes interstitial aggregates in much the same manner as plagioclase.

Micas. Reddish-brown biotite is the most common mica in the rocks but muscovite is also present in the highly altered zones. The biotite occurs in much the same fashion as hornblende, although as it may replace the latter it is clearly later. In the peridotites at Black Narrows, Union and St. Stephen, the biotite occurs as irregular interstitial crystals along the contact between the plagioclase grains and pyroxene crystals. The crystals of biotite have smooth contacts with the orthotectic minerals and appear to be of late orthotectic age.

Chlorite. Chlorite developed in much the same manner as biotite. In many places it is an alteration product of biotite or other minerals. At St. Stephen, the biotite in the more highly altered norite has lathlike lamellae of pennine along the cleavage of the biotite. Veinlets of biotite and chlorite cut across all minerals in these rocks. At all deposits, chlorite develops along crystal boundaries between the mafic minerals and penetrates and replaces these minerals along fractures; here it may also replace the plagioclase.

Serpentine. Except in the highly altered phases of the rocks, serpentine is confined to the mafic types rich in olivine. Single olivine crystals are partly or completely replaced by serpentine and magnetite. In these cases the serpentine is essentially antigorite. It may locally replace other minerals where they touch the olivine but the antigorite does not extend far from the olivine crystals. Even in the peridotite at St. Stephen, where the rock is cut by numerous serpentine veinlets the relationship between

serpentinization and olivine is apparent. The parallel veinlets of serpentine cutting the rock vary from 15 mm. to 1.5 mm. in width and the wider veinlets generally have cores of chrysotile. The smaller of such veinlets cut across all of the orthotectic minerals, increasing considerably in size where they cross olivine crystals. On entering plagioclase or pyroxene crystals, many of the veinlets pinch out entirely only to appear farther on, in the next grain of olivine.

These veinlets may have resulted from microshears in the peridotite but the evidence for such fracturing is not apparent in the rocks. Although none of the olivine or other mineral grains in the specimens examined are broken, the distinctly parallel arrangement of the veinlets and their parallelism to the primary structure in nearby norites both suggest some kind of structural control in their emplacement. In highly altered norite, such as that at the Rodgers and Hall-Carroll deposits, serpentine veinlets cut the rock along fractures with no regard to mineralogy.

Metallic Minerals

Pyrrhotite. By far the most important sulphide mineral in these deposits is pyrrhotite. It makes up more than 95% of the sulphide minerals except in a few local zones of the ores.

Individual crystals of pyrrhotite range from 1.1 to 2 mm. in diameter, their sizes conforming largely to the grain size of the host rock. The grains are usually anhedral in outline with somewhat rounded contacts, but in some cases contacts between individual grains are extremely irregular. In all of the deposits the pyrrhotite is strained to some degree, as shown by slight curvature of crystals, but in the central zone at Katahdin, and in the Rodgers and Hall-Carroll veins, individual grains are clearly bent out of shape. In poorly polished specimens from these deposits, numerous curved fractures are present in the bent crystals. These deformed crystals are generally twinned. The twin lamellae are lath-shaped or flame-shaped bands and, in some cases at least, developed after or during the deformation. Some of the twins at Katahdin have reverse strain patterns on either side of the composition planes. This evidence of strain in the pyrrhotite shows that the deposits have been subjected to some

pressure since their formation but as far as the writer could determine, there is no evidence that the pyrrhotite flowed plastically as a result of the strain, such as appears in the Ducktown ores.

No evidence of alpha and beta pyrrhotite was noted in these ores. The pyrrhotite was essentially homogeneous in the specimens examined.

Pentlandite. Pentlandite in the ore is easily detected microscopically by the brighter, orange to flesh colors in reflected light, compared to pyrrhotite. The mineral also has excellent octahedral parting in most specimens. Many of the grains have been partially replaced by violarite, which is easily stained by HNO_3 leaving the pentlandite in bold contrast.

Pentlandite is found in minor amounts in all of the ores except at Katahdin. In contrast with those of the other deposits, the ores in peridotite (Union, Black Narrows and the peridotite phase of the St. Stephen complex) pentlandite is more abundant compared to total sulphide content. It varies from 10% of the total sulphide content at Union, to 35% at St. Stephen. The overall percentage of pentlandite in the peridotite is low, however, averaging from .1 to 1 percent, since the sulphide content of the peridotite is low. The ores in norite (the Rodgers and Hall-Carroll deposits), on the other hand, have very high total sulphide contents and hence the pentlandite is more abundant in total percentage but it is much less (only 2-3%) compared to the total sulphide content. According to Vogt (1923, p. 307) the content of nickel varies with the content of olivine and hypersthene in igneous rocks. These observations seem to indicate that the nickel content of the sulphide phase varies in a similar fashion.

In the ores in peridotite, pentlandite occurs near the margins of pyrrhotite masses. It is rounded to subhedral with unusually well developed parting. Most of the pentlandite grains have at least one well developed crystal face against the pyrrhotite. The subrounded forms of the pentlandite, suggestive of corrosion, and the fact that the pyrrhotite conforms to the crystal boundaries and enters minor cracks in the pentlandite, seems to prove that pentlandite formed first.

The most striking characteristic of the pentlandite of the ores in peridotite is its close association with magnetite (Plate 3). Veinlets of magnetite penetrate along parting planes of the pentlandite and along contacts between pentlandite and the silicates. Some larger masses of magnetite contain inclusions of subrounded pentlandite and in many cases the pentlandite is rimmed by magnetite. These characteristics are especially developed in the ores at Union, Maine.

The ore at the Exhibition Grounds deposit, St. Stephen, occurs in a rock intermediate in composition between peridotite and norite. In this deposit, the pentlandite occurs as subhedral crystals but grades into veinlike masses which occur along intergranular boundaries of the pyrrhotite. In this ore, then, the pentlandite is probably later in origin than pyrrhotite.

At the Rodgers and Hall-Carroll deposits, the ore occurs in norite and the pentlandite characteristically forms intergranular veinlets between the pyrrhotite grains. It is very sporadic but where concentrated it conforms to the pattern of the pyrrhotite grains. Some pentlandite crystals have subhedral inclusions of pyrrhotite within the veinlets. Here, too, therefore the pentlandite seems younger than the pyrrhotite.

Chalcopyrite. Like pentlandite, chalcopyrite is sporadic in occurrence. It is found in about the same ratio to pyrrhotite as is the pentlandite, except that it is more abundant in the noritic ores. In the ores in peridotite, chalcopyrite occurs in anhedral masses between pyrrhotite grains, as blebs in crystals of pyrrhotite which may be cut by later pyrrhotite veinlets, as irregular veinlets cutting pyrrhotite and as irregular flame-like intergrowths with pyrrhotite, roughly parallel to the (0001) plane. It is found also along the contact between masses of pyrrhotite and the silicate minerals. In this type of occurrence, the chalcopyrite is confined chiefly to small veinlets in the silicate minerals. Such veinlets are controlled by cleavage cracks and microfractures in the silicates. The veinlets are everywhere associated with masses of pyrrhotite and radiate from these pyrrhotite masses like dike swarms from an igneous stock. These facts suggest that chalcopyrite and pyrrhotite are of about the same age. The manner of occurrence just described is characteristic of this

mineral at Union, Katahdin and the peridotitic ores at Black Narrows and St. Stephen. In the Rodgers and Hall-Carroll deposits, however, the chalcopyrite generally occurs along the borders of the veinlike bodies and some of it fills fractures in dikes that cut the norite.

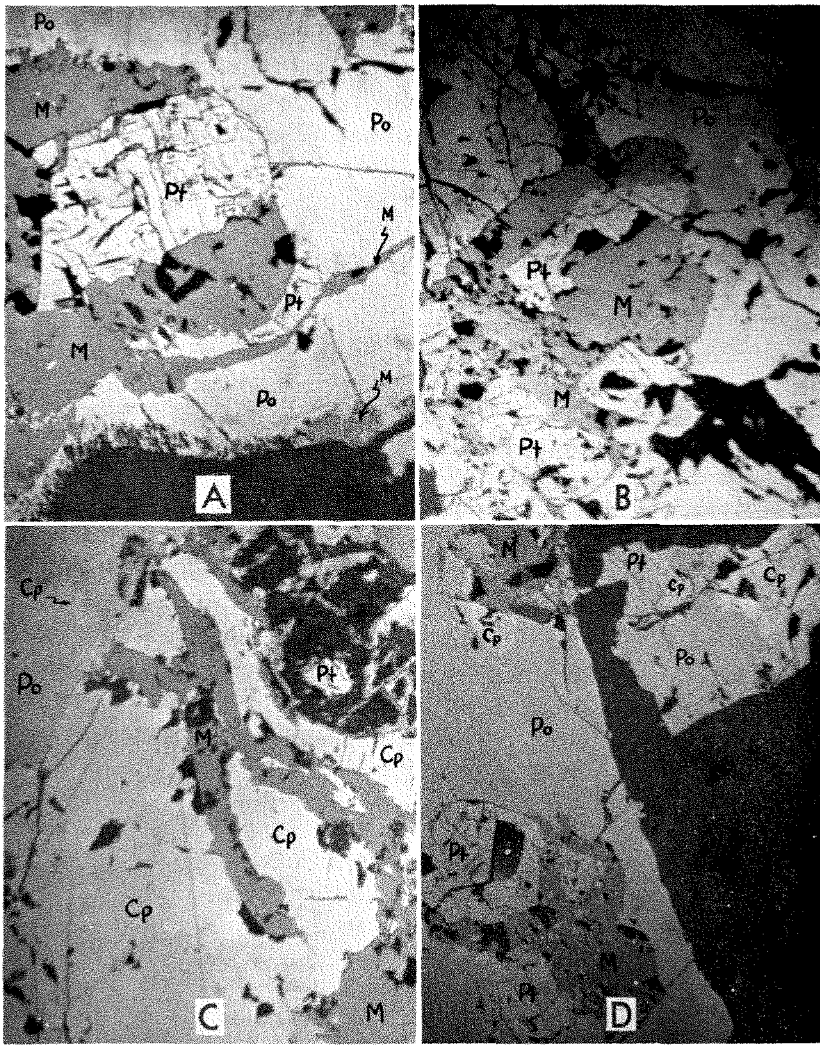
In summary, in the peridotitic ores, some of the chalcopyrite may actually be earlier than the pyrrhotite as shown by veinlets of pyrrhotite which cut masses of the mineral (Plate 3, D). However, the greater part of the mineral is later than the pyrrhotite.

Magnetite. Magnetite occurs in at least two ages and possibly three, in these ore deposits. It is in euhedral crystals, some of which are partially corroded by silicates, in the peridotite at St. Stephen. This may be an early presilicate magnetite. It is found also as "schiller structure" particles in orthorhombic pyroxene which probably formed at the same time as the pyroxene. However, the greatest part of the magnetite in all of these deposits formed after the silicates were solid.

In the norite, particularly at St. Stephen and Katahdin, the magnetite characteristically occurs as anhedral interstitial masses between the silicate grains. Magnetite masses contain inclusions of silicates, send veinlets into silicates along cleavage cracks and cut directly across silicate crystals in some of the St. Stephen ores. Most of the magnetite in these ores is earlier than the sulphides since the sulphides vein the magnetite and contain corroded magnetite inclusions. One or two magnetite crystals were noted, however, which contained bleb-like masses of early (?) sulphide.

In the peridotitic ores and the disseminated mafic norite (Exhibition Grounds deposit), at least a part of the magnetite is later than the sulphides. As previously noted in the discussion of pentlandite, the magnetite in these ores enters along parting planes in the pentlandite and fills contacts between pentlandite and adjacent minerals. Large masses of this magnetite enclose corroded pentlandite crystals and veinlets of the magnetite cut the pentlandite (Plate 3). It also rims masses of both pentlandite and pyrrhotite and one area was noted in the Union deposit in which

PLATE III



A. Polished section showing pentlandite (Pt) and pyrrhotite (Po) cut by magnetite (M). In the lower right section is an irregular intergrowth of serpentine and pyrrhotite with magnetite filling a portion of the irregular border. At the extreme lower right a serpentine veinlet bordered by magnetite cuts the pyrrhotite. Union deposit X 125.

B. Polished section similar to figure one except pentlandite ratio is higher. Union deposit X 125.

C. Polished section showing altered pentlandite (Pt) cut by chalcopyrite (Cp) which is, in turn, cut by magnetite (M). The medium gray mineral in upper left is pyrrhotite. Note the elongate droplet of chalcopyrite in pyrrhotite (upper left). Union deposit X 125.

D. Polished section showing pentlandite (Pt) cut by magnetite (M). Note chalcopyrite (Cp) cutting pentlandite in upper right which is also cut by pyrrhotite (Po) veinlets. Union deposit X 125.

the magnetite cut chalcopyrite (Plate 3, C). This late magnetite is always confined to ores containing considerable olivine. In the serpentinized peridotite at St. Stephen and Black Narrows, much of the late magnetite has formed during the breakdown of olivine and it is this magnetite that cuts the sulphide masses (Plate 7, C and D).

Ilmenite. Ilmenite occurs in every one of the ores examined. It forms characteristic intergrowths with magnetite and is almost invariably associated with that mineral. It is later than the magnetite since the ilmenite intergrowths conform to the already formed magnetite parting. Aside from intergrowths with magnetite, ilmenite also occurs as interstitial masses between silicate crystals. In this type of occurrence it is usually in contact with magnetite which it clearly postdates. In the Union peridotite, ilmenite occurs in separate masses later than the silicates. At Katahdin, where ilmenite is more abundant than magnetite, some of the large ilmenite crystals contain irregular veinlets and blebs of magnetite. The magnetite is probably later in this case. In the Union ores, in particular, ilmenite shows the same relationship to the sulphides as magnetite. It must have originated in a similar manner except that it was slightly later in origin than magnetite. Ilmenite is concentrated in pegmatite phases of the norite at St. Stephen. Chemical analyses made by Dunham (1950, p. 717) show a concentration of titanium in the pegmatite.

Chromite. Chromite is present only in the peridotite at Black Narrows. There it occurs as minute euhedral crystals which probably formed at an early stage in the crystallization of the magma. These crystals are cut by late magnetite and pyrrhotite.

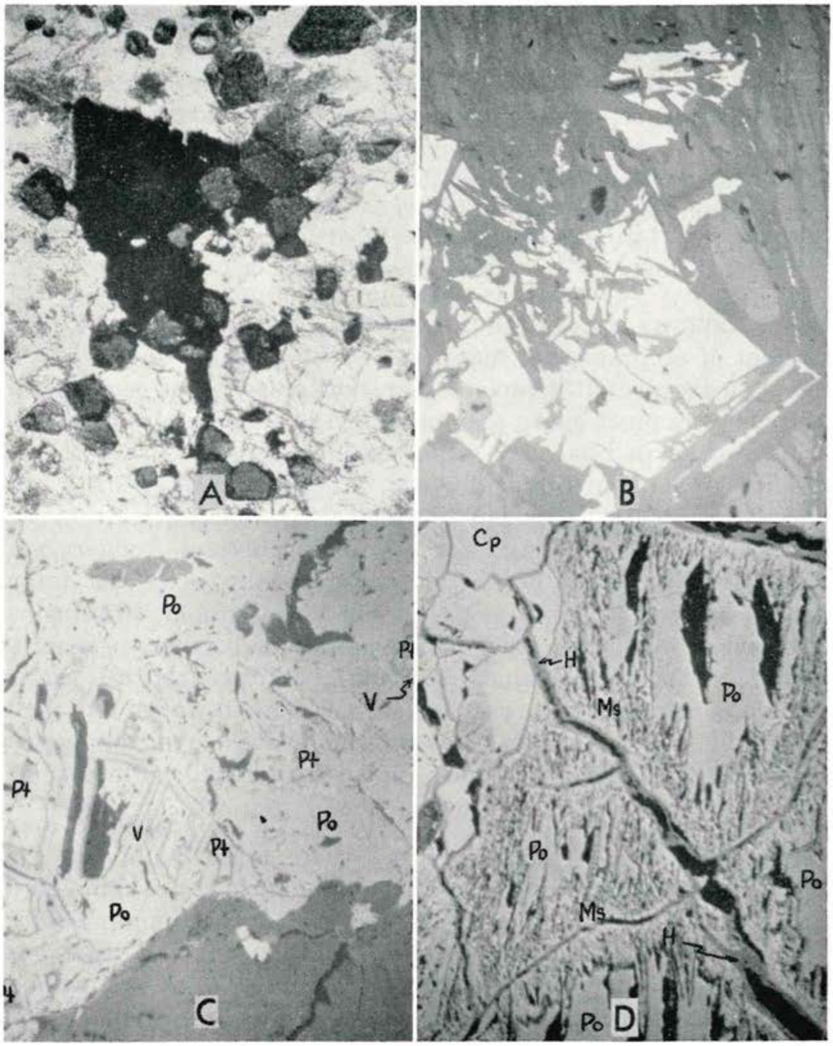
Spinel. Spinel is present in two of the deposits, the Union deposit and the St. Stephen deposit where it is found in the Rodgers and Hall-Carroll mines. At the Union deposit it is present in minor amounts associated with hornblende. Age relations were not established at this deposit for the mineral. In the Rodgers and Hall-Carroll mines, however, small green spinel crystals occur in mineralized zones where they are cut and replaced by the sulphides (Plate 4, A).

Violarite. This mineral occurs exclusively as a replacement of pentlandite. It is found to a minor extent in all of the nickel ores but is particularly common at St. Stephen. It replaces pentlandite by starting from the borders of the crystals and working inward. Some pentlandite crystals at the Rodgers Mine are almost entirely replaced. Small jagged remnants of pentlandite remain in the highly altered grains. The violarite may also cut across the pentlandite in irregular veinlets which have numerous minute fingerlets extending into the pentlandite perpendicular to the trend of the veins (Plate 4, C).

Marcasite. Marcasite is particularly common at St. Stephen, Black Narrows, and Katahdin where it replaces pyrrhotite. The manner of occurrence of marcasite is very similar to that of the violarite except that it replaces pyrrhotite instead of pentlandite. Marcasite is much more abundant in the weathered samples of the ore than in relatively fresh samples. For this reason it is thought to be a supergene mineral. There is an interesting contrast between the texture of the primary sulphides and this secondary mineral. In most of the deposits (except Rodgers and Hall-Carroll) the sulphides characteristically occur as intergranular veinlets and do not as a rule cut across crystal grains. The marcasite, on the other hand, may occur between pyrrhotite grains, cut across grains, or almost entirely replace grains pseudomorphically. The veinlets are not smooth-walled like those of the primary sulphides; instead they have extremely jagged edges, leaving no doubt about a replacement origin (Plate 4, D).

Hematite. The age relations between the violarite and marcasite could not be established but there is no doubt that the hematite is the last mineral to form. Hematite is not confined to any particular host mineral. It replaces sulphides and silicates. Hematite veinlets traverse the altered specimens in all directions. In some cases they appear to be central and most recent parts of larger veinlets of marcasite, in which case they may be derived from the marcasite. The largest part of the hematite actually occurs along borders between sulphides and silicates and in the silicates themselves. In the most highly altered rocks, the hematite replacement reduces the area of sulphides considerably but still occurs principally along contacts between the sulphides and silicates.

PLATE IV



A. Thin section showing pyrrhotite (black) replacing spinel. Hall-Carroll deposit X 83.

B. Polished section showing mass of sulphides (white) cut and disrupted by late serpentine veinlets. Union deposit X 125.

C. Polished section showing pentlandite (Pt) partially altered to violarite (V). Dark gray mineral is pyrrhotite (Po) veined by later pentlandite. Rodgers deposit X 125.

D. Polished section showing marcasite (Ms) replacing pyrrhotite (Po). Note unaltered chalcopyrite (Cp) in upper left and dark gray veinlets of hematite (H) cutting sulphides. Rodgers mine X 125.

Special Textural Relations

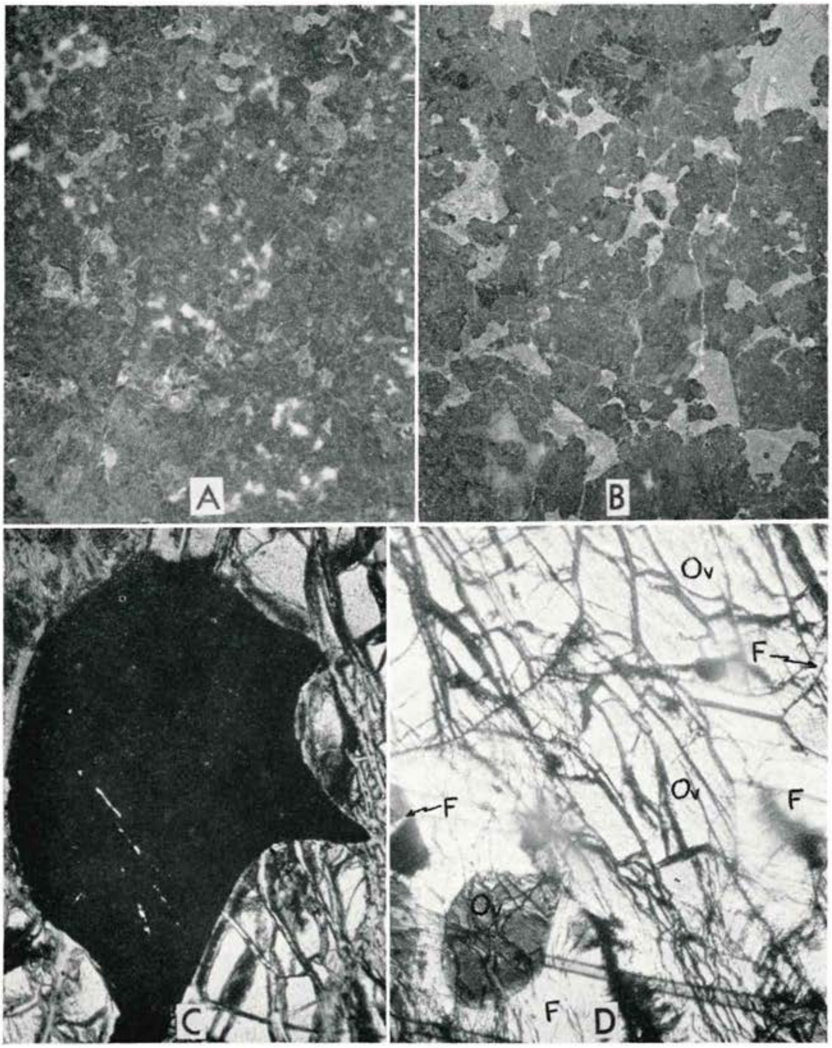
Spatial Relationship of Sulphide and Anhydrous Minerals

In certain of these ores one type of textural relationship between sulphide and orthotectic silicates predominates. At Union, Black Narrows, Katahdin, and the peridotite and Exhibition Ground ores at St. Stephen, the sulphides characteristically occur as irregular interstitial masses between the silicate crystals. Typical ores from two of these localities are shown in Plate 5. The contacts between the sulphide and silicate grains are generally smooth and the sulphides are molded about the early silicate crystals (Plate 5, C). The relationship is similar to that between feldspar and early formed olivine crystals (Plate 5, D).

Although the above relationship is characteristic of these ores, a number of other features are present which suggest a late magmatic or even hydrothermal origin for the sulphides. In some cases, veinlets of sulphide penetrate plagioclase along cleavage planes (Plate 8, A and D). In certain zones irregular contacts between sulphide and silicates suggest replacement. One section from the Union ores showed an irregular intergrowth of pyroxene and pyrrhotite (Plate 9, D). Textures similar to the last one, between ilmenite and feldspar, have been interpreted (Newhouse, 1936) as subgraphic intergrowths. In other zones the sulphide crystals contain corroded inclusions of silicate minerals but silicates also contain rounded bleb-like inclusions of sulphide (Plate 6, A, B, and D). Textures suitable for "proving" several modes of emplacement are present in these ores. It must be emphasized, however, that the ores as a rule show no control of mineralization by microfractures and that the dominant textural relationship is the interstitial sulphide type.

The ores in the Rodgers and Hall-Carroll mines have entirely different relationships to the host rock. Fractured and replaced silicates are the rule rather than the exception. There is no important cleavage control or emplacement between grains. The sulphides cut the silicates along roughly parallel fractures and replace all of the silicates without preference (Plates 10 and 11).

PLATE V



A. Interstitial sulphide texture. Sulphides (dark gray) and plagioclase (white) are similar in spatial relations. Note lack of structural control of mineralization. Peridotite from Black Narrows deposit X 3.

B. Interstitial sulphide texture. White veinlets are cracks in the specimen. Peridotite from Union deposit X 2.4.

C. Thin section showing interstitial mass of pyrrhotite conforming to outline of early formed olivine crystals. St. Stephen peridotite X 92.

D. Thin section showing interstitial feldspar (F) between olivine (Ov) crystals. Note feldspar surrounding broken grain of olivine in lower left and veinlets of feldspar along intergrain borders, upper right. Peridotite from St. Stephen X 92.

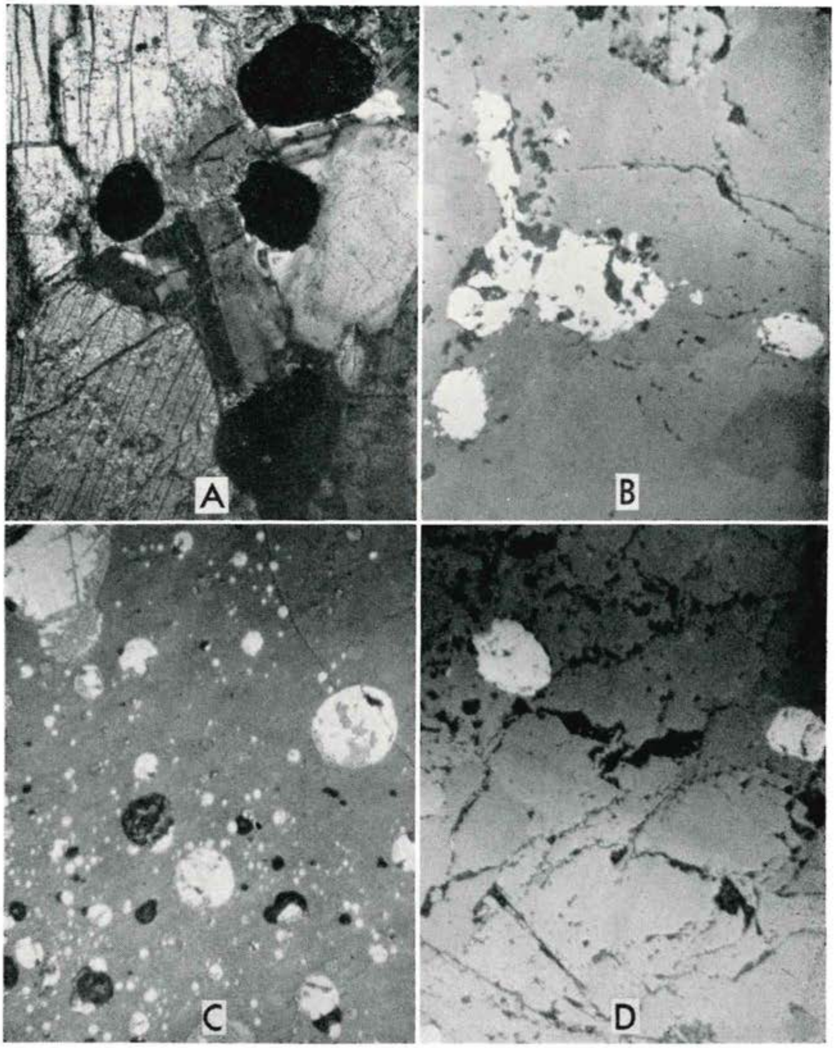
Relationship to Late Hydrous Minerals

One of the most significant questions bearing on the origin of these ores is that of the age relationship between the sulphides and hydrous silicates. In this, these deposits may again be divided into two distinct groups.

At Union, Black Narrows, Katahdin, and the peridotitic and Exhibition Grounds deposits at St. Stephen, most of the hydrous minerals are later than the mineralization. Hydrothermal serpentine, chlorite, biotite and tremolite-actinolite, all cut the sulphides (Plate 7). Hornblende reaction rims between feldspar and pyrrhotite are also later than the mineralization but some of the biotite is definitely early. As pointed out earlier, the position of biotite and hornblende in the crystallization sequence is difficult to establish. It is possible that some of the biotite could have formed from late solutions from which it crystallized more or less in place as a late orthotectic mineral but there is no doubt that some of it is hydrothermal, as shown by cross-cutting veinlets of biotite and chlorite and by biotite which replaces hornblende. It is this interstitial biotite which is cut and corroded by the sulphides and the veinlets of biotite and chlorite which are later than the sulphides. Since most of the alteration is later than the sulphides and since there is this distinction in the occurrence of biotite, it is the writer's opinion that the biotite and sulphide fraction in these ores crystallized at about the same time from residual solutions and that the hydrothermal alteration came later.

Except for the late serpentinization of the peridotite, which is clearly later than the mineralization, the most highly altered zones in the deposits just described are outside the mineralized area. This is especially true at Katahdin. In the Rodgers and Hall-Carroll deposits, the opposite relationship holds. In these deposits the mineralized norite is far more altered than the unmineralized rock. In mineralized zones, hydrous minerals constitute as much as 90% of the silicates in some cases and average at least 25% of the rock. Hydrous minerals replace and vein all of the orthotectic minerals; they are not confined to interstitial bodies but characteristically crosscut the original structure of the rock. It is possible to find conflicting evidence of age between

PLATE VI



A. Thin section showing blebs of pyrrhotite (black) in norite. Katahdin deposit X 87.
B. Polished section showing blebs of pyrrhotite (white) in norite. Note slightly corroded grain in lower left corner. Katahdin deposit X 125.
C. Polished section showing blebs of chalcopyrite (white) in matte for comparison with A, B, and D. Cananea Copper Company slag X 125.
D. Polished section showing blebs of pyrrhotite (white) in felsic dike. In lower left of photograph a single globule of pyrrhotite is in the center of a feldspar crystal. Katahdin deposit X 125.

the hydrous minerals and sulphides in these rocks, but, as Dunham (1950) has suggested, eventually the sulphidization outstripped the development of hydrous minerals.

Replacement Textures

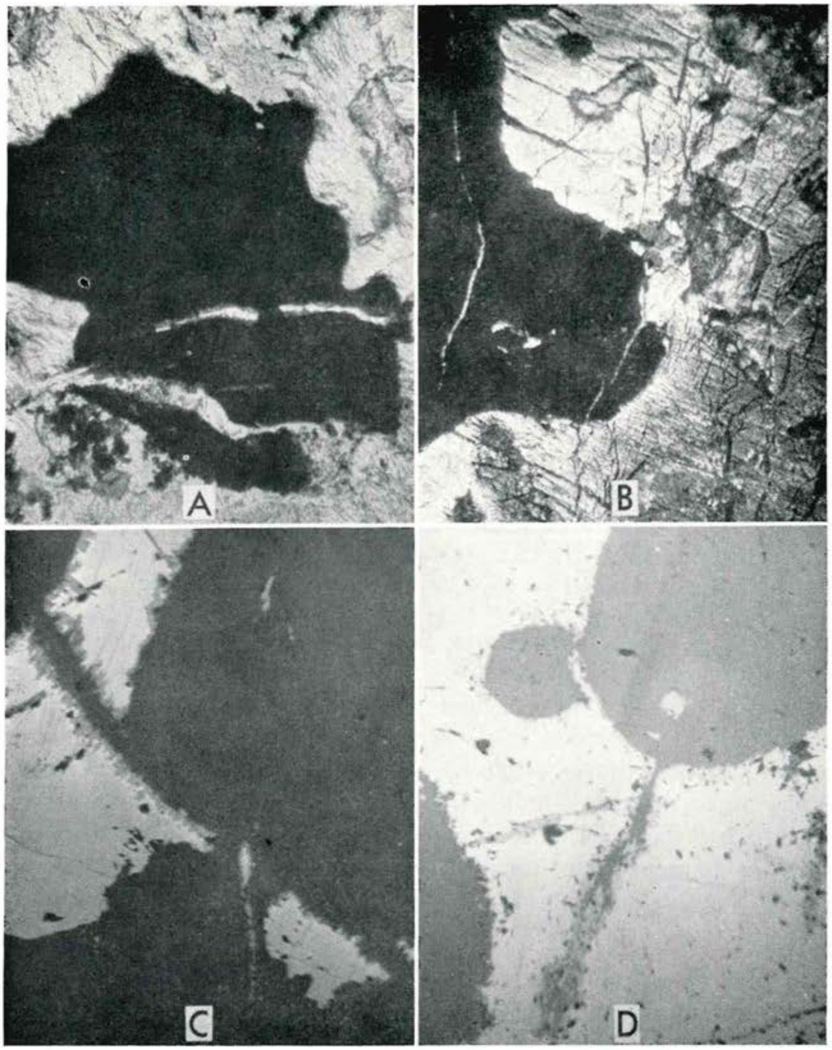
There is little doubt about the replacement origin of the secondary metallic minerals, or certain of the secondary hydrous silicates but the origin of all of the sulphide minerals by a process of replacement seems doubtful.

As previously noted, replacement textures are present in all of the ores to some degree. In the Katahdin, Black Narrows, and Union deposits, sulphides replace silicates, especially in zones of almost massive sulphide. Here many of the included minerals are veined by sulphides along cleavage planes (Plate 8) or along cracks in the silicate crystals; locally a silicate crystal will even have a network of small partially coalescent sulphide veinlets (Plate 8, D). None of these veins are smooth walled and they do not fit together. It is therefore clear that in massive zones, at least, there is local replacement of silicate minerals.

In the majority of these deposits where the ore occurs interstitially, contacts between ore and silicates are smooth. In the peridotite ores, however, where sulphides contact olivine, there is a peculiar intergrowth between the serpentine which separates sulphides and olivine (Plate 3, A). In these ores there is evidence of serpentine cutting the sulphides and vice versa. It is therefore difficult to determine which mineral is doing the replacing, if the process is one of replacement. Furthermore, along these irregular contacts, magnetite occurs which is actually later than either pyrrhotite or serpentine (Plates 3, A, and 7, C and D).

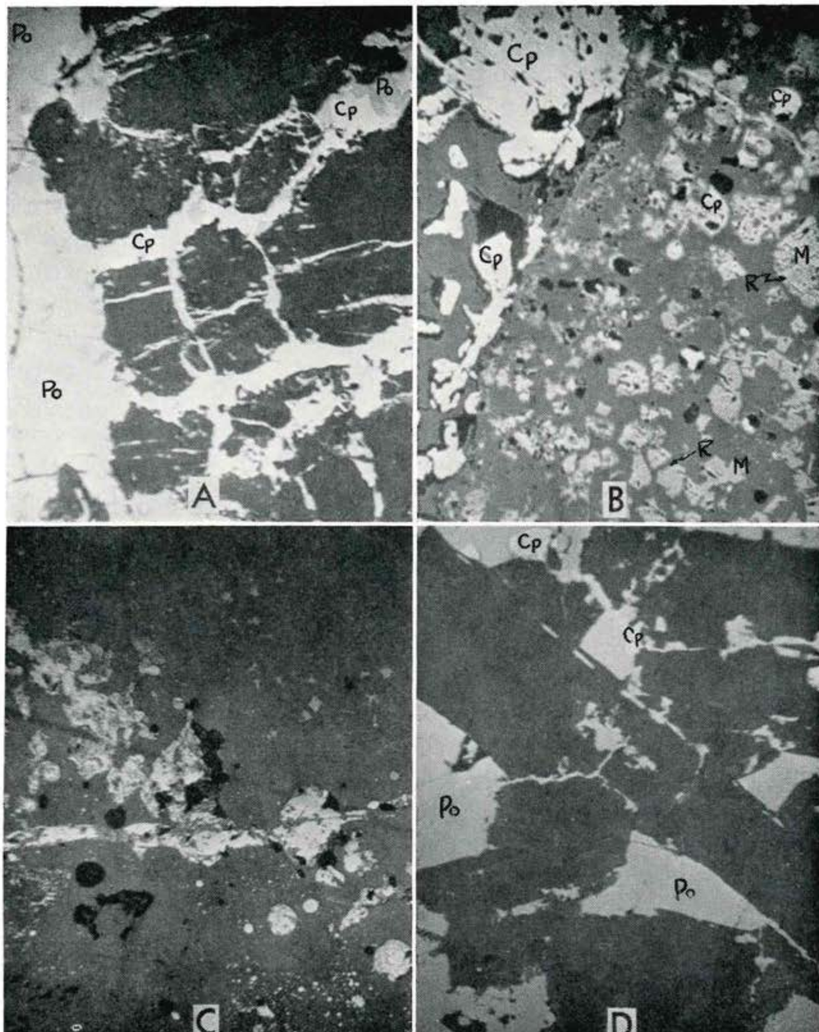
In the Union ore Bastin (1908, pp. 131-136) describes certain "reaction zones" which occur between the olivine and feldspar and pyrrhotite. Along contacts between feldspar and olivine narrow bands of bronzite (?) are present in contact with olivine and these bands grade into hornblende at the feldspar contacts (Plate 9, B). At contacts between feldspar and pyrrhotite Bastin notes a reaction rim of brown hornblende (Plate 9, A). Bastin (1908,

PLATE VII



A. Thin section showing chlorite and biotite veinlets cutting pyrrhotite (black). Katahdin deposit X 90.
B. Thin section showing serpentine veinlets cutting pyrrhotite. Union deposit X 110.
C. Polished section showing veinlet of serpentine trending from lower right to upper left, cutting interstitial mass of pyrrhotite. Gray mineral along the border of the pyrrhotite mass is magnetite. Black Narrows deposit X 125.
D. Polished section showing serpentine veinlet cutting pyrrhotite. Black Narrows deposit X 125.

PLATE VIII



A. Polished section showing veinlets of chalcopyrite (Cp) and pyrrhotite (Po) partially replacing feldspar along cleavage planes. Katahdin deposit X 125.

B. Polished section showing chalcopyrite (Cp) and magnetite (M) in matte. Note interstitial texture of chalcopyrite and fine veinlets of chalcopyrite selectively replacing magnetite along parting planes at R. Cananea Copper Company slag X 125.

C. Polished section showing blebs and veinlets of chalcopyrite in matte. Cananea Copper Company slag X 125.

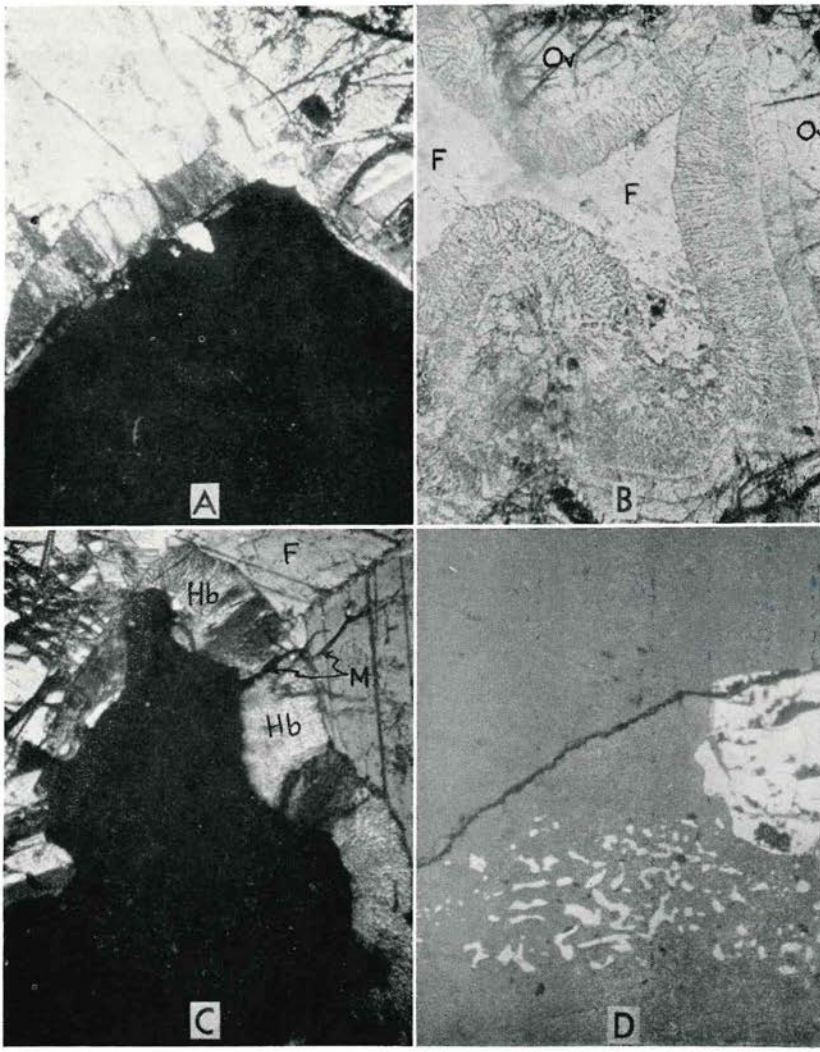
D. Polished section showing pyrrhotite (Po) replacing feldspar (black) along cleavage cracks. Note globules of chalcopyrite (Cp) along contacts of feldspar and pyrrhotite. Katahdin deposit X 125.

pp. 132-133) states, "These relations clearly indicate that hornblende is developed as a result of chemical interchange between plagioclase and the femic minerals, olivine or pyrrhotite." He notes further that these reactions probably involved a loss of soda or an addition of lime or both. These "reaction" zones discussed by Bastin are present only in the Union ores but the zones between pyrrhotite and olivine occur in all the peridotite ores and may be similar in origin to those described by Bastin. In this case the process would involve introduction of water and loss of sulphur with magnetite produced as a by-product of the reaction. In a sense the process of development of the reaction zones might be considered hydrothermal as there is introduction and subtraction of materials and one of the main constituents introduced was probably water. The process is not one of replacement, however, since these zones never occur between grains of the same species and the main constituents involved come from the "reacting" minerals. The significant fact with regard to origin of these ores is that the reaction is later than the mineralization and that the sulphide minerals are affected in the same way as the orthotectic minerals.

The textures of the ores in the Hall-Carroll, Rodgers and Union Bridge properties at St. Stephen contrast considerably with the first group. The sulphides replace all of the silicates, both hydrous and non-hydrous. There can be no doubt that the mineralization was controlled by fractures. The veins actually follow paralleled fractures cutting the silicates, and the sulphides replace the silicates along the borders of these fractures (Plates 10, D, and 11).

Slag Textures

There is a considerable overlap between textures attributed to magmatic ores and those which indicate hydrothermal deposition. Actually a better case can be made from purely textural studies for a hydrothermal origin of all of these deposits than for a magmatic origin. To establish hydrothermal origin, it is somewhat difficult to gainsay some of the evidence such as globules of sulphides in silicates, or the characteristic interstitial occurrence of the sulphides but even in these cases, the globules could be cross-



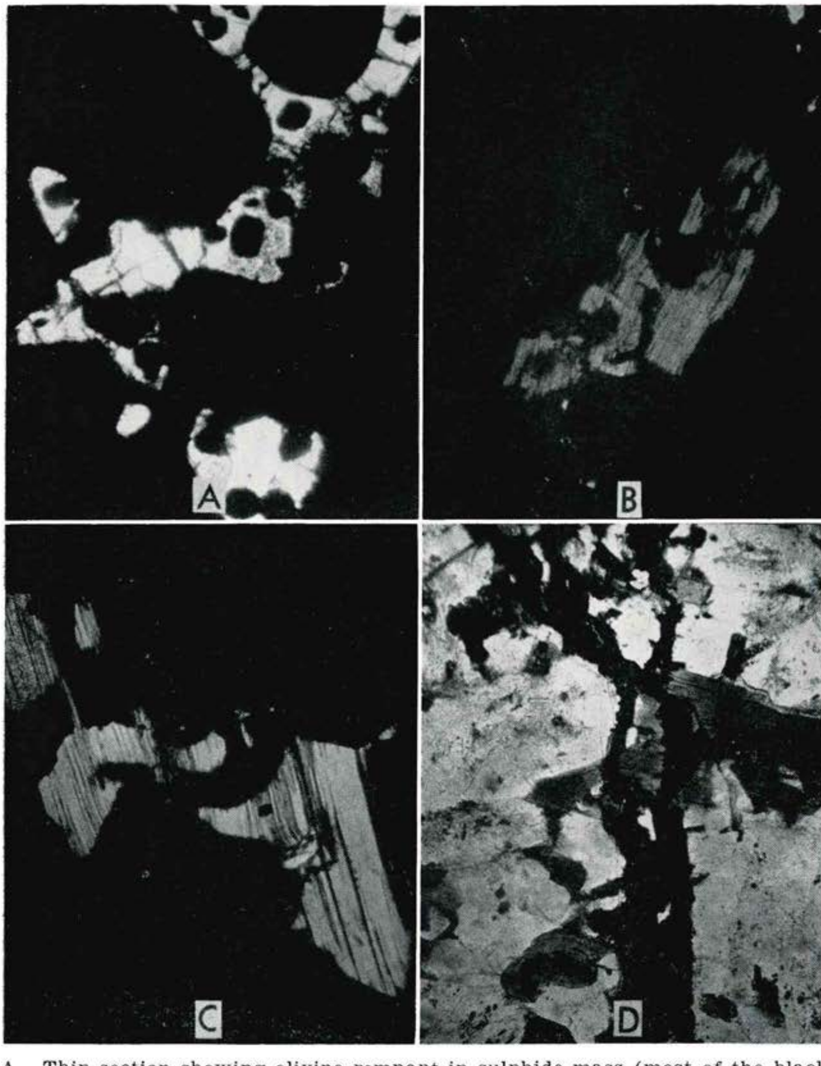
A. Thin section showing reaction rim of amphibole between pyrrhotite (black) and feldspar (gray). Gray mineral in upper right corner of photograph is olivine. In upper left of photograph part of the amphibole border juts into the sulphide. Union deposit X 100.
B. Thin section showing reaction rims of amphibole and orthopyroxene (?) between olivine (Ov) and feldspar (F). Amphibole rim is the wide border nearest the feldspar. Union deposit X 100.
C. Thin section showing reaction rims of hornblende (Hb) between feldspar (F) and pyrrhotite (black). Note veinlets of magnetite (M) cutting feldspar and amphibole. Union deposit X 100.
D. Polished section showing intergrowth of pyrrhotite (white) and pyroxene. Union deposit X 125.

sections of veinlets and the interstitial texture selective replacement. It is difficult to find an ore deposit which has been considered magmatic by all observers to use as a standard in this argument but textures of ore from a slag furnace should come as close to the true magmatic standard as would be possible for a synthetic counterpart.

Mr. R. B. Mulchay of the Anaconda Copper Co. kindly furnished the writer with some specimens of slag from the furnace of the Cananea Copper Company. These slag specimens contained magnetite and chalcopyrite in a matrix of fine-grained silicate minerals. Angular lumps of fine-grained quartz are also present in the slag. The textures exhibited by the slag specimens have every feature found in the deposits of Maine here being described and the surprising thing is that textures showing replacement of silicates by chalcopyrite are actually better shown in the slag than in any of the ore deposits.

The magnetite occurs as irregular masses, rounded blebs and subhedral to euhedral crystals in the fine-grained silicate matrix. In numerous areas, the magnetite replaces the silicates but it has a tendency to occur as discrete crystals of varied habit (Plate 8, B). In certain parts of the same polished section, chalcopyrite occurs both as blebs suggesting immiscible separation from the silicate fraction (Plates 8, C, and 6, C) and in areas where it replaces the magnetite selectively (Plate 8, B). Veinlets of chalcopyrite connect bleb-like masses of the mineral and along the border of these veinlets, chalcopyrite replaces magnetite selectively (Plate 8, C). Veinlets of chalcopyrite cut the quartz grains; chalcopyrite occurs as interstitial aggregates between the individual grains of quartz, and in rich ore zones it replaces the quartz grains. The bleb-like masses must have separated from the silicate fraction of the slag immiscibly and the interconnecting veinlets probably filled fractures which developed before the sulphides had solidified. The writer believes that the replacement of magnetite along the borders of these veinlets is not evidence of a replacement origin for the chalcopyrite but merely a local effect similar to that in natural ores where the sulphides are highly concentrated.

PLATE X



A. Thin section showing olivine remnant in sulphide mass (most of the black is sulphides). Note subrounded crystals of magnetite in olivine. Rodgers mine X 88.
B. Thin section showing chlorite in sulphide mass. Rodgers deposit X 88.
C. Thin section showing biotite remnant in sulphide mass. Rodgers mine X 88.
D. Thin section showing sulphide veinlets (black) replacing biotite (dark gray) and plagioclase (white) along fracture. Note lack of grain boundary or cleavage control. Hall-Carroll mine X 70.

This textural evidence from slag indicates that a great many of the criteria used by economic geologists to signify a hydrothermal replacement origin for ores in mafic rocks is not valid or is dubious, at best. Apparently all that such textural relationships indicate is that the ore minerals solidified late, and that in richer zones, the ore minerals corroded and partially replaced the silicate minerals, as Vogt (Vogt, J. H. L., 1921, p. 639) pointed out long ago. Replacement textures, then, do not always mean that the ore is entirely of replacement origin. Local replacement effects can be very deceiving in this respect.

Nature of Veinlets

The parallel veinlets containing sulphides in the Rodgers and Hall-Carroll deposits are clearly crosscutting. The silicate crystals bordering these veins are broken and displaced. Replacement of the silicates by sulphide minerals may proceed outward from the veinlets (Plates 10, D, and 11). In the other deposits the sulphide veinlets are usually in minor cleavage cracks of the silicate minerals rather than in distinctly crosscutting fractures. Compared to the Rodgers and Hall-Carroll deposits, the veinlets in these deposits are a very minor feature.

An important question bearing on the origin of the ores, is whether the mineralization started from these veinlets and moved outward by preferential replacement of the host rock, or, instead, fractures occurred in the rock before solidification of sulphides and late silicates and were filled by this late crystallizing fraction of the magma. In most of the deposits no definite criteria could be established on this point but in the Exhibition Grounds deposit at St. Stephen, veinlets were well developed and several large specimens were cut into rectangular blocks which exposed the veinlets on four sides.

These veinlets are unusual in many respects. They are not typical walled veins but apparently were formed in the rock just before it solidified. The serpentine and sulphides which fill the veins along different parts of their course do not cut across crystals but move around grains along the course of the veins. Where the veinlets are well defined, euhedral silicate crystals border the

PLATE XI

Thin section showing parallel replacement veinlets of sulphide in fractured norite. Note bent biotite crystal along edge of fracture in upper center of photograph. Hall-Carroll deposit X 125.

vein and the vein material actually "flows" around these crystals. The more persistent veins are composed chiefly of serpentine except where they cross interstitial masses of pyrrhotite, and in these areas pyrrhotite takes the place of serpentine. The zones rich in pyrrhotite in these veins are similar to those of serpentine in that the pyrrhotite apparently worked its way around silicate crystals rather than cutting across them. In some cases where the veins connect large masses of pyrrhotite, they are more regular and filled with chalcopyrite instead of pyrrhotite. In most cases, the veins end by grading imperceptibly into normal norite.

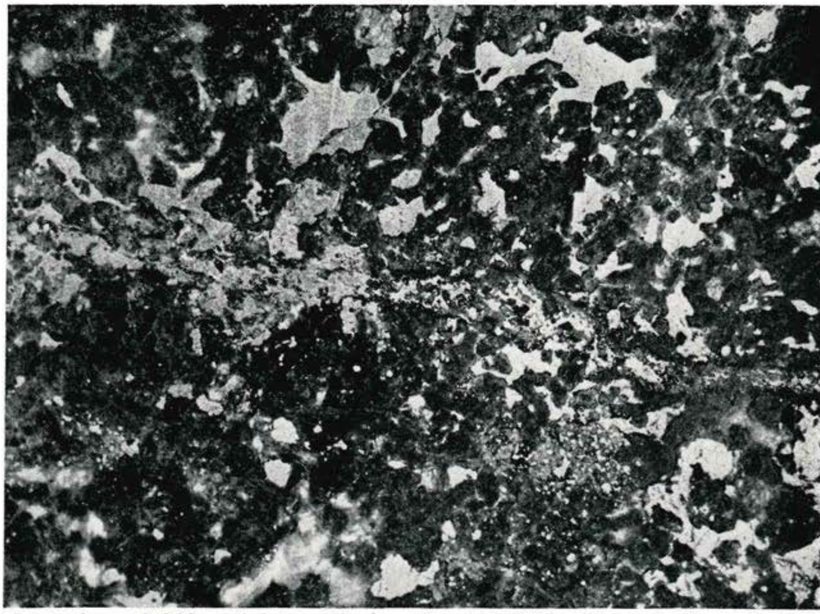
One vein was noted in which part of the vein filling was feldspar which graded into interstitial feldspar just as the pyrrhotite rich zones grade into interstitial pyrrhotite (Plate 12).

These veins do not appear to be the source of the sulphide mineralization. They are not distinct fractures and actually contain relatively small amounts of sulphide. Furthermore, most of the interstitial sulphide masses do not have any feeder connections. The presence of feldspar in one of the veins indicates that at least some of them developed even before all of the orthotectic minerals had crystallized.

Paragenesis

The paragenetic sequence in these ores is approximately the same in all deposits but significant differences occur between the Rodgers and Hall-Carroll ores and those of the other deposits. For this reason two general paragenetic sequences will be given. The primary silicates, called "orthotectic," include olivine, pyroxenes, and feldspars. The later minerals designated as "secondary," include hornblende, quartz, biotite, chlorite, tremolite, actinolite, serpentine, and carbonate. The silicates are treated as a unit unless there is some special significance attached to a particular mineral; if so, it is listed separately. Minerals which occur in two stages (one before, the other after sulphides) are designated by an asterisk and placed in the position in which the major fraction occurs.

PLATE XII



Irregular sulphide veinlet cutting norite. Exhibition Grounds Deposit X 3.

Same veinlet on opposite side of rock but here filled with plagioclase. Note interstitial masses of feldspar grading into vein. Exhibition Grounds Deposit X 3.

Rodgers and Hall-Carroll Deposits

Orthotectic silicates (earliest)
Secondary silicates*
Spinel
Magnetite
Pyrrhotite
Pentlandite
Chalcopyrite
Carbonate
Marcasite
Violarite
Hematite (latest)

Other Deposits: Included here are the Katahdin, Union, Black Narrows and the Exhibition Grounds and peridotitic deposits at St. Stephen:

Chromite (earliest)
Orthotectic silicates
Hornblende
Biotite
Pentlandite (?)
Pyrrhotite
Chalcopyrite
Chlorite
Serpentine
Magnetite*
Tremolite-actinolite
Marcasite
Violarite
Hematite (latest)

Spectrographic Data

A study of the trace elements in pyrrhotite from the different deposits was made by Karl Turekian in the spectrochemical laboratory at Columbia University. Figure 1 shows the results of this study.

FIGURE 1

Deposits	**Cr**	**Ni**	**Co**	**Ag**	**Cu**	**Ti**	**Zn**	**V**	**Al**	**Mn**	**Sb**	**Mg**
Drew Hill	0%	0.01%	0%	0%	0.01%	0.02%	0%	0.01%	0.5%	0.01%	0%	1.0%
Newry Pegmatite	0	0	0	0	1.0	0	0.1	0	0.005	0.005	0	0.01
Katahdin	0.1	0.1	0.1	0	0.1	0.02	0	0.01	0.5	0.01	0.01	1.0
St. Stephen (Rodgers Mine)	0.1	0.1	0.1	0	0.1	0.1	0	0	0.5	0.005	0.01	0.1
Union	0.01	0.1	0.1	0	0.1	0.1	0	0	0.5	0.01	0	1.0
Dracut, Mass.	0.1	0.1	0.1	0	1.0	0.1	0	0	0.5	0.01	0.01	1.0
Ducktown, Tenn. (Mary Mine)	0	0	0.03	0	1.0	0	0	0	0	0.01	0	0.005
Sudbury, Ont. (Frood Mine)	0	0.1	0.1	0	1.0	1.0	0	0	0.05	0.001	0	0.05

No, (Sn, As, Be, Pb, Bi, C, Mo ?)

Each sample was mixed with 2 parts SP 2 graphite to 1 part sample. 5 mg. of this sample was then used for testing under the following conditions: DC arc 17 amps., No. 8 filter only, SP-1 film, high purity electrodes, platform type 36 second exposures.

INTERPRETATION OF DATA AND GENETIC CONSIDERATIONS

Distribution in Host Rocks

The mineralization in the various deposits is not confined to any particular rock type. In both the Union and Black Narrows deposits the mineralization is largely in peridotite, and at Katahdin and St. Stephen norite is the principal host rock. None of the mafic bodies in which the ore occurs can be shown to have any sort of gravity stratification. This is probably due to lack of structural information, but in any case the deposits cannot be considered exact duplicates of magmatic ores like the Insizwa in South Africa where the sulphide deposits have been found at the base of a differentiated intrusion with the heavier immiscible sulphide droplets below the peridotite zone.

This more or less random distribution of mineralization in the intrusions may be evidence in favor of a hydrothermal origin for the ores, since the localization of hydrothermal emanations would be controlled more by fractures in the host rocks than by lithology. Another possible explanation may be that the concentration of sulphur in the magmas, in sufficient quantity to form sulphide minerals, occurred at different times in the different deposits. According to Vogt (1921, p. 664) when the amount of ferrous sulphide in a mafic magma exceeds 0.25% to 0.4% an immiscible sulphide liquid will separate from the magma. Vogt estimated a temperature of 1350-1400°C for separation at this concentration, and stated that a lesser amount of ferrous sulphide would be necessary at lower temperature. Wager and Mitchell (1951, pp. 181-182) in studying the trace elements distribution in the Skaergaard intrusion have shown that the lower and middle layered rocks (hypersthene olivine gabbro, middle gabbro, and hortonolite ferrogabbro) have less sulphur than the original magma, and that with fractionation the amount of sulphur increased in the successive residual liquid. At the fayalite ferrogabbro stage the amount of sulphur had increased abruptly to 4100 ppm and polished sections of this rock showed abundant globular masses of sulphide, which were not found in other rock types. Wager and Mitchell believe that the actual concentration

of sulphur to about 0.2% occurred at a stage even later than fayalite ferrogabbro, after 97½% of the Skaergaard magma had solidified, and that dense sulphide droplets, forming in this late residual liquid, sank and were precipitated along with the crystal phases which formed the fayalite ferrogabbro. The removal of sulphur at this time would reduce the content of later residual liquids and this removal was shown to have taken place.

The fact that the ore occurs in different rock types may then be a question of the time of sulphur concentration rather than evidence of hydrothermal deposition. In any case, the evidence is subject to at least two possible interpretations.

Structural Control

It will be recalled that the Rodgers and Hall-Carroll ore bodies were the only deposits which could be shown to be localized in fractures. The fractures undoubtedly developed after the magma was largely solid, and such evidence certainly suggests a late emplacement for those ores.

Relation to Dikes

Mineralized dikes such as those at St. Stephen and Katahdin are believed to be evidence against a syngenetic origin for ore deposits and their host rocks. Cameron (1943, p. 675-677) contended that the ore deposits at Mount Prospect, Conn., which closely resemble the Rodgers and Hall-Carroll deposits here described, are magmatic in the sense that they appear related to their mafic host rocks, but "not magmatic or even late magmatic in the sense of being syngenetic with any of the rock masses now exposed." Since the dikes are believed to have been emplaced in a previously solid host rock, introduction of sulphides must then follow fracturing of both host rock and dike.

The exact significance of a mineralized dike depends on how the dike originates. Yates (1948, p. 601) states that at Sudbury dikes from the Murray granite are offset by the Frood type of ore breccia. Since the Murray granite is believed to be later than the norite with which the sulphides are supposedly connected, this evidence would place the epoch of sulphide mineralization at a

stage later than the solidification of norite or granite dikes. This is a strong point for hydrothermal origin of the Sudbury deposits.

Scholtz (1936) found mineralized "acid" veins in the Insizwa deposits of South Africa. He believes that the ore deposits in that area originated as immiscible sulphide segregates and that the sulphides separated from the original magma after much of the olivine had crystallized. Since the ore droplets were heavier than the olivine, they settled faster and accumulated on the floor of the intrusion. This ore (segregated at a relatively late stage) was supposed to have associated with it variable amounts of later magmatic products. Sholtz called this volatile-rich ore, "ore magma," and contended that it would contain many of the physical characteristics of a residual granitic differentiate. He believed further that as the temperature of this ore magma dropped, vapor tension increased, making the ore magma an active intrusive. The late magmatic product in the ore might then form veins of variable but acid composition which would be associated with the ore deposits.

Unfortunately evidence was insufficient to determine exactly how the dikes originated in the Katahdin and St. Stephen occurrences. The mafic dike at St. Stephen may be a late differentiate of the norite, but the felsic dikes at Katahdin and St. Stephen could conceivably be remobilized sediments, late differentiates of the norite, or dikes from nearby granitic intrusions. Since both of these felsic dikes contain oligoclase, rather than the albite and microcline which characterize the associated granites, the dikes would not seem to be satellite dikes from nearby granites. The best explanation of the dikes is that they are late differentiates of the mafic magmas or remobilized sediments. Under either explanation the dikes would have filled fractures in already solid host rock. Such evidence as is available, in short, although it does not disprove a magmatic origin for the deposit, does place their stage of solidification as late in the magmatic process.

Relation to Inclusions

Mineralized inclusions such as those at Katahdin and St. Stephen could have been incorporated in the magma before

solidification of the sulphides or could have been mineralized by late hydrothermal solutions. At least, they cannot be considered valid evidence of origin from either viewpoint.

Hydrous Silicate Minerals

Varying amounts of hydrous silicate minerals are present in all of the deposits, and undoubtedly indicate the presence of water associated with the ores. At Katahdin, Union, and Black Narrows, there is no higher percentage of these minerals in the mineralized areas than elsewhere in the rocks, and most of them can be shown to be later than the sulphides. In the Rodgers and Hall-Carroll deposits, however, the greatest development of these minerals is in the mineralized areas and the sulphides can be shown to be later than any of the hydrous silicate minerals.

In the case of the first three deposits the presence of hydrous silicate minerals is not unusual for either mineralized or unmineralized zones, but in the case of the two deposits at St. Stephen the excessive alteration associated with the mineralized areas may be evidence of transport of the sulphides by hydrous emanations. At any rate, there is a definite relationship between the development of hydrous silicate minerals and emplacement of sulphides.

Paragenesis of the Metallic Minerals

Polished section studies show that the metallic minerals follow a general sequence of deposition. This sequence varies slightly with the composition of the host rock, but there is a close resemblance to paragenetic sequences in known hydrothermal pyrrhotite deposits such as those at Ducktown, Tenn. (Ross, 1935, pp. 113-114). If each mineral in the paragenetic sequence could be shown to have been introduced after successive stages of fracturing, a magmatic origin for these ores would be unlikely. Fracturing immediately preceding the deposition of each ore mineral could not be shown, however, in the deposits studied. Furthermore Newhouse (1936) has described the paragenesis of magmatic sulphides occurring in small quantities in igneous rocks and the paragenesis in the Maine deposits, as here described, proves to be the same as that observed by Newhouse. As a mat-

ter of fact many of the microphotographs of sulphides taken by Newhouse showed textures identical with those found in the Maine sulphide ores here described. It does not appear, then, that the paragenetic sequence can be regarded as conclusive evidence for either hydrothermal or late magmatic origin.

Spectrographic Data

The most significant feature of the table of spectrographic data is certain striking contrasts between the trace elements present in those pyrrhotite deposits—Drew Hill, Newry and Ducktown—of undoubted hydrothermal origin and those in the other deposits, all of which appear genetically associated with mafic rocks. Chromium, nickel, and cobalt were present in all of the probably magmatic deposits and, with the exception of a small percentage of nickel at Drew Hill, were absent in the clearly hydrothermal deposits. These data may indicate a genetic difference between the deposits associated with mafic rocks and those of undoubted hydrothermal origin. It is possible, however, that the distinctive trace elements in the pyrrhotite were extracted from the host rocks by leaching of acid solutions depositing the sulphides. There is no doubt about the presence of cobalt, nickel, and chromium in the silicate and oxide minerals of such host rocks (Wager, L. R., and Mitchell, R. L., 1951, pp. 145-159). If the pyrrhotite in all of these deposits had a similar source, then the variation in host rock might account for this difference in trace elements. Therefore the contrast, in trace elements, while suggestive, is not conclusive in determining the origin of the ores.

Replacement Textures

Textures suggesting replacement of minerals of the host rock by sulphides are present in every deposit examined. In general, the replacement of silicates is confined to border zones of massive ore, and the predominant control of replacement is cleavage cracks in the host mineral. The dominant texture of the ores is the interstitial texture with sulphides in masses between orthotectic silicate crystals, a texture very similar to that of late silicate minerals.

Since these replacement textures are present it is at least conceivable that all of these deposits were formed by selective replacement of feldspar, and that the interstitial texture developed because the feldspar was related to other minerals in this manner. Such a theory would demand numerous microfractures through which the ore bearing emanations might migrate. In the ore deposits where the interstitial texture is best developed (Union, Black Narrows, and Katahdin) no such fractures are apparent. Furthermore, the minerals adjacent to the ore are not altered to such an extent as to suggest that large quantities of solutions necessary to carry the ore were present, and since replacement textures can be found in slag where immiscible droplets are common, the textures themselves do not prove a replacement origin. In the case of the vein-like Rodgers and Hall-Carroll deposits where the mineralization is controlled by fractures and where hydrothermal alteration is extensive the previous objections are eliminated and some sort of hydrothermal replacement origin for the ores appears to be the best explanation of their origin.

However, if such a hydrothermal hypothesis is considered feasible for all of these deposits, there still remains the question, why are norites and peridotites generally the favored host rock for such mineralizing emanations. If the emanations did not originate in the host rock, it would seem strange that dense mafic rocks would be the site of deposition when fractured lenses of marble—a carbonate rock, usually preferred by replacing ore solutions—are present in the same area, as is the case for the Union deposit. If the ore solutions originated in the host rock a more feasible explanation might be given for their conflicting characteristics.

The manner of occurrence of sulphides in mafic magmas may depend to a large extent on the amount of sulphur and other volatiles present in the original magma. The stage during the crystallization of the magma when sulphur is sufficiently concentrated to form immiscible droplets may be early in sulphur rich magmas and very late in those deficient in sulphur. Therefore the type of rock in which the ore occurs and its particular characteristics would vary, as it apparently does in the deposits studied.

A magma containing a relatively large amount of sulphur, perhaps slightly higher than the 2,000 g/ton (0.2%) average for gabbro given by Rankama and Sahama (1950, p. 746), may have sufficient sulphur to form an immiscible sulphide phase early in the crystallization sequence. The original sulphur content of the Skaergaard magma was 0.05%, and according to Wager and Deer (1951, p. 180) the concentration of sulphur had risen to one and one-half times this at the ferrohortonolite-ferrogabbro stage. This quantity of sulphur was insufficient to form immiscible droplets in the Skaergaard magma at this stage, but in an average gabbro a corresponding increase from 2,000 g/ton would amount to 0.3%, well above Vogt's lower limit for the formation of the sulphide phase. Whether a sulphide magma actually formed could depend on the size of the original intrusive; that is, if the intrusions were large enough it could have a concentration of immiscible droplets, but if smaller the segregation and localization would be negligible. In the case of small intrusions such as at the Black Narrows and Union masses there may have been sufficient sulphur to form globular droplets of sulphide not long after crystallization of the olivine crystals for the peridotite phase of the rocks was completed. These droplets would sink down into the framework of already crystallized olivine and crystallize along with late interstitial minerals. In the cases cited such sulphide-rich zones would not be expected to be large since the intrusion is small. Their crystallization would be completed before any clearcut hydrothermal alteration occurred and this appears to have been the case in the Black Narrows and Union deposits since most of the alteration can be shown to be later than the crystallization of sulphides. Furthermore, sulphides found at this stage should be rich in nickel since the trace element studies of Wager and Mitchell (1951, p. 187-188) have shown that nickel is more abundant in the earlier fractions. That this is the case is shown by the large quantities of pentlandite as compared to pyrrhotite in these two deposits.

The Katahdin deposit is similar texturally to the Union and Black Narrows, but it is found in norite and has at least one mineralized dike associated with it. The presence of the ore in norite may indicate that immiscibility in this partcular magma

occurred at a period later during fractionation of the magma than at the other two deposits.

Wager and Mitchell believe that the immiscible sulphide phase in the Skaergaard intrusion developed after 97½% of the magma had crystallized and then settled into the partly crystalline fayalite ferrogabbro. Indeed they state (Wager and Mitchell, 1951, p. 135), "Towards the end of the solidification processes there was only a shallow sheet of liquid left in the upper middle part of the complex. This separated into a lower layer of fayalite ferrogabbro of special type and a basic hedenbergite granophyre. Filter press action apparently occurred at about this stage and produced indefinite sill-like sheets of hedenbergite granophyre, together with irregular veins and dyke-like masses." If the concentration of sulphide in the Skaergaard intrusion had been sufficient to form an ore deposit this mineralized zone would have been in the fayalite ferrogabbro, and since Wager and Mitchell believe that immiscibility occurred later than the separation of the fayalite ferrogabbro the droplets may have formed at about the same period as the late acid differentiates. Filter press action could easily explain the presence of ore in these late dikes in the fayalite ferrogabbro. Furthermore, such a late dike might contain minor droplets of sulphide which had failed to settle.

Such a hypothesis may be an explanation for the occurrence of the mineralized felsic dike at Katahdin. The Katahdin norite is more mafic than fayalite ferrogabbro, however, and may have wholly solidified before such a felsic dike could form. A point in favor of the theory, on the other hand, is that the sulphide at Katahdin contains only traces of nickel. This deficiency in nickel would fit a late segregation hypothesis satisfactorily.

Another possible explanation for the dike might be that it formed in a manner similar to that suggested by Scholtz for the "acid" dikes at Insizwa. The sulphide deposit at Katahdin is much larger than those at Union and Black Narrows, and this sizable sulphide magma may have had locally sufficient later magmatic products incorporated in it to form the dikes.

The Rodgers and Hall-Carroll ore bodies are similar in some respects to Katahdin, in that they occur in norite, contain smaller

percentage of nickel than the peridotite ores, and are cut by mineralized felsic dikes. They differ in that they are controlled by northeast trending fractures, have extensive alteration halos, and are dominated by replacement rather than interstitial textures. Most geologists who have examined these deposits (Dickson, 1906, pp. 238-253, MacKenzie, 1940, pp. 31-32) have considered them hydrothermal replacements and their general characteristics certainly favor such a hypothesis. No one, however, has been willing to divorce the mineralization from the host rock. MacKenzie believes that the pyrrhotite separated as immiscible droplets, and that, following fracturing of peripheral sections of the norite, hot water or vapor carrying the nickel and copper sulphide (presumably sulphides which originally separated immiscibly) moved into these fractures and formed ore deposits by replacement.

Since these ore deposits contain small percentages of nickel it seems likely that immiscibility, if it occurred, was at a late stage in the fractionation of the magma. Immiscibility may have been later than the solidification of the norite, and the ore, associated with abundant volatile material present in late fractions, could have been injected in fractured norite. This "ore magma" would be quite different from the sulphide phases previously discussed and may, because of abundant associated volatile constituents, act much like hydrothermal emanations.

CONCLUSION AND SUMMARY

There are many cogent arguments that could be used either for or against each hypothesis, and much of the evidence is subject to two possible interpretations. Regardless of which school of thought may eventually prevail, there must be a clear cut explanation for the characteristic association of these deposits with mafic igneous rocks. It is the writer's opinion that this fact is best explained by the modified magmatic theory presented above.

In summarizing, the facts are briefly stated once more:

1. All of the deposits are in mafic igneous rocks.

2. Two of the deposits are in peridotite and the other two in norite.

3. The mineralogy of all deposits is similar.

4. The content of nickel is higher in the deposits which occur in peridotite.

5. The Rodgers and Hall-Carroll deposits are emplaced in northeast trending fractures in norite, but no structural control is indicated for the other deposits.

6. Mineralized felsic dikes cut the Rodgers and Katahdin deposits.

7. Mineralized inclusions are present at St. Stephen and Katahdin.

8. Replacement textures are found in all deposits.

9. In the Katahdin, Union, and Black Narrows bodies the sulphide is principally in interstitial masses between orthotectic silicates.

10. Sulphide veinlets at the Exhibition Ground deposit are approximately the same age as veinlets of feldspar.

11. At the Rodgers and Hall-Carroll mines sulphide veinlets occur in fractured norite and the sulphides replace bordering silicate minerals.

12. The paragenetic sequence of the sulphide mineral is similar to that of known hydrothermal deposits.

13. Trace elements in pyrrhotite from deposits in mafic rocks all contain chromium, nickel, and cobalt, and these three elements are rare in pyrrhotite of known hydrothermal deposits.

14. The Rodgers and Hall-Carroll deposits have extensive alteration halos, but the other deposits have no more hydrous minerals than are present in unmineralized areas.

15. In the Rodgers and Hall-Carroll mines the sulphides cut all of the hydrous minerals, but in the other deposits most of the hydrous minerals (except brown hornblende and biotite) formed later than the sulphides.

16. Replacement textures similar to those found in these deposits are present in slag which contains numerous globular sulphide masses.

DESCRIPTION OF INDIVIDUAL DEPOSITS

UNION DEPOSIT

The Union deposit is a series of nickel-bearing pyrrhotite zones in peridotite. The peridotite occurs as a lenticular body in an area of regionally metamorphosed sediments, which have been described by Bastin (1908) and classified as lower Paleozoic. The principal rock types in the area immediately surrounding the peridotite are biotite-quartz schist, quartzite, marble, and granite. The metasedimentary complex is isoclinally folded and overturned toward the northwest. It has been intruded first by peridotite and later by granite and pegmatite.

Location

The Union deposit is located three-quarters of a mile southwest of East Union, Maine, in the Rockland Quadrangle (Plate 16). The two main outcrops of pyrrhotite-bearing peridotite are respectively on the farm of Mr. C. Z. Miller, 175 miles S. 56° W. of the dam at East Union and 2.6 miles N. 35° W. of Wattons Mill and another on the northeast bank of Crawford Pond, 0.6 mile S. 20° W. from the first (Plate 20).

History

These deposits have not been mined. The weathered capping from the mineralized rocks east of Crawford Pond has been removed for road material but the several shallow excavations made here expose nothing but oxidized ore.

The deposits were first described by Bastin who made a study of the deposit while mapping the Rockland Quadrangle for the United States Geological Survey. He considered the peridotite a unique rock type, named it lermondose after nearby Lermond Pond, and included a brief description of the rock in the Rockland Folio (Bastin, 1908, p. 5). A more detailed report on the mineralogy of the ore appeared in the same year [Bastin, 1908 (2)].

The writer investigated the area with Dr. R. J. Holmes and Mr. Oscar Strongin of Columbia University in the summer of 1951. Four days were spent in making a preliminary map of the

peridotite and ore deposits at that time. In June, 1952, five more days were devoted to sampling the deposit and completing an outcrop map of the peridotite body. Petrographic and polished section studies were made at Columbia University in the winter of 1952.

Rock Types

Metamorphic Rocks

Biotite-Quartz Schist. The schist is a greyish blue, well foliated rock which occurs throughout the area infolded with quartzite and marble and intimately associated with granite and peridotite. It is probably a highly metamorphosed phase of the Penobscot formation (Bastin, 1908, p. 2) which underlies the greater part of the Rockland area and is thought to be late Cambrian.

The principal areas of schist are two bands parallel to both the eastern and western borders of the peridotite. It occurs inside the areas mapped as peridotite but the contacts nowhere crop out. These exposed schist masses are probably inclusions within the peridotite.

The schist varies considerably in composition. Some phases are quartzitic. Alternate bands of quartz approximately half an inch wide and slightly thicker layers of biotite schist are characteristic of the more gneissic variety. Some phases near the shore of Crawford Pond contain significant amounts of garnet. In other areas near pegmatite and granite bodies, the schist grades into a feldspathic gneiss which contains a high percentage of albite and microcline. Most of the schist, however, is composed dominantly of quartz, sillimanite, and biotite. In this facies, the quartz makes up 30-50% of the rock and the biotite 25-30%. Sillimanite, albite, microcline, garnet, magnetite, pyrite, and zircon are accessory constituents.

Marble. Marble crops out in the western half of the map area; found there it appears as an isolated exposure in a belt trending northeast. Bastin traced this narrow belt for a distance of 2.15 miles from the north shore of Crawford Pond to the western shore of Alford Lake. He considers the marble to be equivalent to the upper Rockport limestone member of his Rockland formation which he assigns to the Cambro-Ordovician.

An isolated outcrop of this marble occurs on the Miller farm a few feet east of the peridotite contact. The marble is a white coarsely crystalline rock which appears unusually pure in the outcrops. A sample examined under the microscope is composed almost entirely of large calcite crystals. Some highly deformed crystals of tremolite, talc, and muscovite were also noted. The texture is granoblastic and the monoclinic minerals are bent around the larger calcite grains.

Quartzite. On the western edge of the map area, an outcrop of very tightly folded white, partly sugary quartzite occurs. Thin bedding planes, the bedding indicated by slender bands of mica, are the only primary structures noted in the quartzite.

Eighty-five to ninety percent of this rock is quartz, which shows strain and signs of recrystallization. Thin bands of muscovite and biotite can be recognized under the microscope, along with minor amounts of microcline and zircon. Although the quartzite lies near the outcrops of marble, the contacts were nowhere exposed. Microscopically and megascopically, the quartzite corresponds to Bastin's Wescag quartzite, which he considers to be the oldest member of the Rockland formation.

Igneous Rocks

Peridotite. The peridotite occurs in an elongated body trending generally N. 20° E. It is bordered on all sides by schist and is intruded by granite along its southeastern border. The relationship between the peridotite and metasediments is not known in the absence of contact outcrops.

The least altered outcrop of the mafic rock is the mineralized body located on the Miller farm. The heavily mineralized parts of the rock are also the most mafic. This variety of the peridotite is dense, massive, and greenish-black. It is composed chiefly of black olivine and pyrrhotite and also contains plagioclase (An_{55}), pyroxene, and accessory magnetite and ilmenite. Late amphibole replaces pyroxene grains, and in some parts of the rock, reaction rims of hornblende occur between plagioclase and sulphide. Further, bands of serpentine surrounding olivine grains grade into amphibole at feldspar contacts. These reaction rims were discussed elsewhere.

The comparatively unmineralized parts of the peridotite contain a higher percentage of feldspar. In fact, one specimen 170 feet west of the Miller ore body could be better classified as norite. This more felsic rock is so highly altered, however, that the original nature of most specimens examined could not be determined. Some of these altered rocks have areas of chlorite and serpentine which apparently are pseudomorphic after olivine, so that it is probable that much of the altered rock was originally peridotite.

The mineralized, relatively unaltered peridotite occurs near the center of the mafic body. Other outcrops examined along the border of the peridotite, are highly altered. The altered rocks consist of serpentine, chlorite, talc, actinolite-tremolite and anthophyllite, with accessory apatite, spinel, magnetite, pyrrhotite, and quartz. In the field, this rock can be recognized by its olive green color and more fibrous texture.

Granite. Rocks of granitic composition and texture occur throughout the area in a great variety of forms, principally in the eastern part of the map area.

By increase in feldspar and quartz, the schist grades into a foliated granite, which has massive phases that appeared to have crystallized from a molten state. The massive granite crosscuts all rock types in the area. It is in places seriate in texture. Pegmatitic phases of the granite occur in the schist with no obvious connecting stringers. Bands of medium-grained material of granitic composition alternate with bands of biotite schist.

The granite outcrops are small, isolated bodies which contain inclusions of schist and peridotite having angular forms embedded in the granite. The reaction between the peridotite and granite has altered the mafic rock to a hornblendite. At the contact between peridotite inclusions and granite, a rim of biotite has developed, less resistant to erosion and therefore slightly depressed. This depressed rim around the inclusions, causes them to stand out in button-like forms in outcrop.

The massive granite is a gray binary granite containing orthoclase, quartz, and albite in approximately equal percentages. These three minerals make up about 70% of the rock. The ortho-

clase crystals are locally unusually large and perthitic intergrowths are common between orthoclase and albite in the larger crystals. Accessory minerals are muscovite, biotite, and microcline. Small quantities of sphene and zircon also occur.

Pegmatite. Pegmatites cut all rock types. The more quartzose pegmatites contain considerable tourmaline. Where pegmatite dikes cut peridotite, there is a pronounced reaction. The contact phases are a coarse biotite schist, which grades through a hornblendite into a peridotite. The pegmatite dikes are associated with areas of mineralization. It does not appear that the dikes influenced the mineralization but they occur in close proximity to the mineralized areas on the Miller farm.

Structure and Metamorphism

The sediments of this area have been altered extensively since their original deposition. The limestones have been changed into marble, the sandstone to quartzite and the shales to phyllite, slate, and schist. Granitizing solutions or emanations from a granitic magma have also altered the sediments. The high albite and potash feldspar content of the schist and the very small granitic injections between layers (lit-par-lit) of the schist are good evidence of introduced material if the schist is regarded as originally an impure marine shale.

These extensive chemical changes in the once typically sedimentary rocks, coupled with tight isoclinal folding, have obliterated most of the original bedding, especially in the present day schists.

As regards structure the recognizable bedding is parallel to foliation except where noses of the isoclinal folds are noticeable. Regionally the foliation strikes N. 20° E. and dips 75-85° southeast, parallel to the axial planes. The isoclinal folds are nearly vertical. Their axial planes generally strike northeast and dip steeply southeast. The plunges of the axial lines vary, but are generally 70-80° to the southwest or northeast.

Bastin interprets the structure as isoclinal, the marble belts having been folded down into the schist. The dip of the axial planes of folds would indicate that the folds have also been overturned toward the northwest in this area.

Ore Deposits

Pyrrhotite occurs throughout the peridotite body. In two localities it makes up approximately 20% of the rock and therefore can be regarded as an ore deposit. The occurrence at Crawford Lake is too badly weathered to yield much information despite the closest study. The weathered ore has decomposed to limonite and clay. Leaching and redeposition gives the surface of the outcrop a layered appearance. Layers, developed in this manner, are rich in limonite and in clay. Two nearly vertical sets of joints, one trending north and the other east, have locally increased the weathering to some extent. However, large amounts of clay, developed from the silicate minerals, decrease the porosity of the gossan and prevent very much transportation of material.

The ore at the Miller farm is a pyrrhotite-rich body of peridotite in which the pyrrhotite content gradually increases from 5% on the edge to 35% in the center of the outcrop. This outcrop is 60 feet wide in an east-west direction and 20 feet long. The surrounding area is covered by glacial drift, but isolated outcrops of peridotite nearby indicate that the mineralized zone is not extensive at the surface.

Olivine with a greasy lustre, pyrrhotite, and chalcopyrite can be identified with the hand lens. The pyrrhotite occurs as interstitial masses between the olivine crystals. Only minor amounts of feldspar are found in the mineralized zones (Plate 5, B).

Mineralogy of the Ores

Olivine (Fe_{80} + —) is the chief mineral constituent of the peridotite. It occurs in proportions from 40 to 60 percent of the rock and makes up approximately 55-60 percent of the mineralized peridotite. Under the microscope, the mineral is colorless but its magnetite alteration mentioned below causes it to be colored black in most outcrops. The freshest grains come from the ore deposit where many of the euhedral crystals are relatively unaltered. Most of the crystals have a border of serpentine alteration and some are criss-crossed by veinlets containing magnetite and serpentine. However, there is no evidence of crushing or fracturing of the olivine grains by tectonic stress.

In the more highly altered zones all stages of alteration of the olivine are present. Some crystals are almost completely altered to serpentine and magnetite, leaving islands of unreplaced olivine inside the area of unaltered minerals. Olivine is the best crystallized mineral present. The euhedral crystals occur as inclusions in orthorhombic pyroxene and feldspar. They are corroded and partly embayed by the pyroxene. Alteration between the feldspar and olivine makes it difficult to determine the exact relationship of these two minerals but the feldspar probably crystallized at a later stage as judged by the relationships determined in numerous other cases cited in the literature. In fact, the form and mineral relationships indicate that the olivine was the first mineral to crystallize from the peridotite magma.

Orthopyroxene ($En_{80}+$ —) occurs as anhedral interstitial grains between olivine crystals and as large crystals which contain poikilitic inclusions of olivine. It makes up approximately 10% of the rock. Originally colorless and non-pleochroic, it has been partially altered to brown hornblende, which replaces the pyroxene along cleavage cracks.

Plagioclase (An_{55}) occurs as interstitial masses between the olivine and pyroxene crystals. It contains some late carbonate veinlets, and where in contact with olivine, is rimmed by fine-grained amphibole.

Hornblende, tremolite-actinolite and anthophyllite occur as secondary products of the original peridotite minerals.

Brown hornblende developed by replacement of orthopyroxene in the fresh mineralized peridotite. The crystals are pseudomorphic after pyroxene. Smaller hornblende crystals occur as reaction rims between labradorite and olivine.

Tremolite-actinolite and anthophyllite occur in the more highly altered, relatively unmineralized peridotite. In some specimens examined, these minerals make up 60% of the rock. Some of the tremolite crystals are very large and can be identified microscopically. These amphiboles are probably derived largely from the pyroxene and feldspar.

Serpentine is found throughout the rock as an alteration product of olivine. It is in veinlets in olivine and in reaction bands

around the same mineral. Along contacts between the two minerals it is very closely intergrown with pyrrhotite. Also veinlets of serpentine cut across the pyrrhotite crystals.

Some late chlorite replaces pyroxene and amphibole.

Characteristically pyrrhotite is in interstitial masses between olivine crystals—much like the feldspar and orthopyroxene. The pyrrhotite contains corroded inclusions of olivine and sends veinlets into the olivine along parting and cleavage planes. It cuts and embays feldspar and orthopyroxene. Along borders of the larger pyrrhotite masses, a very irregular intergrowth is developed, particularly in contact with serpentine. Very fine veinlets of pyrrhotite penetrate the serpentine. This contact zone is in many places filled with magnetite, which has the same textural characteristics as the pyrrhotite (Plate 3, A).

In the more altered phases of the peridotite body, the grains of pyrrhotite are disrupted by growth of later minerals, chiefly amphibole and chlorite. These minerals clearly cut across the pyrrhotite grains and send veinlets into the main sulphide masses. Some of these shattered grains of pyrrhotite can be refitted.

Pentlandite occurs as subhedral grains along the borders of the pyrrhotite masses and is generally associated with magnetite. The magnetite has corroded pentlandite inclusions (Plates 3, A and B). The pentlandite has well developed octahedral parting which in part controls the introduction of magnetite. Pyrrhotite conforms to the pentlandite crystals, and where the two minerals are in contact short veinlets of pyrrhotite enter cracks in the pentlandite.

The most characteristic occurrence of chalcopyrite is in irregular interstitial grains between pyrrhotite crystals. It also occurs as small veinlets, as lath-like bodies in pyrrhotite parallel to (0001) and as large subhedral grains containing veinlets of magnetite similar to those described in the pentlandite.

In some sections, chalcopyrite is common along borders of pyrrhotite masses, where it occurs as veinlets in the silicate minerals.

Throughout the peridotite magnetite appears, partly as euhedral crystals, partly as irregular veinlets crosscutting the silicates. It is a common alteration product of olivine, where it occurs in parting planes associated with serpentine. It is also found along contacts between the silicate and pyrrhotite masses and in veinlets in chalcopyrite and pentlandite. It is the last metallic mineral formed. The euhedral crystals in the silicate may have originated at an early stage but there is no indication of a difference between these minerals in optical or physical properties. As previously noted, some of the magnetite may have formed as an alteration product between olivine and pyrrhotite.

Origin

Bastin believed that the Union Deposit was an example of a magmatic sulphide deposit. In 1908 he stated, "The allotriomorphic relation of nearly all the pyrrhotite to unaltered grains of the original mineral olivine is considered to be conclusive evidence that practically all the pyrrhotite is an original crystallization from the magma and is essentially contemporaneous with other principal constituents of the rock." (Bastin, 1908 (2), p. 128).

In the opinion of the present writer the significant evidence with regard to origin is the following: The more mafic and less altered phases of the peridotite are the more highly mineralized phases; the relatively unmineralized divisions of this mafic body are those parts that are less mafic. If the sulphides at Union were formed from residual hydrothermal solutions as the Ducktown ores are believed to have been, the type of alteration should be the same in both deposits; yet the resemblance between these two is slight as to alteration. Some of the gangue minerals associated with deposits of the Ducktown type (quartz, albite, microcline, biotite, muscovite) (Ross, 1935, p. 41) are locally found in residues of granitic or mafic magmas. In the Union deposit, however, alteration in the mineralized areas is only that normally associated with peridotite bodies. The peridotite inclusions in granite have quartz, zircon and muscovite—which presumably formed by introduction of constituents into the peridotite from the granite—and yet none of these exist in the mineralized areas.

In the altered zones of the peridotite, the sulphides, rather than being altered, have been rearranged by the development of the later, more hydrous minerals. Larger masses have been broken, cut into and shifted by the growth of these later minerals. This indicates that the hydrous minerals developed from an already crystallized peridotite which had sulphide minerals as primary though minor constituents. In other words hydrothermal alteration post-dated primary sulphide minerals.

KATAHDIN DEPOSIT

The Katahdin pyrrhotite deposit is a large sulphide concentration in norite. The norite intrusion occurs in an area underlain by isoclinally folded and foliated slates, phyllites and quartzite of Silurian (?) age.

The sulphide deposit is located 9.15 miles N. 45° W. of the Roundhouse at Brownville Junction, Maine, and 6.7 miles N. 75° W. of Prairie, Maine. It is in the northwest quadrant of the Sebec Quadrangle of the United States Geological Survey (Plate 16).

History

"Ore was first discovered at 'K.I.' (Katahdin Iron Works) in 1843 by Moses Greenleaf, the first map maker of Maine. He had some ore smelted and made a horseshoe which he took to the Maine Legislature to prove his findings" (Stickney, 1952). This discovery was the beginning of a mining industry which lasted until 1890. Mining during that period was restricted principally to the gossan covering of the deposit. In fact, the gossan covering was so extensive during that time that Hitchcock (1861) described the ore as "a deposit of bog iron ore of unknown extent."

In 1890, the Katahdin mine could not meet the competition of the new iron ranges in the Lake Superior District, so mining was discontinued. The mine has not been operated since, although the General Chemical Company of New York did some development work during the mid-thirties. In 1952 the same company

purchased the property from the Piscataquis Iron Works Corporation and some preliminary development work was done on the ore body during the summer of that year. At present the southern end of the ore body is exposed by the early mining operations and the recent development work, and several open cuts along the northern contact serve to delineate the mineralized zone.

Though the geology of the Katahdin deposit is mentioned briefly elsewhere, the only detailed descriptions of the deposits have been those of Bastin (1917, p. 758) and Miller (1945). Bastin states that the ore, rich in pyrrhotite, was intruded into its present position in a molten or plastic condition. Miller's more detailed report includes a reconnaissance map of the norite body and neighboring metasediments, a more detailed map of the ore deposit, and brief petrographic descriptions of the norite and sulphide body. He considers the deposit to be a segregation of sulphides from the norite magma.

Topography and General Geology

The area to the south and southeast of the Katahdin deposit is a great plain covered with drift and underlain principally by Silurian (?) slates. In the vicinity of the norite intrusion the elevation of the surface rises approximately 500 feet and the region to the northwest stands at an elevation of 2,000 feet. This is the front of the Older Appalachian Mountains which extends southwestward into New Hampshire and northeastward to Mt. Katahdin, Maine.

Immediately southwest of the Katahdin deposit, the topography is in part controlled by the bedrock. A large, somewhat oval granite batholith is located here and where it is in contact with slate a resistant hornfels aureole has developed (Philbrick, 1937). The more resistant rocks of the contact aureole stand up as an elliptical ring of hills surrounding the level pluton (Plate 1).

Little is known about the geology northwest and northeast of the area here described. Much of it is a forested wilderness, not easily accessible.

Rock Types

Metamorphic Rocks

The metamorphic rocks consist of fine-grained micaceous slates with interbedded quartzite and zones of phyllite, all tightly folded. The bedding in the slates in the vicinity of the ore deposit is parallel to the northeasterly foliation and vertical in attitude.

The sediments nearest the norite body are chiefly phyllite and quartzite, but the largest part of the district is underlain by slates. Near the granite batholith, the slates have been altered to an andalusite-phyllite and to hornfels. The phyllite extends almost to the norite contact but exposures of metasediments near the norite are so poor as to make it impossible to tell what effect the norite itself may have had on these rocks.

Igneous Rocks

The two principal igneous rocks in the area are granite and norite. Small granite dikes cut the norite and sulphide body and one dacite dike was noted in the northwestern corner of the ore body.

Norite. The norite crops out on the northeastern flank of ore mountain — approximately a mile northeast of Little Houston Pond — and extends downslope to the shore of Silver Lake where most of the surface is covered by glacial drift.

The area known to be underlain by norite, covers about 1½ square miles. Though in large part concealed by drift, the shape of the norite is apparently roughly triangular, and, unlike the granite pluton to the southwest, it does not appear to conform to the regional structural pattern; however, the trend of the sulphide body conforms (Plate 18).

The norite is a massive coarse-grained rock with a granitoid texture. It is dark gray to purplish gray and of a generally lighter hue than normal norite because of the high plagioclase content. It is composed chiefly of plagioclase (An_6), bronzite, augite, and olivine. Though strikingly homogeneous the rock shows minor variations in silicate mineral content, particularly

in the mineralized portions. Almost every norite outcrop contains minor amounts of sulphide minerals, but in proportions of less than 5% except where the outcrops border the ore body. In the relatively unmineralized norite, the chief mineral constituent is labradorite, which here makes up 60% of the rock but generally only approximately 50%. The other primary mineral constituents are orthopyroxene, augite, and olivine.

Olivine (Fe_{75} + —) is much more abundant in the mineralized norite than elsewhere. In the norite the highest percentage noted outside the mineralized zones was 10%. Thin sections of samples from the unmineralized areas contained one or two isolated crystals at most. The mineral occurs as subhedral crystals, averaging 1.1 mm. in diameter. Many crystals are partially altered to antigorite and magnetite.

Next to feldspar in abundance is orthorhombic pyroxene (probably bronzite). In the unmineralized norite, it is present in amounts ranging from 20 to 45%, having an over-all average of 25%. Its crystals vary considerably in size. The majority are medium sized, and about half as large as the olivine crystals but some crystals are 2 mm. in average diameter. These larger crystals contain inclusions of labradorite. Some of the smaller orthopyroxene crystals have fine exsolution lamellae parallel to the (100) plane. In some sections, the orthopyroxene is partially replaced by hornblende, and in the more highly altered zones the pyroxene has changed to fine masses of chlorite and biotite.

Augite is generally less abundant than orthopyroxene, making up approximately 12% of the unmineralized norite. In the more felsic portions of the norite magma, however, clinopyroxene is more abundant than orthopyroxene. The clinopyroxene occurs as subhedral crystals generally larger than the orthopyroxene crystals, and shows distinct twinning, and hour-glass structure. Many of the clinopyroxene crystals are partially replaced by biotite.

Labradorite (An_{60}) is the principal constituent of unmineralized norite. It occurs as anhedral crystals which appear to have formed around the pyroxene and olivine crystals. The growth of the plagioclase crystals ends abruptly against the more mafic

minerals but small crystals of plagioclase also appear as inclusions in the large orthopyroxene crystals. The plagioclase is usually unaltered but some areas contain large amounts of secondary carbonate.

Biotite and hornblende are the most important accessory minerals in the rock. Hornblende is particularly abundant in the felsic phase of the norite where it takes the place of pyroxene. It also occurs in minor amounts in normal norite. The biotite is a reddish-brown, titanium rich variety. It is in minor amounts throughout the rock, usually as interstitial aggregates or as a replacement of pyroxene and amphibole. It appears to be one of the last minerals formed in the magma.

Apatite, chlorite, green hornblende, and quartz are present in minor amounts in the felsic norite, the quartz in veinlets and small interstitial aggregates between pyroxene and amphibole crystals. Magnetite and ilmenite are present throughout but in very small quantities, usually less than 2% of the rock.

Alteration products such as serpentine, chlorite, and carbonate are abundant in some areas. The serpentine is exclusively an alteration of olivine and the carbonate is usually associated with labradorite.

Sulphides—almost everywhere pyrrhotite—appear throughout the rock. Their relationships to other minerals is discussed later in detail.

Granite. The granite is a coarse-grained biotite microcline granite which has been described in some detail by Philbrick. He states (op. cit., p. 7), "Although the pluton is apparently fairly homogeneous lithologically, it contains nine rock types of the quartz-rich sub-alkaline group, ranging from granite through intermediate types to gabbro. They occur in a rather poorly defined series of zones with the acid rocks in the center and basic ones along the border of the intrusive. The center is composed of granite, surrounding which is quartz monzonite and granodiorite. The basic border is composed of quartz diorite, orthoclase-bearing gabbro, quartz norite, quartz gabbro, and gabbro."

One sample of the granite from near Houston Pond was composed chiefly of microcline and quartz with lesser amounts of

biotite, albite, amphibole, sphene, and magnetite. Another sample taken from the railroad cut near Onawa, Maine, was closer in composition to a quartz norite. The latter was near the contact with hornfels and is probably part of the mafic border mentioned by Philbrick. This quartz norite is similar in composition to the more felsic phases of the norite near Katahdin Iron Works but it is not mineralized.

Dikes. Three types of dikes cut the norite and the ore deposit — dacite and aplite, and felsic norite. A poorly exposed dacite dike crops out near the northwest corner of the ore body. The mineral grains are crudely aligned parallel to the strike of the dike. It is composed of zoned plagioclase (An_{50} + —), biotite and quartz with accessory hornblende, chlorite, and zircon. As far as could be determined this dike was unmineralized.

Besides an example cutting a loose piece of outcrop of norite found on the shore of Silver Lake, a felsic dike was noted cutting the edge of the ore body exposed in the open cut near the north-central contact of the mineralized zone. The dike in the boulder is composed of albite, quartz, and biotite and is slightly finer-grained along the contact with norite; the norite is biotitized at the contact.

The third type of dike is in the same locality as one described by Miller (1945, p. 12), who noted an acid dike, four inches thick, which cut a massive ledge of pyrrhotite ore. According to Miller, this dike consists essentially of orthoclase, sodic plagioclase, quartz, and biotite, but it also contains black, opaque ore grains. He considered it an "end-stage product of the differentiation of the gabbro, and to be only slightly later than the formation of the ore body," an explanation that appears acceptable. The dike (?) noticed by the writer, contained microcline, orthoclase, zoned oligoclase (partly altered to reddish-brown iron oxide), quartz, biotite, with accessory garnet, zircon, and magnetite. It looks more like a band of felsic norite than a dike as it can be traced a short distance and the contact with norite is everywhere ill-defined.

The significant thing about the dike just described is that it is mineralized, containing chiefly pyrrhotite with a few inclusions

of chalcopyrite. The pyrrhotite occurs mainly as minute blebs, many of which are perfect spheres. There are no veinlets of sulphide and only one area in which the pyrrhotite is in forms other than as tiny droplets. Here there is a concentration of pyrrhotite, as interstitial aggregates between the silicate crystals. As suggested previously, the bleb-like form of the sulphides indicates that some, while still mobile, were incorporated in the late fraction and crystallized before the other minerals in the felsic dike.

Ore Deposit

The ore body occurs on the northern flank of ore mountain at an elevation of approximately 850 feet. The deposit is located near the northwestern border of the norite, entirely within the mafic host rock. The southwestern border of the deposit is highest and best exposed. The downslope or northern and northeastern contacts of the sulphides and norite are covered by glacial drift and by limonite from the ore body. The sulphide body strikes generally east-west. It is roughly rectangular in shape, approximately 2,000 feet long, and with an average width of 400 feet.

The percentage of sulphides in the mineralized zone increases from 3% in normal norite to 40% in the border zone of the mineralized norite. Near the center of the ore body, the sulphides increase to 75 or 80% of the total. The average content of sulphides in the ore body is about 60%.

No pronounced alteration is associated with the mineralized norite or border zone. The silicate minerals present in the ore are the same as those in normal norite, their only significant difference being the higher percentage of olivine and orthorhombic pyroxene in the mineralized rock.

Structure

The ore body is cut by two major joint sets. The most pronounced trends N. 85° W. and dips from 80° S. to vertical; the other set trends N. 10° E. and dips almost 90 degrees (Plate 13).

The only structure noted in the ore body is a faint foliation along the southern border and a series of rounded inclusions of

a highly quartzoze rock near the south central edge of the mineralized zone, aligned parallel to the contact. The inclusions have been altered considerably by the ore magma. They are composed chiefly of large anhedral quartz grains, clinopyroxene, plagioclase (An_{35}), orthoclase (?) biotite, carbonate, and chlorite. The quartz grains make up 75% of the inclusions and are coarse crystals up to half an inch in diameter. Along the contact with the sulphide-rich norite, the quartz is intergrown with feldspar. This myrmekitic intergrowth is probably a result of recrystallization.

Surface Features and Gossan

At one time during the early development of the mine, the Katahdin deposit must have been completely covered by gossan and glacial drift partially cemented by limonite (Hitchcock, 1861). Today most of this cover has been removed by mining. At the northeastern downslope end of the deposit are small open cuts which expose ore still covered by gossan. The ore in this area is not as rich in iron as in the center of the deposit; hence, the gossan here is probably not as well developed as in other areas. Most of the main features of the gossan can be distinguished, however. The silicate ore grades upward from relatively fresh ore into a zone in which the sulphides have been partially altered to limonite but the feldspars still maintain their original characteristics. Near the surface, the feldspars are kaolinized and the sulphides changed completely to limonite. This weathered covering contains such a high percentage of clay that it is relatively non-porous. In areas richer in sulphide, the gossan looks more normal, that is, it is essentially a boxwork of interconnecting limonite veinlets.

The surface alteration of the ore is controlled in part by the joint sets in the ore body. The weathering is always more intense along the fractures and extends to a considerable depth along these joint planes—at least, as far as the deepest cut into primary ore (20 feet). In the zones of richer sulphide (65-70% FeS) the primary alteration begins with the development of interconnecting veinlets of green melanterite on the surface of fresh ore. If rains do not remove it a crusted coating of yellowish white copiapite develops on the surface along with the melanterite

PLATE XIII

Outcrop of massive pyrrhotite ore at Katahdin showing rectangular joint system in ore body.

(Plate 14). Where ledges afford protection from rain, copiapite has accumulated to a considerable thickness. Most of this soluble sulphate is carried away by sheet wash and by water from two springs in the deposit. Part of it is transported downhill and acts as a cement for the glacial drift, and boulders of ore and norite washed down from the crest of ore hill. This conglomerate covers much of the lower half of the deposit and reaches a thickness of 4 feet in the northeastern corner.

The most striking aspect of the deposit is its general surface appearance. The southern uphill contact of the deposit, well exposed, shows massive ore without much gossan. No really fresh ore can be seen at any point but alteration has not extended below 15 feet except along joint planes (Plate 14). Downslope much of the surface of the deposit is covered by mounds of limonite and hematite left from the early workings, and the area in general is covered by the limonitic conglomerate which increases in thickness downhill. The rusty coating of limonite extends all the way to the swamps bordering Silver Lake and much of the vegetation has been killed by the acid solution. The streams entering Pleasant River below the deposit resemble the red waters of the southern piedmont in contrast with the clear mountain streams of this area. From the air, the ore deposit and the region below it look like a giant red scar on the side of the hill.

Mineralogy

Pyrrhotite occurs predominantly as interstitial masses between the silicate minerals, but also in a great many other ways. Along the border of the deposit numerous rounded blebs of pyrrhotite lie within orthorhombic pyroxenes (Plate 6, B), whereas in the center of the deposit, in sections containing chiefly sulphides the orthopyroxene inclusions are partly rounded and replaced by the sulphides. Two areas were seen where pyrrhotite fills minute veinlets following cleavage cracks in olivine and pyroxene. These relations may indicate that the sulphides were the last minerals to crystallize in the magma, although the blebs, which are definitely not cross-sections of veinlets, suggest early separation in part.

PLATE XIV

Oxidized outcrop of ore body at Katahdin. Note white veinlets of iron sulphate, partly replacing ore.

One interesting relationship between silicates and pyrrhotite is that a certain amphibole clearly cuts the sulphide. In altered relatively unmineralized norite along the southwestern contact of the deposit the pyrrhotite is also veined by late chlorite (Plate 7, B).

Although chalcopyrite is the second most abundant sulphide mineral it is far less common than pyrrhotite, making up less than 2% of the sulphide phase. Its chief occurrence is as irregular grains between pyrrhotite crystals, and along contacts between the pyrrhotite and silicates. Along the contact mentioned it mainly forms small irregular veinlets following cleavage cracks in the silicates (Plate 8, A).

Ilmenite and magnetite are the sole primary oxide minerals in the ore. Only minor amounts of these minerals occur associated with the sulphide rich norite. In fact, in most ore specimens examined with the reflecting microscope the two oxides were absent and where present were invariably associated with the silicates.

Ilmenite is more abundant than magnetite, occurring as irregular interstitial masses in the silicates and showing the same textural relationship to the silicates as the sulphides do. The magnetite occurs as exsolution lamellae in ilmenite and as euhedral grains associated with the silicate minerals.

The only other mineral noted in the deposit was a small bright colored isometric euhedral mineral with a hardness of D, roughly cubic in outline, and tentatively identified as linnaeite. It is negative to all standard reagents. It occurs most commonly near the center of the ore body, but is everywhere in only very small particles and nowhere makes up more than .1% of the sulphides.

Marcasite and hematite occur as alteration products of pyrrhotite. The marcasite alteration is confined almost entirely to the pyrrhotite, but hematite veinlets traverse the entire rock. Marcasite replaced the pyrrhotite along minute fractures which cut the oxidized pyrrhotite in all directions. The mass of replacing marcasite moved outward perpendicular to the fractures and developed irregular jagged contacts with the pyrrhotite. In some cases hematite developed in the center of the marcasite veinlets,

but most of the hematite occurs as walled veinlets without the jagged edges typical of marcasite along contacts between sulphides and silicates. Many of the hematite veinlets have altered inclusions of both pyrrhotite and silicates.

Origin

As stated, the Katahdin deposit is thought to be magmatic. Both Miller (1945) and Bastin (1911) considered it a typical sulphide segregation from a mafic magma. The deposit has characteristics similar to the ores in peridotite at St. Stephen, Union, and Black Narrows, but there are certain significant differences which should be noted. The concentration of olivine in the mineralized norite does not average over 5-10% of the rock, which thus is definitely not as mafic as the peridotites. Very little magnetite or ilmenite appears in the ore, and that present is usually associated with the silicate minerals. No pentlandite is found in the deposit. Except for these differences, the relationship of sulphides to silicates is very similar to that of the peridotite ores.

There is no evidence of structural control of the mineralization or migration of the sulphide fraction, but exposures are really not good. The felsic dike noted in the ore deposit is mineralized, but the blebs of sulphide indicate an early separation, even in the dike.

In the peridotite ores the sulphides may have collected with an olivine fraction that settled early, but in the case of the Katahdin deposit the mechanism of concentration of the sulphides is difficult to visualize. The only other outcrops in which olivine was found were along the southwestern border of the norite. Outcrops here were far too few to demonstrate a concentration along this border, but the banding of the ore body is roughly parallel to it and its dip is towards the northwest. It is conceivable that the sulphides concentrated at this end and larger concentrations of both sulphides and olivine may be found at depth along this border, but until the deposit is better exposed by mining no really sound conclusions can be drawn from the few outcrops available.

BLACK NARROWS DEPOSIT

The Black Narrows Deposit, near the east-central border of Somerset County, Maine, is on the shore of Moxie Pond. The best exposures are at a point in the north-central part of the lake called Black Narrows.

This deposit was discovered in the fall of 1952 by employees of the Great Northern Paper Company. It was subsequently investigated by Forbes Wilson and J. E. Bowenkamp of the Freeport Sulphur Company, and a map of the best exposed areas was prepared by Mr. Bowenkamp (Plate 18). The writer did not study this area in the field hence the following information is based on Bowenkamp's description of the deposit and on a petrographic study of his samples by the present writer.

General Features

The deposit is a mineralized zone in a mafic igneous rock trending northeast. The host rock, a mass of peridotite and altered norite, intrudes Silurian quartzite with which it is in contact on its southeastern border. The exact extent of the mafic rock is not known. The area near the intrusion was investigated briefly by Wilson and Bowenkamp, but glacial drift covers most of the surrounding district and the only evidences of extensions of the mafic body are erratics of norite and peridotite found near the outcrops on the shore of Moxie Pond.

Petrography of the Metasediments

The intrusion is in contact with quartzite on its southeastern border. According to Bowenkamp, the foliation in this rock strikes approximately N. 40° E. and dips 75° northwest (Plate 18). The rock is a quartzite with small quantities of pennine, biotite, and subrounded rutile and zircon crystals. It contains muscovite-chlorite bands about half an inch wide and one inch apart. One sample taken near the contact showed no evidence of contact metamorphism, but the quartz of which the rock is composed does not furnish conclusive evidence as to the capacity of the intrusion for altering the country rock.

Petrography of the Mafic Intrusion

Peridotite occurs along the southeastern border of the intrusion in a band 250 feet wide and grading into an altered norite which extends in a northeasterly direction for at least 600 feet (Plate 18).

Peridotite

The peridotite is almost identical with that at Union, Maine. It is composed dominantly of olivine (Fe_{75}), with minor amounts of plagioclase (An_{70}) and orthopyroxene (En_{70-75}). Biotite makes up about 3% of the rock and occurs as interstitial masses between plagioclase and olivine. This is the only peridotite examined which contained chromite. Small euhedral chromite crystals are scattered through the rock; these crystals are cut by late magnetite and pyrrhotite. The rock is highly altered. Serpentine, talc, and magnetite replace the olivine, and chlorite is a common alteration product of the pyroxene. Phases of the rock, discussed later, contain as much as 20% pyrrhotite.

Norite

The more felsic phase of the rock is similar to the border phases of the peridotite at Union, Maine, but is not so highly altered. A distinct alignment of grains can be seen in hand specimens. The specimen examined was composed chiefly of zoned plagioclase (An_{55}), the only primary mineral that could be recognized. Brown hornblende makes up about 10% of the rock and the nearly rectangular cross section of some of its crystals suggests pseudomorphism after pyroxene. Aggregates of chlorite, talc, and tremolite constitute zones in the rock and irregular veinlets of chlorite cut across all minerals. Accessory minerals are sphene, apatite, pyrrhotite, chalcopyrite, quartz, and rutile. Another alteration mineral is zoisite, which occurs in aggregates associated with chlorite and sericite, replacing the feldspars.

The manner of occurrence of pyrrhotite and chalcopyrite in the rocks is especially interesting. The pyrrhotite makes up interstitial masses drawn out parallel to the foliation. It also is in bleb-like masses, in part elongate and vein-like, trending parallel to the foliation. Small veinlets extend outward from the larger

sulphide masses. Such veinlets are crenulated in a manner suggesting that they were aggregated before becoming completely solidified. Chalcopyrite occurs along the border of these zones and in veinlets similar to those noted at Katahdin. The sulphide masses are cut by late silicates, serpentine, tremolite, and chlorite. The evidence suggests that deformation took place before or during solidification of the sulphides and that most of the alteration is later.

The Ore Deposit

The mineralized phases of the peridotite contain as much as 20% sulphide. They are identical in every respect with those at Union, Maine. The pyrrhotite, pentlandite, and chalcopyrite resemble those at Union, but the associated alteration is more extensive and serpentine, magnetite, and chlorite cut the sulphides. Serpentine veinlets transect large masses of pyrrhotite in many cases partly filled with late magnetite (Plate 11, Figs. 3 and 4).

Origin

It is the writer's opinion that this deposit originated in the same manner as those at Union, Maine, and that it is essentially magmatic.

ORE DEPOSITS OF THE ST. STEPHEN DISTRICT

Location and General Features

The St. Stephen deposits are nickel-copper pyrrhotite bodies which occur near the margins of a large mafic intrusion. The mafic body is located in and around the town of St. Stephen, N. B. It surrounds the town as a sort of half halo to the north, east, and west. Only a small portion of the intrusion extends into the United States, and this is entirely within the town of Calais, Maine (Plate 17).

Topography

This region is part of the upland which occupies much of northern Maine and extends into New Brunswick. The surface

is a series of gently rolling hills spotted with glacial drift and erratics. Outcrops in the area are relatively abundant for so glaciated a region, but still too few for entirely satisfactory geologic mapping. Most of the larger outcrops have smooth polished surfaces, in places distinctly striated by glacial action.

The valleys are drift covered, but the larger streams in the area (e. g., Dennis Stream) cut through the drift, affording good bedrock exposures.

General Geology

The mafic pluton is intruded into a series of metasedimentary and volcanic rocks considered pre-Silurian in age (Alcock, 1945). The pluton was emplaced after Arcadian folding (McKenzie, 1940). This intrusion was followed by invasions of more felsic rocks of granitic composition which cut the mafic intrusion at its southwestern extremity.

Rock Types

Metasedimentary and Volcanic Rocks

The metamorphosed sedimentary and volcanic rocks are part of the "dark argillite" division of the Charlotte group. This series is made up largely of "dark argillitic and quartzitic varieties, locally rusty, and in places metamorphosed into schists and gneisses carrying garnet, staurolite, etc." (Alcock, 1945). Though barren of fossils, these rocks are overlain unconformably by Silurian beds and probably are Ordovician.

The principal rock types in areas adjacent to the mafic body are dark shales and phyllites with interbedded lenses of quartzite. Northwest of St. Stephen some of the slate along the border of the intrusion is altered to an andalusite schist. The micaceous quartzites in contact with norite near the Rodgers deposit are partly recrystallized and contain sillimanite at the contact.

Structure of Metasediments. The regional structural trend of the metamorphic rocks is northeasterly; the dip of the majority of the planes of schistosity is towards the southeast. The trends of foliation of the metamorphic rocks diverge around the mafic intrusions and despite great variation in the foliation from point to point, the general dip is towards the center of the intrusive.

The beds are isoclinally folded and the strike and dip of the bedding and foliation are generally parallel.

Igneous Rocks

Mafic Complex. The mafic body may be divided into three principal rock types—peridotite, norite, and anorthositic norite. The peridotite crops out in the northeastern corner of the complex and is bordered by a zone of banded anorthositic norite. The other part of the complex is chiefly norite, although there are many variations from point to point. It is probable that the variations in the mafic complex are much more complicated than indicated in surface exposures. Drill holes put down in the vicinity of the sulphide bodies and in areas indicated as promising by a geophysical survey show that there are alternate layers of norite and peridotite in the vicinity of the Rodgers mine, and that much of the area shown as anorthosite on the map (Plate 17) is underlain by peridotite.

Structure. The mafic intrusive is, in places, distinctly foliated. The foliation is confined chiefly to the noritic and anorthositic varieties in which there is distinct alignment of the feldspar grains and parallel bands of mafic minerals — orthorhombic pyroxene and olivine.

Banding in the anorthositic and noritic phases of the rock has been described by Dunham who states: "Particularly along Hanson Road and in the small stream valley north of town, banded units with alternations of anorthositic and troctolitic types" occur. The banding and foliation are parallel in strike and dip. The strike of the foliation in the northwestern part of the intrusive is northeasterly — generally parallel to the foliation of the metamorphic rocks; but nearer the center of the deposit it is more nearly east-west. The dip is 90-70° S.

Distinct alignment of grains is not noticeable in the peridotite, but numerous bands of serpentine which replace the olivine give the rocks a banded appearance. These serpentine veinlets are up to one inch in width and are present throughout the rock. Their strike and dip are parallel to the foliation of the anorthositic rock.

An examination of the over-all structural pattern of the adjacent sediments and primary structure in the mafic body indicates that the intrusion may have the shape of an inverted cone or U-shaped body plunging southwestward. The sediments are definitely bowed outward around the pluton and their foliation dips generally toward the pluton which suggests that the latter may have an inverted cone shape, but the structure in the pluton, as far as can be ascertained, does not entirely conform to this pattern. Along the northeastern end of the pluton the primary foliation conforms roughly to the pattern of the surrounding sediments and dips steeply south, but the pluton is cut by granite in the southwest and there the foliation is not distinct. In short, it is questionable whether or not the original structure was actually conical or U-shaped. Dunham (1950, p. 725) has suggested that where the banding is conformable to the country rock, the bands may have originated as horizontal layers prior to the regional folding. A more detailed structural study may settle this question if adequate outcrops can be found.

Petrography. The main body of peridotite is located in the northeastern part of the intrusion. It is an elongate mass with its longest axes trending generally parallel to the regional structure. Drill holes in anorthosite bordering the peridotite indicate that peridotite occurs at depth beneath this rock type. The peridotite is composed chiefly of olivine with interstitial orthorhombic pyroxene and labradorite. Reddish-brown biotite and hornblende are accessory minerals, forming interstitial aggregates. The hornblende is in part a replacement of orthorhombic pyroxene. Euhedral magnetite crystals are scattered throughout; some have exsolution blades of ilmenite. Numerous veinlets of serpentine (antigorite) and secondary magnetite traverse the rock, butting across all the minerals. As noted by Dunham (1950), the most interesting aspect of these veinlets is that they are best developed where they cut across olivine crystals, and that the smaller veinlets narrow when they pass from an olivine crystal through feldspar or orthorhombic pyroxene to another olivine crystal. These bands or veinlets of serpentine that cut across the minerals appear to be replacements as there is no evidence of fracturing of the olivine crystals or otherwise. It is possible that

the serpentine alteration of olivine developed this preferred orientation because of some original strain not now apparent.

Some of the larger serpentine veinlets which cut the rock have borders made of concentric layers of antigorite parallel to the strike of the veinlets. The cores of such veins are cross fibres of chrysolite at right angles to the strike of the veins. Magnetite is not as abundant in the larger veinlets of this kind as in the smaller ones.

Minor concentrations of sulphides are present in some facies of the rock. The sulphide minerals are pyrrhotite, pentlandite, and chalcopyrite. The three main sulphide minerals usually occur together in irregular interstitial masses, between the olivine crystals. The relationship of plagioclase feldspar to the olivine is structurally like that of the sulphides to the olivine (Plate 7, Fig. 3 and 4)

Most of the sulphide masses are composed of pyrrhotite (the most abundant sulphide) enclosing euhedral crystals of pentlandite. Chalcopyrite occurs as veinlets and globules in pyrrhotite and along contacts between silicate minerals and pyrrhotite.

The oxides formed in the rock are magnetite and ilmenite. The former originated in two stages. Early euhedral magnetite crystals were replaced by the later magnetite associated with the serpentine veinlets. This late magnetite may be the last mineral formed in the rock since it cuts the sulphides in a few places.

Anorthositic norite, as pointed out by Hale (unpublished thesis, 1950), occurs chiefly around the borders of the peridotite. The units mapped as anorthosite by the writer include more mafic rocks containing up to 25% olivine and pyroxene, but in which the major part of the rock is over 80% salic. The rock is light colored and distinctly foliated. The feldspar laths are crudely aligned, and in the more mafic phases there are parallel bands of olivine and pyroxene which alternate with zones rich in feldspar. Such texture occurs both on a microscopic and megascopic scale.

Hale (1950) states that the anorthosite is younger than the peridotite as shown by the intrusive relationship of one to the other, but no clear contact between the two rock types was noted

by the writer. In one outcrop on the northeastern border of the peridotite a light colored phase of the magma (possibly anorthosite) contains subrounded inclusions of peridotite. Along the southwestern border of the peridotite the contact is apparently gradational.

The more felsic phases of the rock contain up to 85% labradorite (An_{67}), but an overall average is probably nearer 65%. The next most abundant mineral, olivine, makes up from 5 to 20% of the rock. Troctolitic phases mentioned by Dunham are bands rich in olivine lying in anorthositic norite. Other primary minerals are clinopyroxene, orthorhombic pyroxene, and magnetite. The clinopyroxene was not abundant in the sections examined by the writer, the largest percentage noted being less than 3%. The mineral occurs as subhedral crystals, about the size of the olivine grains, scattered through the rock. Orthorhombic pyroxene occurs as narrow borders around the large olivine crystals and in irregular veinlets between the plagioclase grains.

The degree of alteration of the rock varies considerably; however, it is nowhere as pronounced as in the peridotite and norite. The most pronounced alteration is of the olivine and orthorhombic pyroxenes. The first alteration of the orthopyroxenes is to a brown hornblende; more complete alteration is to a fine-grained talc-amphibole-chlorite mixture. The olivine alters typically around its borders to an antigorite-magnetite mixture, bordered by a band of talc around which in turn is a halo of chlorite. A less widespread alteration is of the plagioclase to carbonate and talc and some biotite, formed last and, at least partially, at the expense of magnetite.

This felsic variety of the mafic complex is not heavily mineralized. In most of the section only a few grains of sulphides were present, generally in bleb-like to subhedral grains. Most of the grains are cut by late silicates — biotite, chlorite, and serpentine; some have magnetite reaction rims. It seems probable that these sulphide crystals are primary and that they formed in the rock before most of the observed alteration occurred.

In contrast to this prevailing form of sulphide content, mineralization of a different kind was noted near the point where

the west branch of Dennis Stream crosses the Basswood Ridge road. Here narrow mineralized bands occur which strike north-south and dip vertically — a trend perpendicular to the foliation in the rock. The host rock is very high in feldspar — approximately 87% — and except close to the mineralized areas is essentially unaltered. Near the mineralized zones the country rock is strongly chloritized, the feldspar being fractured. Here some faulting has apparently taken place. The sulphide minerals are pyrrhotite and chalcopyrite. These two minerals are associated with large subhedral magnetite crystals, and, along with a younger generation of magnetite, they replace the silicate minerals.

The term norite is here restricted to that part of the mafic complex in which the orthopyroxene is more abundant than clinopyroxene, and in which the mafic constituents make up at least 25% of the rock. However, this rock is very heterogeneous; part of it contains as much as 20% olivine and other areas contain chiefly orthopyroxene. The average norite consists of labradorite, orthopyroxene, olivine, and clinopyroxene. The ratios of these minerals varies, like the degree of alteration, from one area to another. Except in the mineralized zones and near contacts with metasediments the minerals found in the norite are nearly identical with those found in the more felsic rocks — the only difference is one of proportion. Dunham (p. 723) has pointed out that the olivine and plagioclase are of uniform composition throughout the different phases of the mafic magma.

Like the anorthositic norite previously described, the norite is also foliated but this feature is more variable in the norite and not as pronounced as in the felsic rocks. In the south-central area its foliation is, however, generally similar to that of the felsic rocks. The norite contains parallel bands of mafic minerals which trend generally N. 80° E. to due E. and dip steeply southward. Along the northwestern border of the deposit the general trend of foliation is not as pronounced and is northeasterly, more nearly parallel to the trend of the invaded sediments. Here it is due to a parallel alignment of large feldspar grains, rather than banding of feldspar and mafic constituents, as farther south. It is possible that the foliation in this area is in part inherited from

the trend of the invaded metasediments, abundant as inclusions in the norite. Dunham (p. 725) states, however, that "where interaction of the igneous complex and the sediments can be studied, mixed rocks rich in hydroxyl-bearing minerals are found"; and that "the large included hornfels masses showing bedding are surrounded by norites which fail to show trending." This fact is borne out by the writer's study of contacts near the Hall-Carroll deposit.

Studies of thin sections along contact zones between the micaceous quartzite and norite near the site of the Rodgers mine essentially substantiates the work of Dunham. The norite grades into a highly altered quartz amphibole diorite near its contact with the micaceous quartzite. The zoned plagioclase makes up about 35% of rock and has the composition $An_{45.0}$. Considerable amounts of biotite, chlorite, and magnetite are also present in the rock. Nearer the contact the content of feldspar decreases and muscovite becomes a major constituent. The reaction zone between metasediments and norite is composed chiefly of biotite, muscovite, calcite, recrystallized quartz, and magnetite. The three micas occur in approximately equal ratios and together make up 65% of the rock. Small needle-like crystals of sillimanite are associated with the quartz. At the contact near the Rodger prospect the metasediment is partly recrystallized. The quartzitic bands contain areas of recrystallized quartz with grain size three times that of the normal quartzite. Cordierite is also present in these quartzite bands. The micaeous zones are chiefly biotite, muscovite, and chlorite. The amphibole noted in the unaltered quartzite has apparently been altered to mica. The major differences between this and unaltered quartzite are in increase in biotite, recrystallization of part of the quartz, appearance of cordierite, and lack of amphibole. Dunham (p. 720) notes apatite in both norite and sediments in this zone.

In the area south and southwest of the Hall-Carroll deposit the norite contains lenticular zones which have minerals up to half an inch in diameter. The minerals noted by the writer in these pegmatitic zones were plagioclase, amphibole, biotite, and ilmenite. Dunham (p. 722) made a detailed study of such a pegmatite area and found the plagioclase to be An_{50} to An_{32} (zoned out-

wards) and the amphibole to have an nZ[1] varying from 1.664 to 1.660. He also noted apatite, chlorite, quartz, and calcite.

Granite. At its southwestern border the mafic complex is cut by granite — part of a larger body of igneous rock underlying the eastern part of Washington County, Maine. This complex is composed of granite and related igneous rocks of widely varying composition; but the northeastern corner of the pluton in contact with norite of the mafic complex is a granite with quartz, microcline, and biotite. In the Eastport area this granite has been dated as pre-Upper Silurian and post Upper Devonian (Bastin and Williams 1914, p. 13).

Along the border between the granite and norite are numerous xenoliths of metasediments. Several kinds of intermediate rocks (diorite, syenite, quartz diorite, and gradation phases) are injected along the border between granite and norite. They are foliated parallel to the structure of the sedimentary inclusions and were probably formed, at least in part, by reaction with the sedimentary rocks. The younger granite crosscuts these gradational phases, and along contacts with the metasediments it generally contains large metasedimentary inclusions with random orientations.

Dikes. Both mafic and felsic dikes cut the norite and ore deposits. Both types of dikes are particularly common in the northwestern part of the mafic complex. The dikes noted by the writer strike generally due N. to N. 20° W. — approximately perpendicular to the foliation of the coarse grained rocks.

Examined microscopically, a mafic dike cutting the ore deposit consists principally of parallel grains of green amphibole and zoned andesine (An_{45}). It also has a few scattered grains of subrounded (corroded?) quartz. Areas in the dike contains spherical aggregates of chlorite and amphibole radiating from several centers. These spherulitic zones are bordered by reddish-brown biotite.

In the Rodgers mine a small felsic veinlet cutting the mafic dike was also noted in the ore deposit. It is composed of quartz and zoned oligoclase (An_{10}-An_{20}), with minor amounts of biotite

and magnetite. The plagioclase is partially altered to chlorite and sericite.

It is evident that these dikes cut the norite after it had solidified and are therefore later than the norite. The mafic dike is probably part of a late stage of activity of the mafic magma. The felsic veinlets could have come from the nearby granite magma or from remobilized sedimentary rocks, or they may represent final differentiates of the mafic magma as suggested by Koch (1930).

Felsic dikes were noted in the granite near its southern contact with the mafic complex. These are considerably more felsic than the one in the ore body. Even the granite, a microcline albite biotite granite, is more felsic than these dikes, since the latter contain chiefly oligoclase feldspar. Aplite dikes derived from the granite may cut the mafic complex, but the dike noted in the ore body more probably came from another source.

Dunham (1950, p. 720-721) discussed the effect of the St. Stephen norite on included masses of country rock and noted that micaceous minerals have been converted into a deep brown biotite and the quartz was recrystallized to a decidedly coarse-grained size. New minerals such as hypersthene and cordierite have been generated in the quartz-chlorite-muscovite phyllites. Dunham notes further that near large xenoliths of hornfels a stage can be recognized representing the feldspathization of the hornfels, or the mingling of constituents derived from the hornfels with crystallizing feldspars. Quartz is the final product of crystallization in this mixed rock and the plagioclase is more sodic and finer grained than in the norite.

Northeast of the Rodgers mine several isolated outcrops expose what appears to be a contact between altered norite and micaceous quartzite. One such outcrop, apparently directly on the contact, consists of brecciated country rock with numerous cross-cutting igneous veinlets. Thin sections of samples taken across this outcrop from norite to quartzite confirm Dunham's statements regarding the highly altered contact norite — that the pyroxenes are largely altered to hornblende and chlorite, and the plagioclase is here more fine grained and sodic. Near the breccia

zone the norite grades into a rock composed of recrystallized quartz, large muscovite crystals, biotite, masses of fine-grained chlorite, sheaf-like aggregates of sillimanite, a few fresh crystals of orthoclase and plagioclase, and scattered grains of pyrrhotite. This rock is probably part of the mixed zone, described by Dunham, where there is a mingling of constituents between the hornfels and norite. In the breccia zone the included fragments are masses of biotite and chlorite, but the apparently igneous material is principally recrystallized quartz with associated muscovite, chlorite, and plagioclase (zoned outward, An_{30-45}). This is probably an area in which the constituents of the micaceous quartzites have been locally remobilized with some introduction and subtraction of material.

Xenoliths of sediments similar to this quartzite have been found in the ore bodies. They are reported in cores from both the Rodgers and Hall-Carroll deposits, but are not exposed at the surface. Except for a higher percentage of plagioclase, the felsic dike found in the Rodgers mine is similar in composition to the remobilized (?) sediments. Although the evidence is far from conclusive it seems possible that such felsic dikes are either remobilized sediments or final differentiates of the mafic magma.

Ore Deposits

Four main outcrops of sulphide ore are within the borders of the mafic intrusion. Three of these (Rodgers, Hall-Carroll, Union Bridge) are near or on the border of the mafic pluton, and the other (Exhibition Grounds Deposit) is in the east-central part of the pluton (Plate 17). All are within the "noritic" phase of the igneous intrusion. Zones with disseminated sulphides occur in several other areas within the intrusive body in both peridotite and norite. As noted previously, the felsic or anorthositic part of the intrusive is mineralized in only one area and there the mineralization is minor and localized to shear zones. No other sulphide deposits are known outside the mafic rock.

The Rodgers and Hall-Carroll deposits are veinlike bodies of sulphides with fairly regular contacts. They are believed to be localized in fractures within the norite. The Exhibition Grounds

deposit is a disseminated deposit of sulphide with no apparent structural control. The mineralogy is similar in all of the deposits. The variations are principally in proportions of the various minerals rather than in new species. Details are given below.

The surface cover at the Rodgers and Hall-Carroll deposits is a conglomerate of glacial drift cemented by limonite, very much like the one at Katahdin. Thin gossan, identical to that at Katahdin, has also developed over the richer ore zones.

History

In his detailed account of the history of these deposits, McKenzie (1940, p. 24) states: "The presence of nickel in the area was first recorded by Bailey and Matthew (1870-71, p. 238) as a result of an analysis of a specimen of serpentine from north of St. Stephen. Traces of chromium are also reported in the same analyses. In 1880 pyrrhotite carrying some nickel and accompanied by chalcopyrite was discovered at St. Stephen. The deposits were examined and described by Bailey (1897, pp. 23-30) who gives a good summary of early discoveries and development work. Various analyses of the ores are published in early reports of the Geological Survey of Canada. Features which have a bearing on the origin of the deposits are described by Dickson (Dickson, C. W., 1906), and polished specimens of the ore are described in a paper by Campbell and Knight (1907, p. 274). Interest in the deposit lapsed when no ore bodies of a size and value comparable to those at Sudbury, Ontario, were discovered." McKenzie also describes further activity in the area between 1928 and 1939. A number of different parties held mineral rights on the various properties during that time and some trenching and geophysical prospecting was done in the area. The most intensive prospecting was that by Combined Geophysical Methods of New York under the direction of Mr. Bela Low and Hans Lundberg Limited under the direction of Dr. R. Grimes-Graham.

In 1947-48 the property was investigated by the International Nickel Company of Canada, Ltd. During that time 32 diamond drill holes totalling 15,911 feet were put down, and further magnetometric surveys were made by Hans Lundberg, Ltd. The mafic complex was mapped by Ernest Hale in 1950, and a detailed

petrographic study of the mafic complex was made by Dunham (1950). The properties were claimed in April 1952 by a company of Toronto, Canada, but no development work has been done to date.

Mineralogy

The metallic minerals in the deposits are pyrrhotite, chalcopyrite, pentlandite, niccolite, violarite, magnetite, and hematite.

Pyrrhotite is the chief constituent of all the ore deposits. Microchemical tests show no unusual characteristics of the mineral nor do they indicate variation from one rock host to another. The pyrrhotite usually occurs in masses which contain anhedral crystals 0.4 mm. in average diameter. Two specimens examined from the Hall-Carroll property were distinctly strained. The direction of strain varies from one grain to another, as if each grain were affected in a different manner by the forces causing the rearrangement.

In relation to the other metallic minerals, pentlandite occurs in a number of ways, which to some extent depend on the host rock. It is more abundant in the peridotite where it occurs as subhedral crystals included in interstitial masses of pyrrhotite. In the disseminated deposits of norite (Exhibition Grounds deposit) it is either in subhedral crystals included in pyrrhotite or in short veinlike bodies apparently later than the pyrrhotite. In the veinlike deposits in norite the pentlandite is in intergranular veinlets between pyrrhotite crystals (Plate 4, C).

Chalcopyrite in the Exhibition Grounds deposit occurs in the same manner as at Union and Katahdin. At the Rodgers and Hall-Carroll mines it is more abundant along the borders of the mineralized zones, where it is found in fractured silicates and replaces pyrrhotite. It is also present in veinlets in dikes which occur in these ore bodies. It was the last metallic mineral to solidify in all of these deposits.

A few minute euhedral grains of niccolite are present in the Hall-Carroll and Union Bridge deposits, between pyrrhotite crystals.

In the peridotite and the Exhibition Grounds deposit magnetite occurs as in the Union deposit. Some euhedral crystals of mag-

netite in the peridotite may have formed before the silicates. At the Rodgers and Hall-Carroll deposits the magnetite is later than the silicate which it cuts and is molded upon, but it is cut by the sulphides. As previously noted, part of the magnetite in this deposit may be remnants of altered olivine crystals that have been completely replaced by pyrrhotite.

Violarite replaces pentlandite to a greater or lesser degree in all of the deposits. It is particularly common in the Hall-Carroll deposit. No area was noted in which pentlandite had been completely replaced, but some of the former pentlandite crystals are so highly altered that only small "island like" remnants remain in a mass of the replacing violarite (Plate 4, C).

Marcasite is present in minor amounts as an alteration of pyrrhotite in all of the deposits. It is particularly common at the Hall-Carroll deposit where it occurs in the same manner as at Katahdin.

Hematite is an alteration product of pyrrhotite and commonly replaces that mineral in the more highly altered specimens. Veinlets traverse the pyrrhotite masses and fill fractures in the silicate minerals. The most common form of occurrence is along contacts between pyrrhotite and the silicates.

Alteration Associated with Mineralization

In three of the deposits (Rodgers, Hall-Carroll, and Union Bridge) the mineralized norite is much more highly altered than unmineralized phases of the rock. The intensity of the alteration varies from point to point, but evidence at the Hall-Carroll deposit suggests that the alteration is most intense along contacts between mineralized and unmineralized norite.

The olivine in the mineralized rock is nowhere fresh. It is partly replaced by irregular veinlets of magnetite and serpentine or is completely altered to masses of magnetite, serpentine, and chlorite. The pyroxenes are altered partly to brown hornblende and reddish-brown biotite. In the more highly altered areas the formation of hornblende is accompanied by that of secondary quartz. The feldspars are replaced by chlorite, sericite, and carbonate. Chlorite veinlets up to 1 mm. in width are developed in

the highly altered rock. The alteration of the orthotectic minerals (olivine, pyroxene, and feldspar) is, in general, similar to the minor deuteric alteration of the minerals throughout the norite, but it is much more pronounced in the mineralized areas and clearly controlled by crosscutting fractures. Furthermore, the feldspars are more sodic (An_{55}) and according to Dunham (1950) the orthopyroxenes contain higher percentages of iron.

Certain minerals are present which do not normally occur in unmineralized areas. Apatite is abundant at the Hall-Carroll prospect. Veinlets of green spinel cut the rock in all of the mineralized areas. Zircon also occurs in the mineralized zone. Secondary quartz is present in the more highly altered parts of the Rodgers prospect.

The relationship between the sulphides and the secondary minerals is significant. The sulphides vein and replace all of the late minerals. In certain zones where sulphides are not abundant biotite and chlorite cut sulphides, but in the majority of the sections examined the reverse is true. The sulphide minerals clearly replace the spinel and apatite, but relationships between the sulphides, zircon, and quartz were not established.

Since sedimentary inclusions are particularly common near the ore deposits and since zircon and quartz occur both in the metasedimentary rocks and in the norite where it is in contact with the metasediments, it is possible that the zircon, apatite, and perhaps a part of the quartz came from sediments partially assimilated by the mafic magma.

The evidence suggests that the alteration of the orthotectic silicates and the sulphide mineralization must have occurred at about the same time. As Dunham suggests, the sulphide mineralization appears to have outstripped the silicate alteration in the final stages.

Replacement

Replacement of rock-forming minerals by the sulphides is evident in all of the deposits except the disseminated ore in peridotite. In the Rodgers and Hall-Carroll deposits especially, the sulphide minerals replace the silicates outward from parallel

fractures which cut the norite. Typical replacement veinlets are shown in Plates 10 and 11. The veinlets cut squarely across all minerals. As far as could be determined the replacement is not selective. In one area a large interstitial orthorhombic pyroxene crystal was replaced, leaving corroded and partially replaced plagioclase crystals in the sulphide mass, but along the borders of other fractures the front of mineralization appears to advance by preferential replacement of feldspar and other minerals, leaving corroded orthopyroxene. Since the mineralization is controlled more by fractures than by the composition of the host mineral, the interstitial type of texture is not well developed in the Rodgers and Hall-Carroll deposits.

Structural Control of Mineralization

The mineralized zones at the Hall-Carroll and Rodgers deposits are somewhat irregular in outline, but they have definite contacts with norite and trend generally northeastward. The norite host and ore have been fractured in the mineralized area, although at least part of this fracturing was later than mineralization.

Microscopic evidence shows that the sulphides replace fractured silicates along parallel fractures, and the vein-like forms of the ore bodies indicate control of fracture zones, presumably shears. Moreover, small fractures in the anorthositic norite which are parallel to the larger bodies are mineralized. The ores have been further deformed after their emplacement, as indicated by strain in the pyrrhotite.

Relation to Dikes

Two north-trending mafic dikes cut the norite and ore at the Rodgers property. The western mafic dike is in turn cut by small felsic veinlets. Logs of the diamond drill holes and some of the core remaining on the Rodgers property show that dikes of both types also cut the ore deposit at depth.

A portion of the western mafic dike was noted in contact with ore. Several veinlets of chalcopyrite starting at the contact between the ore and dike cut across both the mafic and felsic dike (Plate 2). The veinlets of chalcopyrite which transect the dikes

are parallel to the general trend of the ore body. They apparently fill fractures in the dikes. No alteration accompanies the chalcopyrite and none of the other sulphide minerals are present in the veinlets. Along the contact between the main sulphide mass and the mafic dike a strongly chloritized and biotitized zone is developed. Both chlorite and biotite developed in this zone are replaced by the sulphides (Plate 2). Near this contact the ore also contains inclusions of biotite and chlorite.

In neither type of dike is there a change in grain size from center to border. As noted previously, all of the evidence suggests that the sulphides are later in origin than either the mafic or felsic dike.

Local Deposits

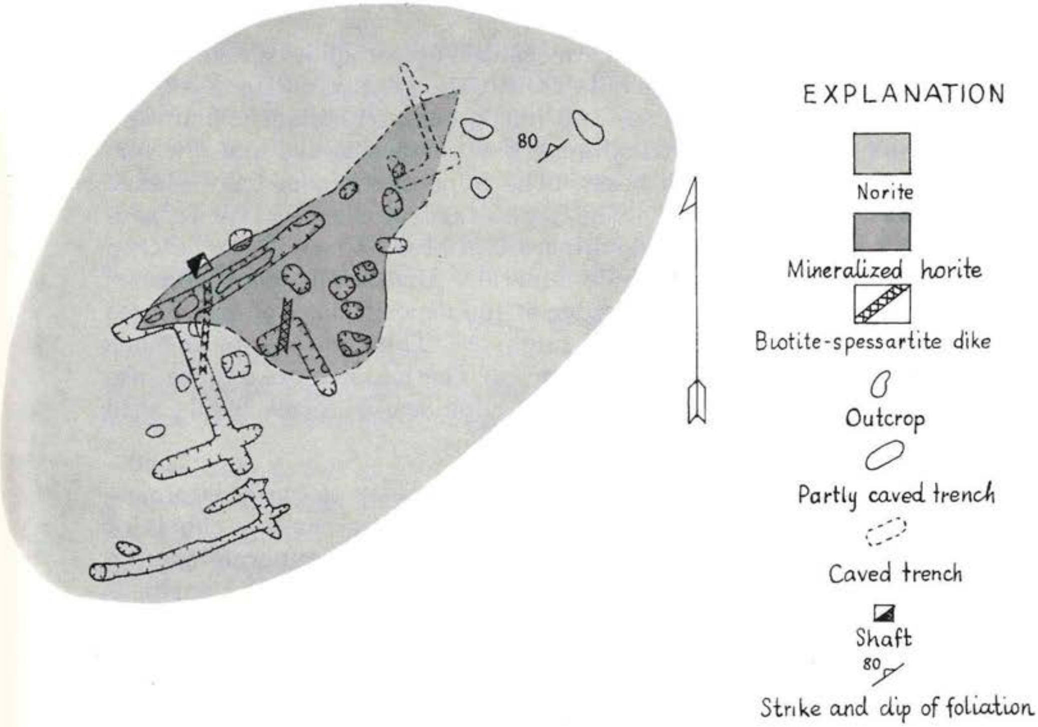
Rodgers Deposit. The Rodgers Deposit is located 2.25 miles N. 28° W. of the Customs Bridge at St. Stephen, N. B., and 3.55 miles N. 5° E. of the reservoir at Milltown, N. B.

The deposit is a mineralized zone in norite trending roughly northeast and is located near the contact of norite and metasediments. It has been explored by trenches, diamond drill holes and one shaft. At the present time the shaft is inaccessible and the trenches are partly caved, but the surface exposures indicate a roughly triangular outline of the deposit with the apex of the triangle towards the northeast (Fig. 2). At its base, the triangle is approximately 120 feet wide. (See map, Fig. 2). Two mafic dikes, trending north, cut the ore body and norite. These dikes are poorly exposed today (1952), but their trend had been previously established by Low (1930, Fig. 1).

Directly beneath the surface exposures, drilling indicates that the mineralized zone pinches out at depth. Drill holes put down by the International Nickel Company (1947) did not encounter ore below 270 feet and at this depth the mineralization is very weak. Information gained by Bela Low from drilling in 1930 led him to assume that the ore body had the shape of an inverted pyramid, with the apex at 250 feet and the base outlined by the body at the surface.

Further drilling by the International Nickel Company (1948) showed that there is a southwestern extension of the mineralized

FIGURE 2



RODGERS MINE

St Stephen, New Brunswick

Scale 1" = 100'

0 50 100 200 Feet

zone beneath the surface. Mineralization extends at least 400 feet southwest of the surface outcrop, and in this southwest area sulphides had been found by drilling to a depth of 1140 feet. However, the deep mineralization is much weaker than in the surface exposures.

The exact outline of the mineralized area cannot be determined from the information available, but the general outline seems to be one of parallel lenses and bands very irregular in plan and cross section. They trend generally northeastward and dip vertically or steeply southeast. The mineralized zone may plunge gently southeastward. The percentage of silicates varies considerably throughout the mineralized area. Zones in the outcrop average over 50% sulphide minerals. Drilling by Low indicates that along the western border of the deposit massive ore carries more than 75% of combined sulphides. This zone may be as much as 75 feet wide and 183 feet deep. The massive ore grades into norite containing less than 5% sulphides or forms bands with sharp contacts against the host rock.

The disseminated mineralized area appears to grade into massive norite. The unaltered norite in this area consists chiefly of olivine, orthopyroxene and feldspar, the mafic minerals making up approximately 30% of the total. Alteration of the norite is not pronounced in the unmineralized zones. In mineralized zones alteration of all of the silicate minerals is extensive and takes the form of partial or complete alteration to more hydrous minerals such as serpentine, chlorite, and hornblende. New minerals are also present. Apatite, zircon, spinel, and quartz are most common.

Aside from the two mafic dikes which cut the ore body and norite, the surface outcrops are norite, locally mineralized. Drill holes indicate however, that the norite contains bands of peridotite and fine-grained phases and inclusions of micaceous quartzite. This whole complex is cut both by mafic dikes up to 2 feet in width and by narrow veinlets of felsic igneous rock.

This whole complex of rocks is mineralized. By far the majority of the sulphide mineralization occurs in phaneritic norite, but sulphides are also disseminated in the peridotite, fine-grained

norite and quartzite. Veinlets of chalcopyrite cut both types of dikes and specks of pyrrhotite occur in the mafic dikes. It is significant to note that the grain size of the pyrrhotite varies directly with the grain size of the host rock in all these rocks, highly varied though they are.

The main sulphide constituent of the Rodgers deposit is pyrrhotite. Chalcopyrite and pentlandite occur in much smaller quantities. Magnetite, younger than the silicate minerals, is common in the mineralized rock. This magnetite is in turn partly replaced by pyrrhotite. The sulphide minerals replace all of the silicates, including chlorite, biotite, hornblende, and spinel, and it is clear that the sulphides originated by replacement of the norite host rock outward from parallel fractures in the rock.

Hall-Carroll Prospect. This deposit consisting of northeast trending mineralized zone in norite is located 0.6 mile southwest of the Rodgers prospect which it strongly resembles. The mineralized area is smaller and even more veinlike, however.

The Hall-Carroll deposit has been prospected by a shaft, two pits, and 14 diamond drill holes. The most northeasterly pit has the best exposure of ore. The mineralized zone is 10 feet wide and bears 5% sulphides at its western contact to over 50% sulphides 5 feet from the contact. The massive ore zone is 5 feet wide and has a sharp contact with norite on the eastern border of the zone. Evidence of fracturing and displacement of the silicate minerals in the norite can be seen in both hand specimen and under the miscroscope. The ore itself is fractured along the border of the deposit, and these fracture planes are coated with slickensided serpentine (McKenzie, 1940, p. 27).

Some 250 feet southwest of the first pit is a shaft sunk in a mineralized zone 30 feet wide. The shaft is inaccessible, being partially filled, but exposures south of it indicate that the ratio of sulphides increases towards the center of the zone where massive ore contains as much as 75% sulphides.

The third pit, 300 feet southeast of the shaft, is a weakly mineralized area in the norite. This pit is not along the line connecting the first pit and shaft. There are no outcrops between the shaft and two pits; it is therefore not possible to determine on

the surface whether these workings are along a continuous but curved mineralized zone. Information from drill holes, however, indicates that the mineralization on the Hall-Carroll property is probably a series of discontinuous lenses or pods of sulphides rather than a continuous vein-like deposit. The maximum depth at which mineralization was encountered was 247 feet. South of the shaft a series of drill holes found sulphide mineralization, but these drill holes were located 150 feet apart and it is questionable whether or not they delineate a single zone or several zones, each mineralized. At the Hall-Carroll property discontinuous mineralization was confirmed for a distance of 1050 feet roughly in a northerly direction. The maximum width of one mineralized zone, 100 feet south of the Hall-Carroll shaft, was 115 feet.

The mineralization in the Hall-Carroll area is thus similar to that at the Rodgers deposit. The sulphide minerals are pyrrhotite, pentlandite, chalcopyrite, and niccolite (?). Pentlandite is altered to violarite and pyrrhotite to hematite. The percentage of pentlandite is less in this deposit, but at the Carroll shaft chalcopyrite is more abundant than in any other part of the area.

The silicate minerals are the same as those on the Rodgers prospect, and the degree of alteration in the mineralized zones is similar. The silicate minerals are fractured and replaced by sulphides. Evidence of fracturing and replacement of feldspar is particularly marked here.

Magnetite is also present in this deposit. The magnetite is later in origin than the silicates, but fractured crystals of magnetite are replaced by the sulphide. No late magnetite was noted in this deposit.

Union Bridge Deposit. The Union Bridge deposit is located near the contact of the mafic complex and granite. It is on the Canadian side of the St. Croix River at the foot of Union Bridge. Most of the outcrop is below water level at high tide.

The deposit is massive sulphide (50-75%) in norite. The outcrop is fifty-five feet wide along the river bank. Very little was determined about this deposit because of poor exposures. Examination of fresh specimens of the noritic host rock show it to be

closely similar to that on the Rodgers and Hall-Carroll properties. The norite contains more felsic bands, composed chiefly of recrystallized plagioclase. These bands contain up to 15% spinel and minor amounts of biotite and are partly serpentinized. It is possible that the bands developed in the norite by attack from emanations of the norite magma. Whatever their origin, the zones are mineralized, with small grains of sulphides similar in size to the silicate minerals and disseminated throughout the rock. The mineralization is especially rich in pyrrhotite and is similar to that in the other deposits except that pentlandite is very rare and one or two grains of niccolite are present in the pyrrhotite masses.

Exhibition Grounds Deposit. The Exhibition Grounds deposit is near the eastern contact of the mafic body with metasediments. It is located at a point north of the racetrack, west of the Canadian Pacific Railroad and south of the west half of Hemby Creek (Plate 16).

This is a small deposit of disseminated sulphides in a more mafic phase of the norite, probably trending northeast. It has been prospected by means of a pit and three small trenches approximately 20 feet apart. The pit exposes a band of disseminated pyrrhotite five feet wide. No mineralization is visible in the trenches.

The host rock contains over 50% mafic minerals. Orthopyroxene makes up 35-40% of the rock and olivine about 7%. The silicate minerals are similar to those in the norite at the Rodgers and Hall-Carroll prospects, but the proportion of mafic minerals and the extent of alteration are different.

Serpentine and biotite are the most common secondary minerals in the deposit. Tremolite-actinolite is also present and in larger quantity than in any other part of the mafic body. Except for tremolite-actinolite the secondary minerals are replaced by the sulphides, but veinlets of serpentine and biotite also cut the sulphide masses. The tremolite-actinolite is invariably later than the sulphide.

The sulphides occur as large bleb-like masses or as smaller masses scattered through the norite and as irregular interstitial

veins. Masses of serpentine surround the sulphide masses and appear as halos of alteration around the irregular sulphide bodies. Veinlets of sulphide which cut the norite pass into veinlets of serpentine.

As previously noted, these veinlets probably developed before complete crystallization of the magma and may have acted as an outlet for some of the late crystallizing fraction of the magma. The deposit is magmatic, but at least a fraction of the sulphide and associated serpentine have migrated along fractures developed before complete solidification of the norite.

DREW HILL DEPOSIT

Location and General Features

The Drew Hill prospect is on the northeastern slope of Drew Hill, approximately eight miles west of Houlton, Maine. This pyrrhotite deposit is a fault-controlled replacement along a contact between a calcareous hornfels and marble. In the immediate area are quartz veins containing stibnite, galena, and chalcopyrite.

Topography

This area is part of the "Aroostook Plain" of Maine, actually a series of low, rounded hills which closely resemble those at St. Stephen, N. B. The major topographic feature in the immediate area is a horseshoe-shaped ring of hills of about 600′ relief which surround the Meduxnekeag granite intrusion.

Glaciation

The most conspicuous physiographic features resulting from glaciation in this district are the eskers, of which several trend in a southward direction across the area. One west of the city limits of Houlton, Maine, extends across the entire length of the Houlton quadrangle, a distance of 15 miles.

Other effects of glaciation are the drift cover, relatively shallow, and the lakes which fill areas gouged out in the less resistant

rocks. Despite the drift cover, outcrops are fairly common on hilltops and along stream beds.

Regional Geology

Stratigraphy

This district is included by White (1943) in the southern manganese district of Maine. It is underlain predominantly by complexly folded and faulted limestone, slate, and quartzite of Ordovician and Silurian age. Low grade manganese ore is associated with the slates. Miller (1947) made a reconnaissance map of the district around Houlton, Maine, and outlined broad lithologic divisions, but his lithologic map ends at the foot of Drew Hill. The general sequence of formations as outlined by Miller consists of the Aroostook limestone and an older calcareous sandstone, both of Silurian age, underlain by manganese bearing slates, probably of Ordovician age.

In the northern manganese district near Presque Isle, Maine, White and Cloud (1942) have divided the Aroostook limestone into three units, a lower slate member composed of gray and green slate, phyllite, calcareous slate, and shaly limestone; a middle "ribbon" member composed of platy beds of fine-grained gray limestone separated by shale partings; and an upper member of argillaceous limestone. Near the Drew Hill deposit the Aroostook limestone has the typical banding structure that justifies the application of the term "ribbon" member.

Igneous Intrusions

The metasedimentary rocks are cut by felsic igneous intrusions. The largest of these intrusions, located south of the town of Ludlow, is an igneous pluton, oval in plan, which closely resembles the Onawa granite in outline of outcrop and mineralogical character. Like the Onawa granite this pluton grades from a coarsely granular biotite microline granite near the center of the intrusion to finer-grained, more mafic phases along its border.

At its northeastern margin the pluton is in contact with the Aroostook limestone, and around the other edges with slate.

Where the intrusion is in contact with limestone the granite becomes syenitic in composition. It is composed chiefly of perthitic orthoclase and microcline with small interstitial grains of albite. Quartz makes up less than 5% of the rock, but sphene, green hornblende, diopside, phlogopite, garnet, tremolite, wernerite, and one or two grains of pyrrhotite are present at the contact. At the shale contact the granite is foliated parallel to the foliation of the shale and two specimens of the igneous rock proved to be hornblende-quartz diorite composed of andesine, hornblende, and quartz, with accessory biotite and magnetite. This variation in composition along contacts indicates that the granite was modified considerably in composition by the invaded sediments.

Contact Metamorphism. Another similarity between this granite and the Onawa pluton is the contact metamorphism of the adjacent sediments and the ring of hills which surround the pluton where the granite is in contact with slate. These rocks have been changed into a resistant cordierite hornfels. The hills underlain by the hornfels surround the granite on three sides. To the northwest where the granite is in contact with limestone, the latter has been recrystallized to marble and numerous new minerals such as garnet, sphene, and diopside have developed, but the scarn facies is not resistant and the hills around the pluton are in the shape of a horseshoe rather than an ellipse as at Onawa.

Structure

Miller (1947, p. 18) states that the structure in the southern manganese district is extremely complex. He notes that all of the rocks have been greatly compressed, and that the axial planes of most of the folds are nearly upright. His study of the manganese deposits indicates that the beds are cut by numerous high-angle faults, and that these faults do not exhibit a regional trend but strike at various angles.

Study of the area around the Drew Hill deposit and the Meduxnekeag granite by Dr. R. J. Holmes and the writer shows a roughly northeastern trend of the regional structure, although there are numerous local variations. In the area northeast of the

Meduxnekeag granite the regional trend is actually due east. The most pronounced or most clearly shown folding is in the ribbon member of the Aroostook limestone which is isoclinally folded; in addition, there has been tilting to such an extent that the axial lines of many of the folds plunge vertically (Plate 15). As indicated by Miller (1947, p. 28) there is no pronounced overturning of these folds despite their tightness and the axial planes stand vertical.

Ore Deposit

History

The Drew Hill deposit was first discovered in 1901 by H. Briggs of Houlton, Maine, while on a fishing trip to Meduxnekeag Lake. Mr. Briggs has been interested in the deposit since that time and has instigated several investigations of the property by mining companies. According to Briggs, the Hollinger Corporation made a survey of the deposits and put down 15 drill holes in the area. Since that time a group of business men in Houlton organized a company to develop the property and did considerable trenching and bulldozer work. In 1952 the property was under option to this corporation, but no development work was being done.

Only two references to these deposits in the literature are known. One is a notation by Miller (1947, p. 39) to the effect that the sulphide deposit is too small to supply the necessary sulphurous acid for smelting the manganese in the area. The other is a description of the sulphide body by Trefethen (1945, p. 17) in discussing the marble deposits of the area: "At the east end of the marble body there has been some mineralization, with the introduction of pyrite and pyrrhotite, replacing the marble and wall rocks, possibly along a fault."

Geology of the Mineralized Area

Drew Hill is part of the circle of hills made up of the resistant rocks surrounding the Meduxnekeag granite. The mineralized area crops out at the northeastern corner of the hill.

From the granite contact eastward, the rock types which underlie the hill are a blue-gray, very hard, quartz cordierite horn-

fels, a calcareous hornfels with marble lenses, a phyllite, and the middle or "ribbon" member of the Aroostook limestone. It is a matter of debate just where the hornfels and phyllite underlying Drew Hill fit into this stratigraphic picture. On the state map of Maine by Keith (1933) these rocks are considered Cambro-Ordovician—that is, should be older than the Aroostook limestone, but more detailed stratigraphic and structural studies will have to be made before this question is settled.

Petrography

Phyllite. The phyllite is a highly contorted and fractured rock composed chiefly of mica and quartz. Crenulated bands of quartz alternate with micaceous bands. Lenticular cordierite crystals with numerous inclusions of sericite are present in the micaceous bands where they are associated with biotite, and with small quantities of muscovite and chlorite. The micaceous bands also contain accessory quartz, garnet, and magnetite.

Calcareous Hornfels with Marble Lenses. Laterally the phyllite grades into a more massive calcareous rock in which recognizable bedding consists of the alternating bands of magnesian limestone and calcareous shale. The limestone layers are easily identified in hand specimens because their gray color contrasts with the blue-black color of the rest of the rock. These beds have been tightly folded and in part broken, their fragments being drawn out into lenticular masses.

The rock has been further altered by the effect of the nearby intrusion. The magnesian limestone bands have been recrystallized into coarse-grained white carbonate. Along the borders of these coarsely crystalline bands diopside is present. The argillaceous bands have been changed into green hornblende associated with detrital quartz grains. Lesser amounts of biotite, chlorite, sphene, magnetite, and pyrrhotite also occur in the argillaceous bands.

Infolded into this carbonate rich rock are large lenses of pure white marble. Three such lenses occur within the area studied, the largest of which is 125 by 75 feet. The lenses have been almost entirely removed to be used for fertilizer (Plate 15).

Hornfels. The unit designated hornfels is a massive bluish-black rock containing numerous folded laminae of quartzite. These are narrow bands less than 8 inches in thickness. Some of the quartzose laminae contain small amounts of pyrrhotite and pyrite. The greater part of the rock is composed of biotite and sericite as matrix, with numerous porphyroblastic crystals of cordierite. The cordierite is less well oriented in the hornfels than in the phyllite, and generally contains fewer sericite inclusions.

Dikes. Two types of dikes cut the metamorphic rocks. A dark foliated rock intrudes the hornfels in the north central part of the mapped area. Well oriented hornblende crystals are recognizable at the outcrop. The dike is 2 feet wide and approximately 25 feet long and trends parallel to the poorly developed foliation of the hornfels. It is probably a metamorphosed mafic dike, but was not petrographically studied.

A larger, porphyritic diorite dike cuts across the largest marble lens, ending abruptly against the fault at the contact between the marble lens and hornfels and extending southwestward for a distance of approximately 75 feet. The groundmass of this dike is composed chiefly of fine-grained crystallites of plagioclase feldspar with lesser amounts of biotite, magnetite, chlorite, muscovite, and pyrrhotite. Quartz also appears to be an important constituent of the groundmass, but the grains so regarded are too small to identify positively. Large zonal phenocrysts of andesine and euhedral crystals of augite are scattered throughout the matrix. The augite is altered to irregular masses of chlorite and biotite, and a few of the feldspar crystals are partly converted to muscovite.

Quartz Veins

Small discontinuous lenticular quartz veins, trending roughly parallel to the foliation of the metamorphic rocks, are found in the hornfels and phyllite and one large tabular vein of massive quartz cuts directly across the foliation near the center of the area (Plate 21). The large vein varies in width from 2 to 12 feet and can readily be traced for 80 feet in a direction at right angles to the foliation; indeed, intermittent outcrops indicate that it

may extend for a distance of 285 feet within the mapped area. Outcrops of vein quartz west of the map area suggest an even greater extension of this vein. There is no megascopically recognizable structure in the quartz; a few small vugs filled with quartz crystals occur in the wider segments of the veins. The contact with the wall rock is sharp and alteration is apparently lacking. The vein is composed of white massive quartz, the so-called "bull" quartz of miners, and surface exposures indicate that sulphides are sparse in this vein. The only ore minerals noted were galena, chalcopyrite, and pyrite disseminated in minor amounts in the quartz.

Two series of lenticular quartz veins having approximately parallel strikes are present (Plate 21). Each series lies in a straight line with intervals of unveined country rock between along the same strike. The easternmost series is in the highly deformed and fractured phyllite. The largest vein in the phyllite is only 2 feet wide and the largest continuous outcrop is 25 feet long. The veins contain numerous inclusions of seritized phyllite. The ore minerals pyrite, chalcopyrite, and arsenopyrite are present in small amounts. Near the veins the wall rock and inclusions also bear a few sulphides but this lesser mineralization is not much more intense than is found widely scattered in the country rock.

Another series of small lenticular veins is parallel to and 150 feet west of the first. These veins are in fractured hornfels and are more regular in outline than those in the phyllite. The best exposed vein in this series is 30 feet long and 1 foot wide. Veins of this series also contain sericitized inclusions of country rock, whose schistosity is differently oriented than that of the local foliation. The only sulphide mineral noted here was stibnite which fills brecciated sections of the veins and occurs in the center of well developed cockscomb structure. Euhedral quartz crystals grow from both vein walls and in some veins the center is completely filled with stibnite to a maximum width of six inches.

Sulphide Deposit

At the southern border of the largest marble lens is a massive pyrite-pyrrhotite deposit. Its shape is very irregular and con-

forms in general to the folded contact between the marble and calcareous hornfels. The mineralized zone is from 2 to 5 feet wide and 80 feet long. The only metallic minerals are pyrrhotite and pyrite. These are in quartz that preceded them and partially replaced the marble at its contact with calcareous hornfels. The ensuing pyrite deposition was apparently almost wholly confined to the silicified zones in the marble as very little actually replaces the marble itself. Following the pyrite, the pyrrhotite was introduced.

The calcareous hornfels in the mineralized zone is similar to that previously described, but somewhat more finely granular. Small crystals of wernerite are present in the highly mineralized hornfels.

Mineralogy. Pyrite occurs in veinlets, irregular replacement masses, and finely disseminated grains in all of the rock types. Most commonly it is found in silicified marble, where it forms excellent crystals. Crystals weathered out of the host rock are pyritohedra, cubes, and octahedra.

Pyrrhotite occurs chiefly as massive replacement in the host rock. Small euhedral crystals of pyrite are generally associated with the pyrrhotite. The age relationship between the two minerals is difficult to establish. Most of the pyrite grains have well developed crystal faces and are unmodified by the surrounding pyrrhotite. One crystal of pyrite was noted, however, which contained fractures partially filled by pyrrhotite.

Marcasite replaces the pyrrhotite along minute fractures in the mineral. The veinlets are small and replacement did not advance very far in the specimens examined.

Secondary pyrite is commonly associated with the marcasite. Small subrounded masses, apparently colloidal in origin, occur along the border of the marcasite veinlets.

In the more highly altered specimens hematite replaces pyrrhotite selectively. This is almost certainly an oxidation process, however.

PLATE XV

Northern face of sulphide ore body in marble quarry at Drew Hill.

Isoclinal folding in ribbon member of Aroostook limestone, Drew Hill.

The paragenesis of the minerals can be summarized by the familiar paragenetic diagram:

Quartz
Pyrite
Pyrrhotite
Marcasite
Pyrite
Hematite

Oxidation. The surface of the deposit and the surrounding rocks is stained with multicolored oxidation products of the sulphides, probably iron sulphates of various types. Because of the sporadic distribution of sulphide-rich zones along the marble contact, a typical gossan does not cover the entire mineralized zone. In areas where the sulphide bodies occur at the surface, oxidation and leaching have produced surface cappings of "limonite" which are open boxworks over pyrite rich zones, but relatively nonporous "limonite" masses cover the areas rich in pyrrhotite.

Origin of the Deposits

Structural Control. The major structural feature of the area is the steeply dipping foliation developed in the metamorphic rocks. The beds in the metasediments are isoclinally folded and in the mineralized area the majority of the folds plunge 50-85° south. Superimposed on the folding is the development of north-south shear faults parallel to the foliation. The extent of the displacement along these faults has not been established, but grooves on the west wall of the two larger marble quarries in the area indicate that at least the later part of the movement was horizontal or inclined not over 15° in the direction of the plunge of the minor folds. The direction of movement along the shear faults is shown by the general trend of the folding of the beds (Plate 21). This suggests that the west side of the faults moved southward.

The lenticular quartz veins were probably localized in the shear planes, but the largest quartz vein, the sulphide ore body, and the mafic dike all strike at an acute angle to the shear faults and are approximately parallel to one another.

It is assumed that the movement along the faults is caused by a couple, the fractures in which the dike, massive quartz vein, and sulphide deposit were emplaced can be considered tension fractures. The age relationship between these fractures has not been established. They may have formed simultaneously.

Source of the Mineralizing Solutions. The proximity to the Meduxnekeag granite suggests that the metallic minerals may have originated as residual emanations from the granitic intrusion. The composition of the zone along the contact between granite and limestone shows that there was an exchange of cations between the granite and limestone, an impoverishment of silica in the granite and a growth of new silicates in limestone. Pyrrhotite is also present in small amounts in the limestone along these contacts. If the iron sulphide was derived from the granite, it would only require a localization in fractures and a favorable host rock to form the replacement sulphide deposits.

Temperature of Formation. An interesting feature of the mineralization is the existence of supposedly high and low temperature deposits in the same area. The stibnite veins and pyrrhotite-pyrite deposit are actually at opposite ends of Lindgren's temperature classification, and it seems probable that these deposits formed at about the same time. Successive stages of emplacement, then, do not explain this anomaly. It is not necessary, however, to have high temperatures for the formation of pyrrhotite. A deficiency in sulphur through escape might explain the presence of the pyrrhotite as the well known pyrrhotite-pyrite vapor pressure-temperature curve shows. The arsenopyrite noted in the area indicates that such a deficiency may have existed (Rankama and Sahama, 1950, p. 669).

Pyrrhotite-Pyrite Relationship. Although pyrite is more stable at low temperature and pyrrhotite is more stable at high temperatures, the relationship between these two minerals shows that the pyrrhotite formed last. This reversal in order of formation for these two minerals, so generally observed in pyrite-pyrrhotite ores, may be a result of sulphur deficiency. As suggested by Behre (1949, p. 37) for the similar relationship in the Ducktown deposits, it may indicate "not so much a rise in tem-

perature as a greater opening of the ground as ore deposition proceeded."

The above explanation may hold for these particular deposits, but the early pyrite followed by pyrrhotite is also present in many deposits, where pyrrhotite is followed by galena and other sulphides not deficient in sulphur (Schwartz, 1937). Furthermore, early pyrite is known to occur in magmatic sulphide deposits (Vogt, 1921, p. 636-637) in which the temperature is supposedly high. Jensen (1942, p. 705) found that in an iron sulphur melt, in which there was an excess of sulphur over that needed for the formation of pyrrhotite, pyrite was able to crystallize first as shown by polished sections with early pyrite in a matrix of pyrrhotite. This relationship may be explained by a stronger power of crystallization for pyrite and may apply to the magmatic deposits. At any rate, it appears that the relationship observed in the Drew Hill deposits may occur in a variety of pressure-temperature-composition combinations, and is probably explained by a different combination of factors in different deposits.

Summary. These deposits originated as residual emanations from the Meduxnekeag intrusion, and the emanations from the magma were emplaced in fractures formed in the hornfels by a couple movement. The temperature of formation was probably low, as indicated by the presence of stibnite, and the pyrrhotite deposit may have formed at a low temperature as a result of a deficiency of sulphur.

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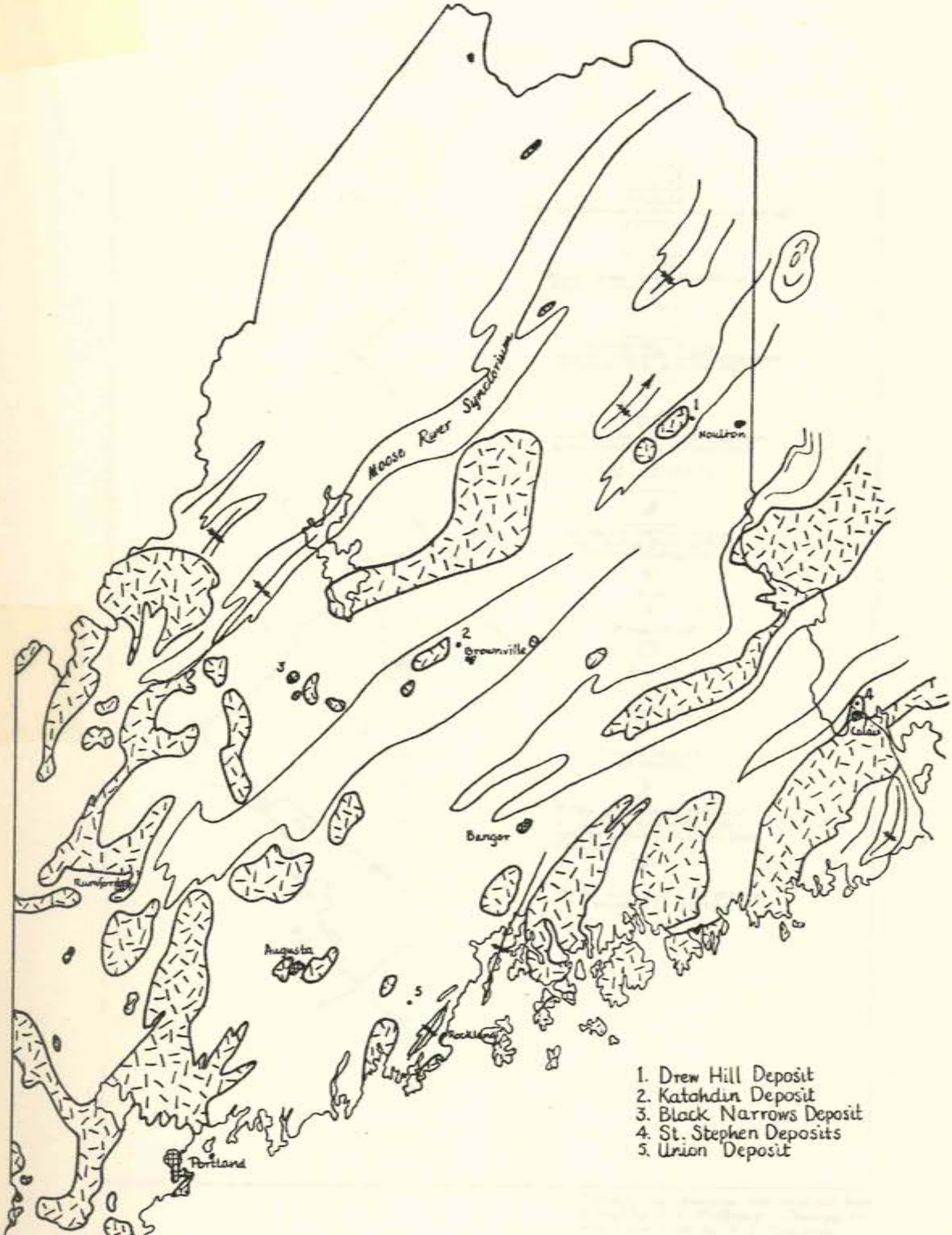
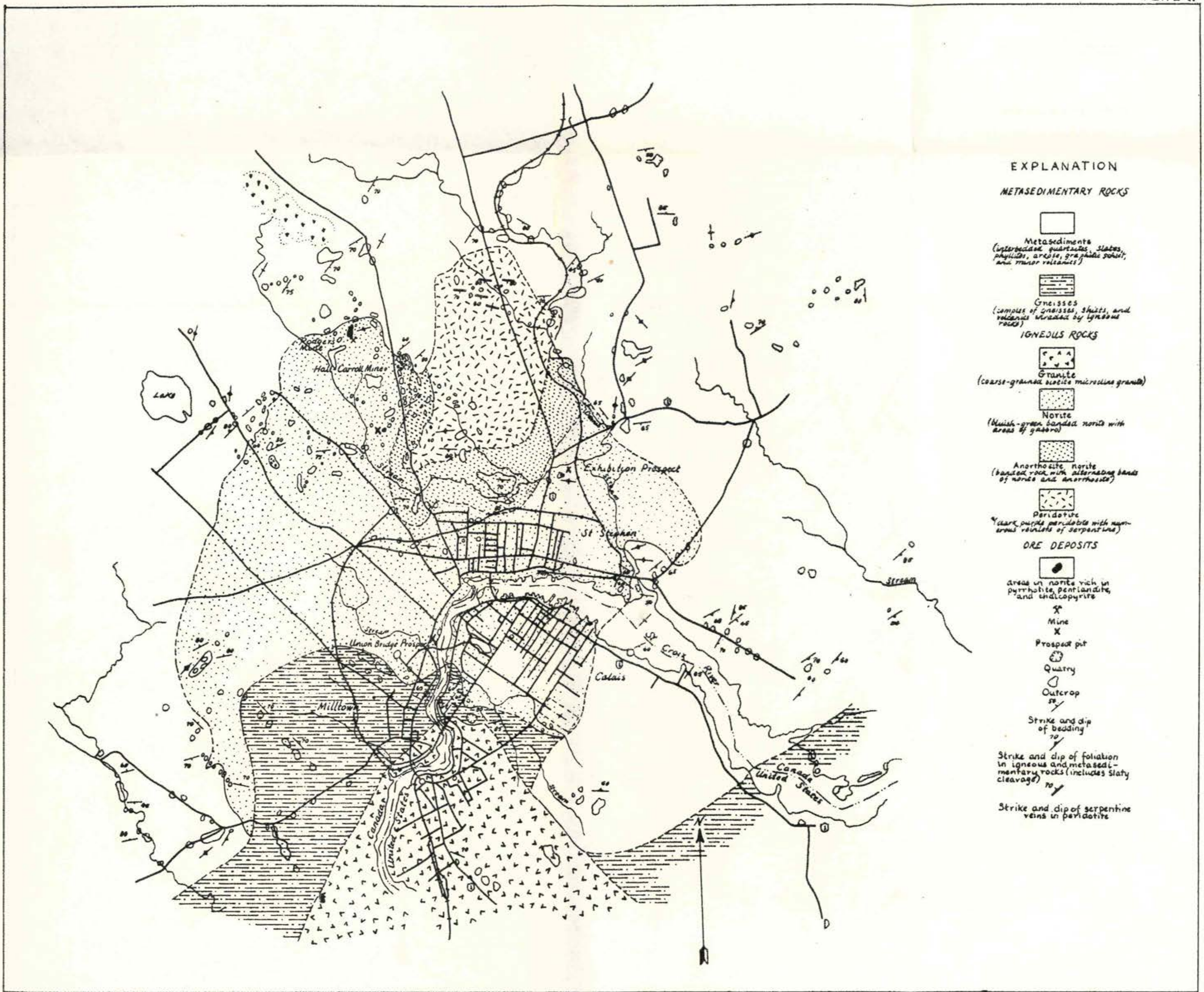
PLATE 16



GENERALIZED MAP OF MAINE AND ADJACENT NEW BRUNSWICK SHOWING OUTLINE OF INTRUSIVE IGNEOUS ROCKS, STRUCTURAL TRENDS, AND LOCATION OF DEPOSITS



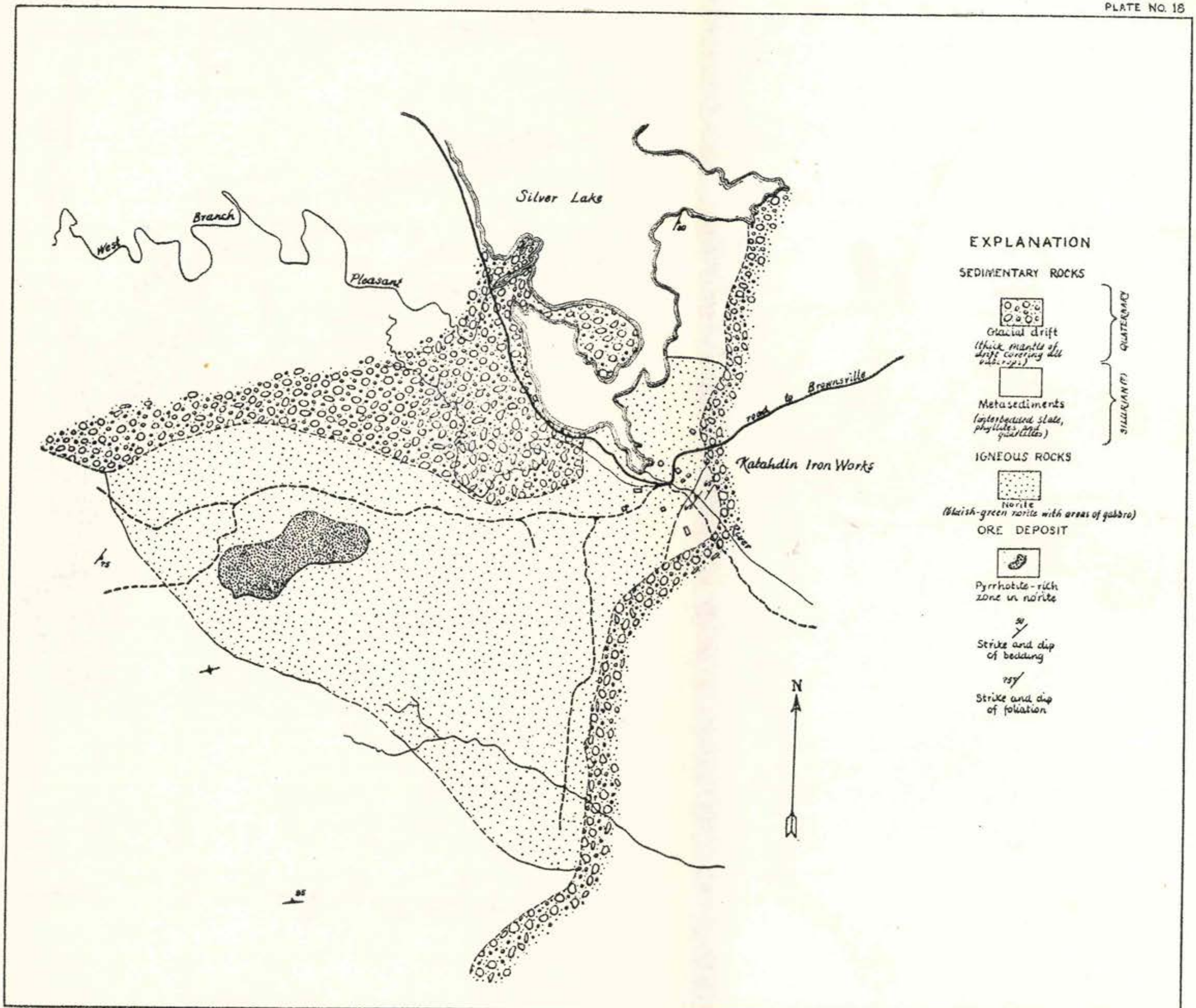
Geology on Canadian side modified from a map by G. S. McKenzie. Geology on American side by R. S. Houston.

ST. STEPHEN AREA

ST STEPHEN, NEWBRUNSWICK – CALAIS, MAINE

Scale 2 inches = 1 mile

0 1 2 3 Miles



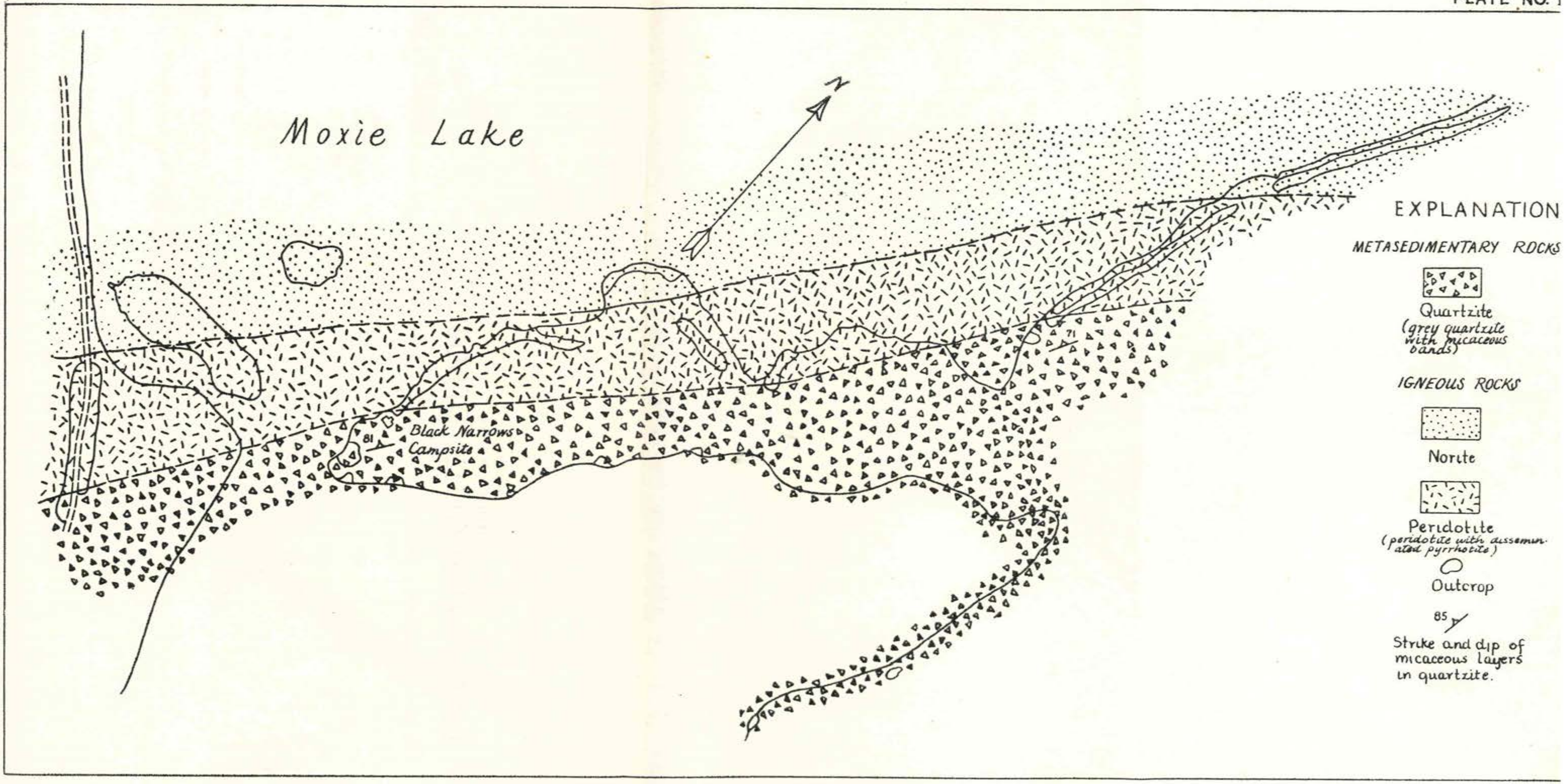
Geology by R. S. Houston

KATAHDIN DEPOSIT

Brownsville Junction, Maine

Scale 1" = 880'

1953



Modified from a map by J E Bowencamp

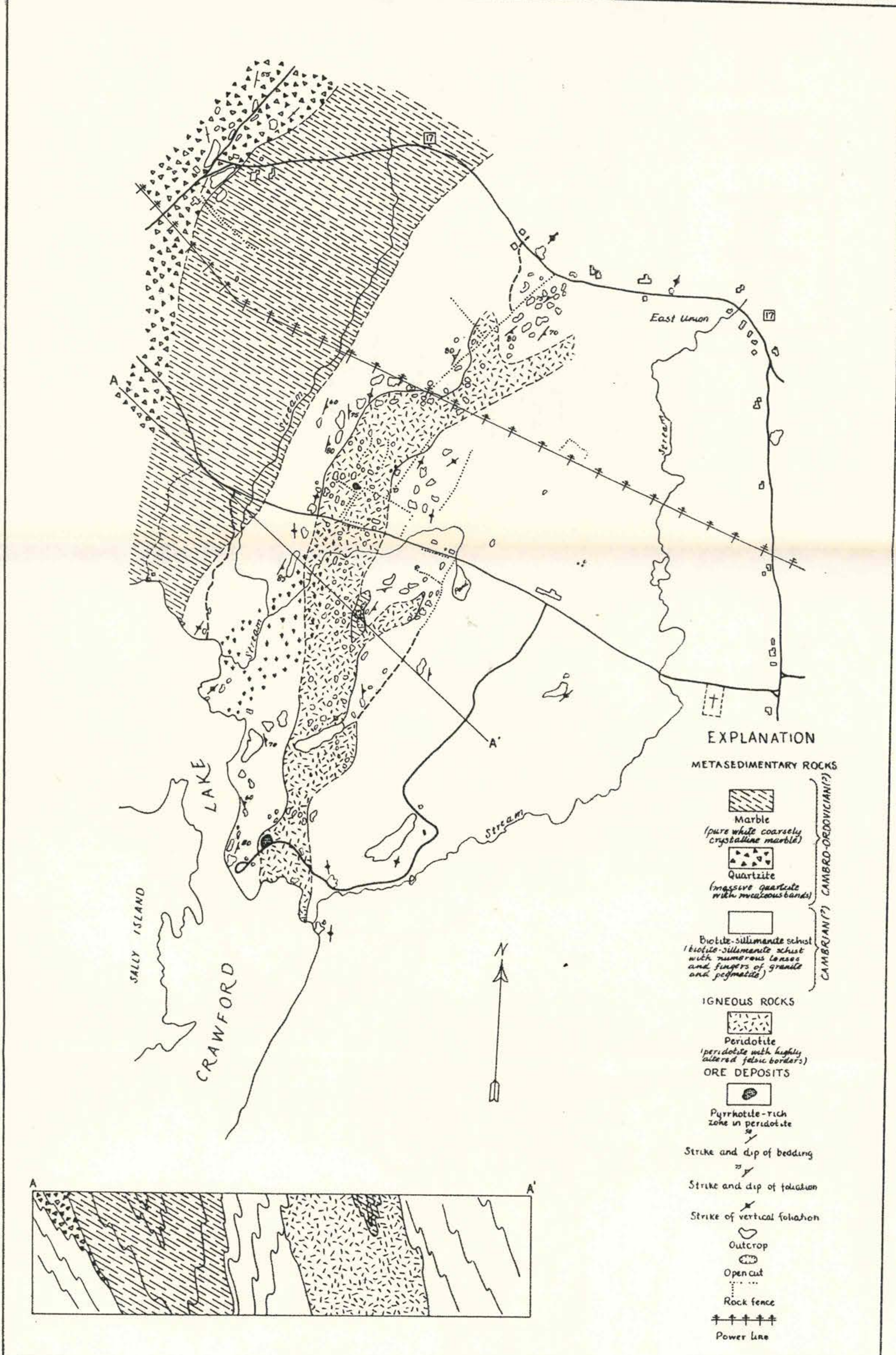
BLACK NARROWS DEPOSIT

MOXIE, MAINE

Scale 1" = 200

0 50 100 200 400 500 800 1000

1953

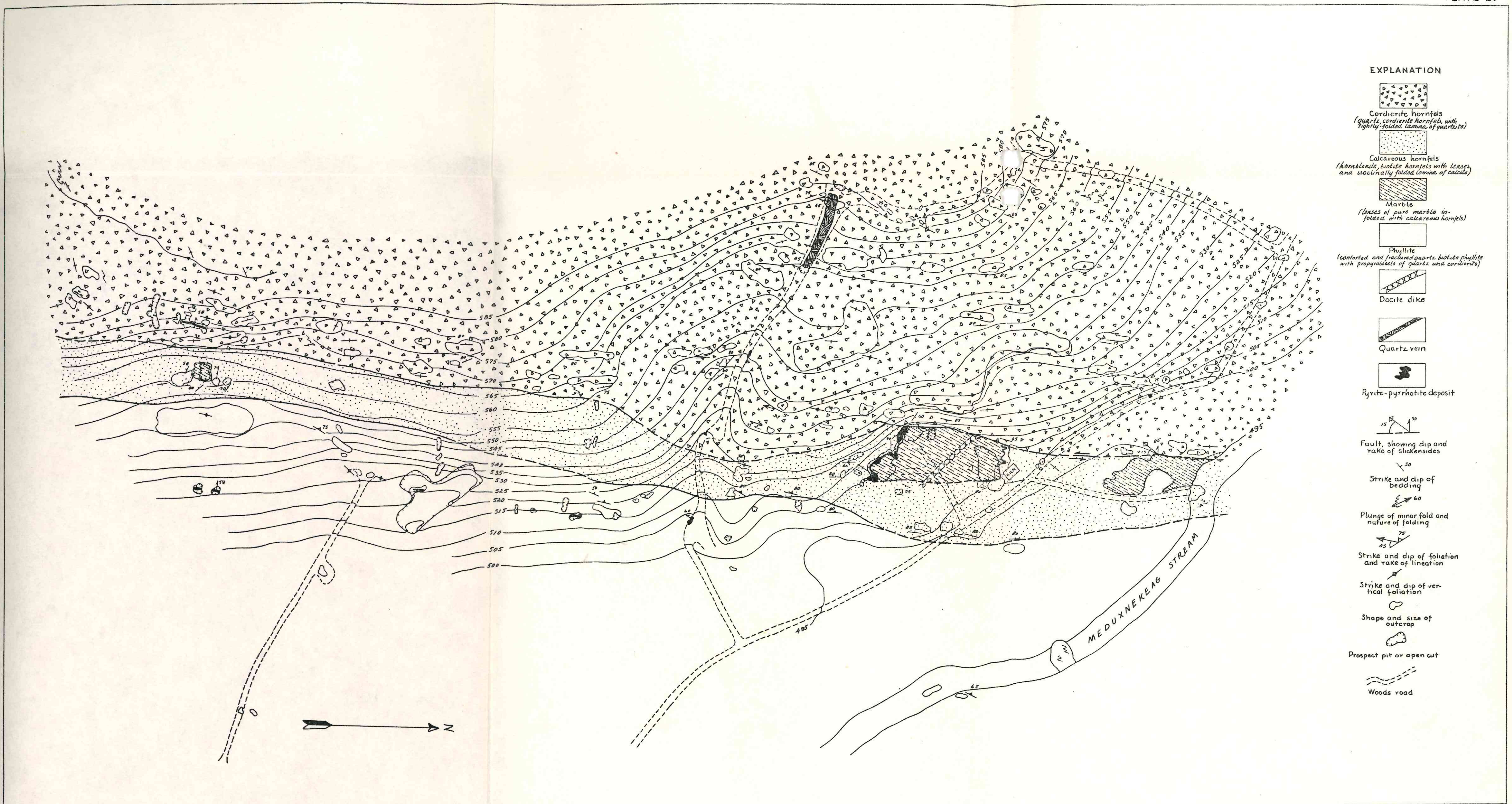


Geology by R. S. Houston
assisted by Oscar Strongin

UNION PYRRHOTITE DEPOSIT

EAST UNION, MAINE

Scale 1" = 660'



Geology by R.S. Houston
assisted by Noel Raxnberg
Surveyed in 1952

DREW HILL DEPOSIT

Scale one inch = fifty feet

0 5 10 20 40 60 80 100 120 140 160 180 200 220 240 Feet

Contour interval = five feet
(assumed datum)

1953