Geology of the Dover Magnetite District Morris County New Jersey

By PAUL K. SIMS

A CONTRIBUTION TO ECONOMIC GEOLOGY

GEOLOGICAL SURVEY BULLETIN 982-G

A preliminary report prepared in cooperation with the Bureau of Mineral Research, Rutgers University

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1953

UNITED STATES DEPARTMENT OF THE INTERIOR

Douglas McKay, *Secretary*

GEOLOGICAL SURVEY

W. E. Wrather, *Director*

For sale by the Superintendent of Documents, U. S. Government Printing Office
Washington 25, D. C.

CONTENTS

ILLUSTRATIONS

A CONTRIBUTION TO ECONOMIC GEOLOGY

GEOLOGY OF THE DOVER MAGNETITE DISTRICT, MORRIS COUNTY, NEW JERSEY

By Paul K. Sims

ABSTRACT

The Dover district, the largest iron ore producing district in New Jersey, occupies an area of 80 square miles in Morris County, New Jersey. The district is in the New Jersey Highlands, a region characterized by northeast-trending ridges and valleys.

The oldest rocks exposed in the Dover district are metasedimentary rocks of pre-Cambrian age. Little is known about the thickness or age sequence of these rocks, which were intruded successively by quartz diorite, albite-oligoclase granite, and hornblende granite and alaskite. The intrusive rocks are pre-Cambrian in age and were emplaced during a period of orogeny. Mixed rocks formed by the injection of igneous material into metasedimentary rocks are common.

The pre-Cambrian rocks are intruded locally by small diabase dikes of Triassic(?) age, and are overlain along the western edge of the district by sedimentary rocks of early to middle Paleozoic age. Quaternary glacial, extra-glacial, and alluvial deposits cover the bedrock to variable depths.

The pre-Cambrian rocks are isoclinally folded throughout the district, and the rocks in most places dip more than 45°. The prevailing direction of strike is northeast, and the prevailing direction of dip is southeast, but there is some variation. The folds plunge gently to moderately northeast.

All the rocks in the district are foliated. The metasedimentary rocks have a fair to excellent lithologic layering that is parallel to the dimensional orientation of the mineral components. The quartz diorite has a granoblastic texture; the albite-oligoclase granite is partly deformed but for the most part has a primary igneous texture; the hornblende granite has a primary igneous texture upon which was superimposed locally a secondary foliation.

Lineation is remarkably uniform throughout the district, and is predominantly parallel to the fold axes (b-axis). The mean lineation obtained from measurements in both igneous and metasedimentary rocks is 17° N. 52° E.

The faults fall roughly into two sets, one of which trends northwest and the other northeast. The faults displace the ore deposits and cause major mining problems in many mines, although the displacement on individual faults generally is small.

The magnetite deposits in the Dover district are in three principal types of host rocks—oligoclase-quartz-biotite gneiss, albite-oligoclase granite, and skarn. In addition magnetite concentrations occur locally in amphibolite and granite pegmatite. The gneiss and skarn ores are massive; the granite ore is dissemi-

nated. Each type of ore has yielded a substantial proportion of the production from the district.

The magnetite deposits, except for the skarn deposits in the Green Pond ore belt, are tabular, ruler, or lath-shaped bodies whose longitudinal planes dip nearly parallel to the foliation and whose longitudinal axes plunge parallel to the linear structures in the enclosing rocks. The deposits range in thickness from less than 1 foot to about 60 feet and average between 5 and 20 feet. The breadth of the known ore bodies ranges from about 100 to 2,400 feet. The length of the deposits along the rake has not been determined by mining although several ore bodies have been mined for more than 8,000 feet. The end of a lath- or tabular-shaped deposit has never been reached.

The magnetite deposits are grouped into seven ore belts: Wharton, Hibernia Pond-Hibernia, White Meadow-Cobb, Dalrymple, Beach Glen, Green Pond, and Splitrock Pond-Charlottesburg. Most of the production has come from the Wharton ore belt. The Hibernia Pond-Hibernia ore belt ranks next in production.

The Wharton, Hibernia Pond-Hibernia, White Meadow-Cobb, and Dalrymple ore belts are on the limbs and nose of the Hibernia anticline. The structure within the individual ore belts is only known in part, however. Most of the deposits in the Wharton and Green Pond ore belts are in synclines. In the important Wharton ore belt there are several parallel deposits of workable size. Many of the deposits lie one above another in the same plane, and are separated either by a "pinch" or by barren country rock. The Hibernia Pond-Hibernia ore belt consists of a single nearly continuous mineralized zone that contains "shoots" which constitute the ore bodies or magnetite concentrations. The deposits in the Green Pond ore belt are isolated small bodies that form a complex pattern.

The presence of ore in several different types of host rocks and the relationship of the magnetite to these rocks demonstrates that the magnetite was introduced into the host rocks after their formation. From the presence of ore in granulated zones in the host rocks it is concluded that these zones were the principal centers of deposition of the ore.

The mineralogy of the ore is relatively simple. Magnetite is the principal ore mineral; hematite constitutes about 15 percent of the ore in disseminated deposits, but constitutes less than 1 percent of the ore in massive deposits. Ilmenite almost never exceeds 1 percent of the ore. Sulfides are almost entirely absent except in the deposits in the Green Pond ore zone where a few percent of pyrrhotite, chalcopyrite, and pyrite are present in the ore. The principal gangue minerals are unreplaced fragments of the host rock—chiefly pyroxene, hornblende, feldspar, quartz, and biotite. Several minerals were introduced, however, by the ore-forming solutions—apatite, calcite, chlorite, serpentine, biotite, quartz, pumpellyite, tourmaline, sphene, and spinel.

The magnetite deposits are high-temperature replacement bodies. The magnetite was deposited from hydrothermal and pneumatolytic solutions that were derived from the granite magma that consolidated to form alaskite.

The grade of the massive ore ranges from 40 to 60 percent iron and the average grade of the disseminated ore (Scrub Oaks mine) is about 30 percent iron. All massive ore is of non-Bessemer grade; the concentrate of the disseminated ore is of Bessemer grade.

Since the beginning of mining activity the Dover district has yielded an estimated 26 million tons of iron ore valued at about 100 million dollars. This tonnage is about 70 percent of the total iron ore production for New Jersey. The district now yields about 500,000 long tons of shipping ore annually from three mines—the Scrub Oaks, Richards, and Mount Hope.

The reserves in the Dover district are large and will provide iron ore for many generations at the present rate of exploitation. The possibility of finding large new deposits is slight, however, as the region has been thoroughly prospected by ground magnetic instruments.

INTRODUCTION

The Dover district has been an important source of iron ore for over 100 years, and has been active since about 1710. The total production from the district is estimated to be about 26 million tons of iron ore valued at about $100,000,000. This is approximately 70 percent of the total iron ore production from New Jersey. The district now produces about 500,000 long tons of iron ore annually from three mines—the Scrub Oaks, Richard, and Mount Hope. This is about 10 percent of the total annual iron ore production from the Northeastern States.

Inasmuch as a comprehensive geologic survey of the Dover district had never been made, a detailed study was begun in 1947 by the U. S. Geological Survey, in cooperation with the New Jersey Bureau of Mineral Research at Rutgers University. The work was carried out by the writer under the general supervision of A. F. Buddington.

This report contains a brief description of the geology, magnetite deposits, and principal mines. A comprehensive report that will record detailed descriptions of all mines, geologic maps of accessible mine workings, and a more interpretative discussion of the geology is in preparation for publication as a Professional Paper by the U. S. Geological Survey.

The more important geologic studies that have been made in the region are those of Rogers (1836, 1840), Kitchell (1856), Cook (1868), Putnam (1886), Nason (1889), Wolff (1894), Bayley (1908, 1910, 1914), Spencer (1908), and Smith (1933). These reports deal primarily with the broader features of the geology or with descriptions of individual mines; none are comprehensive in their scope. Many able geologists of the New Jersey State Geological Survey have studied the New Jersey iron deposits during the past century, and the principal report on these studies (Cook, 1868) contains much information on individual mining properties together with a summary of the geology known at that time. During the first decade of this century, Bayley surveyed the region that includes the Dover district and the results are recorded in three principal publications (Bayley, 1908, 1910, 1914). His investigations were carried out when mining in New Jersey was more widespread than at present and he was able to examine some mines that are now completely inaccessible, or even destroyed. The report on the iron mines of New Jersey (Bayley, 1910) is now the most complete source of data on the history and production of the mines in the district, but it gives only a brief summary of the geology.

The present investigation was made during 1947, 1948, and 1949, and 14 months were spent in the field, surveying the surface and underground geology. The district was mapped on 7½-minute topographic maps prepared by Army Map Service (scale: 1–25,000). Where greater accuracy was desired the geology was plotted on contact prints of aerial photographs having a scale of approximately 1,700 feet to 1 inch, and later was transferred to the topographic maps. About 25,000 feet of underground mine workings were mapped in the Scrub Oaks, Richard, and Mount Hope mines on scales of 30 or 50 feet to 1 inch. A plane table geologic map (scale 200 feet to 1 inch) was prepared at Mount Hope mine.

To support the field investigation about 650 thin sections and 25 polished sections of ore were studied.

During the field work the writer was ably assisted by several members of the U. S. Geological Survey. P. E. Hotz spent 2 weeks in the field with the writer during June 1947. E. S. Davidson assisted for 9 weeks during 1947 and for 16 weeks during 1948; G. S. Koch assisted for 16 weeks during 1949; and L. Pavlides assisted for 6 weeks during 1948.

The mining companies in the district cooperated fully in every way possible. Although it is impossible to list separately all those who have been helpful the writer wishes to acknowledge especially the contributions made by the late Harry Davenport, F. G. Woodruff, T. J. Holland, and Allan James of Mount Hope mine, Warren Foundry and Pipe Corporation; W. P. Schenck and W. Keats of Scrub Oaks mine, Alan Wood Steel Co.; and M. J. Brophy, M. T. Hoster, R. Dockeray, and A. Getz of Richard mine, Richard Ore Co. Dr. Meredith Johnson, New Jersey State Geologist, provided some of the production data.

The writer is indebted to A. F. Buddington of the Geological Survey and to Professor E. Sampson of Princeton University for their guidance and counsel during the investigation.

The laboratory studies were carried out in the geology department at Princeton University. The chemical analyses and some of the thin sections were furnished by Princeton University.

GEOGRAPHY

The Dover district occupies an area of about 80 square miles in Morris County and includes parts of the Dover, Boonton, Mendham, Chester, and Newfoundland 7½-minute quadrangles. The district is about 18 miles long, extending from the village of Ironia on the south to the Pequannock River on the north, and is 4 to 5 miles wide. It is bordered on the west by sedimentary rocks of early to middle Paleozoic age; the eastern limit of the district is arbitrarily established. Dover, which has a population of 11,210 (1950), is in the central part of the district; New York City is 35 miles southeast, and Franklin, N. J., is 20 miles northwest. (See fig. 58.)

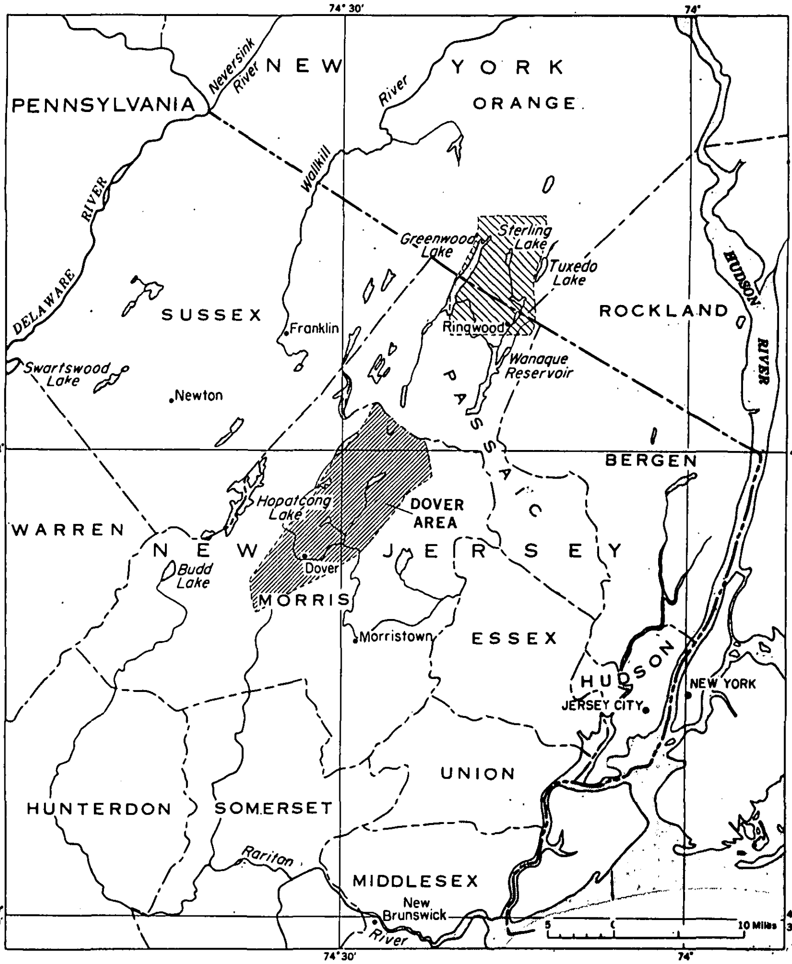

FIGURE 58.—Index map showing the location of the Dover district, Morris County, N. J. (Sterling Lake-Ringwood district, also shown, is covered by Bull. 982–F.)

The district is in the New Jersey Highlands, which is within the Reading prong of the New England physiographic province. The surface is characterized by northeast-trending accordant ridges that are separated by broad valleys that lie 200 to 300 feet below the ridge crests. Altitudes range from approximately 500 to 1,100 feet.

The trend and shape of the ridges are principally the result of stream erosion that was controlled largely by the structure and lithology of the bedrock. The topography, however, also reflects the Pleistocene glaciation which modified the region to different degrees (Salisbury, 1902).

The terminal moraine of the Wisconsin stage forms an east-west belt from about 1 to 3 miles wide through the central part of the district, and in general is parallel to the Rockaway River (Bayley and others, 1908, 1914). The moraine completely obscures the bedrock in the region between Dover and Mount Hope where it locally is at least 150 feet thick; the moraine is much thinner, however, on the hills in the vicinity of Wharton, where it is generally less than 50 feet thick.

North of the Wisconsin terminal moraine the topography is moderately rugged and the bedrock is well exposed, except in the valleys. South of the Wisconsin terminal moraine the bedrock is poorly exposed—the lowlands are covered by outwash derived from the Wisconsin glacial sheet, whereas the uplands are largely mantled by pre-Wisconsin drift (MacClintock, 1940; Bayley and others, 1908, 1914).

The central and northern parts of the Dover district are heavily wooded and mostly covered by second-growth forest. The southern part of the district is partially cleared and extensively farmed.

ROCK UNITS

The bedrock in the district consists almost entirely of rocks of early pre-Cambrian age, and includes a wide variety of metasedimentary rocks, mixed rocks, and igneous rocks that range in composition from diorite to granite. The distribution of the various rock types is shown in plate 24.

The pre-Cambrian rocks are intruded locally by small diabase dikes of Triassic(?) age. Along the western edge of the district the pre-Cambrian rocks are overlain by the Hardyston quartzite and the Green Pond conglomerate of Paleozoic age (Kümmel and Weller, 1902; Bayley and others 1914), but as these rocks were not studied in detail by the present writer they are not discussed in this report. Unconsolidated Quaternary glacial and alluvial deposits mantle the bedrock throughout the district.

The pre-Cambrian rocks of the Highlands region have been divided into three formations by Spencer (1908) and Bayley (1908; 1914)—the Pochuck, Losee, and Byram gneisses. Bayley (1941) refers to these formations as the Pochuck gabbro gneiss, Losee diorite gneiss, and Byram granite gneiss. The subsequent detailed work in the Highlands by the present writer and by Hotz (1953) indicates, however, that the formations mapped by Bayley and Spencer include rocks of widely different origin and different petrographic character. The present writer, therefore, uses mineralogic adjectives to describe the rocks rather than the previously used nomenclature, for classification of such varied rock types is too subjective when formation names are applied.

METASEDIMENTARY ROCKS

Metasedimentary rocks are the oldest rocks in the district, and they constitute approximately 25 percent of the bedrock. They occur as distinct layers and lenses of different widths and lengths and as concordant inclusions within the igneous rocks. The metasedimentary rocks are high-grade metamorphic rocks derived from calcareous and quartzose sedimentary rocks. Most primary textures and structures have been completely obliterated by metamorphism.

CALCAREOUS ROCKS

A varied assemblage of rocks of calcareous derivation was mapped in the district—marble, serpentine, pyroxene gneiss, skarn, and amphibolite. Marble, serpentine, pyroxene gneiss, and skarn are shown as a single map unit on plate 24 as skarn and related rocks. Amphibolite is by far the most abundant and widespread rock type of the group and has been mapped separately.

MARBLE

A layer of marble about 50 feet wide crops out on a few small hills in Timber Brook valley, 1¼ miles north of Splitrock Pond; and silicated marble that contains several percent of chondrodite and diopside is found on the rock dump at Splitrock Pond mine. Probably marble constitutes only a small part of the bedrock, although its presence is suggested here and there by linear depressions or by alteration products of limestone. Judging from the present distribution and structure of marble and skarn, limestone was a minor constituent of the ancient sediments in the district, and formed relatively thin layers, probably lenticular in shape, that were interbedded with predominantly clastic rocks.

The marble in Timber Brook valley is white to gray, and medium- to coarse-grained. It has a rude layering that is parallel to the foliation in the surrounding gneisses and igneous rocks. The marble is altered to diopside skarn at its contact with albite-oligoclase granite along the east border of the layer, but is unaltered where in contact with quartz diorite.

SERPENTINE

Dark-green massive serpentine is found at Winters mine and on the dump at Splitrock Pond mine where it is associated with pyroxene skarn, chondrodite marble, and magnetite.

The serpentine at Splitrock Pond mine is composed predominantly of antigorite. From place to place it contains variable quantities of diopside, chondrodite, magnetite, and a pale-green mica. The diopside and chondrodite from "islands" in the antigorite, and represent unaltered relics of pyroxene skarn and chondrodite marble. During the serpentinization of pyroxene skarn and chondrodite fine-grained magnetite formed as a byproduct of the alteration. This magnetite forms small trains and irregular masses of dustlike particles that are intergrown with antigorite. The magnetite ore that was mined is coarse-grained and forms irregular veins, blebs, and larger masses that replace the antigorite. This generation of magnetite was introduced into the host rock by the ore-forming solutions.

PYROXENE GNEISS

Thin layers and lenses of pyroxene gneiss are intercalated with plagioclase-quartz gneiss and skarn at a few places in the district. Pyroxene gneiss is most abundant in the region near Kitchell. The gneiss contains an average of about 55 percent plagioclase (An_4–An_{15}) and 40 percent diopside. Scapolite locally replaces the plagioclase and is the only light-colored mineral in some layers. Sphene is a prominent accessory mineral that in places constitutes as much as 7 percent of the rock. Locally quartz and calcite are minor accessory minerals.

SKARN

Skarn is the term applied to all aggregates of dark silicates believed to have resulted from the metasomatic alteration of limestone. It is found as podlike or lath-shaped bodies that are intercalated most commonly with biotite-quartz-feldspar gneiss and amphibolite. Marble, pyroxene gneiss, and feldspathic (or scapolitic) skarn are in places intimately associated with skarn.

The principal types of skarn in the Dover district are pyroxene skarn and hornblende skarn. Pyroxene skarn is the host rock for most of the ore deposits in the Green Pond ore belt; hornblende skarn is the host rock for many of the important magnetite deposits in the Wharton ore belt.

Pyroxene skarn is a light- to medium-green, medium- to coarse-grained, equigranular massive rock that is composed almost entirely of pyroxene. A small percentage of hornblende that is secondary after pyroxene, calcite, scapolite, and quartz is present locally. The pyroxene from barren skarn in the district ranges in composition from diopside containing 9 percent Fe atoms in total Ca+Mg+Fe (Hess, 1949, table VI, p. 641) to salite containing 16 percent Fe atoms. Preliminary petrographic data indicate that skarns containing magnetite ore typically are composed of salite containing 18 to 22 percent Fe atoms.

Hornblende skarn is a dark-green to black, medium- to coarse-grained equigranular rock that has a prominent layered structure and a good to excellent linear structure. The layering is marked by alternate laminae of different mineral composition. Pegmatite locally intrudes and disintegrates the skarn.

AMPHIBOLITE

Bodies of amphibolite ranging from lenses less than 1 foot wide to layers 2,000 feet wide and 3 miles long are present throughout the district, but only the larger bodies were mapped. The amphibolite is a weakly to moderately foliated equigranular rock that is composed principally of 45 to 65 percent plagioclase (An_{35}–An_{41}) and one or more mafic minerals—hornblende, augite and hypersthene. Biotite is a local varietal mineral; apatite and magnetite are common accessory minerals. Many of the amphibolite bodies have been injected by abundant granite or pegmatite and are migmatites. The migmatitization resulted mainly from the mechanical injection of granitic material along the foliation planes of the amphibolite during and preceding the emplacement of the main mass of the granites.

ORIGIN OF CALCAREOUS ROCKS

The distribution of metamorphosed calcareous rocks indicates that calcareous beds constituted subordinate amounts of the original sediments in the Dover region. Although the calcareous beds were thin, some of them probably extended over a wide area.

The metamorphosed calcareous rocks mapped in the Dover district reflect both differences in the bulk composition of the parent material and differences in the degree of modification of the parent rocks by magma and fluids of magmatic origin. There is no indication of appreciable variations in the degree of dynamothermal-metamorphism in different parts of the district.

Marble, which constitutes a very small amount of the bedrock, was formed by recrystallization of carbonate rocks. It is believed equivalent to the Franklin limestone described by Spencer and others (1908). Silicated marble, a local facies of the marble containing scattered chondrodite and diopside crystals, probably was formed by the addition of magnesia, silica, and fluorine to the limestone by metasomatic solutions derived from nearby magma of granitic composition. Possibly, however, the silicate minerals in this facies locally were derived from the metamorphism of impure magnesian limestone.

The serpentine was formed by the alteration of chondrodite and diopsidic pyroxene by hydrothermal solutions attending and shortly preceding the introduction of magnetite. It occurs only with the pyroxene skarn ores at Splitrock Pond and Winters mines.

Pyroxene gneiss was formed from the alteration of impure carbonate-bearing sediments. The scapolite, which takes the place of plagioclase in parts of gneiss, probably occurs in deformed zones within the pyroxene skarn; it was introduced into these channelways by metasomatic solutions.

Pyroxene skarn is associated with marble; in addition it usually occurs adjacent to or within granite or pegmatite. These facts indicate that the skarn was formed by the alteration of limestone. Field observations suggest that the skarn is due to the metasomatism of limestone by solutions moving in advance of a granitic magma, for the skarn is locally disintegrated and included within granite or pegmatite. To judge from the mineralogy of the skarn, the chemical change resulted from an addition of silica, magnesia, iron, and alumina by metasomatic solutions.

The genetic relationship of hornblende skarn to pyroxene skarn is not entirely clear. In bodies of hornblende skarn in the Wharton ore belt, thin layers of pyroxene skarn locally are intercalated with hornblende skarn. Furthermore, hornblende is noted microscopically to replace pyroxene. The present writer believes, therefore, that the hornblende skarn represents a more advanced stage in the alteration of limestone than the pyroxene skarn and is analogous to certain amphibolites in the Laurentian area of Canada (Adams, 1909, pp. 10–17) and in the Urgebirge (Barth, 1928, pp. 122–125). This mode of origin was suggested by Eskola (1914, p. 229) to explain the bodies of hornblende skarn in the Orijärvi region in southwestern Finland. In the Marysville mining district, Montana, Barrell (1907, pp. 140–141) noted that diopside may be changed into a hornblende, crystallizing on a coarser scale, if much iron or magnesia is introduced in the presence of the necessary amount of silica. An alternative explanation for the origin of hornblende skarn is that it formed by the metasomatic alteration of impure limestone beds.

The intimate association of amphibolite with other metasedimentary rocks suggests that most of the amphibolitic rocks in the Dover district were derived from sedimentary rocks. Since the primary fabrics have been completely obliterated by metamorphism, however, a sedimentary origin for the amphibolitic rocks cannot be proved. Adams (1909, pp. 3–4) recognized three diverse modes of origin for the amphibolitic rocks in the Laurentian area of Canada: metamorphism of mafic igneous rocks, metamorphism of impure calcareous and magnesian sedimentary rocks, and metasomatic replacement of limestone by granitic solutions. The present writer favors an origin by metamorphism of impure calcareous sedimentary rocks for most amphibolites in the Dover district; but possibly the amphibolitic inclusions in quartz diorite, and the large mass of amphibolite in the vicinity of Cedar Lake (Boonton quadrangle) are derived from the metamorphism of mafic igneous rocks.

QUARTZOSE ROCKS

The types of quartzose rocks that were mapped in the district are biotite-quartz-feldspar gneiss and oligoclase-quartz-biotite gneiss.

BIOTITE-QUARTZ-FELDSPAR GNEISS

Six prominent bodies of biotite-quartz-feldspar gneiss were mapped in the district. The bodies are 100 to 2,500 feet wide and as much as 10 miles long. Because of their length the gneiss bodies are excellent "marker beds" useful in the interpretation of larger structural features. Outcrops of the gneiss are distinctive because of their reddish color, and even where exposures are absent the gneiss frequently can be identified by the rusty appearance of the soils.

This rock is lithologically similar to the garnetiferous quartz-biotite gneiss of the Sterling Lake and Ringwood districts, New York and New Jersey (Hotz, 1953). (See fig. 58.)

In the Dover district the gneiss differs from place to place in composition, texture, and structure. The differences depend upon the original composition of the sediments and upon the degree of modification by igneous material.

The least-modified facies of the gneiss is a conspicuously layered rock composed principally of biotite, quartz, and oligoclase. More strongly modified facies have widely different compositions, but typically contain garnet (almandite?), which occurs as porphyroblasts ranging from 1/8 to 2 inches in diameter, and microperthite, in addition to the other essential constituents. Some layers have several percent of graphite; others contain bundles of sillimanite that in places is intergrown with rutile. Pyrite, muscovite, apatite, and zircon are common accessory minerals. Small lenticular bodies of amphibolite, pyroxene skarn, and other metasediments locally are present within the gneiss. The gneisses are similar to the permeation gneisses described by Read (1931, p. 120). They were permeated by juices from the injecting granite magma; arteritic migmatites are almost absent.

OLIGOCLASE-QUARTZ-BIOTITE GNEISS

Large bodies of oligoclase-quartz-biotite gneiss occur in Beaver Brook valley and in the region between Kitchell and Charlottesburg. A few smaller bodies, important because they contain magnetite deposits, are present also, and the largest of these is in the Wharton ore belt.

The gneiss is a greenish gray, medium-grained equigranular rock that is composed essentially of 50 to 75 percent oligoclase (An_{11}–An_{18}), 18 to 36 percent quartz, and as much as 12 percent biotite. A few percent of hornblende occurs in some layers, and magnetite is a common accessory mineral. The biotite tends to be concentrated into layers and has a marked alignment that gives a prominent lineation to the rock. The gneiss is distinguished from biotite-quartz-feldspar gneiss mainly in that it is uniform, both in composition and texture.

The chemical analysis and norm of a typical specimen of oligoclase-quartz-biotite gneiss (28C-1) is given in table 1.

TABLE 1.—*Chemical analyses, norms, and modes of rocks from the Dover district*

	28C-1	DE53	S156-48	1
Analyses				
SiO_2	67.96	68.81	74.89	77.07
Al_2O_3	16.13	17.65	12.53	12.61
Fe_2O_3	.36	.85	.69	.71
FeO	2.04	.36	1.50	.73
MgO	2.00	.20	.16	Tr.
CaO	1.53	.71	.91	.87
Na_2O	6.54	7.77	2.95	3.43
K_2O	1.78	1.83	5.38	4.06
H_2O+	.52	.66	.35	.62
H_2O-	.08	.14	.10	.23
TiO_2	.87	.69	.21	.12
P_2O_5	.02	.07	.04	Tr?
MnO	.01	Tr.	.03	.09
CO_2				Tr.
Total	[1] 99.84	[1] 99.74	[1] 99.74	[2] 100.54
Norms				
Quartz	15.87	15.72	34.18	39.12
Orthoclase	10.56	10.56	31.69	24.46
Albite	55.23	64.98	25.15	28.82
Anorthite	7.51	3.06	4.17	4.45
Corundum	.63	1.94	.31	.92
Diopside				
Hypersthene	6.85	.50	2.30	.79
Magnetite	.46		.93	.93
Ilmenite	1.67	.76	.46	.15
Hematite		.80		
Rutile		.32		
Apatite	.03	.17	.10	
Water	.60	.80	.45	.85
Normative plagioclase	$Ab_{88}An_{12}$	$Ab_{95}An_5$	$Ab_{86}An_{14}$	$Ab_{87}An_{13}$
Modes				
Microperthite				
Plagioclase [3]	73	78		
Quartz	18.5	18		
Hornblende				
Biotite	6.5			
Magnetite	Tr.	Tr.		
Apatite				
Muscovite		1.0		
Sericite	2			
Hematite		1.0		
Zircon	Tr.			
Chlorite	Tr.			
Microcline		2.0		

[1] Analyst: E. Chadbourn.
[2] Analyst: W. T. Schaller.
[3] Contains some orthoclase in antiperthitic intergrowth.

28C-1. Oligoclase-quartz-biotite gneiss, one-half mile northeast of the New Leonard shaft, Mount Hope mine, Dover quadrangle. The plagioclase is An_{11}.
DE53. Albite granite, a third of a mile northeast of Lake Telemark, Boonton quadrangle.
S156-48. Hornblende granite, from small bare knob on hill three-fourths of a mile east of upper end of Splitrock Pond, Boonton quadrangle. Contains microperthite, quartz, oligoclase, ferrohastingsite, and traces of magnetite.
1. Light-colored Byram gneiss [alaskite], from abandoned quarry 1 mile west of Hibernia. Reference: Bayley, 1914, p. 9.

ORIGIN OF QUARTZOSE ROCKS

Biotite-quartz-feldspar gneiss was mapped by Bayley (1908; 1914) as graphitic schist, and he recognized two varieties—graphitic quartz-mica schist and garnetiferous graphite schist. In regard to the origin of the graphitic quartz-mica schist he stated (1914, p. 7) : "Because of its common association with the limestone [Franklin], its occurrence in small lenticular masses, and its composition, it is inferred that the schist is a metamorphosed sedimentary rock older than the gneisses by which it is surrounded." Bayley regarded the garnetiferous graphite schist, on the other hand, as being in part sheared pegmatite dikes. In the Delaware Water Gap and Easton quadrangles he mapped these gneisses as Pickering gneiss (Bayley, 1941, pp. 12–19). He interpreted the graphitic schists as having formed from siliceous muds (1941, p. 16).

The present writer considers the biotite-quartz-feldspar gneiss to be metamorphosed alumino-siliceous sedimentary rocks that have for the most part been thoroughly permeated, injected, and locally disintegrated by granitic and pegmatitic material. The variations in the gneiss are in part the result of metamorphism of an original bedded series of sedimentary rocks, and in part the result of the addition of magmatic material that was introduced during the orogeny that deformed and recrystallized the sedimentary rocks. The lithologic layering reflects the primary bedding of the sedimentary rocks, as well as the lit-par-lit injection of magmatic materials. The garnet and sillimanite in the rock were formed by reaction between the granitic material and the country rock; they do not reflect differences in the grade of regional metamorphism. The graphite and most of the pyrite are believed to be indigenous to the sediments, reflecting the presence of original organic material. The lenticular skarn bodies associated with the gneiss represent altered limestone layers and the amphibolitic rocks impure calcareous sedimentary rocks.

Bayley (1908, 1914) did not map oligoclase-quartz-biotite gneiss as a separate formation, but instead he included it in the Losee, a light-colored gneiss containing sodic plagioclase, that he considered to be dominantly of igneous origin. Because of its marked layering and lineation and its metamorphic texture the present writer interprets oligoclase-quartz-biotite gneiss to be entirely of metamorphic origin. The original sediments were probably clastic or pyroclastic alumino-siliceous sediments.

UNDIVIDED METASEDIMENTARY ROCKS

In the Kitchell region a series of fine- to medium-grained rocks are exposed that were not differentiated on the geologic map (pl. 24). These rocks, mapped as undivided metasedimentary rocks, consist largely of interlayered plagioclase-quartz gneiss, pyroxene gneiss, pyroxene skarn, and amphibolite.

MIXED ROCKS

During the emplacement of the intrusive igneous rocks mixed rocks were formed locally by the intimate injection of magma and magmatic fluids into the country rock. The mixed rocks range from migmatites, which represent small scale alternations of igneous and metasedimentary rocks, to igneous rocks containing different amounts of metasedimentary inclusions. Migmatites are found from place to place in nearly all the metasedimentary rocks although they are more abundant in some types of rocks than in others. They generally are more abundant near the contact of metasedimentary and igneous rocks and less common in the interiors of the larger bodies of metasedimentary rocks. The mixed rocks were formed principally by the injection of magmatic material of granitic composition into country rock in a manner similar to that proposed by Fenner (1914, pp. 594–612; 694–702). Replacement of metasedimentary rocks in situ was subordinate and was restricted to short distances from the magmas. Two types of mixed rocks are shown in plate 24: hornblende granite and alaskite containing greater than 20 percent metasedimentary rocks, principally amphibolite; and albite-oligoclase granite containing greater than 20 percent metasedimentary rocks.

IGNEOUS ROCKS (PRE-CAMBRIAN)

During the long period of orogeny that deformed the metasedimentary rocks several types of igneous rocks were emplaced. The oldest igneous rocks were emplaced early in the orogeny and consolidated to form quartz diorite and diorite. Much later in the period of the orogeny a wide variety of granitic rocks were emplaced—albite-oligoclase granite is the oldest; hornblende granite and related facies are the youngest.

QUARTZ DIORITE AND RELATED FACIES

The oldest igneous rocks are hypersthene quartz diorite and minor diorite. These rocks form folded bodies in the Kinnelon and Splitrock Pond areas and sheets several miles long and as much as 1½ miles wide in the regions near Mount Freedom and Dover.

The dioritic rocks are dark gray to brown, medium-grained and equigranular, and are composed principally of 50 to 80 percent andesine (An_{30}–An_{38}), as much as 26 percent quartz, 6 to 13 percent hypersthene, as much as 6 percent augite, and as much as 5 percent hornblende. Quartz diorite predominates greatly over diorite. The rocks are characterized by a conspicuous layering; all have a granoblastic texture.

ALBITE-OLIGOCLASE GRANITE

There are several small sheets of albite-oligoclase granite in the Dover district. A phacolith-like body was mapped in the Hibernia region. (See pl. 24.)

The granite is a buff to red, medium-grained rock that is composed almost entirely of plagioclase (An_8–An_{15}) and quartz. Muscovite is a common accessory mineral. A few percent of augite, hornblende, and biotite, derived from contamination by assimilation, are present locally, particularly near mafic inclusions.

Small irregular bodies of albite granosyenite pegmatite are associated with the granite, particularly at the Scrub Oaks and Beach Glen mines.

The chemical analysis and norm of a specimen of albite granite (DE 53) from the phacolith-like body northeast of Hibernia is given in table 1.

HORNBLENDE GRANITE AND RELATED FACIES

Hornblende granite and its related facies are the youngest of the pre-Cambrian igneous rocks and constitute about 40 percent of the bedrock in the Dover district. Five principal facies of the granite were recognized: hornblende granite, alaskite, microantiperthite granite, biotite granite, and pegmatite.

HORNBLENDE GRANITE

Hornblende granite is the most abundant facies of the granite, constituting about 60 percent of the granitic rocks. Hornblende granite forms sheets, from 1,000 to about 5,000 feet wide, and phacoliths of moderate size. The granite is well-exposed throughout most of the district and caps many of the higher hills.

The hornblende granite is a buff, medium-grained, but locally coarse-grained, equigranular, uniform gneissoid rock. It weathers to brown, tan, or white. The granite is composed of 35 to 65 percent microperthite, 6 to 35 percent oligoclase, about 25 percent quartz, and 5 to 10 percent hornblende. Preliminary petrographic studies indicate that the hornblende is probably ferrohastingsite. The chemical analysis and norm of a typical specimen of hornblende granite (S 156) is given in table 1. The writer believes that the hornblende granite correlates with the Storm King granite of southeastern New York (Lowe, 1950, p. 146).

MICROCLINE GRANITE GNEISS

Lenticular bodies of microcline granite gneiss, a deformed facies of hornblende granite that is composed of microcline and albite-oligoclase instead of microperthite, are found locally in the axial area of Splitrock Pond syncline and on the nose of Cobb anticline. This facies has a granoblastic texture produced by cataclastic deformation and recrystallization of hornblende granite. It is observed to grade into undeformed hornblende granite.

ALASKITE

Bodies of alaskite are found at and near the contacts of hornblende granite and country rock, in mixed rock zones, and along the anticlinal crests of large folds. Alaskite occurs in close proximity to nearly all ore deposits; it forms an envelope around the oligoclase-quartz-biotite gneiss layer that contains many of the important deposits in the Wharton ore belt.

The alaskite is composed essentially of microperthite and quartz. Mafic minerals, principally hornblende, augite, and biotite, constitute less than 5 percent of the rock. The chemical analysis and norm of a specimen from the alaskite body west of Hibernia is given in table 1 (specimen 1).

MICROANTIPERTHITE GRANITE

Narrow linear bodies of microantiperthite granite are found in places in the contact zones between alaskite and quartzose country rocks. The granite differs mineralogically from alaskite principally in containing microantiperthite rather than microperthite as the chief feldspar. Much of it contains a few percent of augite or hornblende. Because of the intimate association of microantiperthite granite and alaskite, these granites are shown as a single map unit on plate 24.

BIOTITE GRANITE

Small bodies of biotite granite are associated locally with biotite-quartz-feldspar gneiss. The granite grades on the one hand into hornblende granite or alaskite and on the other hand into biotite-quartz-feldspar gneiss. Biotite granite is composed chiefly of microperthite, quartz, oligoclase, and biotite, although microcline locally is the principal feldspar.

GRANITE PEGMATITE

Granite pegmatite forms irregular bodies with ill-defined boundaries in granite, and sharply defined conformable or cross-cutting bodies in country rocks. It is common, but usually not abundant, except near ore deposits.

The pegmatites are simple, nearly homogeneous bodies composed of perthite, quartz, and sodic plagioclase, with accessory magnetite, allanite, and zircon. Locally large crystals of hornblende or augite, as much as 6 inches in length, derived from contamination, are present. As all the pegmatites appear to be homogeneous, individual bodies were not studied in detail.

ORIGIN OF THE PRE-CAMBRIAN IGNEOUS ROCKS

As it is essential in the interpretation of the magnetite deposits to have some knowledge of the origin of the igneous rocks, a summary of the writer's views is given below.

The hypersthene-quartz diorite and diorite resemble in composition and texture certain pyroxene granulites and charnockites described from many parts of the world. The rocks are characterized by the presence of hypersthene (and augite), and by a conspicuous layering. There is no general agreement as to the origin of these rocks—some favor an igneous origin; others favor a metamorphic origin. The writer favors an origin through primary crystallization from a relatively dry magma, similar to Goldschmidt (1922, p. 9), but there is no definite evidence that these rocks are not metamorphosed sedimentary beds, and further study is needed to clearly demonstrate the origin of the dioritic rocks.

The albite-oligoclase granite in the Dover district is similar to soda granites in pre-Cambrian rocks elsewhere, and its origin is indeed a perplexing problem. The present writer favors an origin for albite-oligoclase granite similar to that postulated by Buddington (1948, pp. 39–40) in the northwest Adirondacks. Prior to the emplacement of the hornblende granite into the level now exposed by erosion, a magma of a composition near that of the albite-oligoclase granite was generated at depth by anatexis or differential fluxing of oligoclase-quartz-biotite gneiss. This magma rose during the period of orogeny that deformed the metasedimentary rocks, and was emplaced as conformable sheets or as phacoliths. To a lesser extent albite-oligoclase granite formed by the modification of amphibolite by soda-rich solutions. The irregular distribution of augite, hornblende, and biotite in the granite indicates that these minerals are due to contamination by assimilation.

Hornblende granite and alaskite are interpreted as having formed by consolidation from magma of essentially the same composition as the resultant rock. Both the hornblende granite and alaskite are remarkably uniform in composition throughout the district, and both, where not recrystallized by later metamorphism, have a texture in which the feldspars are intergrown as in crystallization from a magma. Both granites locally transect the layering of the metasedimentary rocks, and from place to place contain angular inclusions of amphibolite. Contacts with inclusions characteristically are sharp. The presence of microperthite as the dominant feldspar in the granites seems to the writer to indicate that the granites formed from a fluid whose temperature was higher than that of metasomatic solutions.

The alaskite grades into hornblende granite and its relation to the latter is that of a felsic differentiate. It formed at the contacts and in the crests of anticlinal masses of hornblende granite.

Microantiperthite granite, found from place to place in the contact zones between alaskite and quartzose sodic country rocks, is thought to have formed in part by crystallization from a highly volatile magma of alaskitic composition and in part by replacement through potash metasomatism, but because of our lack of knowledge concerning microantiperthic intergrowths in feldspars it is not possible at present to determine the proportions of this rock of each origin. The microantiperthite on the alaskite side of the contact typically contains oriented blebs of potash feldspar. This type of intergrowth may have formed by reaction between the alaskitic magma and the sodic country rocks, whereby equilibrium in the granite melt was upset, causing potash feldspar to be exsolved from plagioclase, rather than the more common reverse process. The microantiperthite on the country-rock side of the contact typically is patch microantiperthite, which is characterized by irregular intergrowths of potash feldspar. Chessboard plagioclase typically is associated with this variety of microantiperthite. By analogy with patch perthites, which are considered by Alling (1938) to be of replacement origin, this variety of microantiperthite also is considered to be due to replacement—the sodic plagioclase of the country rock is altered by potash metasomatism.

The occurrence of biotite granite in the field and its petrographic character strongly suggests that its origin was in part by consolidation from a magma and in part by assimilation and modification of biotite-quartz-feldspar gneiss. Biotite granite occurs only in intimate association with biotite-quartz-feldspar gneiss, and there are all gradations between the two. The transition from granite to gneiss is marked principally by an increase in the amount of biotite and plagioclase, concomitant with a decrease in microperthite. The process of formation was complex. During folding a mobile facies of the granite (alaskite) was emplaced by a gradual intimate injection along planes of structural weakness in the biotite-quartz-feldspar gneiss. The main body of the magma was preceded, and perhaps accompanied, by a more dilute fraction that had the consistency of a hot gaseous fluid, and which was able to permeate short distances into the gneiss. These fluids rendered the gneiss somewhat mobile along the contacts and the original separate identities of the components was lost. Microperthite was introduced into the gneiss, and biotite was assimilated by incorporation from the gneiss. Local layers of the gneiss were not completely modified and these remain as inclusions within the biotite granite.

The pegmatites in the district are of two general types—those containing perthite as the dominant feldspar, and those containing albite or oligoclase as the dominant feldspar. The perthite granite pegmatites are interpreted as differentiates of the magma that consolidated to form hornblende granite and alaskite; the albite or oligoclase pegmatites are genetically related to albite-oligoclase granite.

DIABASE (TRIASSIC ?)

Several diabase dikes, 20 to 75 feet wide and as much as 1 mile long, intrude the pre-Cambrian rocks in the region northeast of Denville (see pl. 24). The dikes generally cross-cut the foliation in the country rock at a very small angle. The contacts are sharp, and there is no evidence of alteration of the country rock. A few aphanitic dikes, generally less than 5 feet thick, were observed in the Mount Hope mine.

The diabase is aphanitic to fine-grained and has a felty texture. It is greenish gray where fresh and brown on weathered surfaces. All the rocks are altered to various degrees by hydrothermal solutions. The diabase outcrops are distinctive because of prominent closely spaced intersecting joints.

The diabase shows no evidence of crushing or recrystallization. Further, the presence of chilled microcrystalline borders indicates hypabyssal intrusion into relatively cold country rocks, and therefore, the diabase is tentatively correlated with the diabase of known Triassic age in the Triassic Lowlands.

STRUCTURE

FOLDS

The pre-Cambrian rocks are folded throughout the district, and the rocks in most places dip more than 45°. The prevailing direction of strike is northeast, and the prevailing direction of dip is southeast, but there is some variation, as is shown by the structure symbols in plate 24.

Folds range from less than a foot to about 1 mile in width. Small-scale folds are visible throughout the district; large-scale folds were mapped only in the northern part where exposures are exceptionally good. The crests of flexures or large folds are not exposed in the southern part of the district because of moderately deep weathering, but the prevailing attitudes suggest that there are folds here as well as to the north. Drag folds useful for the determination of large folds were observed only locally.

The folds are isoclinal and generally overturned to the northwest. Their axes strike northeast and almost without exception plunge northeast (see pl. 24). The axial trends and plunges of the folds are in accord with other folds described from the New Jersey-New York Highlands (Lowe, 1950; Hotz, 1953).

STRUCTURE OF THE METASEDIMENTARY ROCKS

The metasedimentary rocks form parallel belts that trend northeast. The long parallel layers have a superficially uniform structure, but the apparent structural simplicity is deceptive as the layers are complexly deformed.

The metasedimentary rocks characteristically have a prominent lithologic layering that in places resembles bedding. Individual laminae range from a fraction of an inch to several feet in width and from a few feet to more than 100 feet in length. The layering is believed to reflect the original stratification of the sedimentary rocks for the most part, but to some extent it represents microshearing and lit-par-lit injection. All original textures have been completely destroyed by the profound deformation and complete recrystallization, and all the metasedimentary rocks now have a wholly crystalloblastic texture.

Differences in the form and internal structure of the different types of metasedimentary rocks indicate some anisotropism in their behavior during deformation. Amphibolite forms small to large lenticular layers intercalated with other metasedimentary rocks, boudins, and generally concordant xenoliths in igneous rocks; long continuous layers are generally absent, but a few were mapped, as shown on plate 24. Migmatites constitute a large part of most amphibolite bodies.

Biotite-quartz-feldspar gneiss characteristically forms long parallel layers that are as much as 10 miles long. In detail the gneiss ranges from a conspicuously layered rock to a massive rock consisting largely of granite or pegmatite. The rocks are permeation gneisses that were formed by juices from the magma that permeated and soaked into the country rock. Rocks very similar to these have been described by Read (1931, p. 120) from central Sutherland in Scotland, and they are distinguished from injection gneisses (arteritic migmatites) in that in the latter the igneous material occurs as distinct layers or patches, whereas in the permeation gneisses there is no such separation of components.

Oligoclase-quartz-biotite gneiss is a relatively homogeneous rock that has a fair to excellent layering produced chiefly by slight differences in the proportions of biotite. It is found mostly as large layers and bodies of remarkable persistence. Albite-oligoclase granite and albite pegmatite bodies locally are present in the gneiss. The gneiss in most places is deformed into tight isoclinal folds that are difficult to recognize because the flexures of the folds can rarely be observed.

Marble and the silication products of limestone occur as widely separated bodies as much as 100 feet wide. To judge from the present distribution and form of the bodies, the original limestone formed thin layers, probably of considerable extent, that were interbedded with rocks primarily of clastic origin. During the pre-Cambrian orogenic deformation the thin limestone layers were squeezed and locally constricted between the more competent clastic rocks that enclosed them to form small isolated bodies. The more competent rocks that surrounded the limestone confined the flowage of the limestone and prevented the formation of billowing, highly irregular structures that are so common where marble is the predominant rock in the metasedimentary series (Engel, 1949, p. 777).

The skarn bodies in the Dover district have two contrasted forms and shapes. The hornblende skarn bodies are lath-shaped and persist for several thousands of feet in the direction of the rake, parallel to the lineation, whereas the pyroxene skarn bodies are lenticular or podlike in shape. The form and continuity of bodies of hornblende skarn are well known from mining operations in the Wharton ore belt. At Richard and Mount Hope mines, mining has clearly demonstrated that these bodies resemble laths in shape and that they extend below the deepest mine openings. Furthermore, there is no evidence that the hornblende skarn bodies will pinch out or diminish greatly in size as mining progresses to greater and greater depths. The Mount Pleasant and Taylor hornblende skarn ore bodies have been mined along their pitch lengths (Lindgren, 1933, p. 192) for distances greater than 11,000 and 8,500 feet respectively without appreciable decrease in thickness or breadth.

The pyroxene skarn bodies, on the other hand, are mostly, if not entirely, lenticular or podlike in shape. Many small barren pyroxene skarn bodies in the region near Kitchell are clearly podlike in shape, and are discontinuous along their rake or pitch length. The shape of the ore-bearing pyroxene skarn bodies in the Green Pond ore belt is not definitely known, however, as the bodies have been mined only to relatively shallow depths, but it is probable that these bodies too pinch out in relatively short distances along their pitch length. Further mining, or core drilling, is needed to determine the form and continuity of these bodies.

The intricate series of folds in the metasedimentary rocks were induced prior to and during the emplacement of the granitic rocks, and these structures exerted a marked control over the emplacement of the igneous rocks.

STRUCTURE OF THE IGNEOUS ROCKS

The igneous rocks were emplaced during the orogeny that produced the folding, and accordingly they may be classed as synkinematic intrusives.

The oldest igneous rocks, quartz diorite and diorite, were intruded as conformable sheets during the early stages of orogeny, but subsequent to their consolidation the rocks were recrystallized and folded.

The granitic rocks were emplaced as conformable sheets and phacoliths during a late stage of the orogeny. The granite was intruded along pre-existing structures in the older rocks and cross-cutting relations are uncommon.

The igneous sheets range from lenticular bodies less than 1,000 feet wide to bodies several miles long and ½ to 1 mile wide. The structure of the sheets is quite uniform, and the foliation commonly is consistent for several miles along the trend. Here and there the granitic rocks contain abundant layers and streaks of metasedimentary rocks. (See fig. 59.) These rocks are similar to those in the Halliburton-

FIGURE 59.—Alaskite with conformable layers, streaks, and wisps of metasedimentary rocks. The dark layer in the right of the picture is amphibolite. The layering trends parallel to the handle of the hammer. West side of road, near southwest end of Hibernia ore body, Hibernia mine.

Bancroft area, described by Foye (1916), and to which he applied the term "stromatolith," meaning a rock mass consisting of many alternating layers of igneous and sedimentary rocks in sill relationship.

Two anticlinal phacoliths and one synclinal phacolith were mapped (pl. 24). The phacoliths are on the noses of large flexures—Telemark and Cobb anticlines and Splitrock Pond syncline. The phacolithic mechanism of emplacement is indicated by the conformable relations to the country rock, a moderate thickening in the axial area, and the existence of domical foliation. The interpretation of these masses as phacoliths depends upon the hypothesis that the internal structure of the granite originated prior to the complete consolidation of the magma. The granite in all phacolithic bodies has a predominant gneissoid texture characterized by interlocking feldspars, and evidence of granulation and recrystallization is seen only locally.

Pegmatites genetically related to the granites are mostly massive and undeformed. They were emplaced near the close and in part after the cessation of deformation. The pegmatites were in part emplaced as lit-par-lit injection bodies and in part as cross-cutting dikes.

FOLIATION

All the rocks in the Dover district have a fair to excellent foliation marked by the dimensional orientation of platy and tabular minerals and by the parallelism of layers, streaks, and lenses. Foliation is more conspicuous in the metasedimentary rocks than in the igneous rocks, and is marked by a lithologic layering formed by alternate layers of different composition, or texture, or both. The layering is nearly always parallel to the dimensional orientation of the mineral components of the rocks.

The foliation of the granitic rocks is mainly of primary origin and resulted from consolidation of the magma under directed stress. In places a secondary foliation was superimposed upon the primary one.

LINEATION

Lineation is remarkably uniform throughout the district, as shown by the structure symbols in plate 24. The mean lineation obtained

FIGURE 60.—Lineation in biotite-quartz-feldspar gneiss, one-half mile south of Splitrock Pond. The lineation plunges toward the right and is marked by fluting on foliation plane.

from measurements in both igneous and metasedimentary rocks is 17° N. 52° E. Throughout the northwest part of the district, in the region containing the magnetite deposits, the lineation plunges 10° to 40° northeast, the steeper plunges occurring in the northeast part of the area. In the southeastern part of the district, however, in the region north of Denville, the lineation plunges much less steeply to the northeast, and even locally plunges southwest.

The lineation is expressed by subparallel elongate or rod-like minerals, crinkling and fluting (see fig. 60), crumples and crenulations, boudins, and by intersecting planar structures. The lineation is for the most part parallel to the axes of minor, as well as major folds, and therefore conforms to the direction of intermediate elongation of folding deformation, or the *b*-axis of the coordinate system (Sander, 1930, p. 119). The longest dimension of the ore bodies is parallel to the lineation (*b*-axis). Petrofabric diagrams of pre-Cambrian gneisses from the area near Oxford, N. J., (Broughton, 1940, p. 22) indicate the existence of quartz girdles around the lineation, suggesting that the lineation was an axis of rotation.

On the east limb of Splitrock Pond syncline, north of Splitrock Pond, small folds, crumples, and mineral lineation in both quartz diorite and alaskite trend essentially parallel to the dip of the foliation (see pl. 24), about 45° from the normal *b*-axis lineation. This deviation from the normal lineation probably is due to the intense deformation that deformed the rocks in this area.

FRACTURE CLEAVAGE

Later than the gneissic structure is a fracture cleavage consisting of closely spaced, slightly curved shear surfaces that cut across the foliation in some places. The cleavage was produced by fracturing together with subordinate rearrangement of platy minerals, largely due to mechanical reorientation without recrystallization.

FAULTS

The pre-Cambrian rocks and the magnetite deposits in the district are intersected by faults that can be classified as transverse, longitudinal, and oblique, according to their attitude relative to the prevailing structural trends. Most of the faults apparently are short and their displacements are relatively small, but some, particularly the transverse breaks, are quite long and have displacements ranging from several tens to a few hundred feet. Direct evidences of faulting are generally absent at the surface, but the trace of some transverse faults is indicated by an apparent horizontal displacement of certain magnetite deposits and gneisses, and by some geomorphic features. (See pl. 24.) Longitudinal and oblique faults have small displacements and were observed only in mine workings, hence they are not shown in plate 24.

The transverse faults are normal faults that strike N. 45°–80° W. and generally dip 60°–70° S. The relative movement along the surface of dislocation is almost always to the right, as one faces the fault, and the net slip is generally less than 350 feet (see pls. 24, 25, and 28).

The longitudinal and oblique faults are principally high-angle reverse faults that dip moderately to steeply northwest (see pl. 27). The throw of known faults ranges from a few inches to about 80 feet; the lower figures are more common. A few low-angle reverse faults were mapped in the Richard and Mount Hope mines, but the horizontal displacement on these is not known to exceed 40 feet. The largest known reverse fault is the Taylor fault at Mount Hope mine, which is shown in plates 25 and 27.

A longitudinal fault, herein named the Green Pond fault, trends essentially parallel to the longitudinal faults that were mapped in the mines, and separates rocks of pre-Cambrian age from rocks of early to middle Paleozoic age in the Copperas Mountain region. According to Kümmel and Weller (1902, p. 28) this fault, a mile north of Green Pond, has a throw of 1,500 feet and uplift on the west.

JOINTS

All the pre-Cambrian rocks are jointed, and the joints can be classified with respect to the prevailing structural trends as transverse, longitudinal, and diagonal. Other less well defined joint sets were observed, but these are present only locally. Transverse joints trending northwest and dipping almost vertically are the most prominent as well as the most abundant type. Longitudinal joints that trend N. 45° E. and dip 45° NW. are next in abundance, and diagonal joints striking slightly east of north are still less abundant. The writer believes, because of the systematic relationship of joints to the gneissic structures, that the joints were formed primarily during the waning stages of the pre-Cambrian orogeny, and that they are not related to post-Cambrian deformation as suggested by Appleby (1942, p. 25).

MAGNETITE DEPOSITS

GENERAL CHARACTER

The ore deposits in the Dover district are in three main types of host rocks—oligoclase-quartz-biotite gneiss, skarn, and gneissic albite-oligoclase granite. Each type has yielded a substantial proportion of the iron-ore production from the district. Magnetite concentrations (sub-ore) occur locally in amphibolite and granite pegmatite.

The principal deposits in gneiss are in oligoclase-quartz-biotite gneiss; a few minor deposits are in amphibolitic rocks, but these deposits have never been mined on a commercial scale in the district.

The ore deposits in gneiss consist predominantly of massive magnetite that commonly contains only small quantities of gangue minerals. A typical specimen of this type of ore is shown in figure 61. The

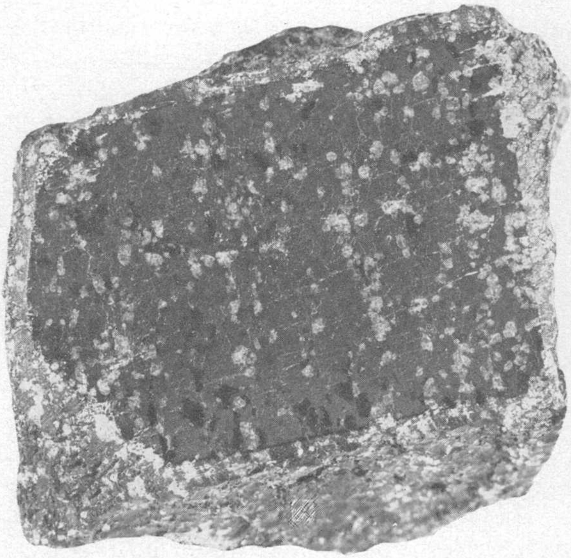

FIGURE 61.—Polished specimen of gneiss ore from the Mount Hope mine. Magnetite (dark-gray) contains several percent of apatite (light-gray) and a small amount of pyroxene (black).

tenor of the ore generally ranges between 40 and 60 percent iron. The ore commonly is black, finely granular, compact, and has a prominent blocky structure formed by three closely spaced, intersecting joint sets. To a lesser extent the magnetite is coarsely crystalline, crumbly, and nearly structureless, and this ore is referred to by the miners as "shot ore." Both kinds of ore may be present in the same ore body, in which case the blocky (hard) ore commonly is in the hanging wall of the deposit. In addition to apatite, the most abundant gangue mineral, a few percent of pyroxene, amphibole, and sparse quartz and feldspar, locally are present in the ore. For the most part the gangue minerals are arranged in rude laminae parallel to the ore contacts. In places, either along the walls or in thin layers within a deposit, the magnetite may be intimately mixed with biotite and lesser amounts of feldspar and quartz. Much of this material has an average tenor of 30 to 40 percent iron and constiutes low- to medium-grade ore.

The contacts of massive ore against wall rocks are sharp; there is an abrupt transition from ore to wall rock that contains variable but generally small amounts of magnetite, mostly as disseminated grains. In places small veinlets of magnetite penetrate into the wall rocks for short distances from the main body of ore. The contacts of many of the gneiss deposits are marked by one or more nearly parallel faults that may lie either along the contact or a few feet from it. Faults of this type often cause serious mining problems, particularly in steeply dipping ore bodies.

Biotite selvages, a few inches to about 2 feet thick, that are known to Swedish geologists as sköls, occur from place to place along one or both walls of many gneiss ore deposits.

Two principal varieties of skarn ore have been distinguished in the Dover district: deposits in hornblende skarn and deposits in pyroxene skarn. The two varieties differ considerably in appearance, structure, and form, and therefore are discussed separately below.

Hornblende skarn ore deposits are well-known from mining operations in the Mount Hope and Richard mines. In these deposits the ore is in part massive and in part laminated. The massive ore is similar to the finely granular massive ore in gneiss ore deposits and it is either blocky or crumbly. Most of the ore, though, contains abundant granules of pyroxene, hornblende and biotite as shown in figure 62.

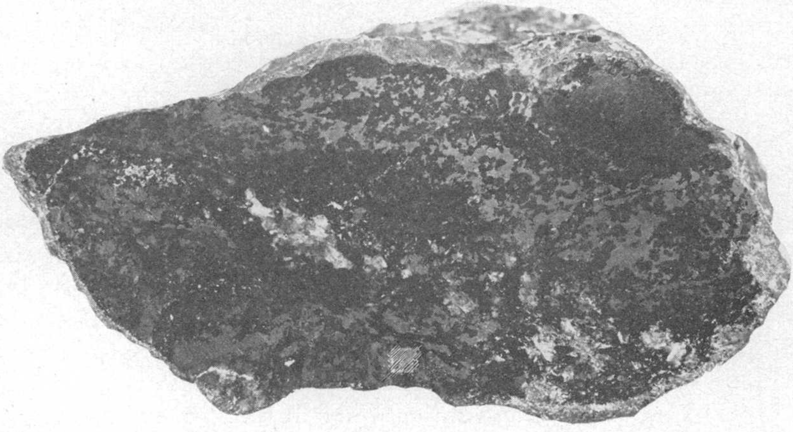

FIGURE 62.—Polished specimen of low-grade skarn ore from Taylor ore body, Mount Hope mine. The magnetite (gray) forms irregular veinlets in hornblende skarn (black). White patches are granite pegmatite that locally replaced the skarn prior to the introduction of magnetite. Specimen 11423, Princeton University collection.

This ore typically is laminated and is composed of alternating layers of massive magnetite and skarn, which is partly replaced by magnetite. The layers range from less than an inch to about 5 feet in thickness. The skarn has a prominent kneissic structure; individual grains are oriented parallel to one another, but are not necessarily arranged parallel to the foliation in the wall rocks. Indeed, the skarn in the

Taylor deposit, Mount Hope mine, is discordant to the granite wall rocks in many places.

The ore in pyroxene skarn deposits tends to be massive, and commonly forms irregular bunches and veinlets.

The wall rock for hornblende skarn deposits is principally alaskite (see pl. 27), or less commonly granite pegmatite or amphibolite; the wall rock for pyroxene skarn deposits in the Green Pond ore belt is either albite-oligoclase granite or quartz-plagioclase gneiss.

Most contacts between skarn ore and its walls are sharp, although in a few places magnetite replaces the wall rock to distances of 1 to 2 inches from the skarn contact.

The ore deposits in albite-oligoclase granite gneiss differ from the other ore types in several respects. The largest deposit of this type, and the only one now being mined, is the Scrub Oaks ore body. In this deposit the ore minerals form finely disseminated grains and, less commonly, irregular veinlets and lenses. Quartz and albite are the principal gangue minerals; apatite is sparse. The average tenor of the ore now being mined is about 27 percent iron and 0.075 percent phosphorus. Because of the low phosphorus content the ore, after concentration, is of Bessemer grade.

The ore contacts in disseminated deposits are not as well defined as they are in massive deposits. The foot and hanging walls, as well as the bottom and top rock (see p. 275) are in part determined by assay limits.

DISTRIBUTION

The magnetite deposits in the Dover district are grouped into seven ore belts according to geographic distribution and structure: Wharton ore belt, Hibernia Pond-Hibernia ore belt, White Meadow-Cobb ore belt, Dalrymple ore belt, Beach Glen ore belt, Green Pond ore belt, and Splitrock Pond-Charlottesburg ore belt. The mines, prospects, and principal shafts within each ore belt are shown on plate 24.

Most of the large mines in the Dover district are in the Wharton ore belt. This belt extends from the village of Ironia northeastward for a distance of 10 miles, and includes the Scrub Oaks, Richard, and Mount Hope mines, the only producing mines in the district, as well as many of the formerly important mines (pl. 24).

The Hibernia Pond-Hibernia ore belt includes the deposits in the mineralized zone that wraps around the plunging nose of Hibernia anticline (pl. 24). The Hibernia mine, which is on the east side of the zone, is the only mine in the ore belt that has yielded large tonnages of ore.

The White Meadow-Cobb ore belt includes the deposits that lie between White Meadow Lake and the Cobb mine. None of the mines have been large producers.

The Dalrymple ore belt is northeast of Ironia, and includes the George, David Horton, DeHart, Lawrence, Dalrymple, and Trowbridge mines. Most of the mines in the belt exploited only one deposit, except for the David Horton mine which prospected five closely spaced deposits across a width of about 500 feet.

The Beach Glen ore belt includes the Beach Glen and Swedes mines. The mines are separated by the Wisconsin terminal moraine, and the structural relations of the two mines are, therefore, not clear.

The Green Pond ore belt includes a number of small widely spaced mines that are on the east side of Copperas Mountain (see pl. 24). The Green Pond and Davenport mines have been the largest producers in the belt. The ore in these deposits, as in most others in this belt, contains small amounts of sulfides.

The Splitrock Pond-Charlottesburg ore belt includes the deposits that lie on the east side of Timber Brook valley, north of Splitrock Pond. The deposits are small and widely separated.

A few small deposits lie outside of the ore belts, but none of these are economically important.

STRUCTURE OF DEPOSITS

Most of the deposits in the district are on the limbs and nose of the northeast-trending Hibernia anticline (see pl. 24). The Wharton ore belt is on the northwest limb, the Dalrymple ore belt is on the southeast limb, and the Hibernia Pond-Hibernia ore belt is on the plunging nose of the anticline. The White Meadow-Cobb ore belt is on the southeast limb of Hibernia anticline, to the southeast of the Hibernia deposit.

The deposits in the Beach Glen ore belt are on the northwest limb of Beach Glen anticline and, unlike most other deposits, dip to the northwest.

The position of the Splitrock Pond-Charlottesburg ore belt relative to major as well as minor structures is not clear (see pl. 24).

The deposits in the Green Pond ore belt are in small subsidiary folds on the limbs of synclines, the largest of which is about 1,500 feet wide.

The magnetite bodies are referred to locally as veins. This term was first applied to the deposits by Rogers (1836; 1840), and subsequent workers in the district have followed his usage because of the tabular shape of most of the bodies (see fig. 63).

The general form of the magnetite deposits in the district has been described a number of times, and is discussed in some detail by Bayley (1910, pp. 135–140). Recent mining operations have not appreciably changed the general concepts of the form, but have disclosed additional pertinent details.

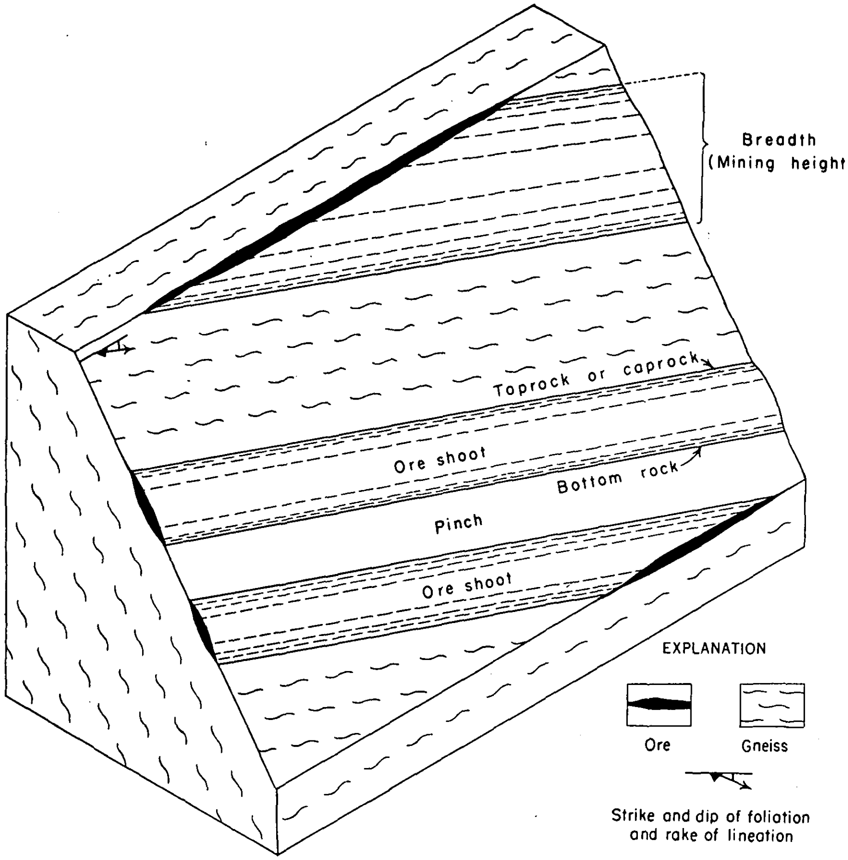

FIGURE 63.—Block diagram showing idealized structure of ore bodies in the Dover district.

Except for the pod-shaped(?) pyroxene skarn deposits in the Green Pond ore belt, the ore deposits in the Dover district are tabular, ruler, or lath-shaped. (See pls. 25 and 26; fig. 63.) The longitudinal planes of the bodies dip nearly parallel to the foliation and the longitudinal axes plunge parallel to the lineation in the enclosing rocks. The Taylor ore body is a typical lath-shaped deposit. (See pls. 25 and 27.) The Scrub Oaks deposit has a much greater mining height and is a tabular deposit. (See pl. 28.) The thickness and height of individual deposits differ considerably. Thicknesses range from less than 1 foot to about 75 feet, and commonly average between 5 and 20 feet; breadths or mining heights (measured at right angles to the plunge) range from about 100 to 2,400 feet. (See fig. 63.) The length along the rake, or pitch length (Lindgren, 1933, p. 192; see also fig. 63, this report), has not been determined although several ore bodies have been mined to lengths greater than 8,000 feet. The important Mount Pleasant deposit, a hornblende skarn ore body, has been mined for a length of 11,000 feet. Another hornblende skarn deposit, the Taylor ore body at Mount Hope mine (see pl. 25), has been worked along its pitch length for more than 8,500 feet and to a depth of 2,000 feet. The known deposits remain more or less uniform in tenor, thickness, and height as depth increases. Because of their remarkable persistence along the pitch length the ore bodies in the Dover district are believed to be unique among magnetite deposits. Possibly, though, the deposits in the Klodeberg area in the Arendal district, Norway (Bugge, 1940, pp. 103–104) are similar, for these are described as occurring in limestone lenses or rulers that have their axes parallel to the lineation in the country rock. Unfortunately, however, Bugge does not give exact data on the pitch-length of the deposits, nor does Vogt (1910, pp. 138–162; 1918, pp. 30–55) who studied the deposits earlier.

The tabular- and lath-shaped bodies generally pinch and swell to different degrees. (See fig. 63.) A few large deposits, as for example the Mount Pleasant, contain definite shoots formed by pinches (see fig. 63). The pinches are marked by thin seams of massive magnetite or by narrow mineralized zones containing sparse disseminated magnetite. Others, as the Hibernia deposit which has a mining height of about 2,400 feet, do not contain marked pinches and these deposits are minable throughout their height, although there are some differences in thickness.

The cross-sections of the ore-bodies are relatively uniform along the pitch-length. The toprock and bottom rock (see below), and most of the pinches and swells, rake parallel to the linear elements in the country rock. (See fig. 63.) In gneiss deposits and granite deposits the ore walls in most places are parallel to the foliation in the wall rock, and thus they conform to minor irregularities, such as rolls, in the foliation of the wall rock. (See pl. 28.) Where the foliation in one wall converges toward that in the other wall a pinch is produced. Conversely where the foliation on opposite walls diverge a swell is formed. Most swells and pinches result from small rolls in the foliation.

Detailed studies in the mines indicate, however, that the ore in gneiss deposits locally cuts across the gneissic structure in the country rock. At Mount Hope mine, the Richard deposit on the 1,700 level in many places cuts across the strike of the foliation at a small angle, and the Teabo deposit in nos. 3 and 7 stopes on the 1,000 level locally cuts across the dip of the foliation.

The rock overlying the deposits, in the plane of the ore, is known locally as "top rock" or cap rock; that beneath the deposits is termed "bottom rock."

In gneiss deposits the pinches that form the bottom rock and top rock are due principally to a convergence of the foliation in opposite walls. The bottom rock of the Richard (South) deposit was observed on the 900 level of the Richard mine, and here it is demonstrated that the pinch which formed the bottom rock of the deposit was due to a convergence of the foliation in opposite walls. A short distance above the bottom rock the hanging wall of the deposit dips about 60°; the footwall dips at a similar angle. Toward the bottom rock, however, the foliation in the footwall gradually flattens and at the 900 level it dips only 35°, whereas the dip of the hanging wall remains about 60° SE. Thus there is a rather abrupt pinch in the ore.

The top rock and bottom rock of ore deposits in skarn are marked by a pinch in the skarn, the host rock for the ore, as well as the ore. (See pl. 27.) The magnetite usually ends abruptly against the granite country rock, and therefore pinches in the skarn cause the ore to pinch also. Stringers of massive magnetite a few inches thick commonly extend from the ore bodies into the country rock for some distance in the plane of the deposit, however, and in ore bodies with marked shoot structures, as the Mount Pleasant deposit at Richard mine, these stringers commonly extend from one ore shoot to another.

Magnetite ore bodies that exhibit fold structures resulting from the replacement of folded country rocks have previously been described from the New Jersey Highlands. The deposit at Hurd mine, at Hurdtown, which is 4 miles northwest of the Dover district, is a well known example in the Highlands of a magnetite deposit in a fold (Bayley, 1910, p. 138). This deposit is in an asymmetrical syncline that plunges to the northeast. The ore is on the northwest limb, on part of the southeast limb, and in the trough of the fold, and is thus structurally similar to the zinc deposits at Franklin, N. J., (Spencer and others, 1908, pp. 24–25). Magnetite deposits associated with folds have been described also from the Sterling Lake and Ringwood districts, New York and New Jersey (Hotz, 1953) and from the St. Lawrence County district, New York (Leonard, 1953). In the Dover district ore bodies in folds also are present. The deposits in the Mount Hope and Richard mines are associated with the Mount Hope syncline. At Mount Hope mine the Leonard and Finley deposits are on opposite limbs of the northeast-plunging syncline. (See pl. 25.) The two deposits converge in the axial area of the syncline, but there is no marked thickening of the ore in the axial area as there is in the Hurd deposit (Bayley, 1910, p. 138). The Hibernia Reservoir-Hibernia ore belt is on the nose of Hibernia anticline. Several deposits in the Dover district also exhibit folds of a smaller scale. A few folds that have amplitudes ranging from 5 to 20 feet were mapped in the Mount Pleasant (North) ore body at Richard mine. These folds are interpreted for the most part as drag folds on the limbs of the Mount Hope syncline.

MICROBRECCIATION

Microscopic study of thin sections indicates that many of the deposits in gneiss and granite are in linear microbrecciated zones in the country rock. The magnetite in hornblende skarn deposits also occupies, in part, microbrecciated zones.

The rocks in the microbrecciated zones were granulated by pre-ore cataclastic deformation. The granulation tends to follow narrow linear zones that are nearly, but not always, conformable to the gneissic structure.

The magnetite is clearly later than the cataclastic textures (fig. 64) and there is evidence that it is more abundant within and near granulated zones in the rock than in uncrushed parts of the rock. The magnetite cuts across the individual grains and replaces them.

Generally cataclastic structures do not seem to be present, except locally, in the wall rocks of deposits or in the country rock, and it is suggested, therefore, that the magnetite was introduced selectively into the microbrecciated zones by the iron-bearing solutions.

It has been demonstrated that the magnetite in the ore deposits in Clinton County, N. Y. (Postel, 1952), and at Cranberry, N. C. (Ross, 1935, p. 116), is in granulated zones in the country rock. Evidences of cataclastic deformation are generally absent, however, in the magnetite deposits of the St. Lawrence County district, New York (B. F. Leonard, personal communication).

MINERALOGY

The mineralogy of the ore is relatively simple. Magnetite is the chief ore mineral; hematite constitutes about 15 percent of the ore in one deposit—the Scrub Oaks. Ilmenite almost never exceeds 1 percent of the ore. Sulfides are absent except in deposits in the Green Pond ore belt which contain a few percent of pyrrhotite, chalcopyrite, and pyrite. The principal gangue minerals are unreplaced fragments of the host rock, mostly pyroxene, hornblende, feldspar, quartz, and biotite. Several minerals were introduced, however, by solutions attending the deposition of the ore. The most important of these, in addition to the opaque minerals mentioned above, are apatite, calcite, chlorite, serpentine, biotite, quartz, pumpellyite, tourmaline, sphene, and spinel.

OPAQUE MINERALS

MAGNETITE

The magnetite in most deposits is medium- to course-grained and appears to be homogeneous, but high magnification shows that most of the magnetite contains minute amounts of other minerals. In some specimens a few percent of ilmenite, hematite, and spinel are intergrown with magnetite. Ilmenite is in small irregular bodies that embay magnetite and replace it. Hematite and spinel form laths and blades that are for the most part oriented along the (111) direction of magnetite.

HEMATITE

Hematite constitutes about 15 percent of the ore in the Scrub Oaks deposit, but it seldom forms more than 1 percent of the ore in the massive gneiss and skarn deposits. At Scrub Oaks mine the hematite is crystalline, and it is intimately intergrown with magnetite. It can be distinguished from magnetite with difficulty by its bluish-gray hue and its reddish streak. The hematite forms variable amounts of the ore. Throughout most of the deposit it constitutes less than 5 percent of the ore, but in a few stopes it constitutes about 30 percent of the ore. The hematite is primary and was deposited locally from the same solutions that deposited the magnetite. In part it appears to be contemporaneous with magnetite, but in part it embays and replaces magnetite. There is no evidence that martite is an important constituent of the ore.

In addition, hematite occurs as sparse blades or laths that are intimately intergrown with magnetite from massive ore bodies.

ILMENITE

Small irregular grains of ilmenite are associated with magnetite at Birch mine. The ilmenite is later than the magnetite and locally replaces it. Small quantities of hematite and spinel form oriented intergrowths in the ilmenite. Most other ores in the district contain practically no ilmenite.

PYRRHOTITE

The deposits in the Green Pond ore belt contain a few percent of pyrrhotite. The pyrrhotite replaces the magnetite.

CHALCOPYRITE

Small quantities of chalcopyrite also are associated with the ore in the Green Pond ore belt. It does not exceed 1 percent of the ore, and generally is even less abundant, to judge from ore specimens on dumps at the Green Pond mine. The chalcopyrite is later in the paragenetic sequence than pyrrhotite and replaces both magnetite and pyrrhotite.

PYRITE

Pyrite constitutes a few percent of the ore in deposits in the Green Pond ore belt, and it also occurs in the ore at J. D. King and Denmark mines. It is not present in ores from the other deposits, however, except as local late veinlets. Nevertheless, at the Mount Hope and

Richard mines the wall rocks of some gneiss ore bodies locally contain sparse disseminated grains and veinlets of pyrite.

NONOPAQUE MINERALS

APATITE

All the ores contain some apatite. In massive deposits apatite constitutes from about 1 to 40 percent of the ore; in disseminated deposits, as at Scrub Oaks mine, it constitutes less than 1 percent of the ore. Megascopically the apatite appears as white granules in the ore, commonly forming laminae that are parallel to the ore walls (see fig. 61). Two deposits, the "Gold Diggings" vein at Mount Hope mine, and the Canfield phosphate vein, contain more than 25 percent apatite. The Canfield deposit was tested as a possible source of phosphorus (Bayley, 1910, p. 381), but a process was never satisfactorily worked out for the recovery of phosphorous on a commercial scale.

SPINEL

The magnetite in some massive ore deposits contains a small amount of a silicate mineral that can be seen only under sigh magnification, and which is tentatively identified as spinel. In the magnetite, the spinel forms laths and blades, and less commonly unoriented blebs that formed by exsolution from the magnetite.

QUARTZ

Quartz may be classified as magmatic, pegmatitic, ore-stage, and post-ore. At Scrub Oaks mine pegmatitic quartz is abundant locally within and near the ore, and in some places it constitutes nearly 50 percent of the host rock. Ore-stage quartz occurs in minor amounts in some massive deposits. It forms rims around unreplaced mineral grains in ore, inclusions in magnetite, and veinlets that replace magnetite. Post-ore quartz that cements breccia fragments of ore was observed locally in the Richard ore body on the 1,700 level at Mount Hope mine, and was reported by Bayley (1910, p. 404) from the Allen deposit. This quartz often is associated with carbonate.

CALCITE

Veinlets of a white to pink carbonate, probably calcite, that range from a fraction of an inch to several inches in width, can be seen in several deposits. At Mount Hope mine pink carbonate veinlets locally cut magnetite near the toprock of the Teabo deposit. Thin sections of ores and wall rock from many other deposits also disclose the presence of microscopic veinlets of carbonate. Carbonate, that commonly is associated with milky quartz, cements brecciated fragments of magnetite in the Allen and Richard ore deposits.

BIOTITE

In many gneiss ore deposits a dark-reddish-brown biotite, probably lepidomelane, forms rims around magnetite (see fig. 64) and veinlets that cut both magnetite and the host rock. Probably some of the biotite that forms thin foliae in many hornblende skarn and gneiss ore deposits also was introduced by the ore-forming solutions.

PUMPELLYITE

Pumpellyite was identified by B. F. Leonard from several deposits in the Dover district. It has been recognized in the Middle vein at Richard mine and in the Scrub Oaks and Beach Glen deposits. The pumpellyite occupies cracks in magnetite, forms rims around magnetite, and replaces feldspar in the wall rock. At Scrub Oaks mine it is found in the wall rocks as far as 30 feet from the ore body. B. F. Leonard, in a personal communication, reported the presence of pumpellyite in the magnetite deposits of the St. Lawrence County district, Adirondack Mountains, New York. Pumpellyite has not been described in other magnetite deposits.

CHLORITE

Unreplaced fragments of feldspar and mafic minerals in ore deposits commonly are slightly to moderately altered to chlorite. Chlorite also locally forms rims around magnetite.

SERPENTINE

Serpentine is associated with the ores in the Splitrock Pond deposit and the northwest deposit at Winter mine. At Splitrock Pond mine serpentine was formed by alteration of pyroxene and chondrodite from hydrothermal solutions that attended the ore-forming solution.

TOURMALINE

The ore in the Scrub Oaks deposit contains small quantities of tourmaline. The tourmaline is strongly pleochroic, ranging from pink to dark olive green, and forms euhedral crystals. It was deposited after magnetite and before calcite. Tourmaline is not known to be present in the massive ores.

SPHENE

Sphene forms rims around magnetite and isolated grains closely associated with magnetite in some low-grade ores and in the adjacent wall rocks. It has not been observed, however, in massive high-grade ores. The sphene was deposited from solutions that attend the iron-bearing solutions, and apparently was deposited around magnetite grains because of an affinity for it. There is no evidence that the sphene rims are "reaction rims" or coronas.

CHEMICAL COMPOSITION

The chemical composition of the pure mineral magnetite is 72.4 percent Fe and 27.6 percent O. The massive ore in the district approaches this composition, but never attains it, as some impurities are always present.

Many analyses of iron ores from the Dover district are recorded by Bayley (1910, pp. 93–114), and a few of the more reliable and complete ones are reprinted here in table 2. In addition, a new analysis of ore from the Scrub Oaks mine is given in table 2.

By reference to table 2 it may be seen that the analyses of massive ore deposits are similar; the principal differences in chemical composition of the ores are due to differences in the amount and kind of unreplaced fragments of host rock in the ore. The disseminated ore deposits differ greatly from the massive ore deposits in chemical composition, however. Analysis No. 8 (table 2), from the Scrub Oaks mine, shows a high content of SiO_2 and a proportionally low content of Fe_2O_3 and FeO. This analysis reflects the high quartz and feldspar content, and the relatively low iron content of the ore.

The P_2O_5 content of all the ores is due to apatite; the TiO_2 is due almost entirely to ilmenite, as sphene and rutile are generally absent. The MnO and V_2O_3 probably are contained in the magnetite.

TABLE 2.—*Chemical analyses of magnetite ores from the Dover district*

[Bayley, 1910, pp. 112-114 (analyses 1-7, inclusive)]

	[1] I	[2] II	[2] III	[2] IV	[2] V	[2] VI	[2] VII	[3] VIII
SiO_2	9.25	7.14	3.77	2.22	3.56	1.38	1.51	26.04
Al_2O_3	1.98	1.23	.79	.59	.44	.55	.37	2.11
Fe_2O_3	55.71	60.89	61.16	62.76	61.47	65.26	64.87	47.17
FeO	26.64	25.94	29.56	28.59	29.04	30.20	31.11	21.58
MgO	1.11	1.40	.64	.74	1.68	.10	.40	.40
CaO	1.89	1.31	1.23	2.54	1.66	.68	.51	.40
Na_2O	.57	.08	.12	tr	.10	tr	tr	1.06
K_2O	.12	.13	.14	tr	.12	tr	tr	.24
H_2O+	.56	} .25	.16	.13	.16	.12	.09	{ .38
H_2O-	.43							.06
TiO_2	.54	1.25	1.30	.30	1.15	1.09	1.05	.49
CO_2	.35	------	------	------	------	------	------	.17
P_2O_5	.86	.529	.448	1.89	.541	.49	.053	.22
S	.07	.014	.011	.14	.021	.01	.007	------
Cr_2O_3	.01	0	0	0	0	------	0	------
NiO	.02	0	0	0	0	0	0	------
MnO	.05	.03	.06	.04	.03	.03	.08	.03
V_2O_3	.14	.15	.095	.11	.08	.08	.13	.003
Total	[4] 100.30	[5] 100.343	[5] 99.484	[5] 100.05	[5] 100.052	[5] 99.99	[5] 100.18	100.353
Fe	59.78	62.85	65.87	66.23	65.68	69.24	69.68	49.85
P	.37	.23	.19	.81	.23	.18	.02	.09

[1] Analyst: W. T. Schaller.
[2] Analyst: R. B. Gage.
[3] Analyst: Charlotte M. Warshaw.
[4] Analyzed also for ZrO_2, CoO, CuO, ZnO, BaO, SrO, Li_2O; none present.
[5] Analyzed also for CoO, BaO, and SrO; none present.

I. Cobbed ore, Hibernia mine. Representing shipments of 1906.
II. Hibernia mine. Average sample, 1908.
III. Richard mine. Ore of North (Mount Pleasant) vein. Average sample, 1908.
IV. Richard mine. South (Richard) vein. Selected sample, 1908.
V. Leonard mine, Mount Hope. Selected sample of Leonard vein, 1908.
VI. Elizabeth mine, Mount Hope. Selected sample of Elizabeth vein, 1908.
VII. Hurd mine, Wharton, N. J. Selected sample of Hurd vein, 1908.
VIII. Scrub Oaks deposit, no. 5 level, Scrub Oaks mine, Dover quadrangle (Field no. SO5-26).

ORIGIN AND CLASSIFICATION

The magnetite deposits in the Dover district are in three principal types of host rocks—oligloclase-quartz-biotite gneiss, albite-oligoclase granite, and skarn. In addition, magnetite concentrations are found locally in amphibolite and granite pegmatite. The occurrence of ore in several different types of host rocks and the relationship of ore to these rocks demonstrates that the magnetite was introduced into the host rocks after their formation. From the presence of ore in granulated zones in the host rocks it is concluded that these zones were the principal centers of deposition of the ore.

Both field and laboratory evidence suggest that all the magnetite deposits originated by metasomatic replacement of favorable host rocks. Megascopically, as well as microscopically, it can be seen clearly that the disseminated ore in the Scrub Oaks deposit formed by replacement of the granite host rock. Veinlets and streaks of magnetite cut across the granite; scattered grains of magnetite penetrate and replace the minerals of the granite. All gradations exist between ore and barren country rock. All of the ore contains unreplaced fragments of feldspar and quartz; these are identical with the minerals in the albite-oligoclase granite country rock. The centers of deposition were granulated zones in the granite.

A replacement origin for the ore can also be demonstrated for skarn deposits. The magnetite in pyroxene skarn deposits forms irregular veinlets, bunches, and layers that replace the skarn minerals; the replacement proceeds along grain boundaries. (See fig. 64.) The ore in hornblende skarn deposits preferentially replaces certain layers in the skarn.

Evidences for a replacement origin of the magnetite are less apparent in the massive gneiss ore deposits as the replacement is nearly complete. In these deposits, however, magnetite cuts across layers in the gneiss and replaces individual mineral grains of the host rock. In places small veinlets penetrate and replace the wall rock.

Smith (1933, p. 671) favors a mechanism of origin in which the growth of magnetite grains would progressively force the walls apart. He interprets the strained and broken grains of the host rock to be the result of dilation caused by the growth of magnetite grains (Smith, 1933, pp. 672–673). The present writer, however, believes that the broken grains are due to granulation (microbrecciation) produced by pre-ore cataclastic deformation, as discussed on page 277.

The replacement must have taken place under a relatively heavy load as there is no evidence of open-fracture filling in the rocks. The ore-forming fluids did not, therefore, have large openings through which to migrate, but instead had to migrate along intergrain boundaries, discontinuous small fractures, and granulated zones that were

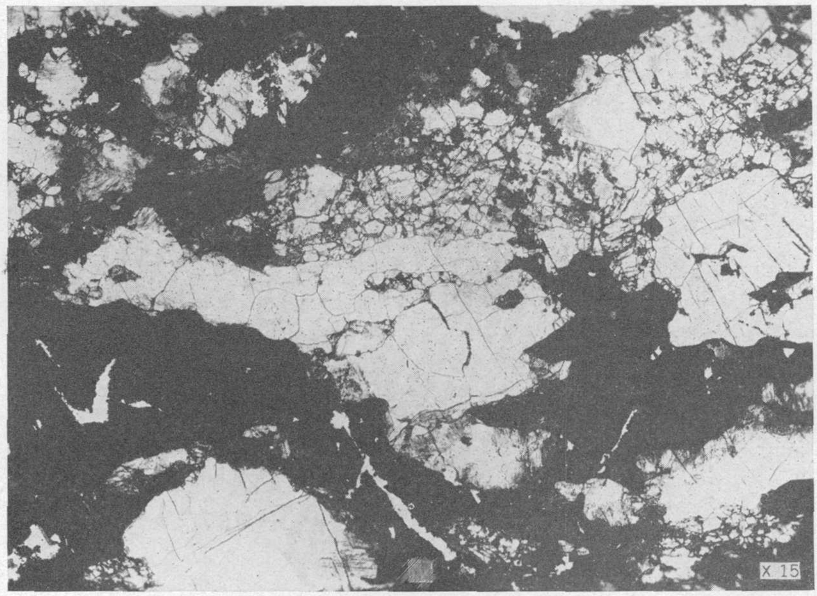

FIGURE 64.—Photomicrograph of sub-ore from dump at Brotherton mine, showing magnetite in cataclastic zones in microantiperthite granite gneiss. Large recrystallized quartz masses are only slightly replaced by magnetite. Note partial rims of biotite around magnetite. *Plain light.* ×15.

rendered more permeable than the surrounding rock by microbrecciation. To penetrate for long distances in these zones the fluids must have had a high degree of mobility, and were either pneumatolytic or hydrothermal, or more probably both. Evidence is strong against the tenet that the magnetite was introduced as a liquid melt, as suggested by Shand (1947).

The source of the ore-forming fluids was a cooling igneous mass. The process whereby the residual liquor of a magma undergoing progressive crystallization is continually enriched in volatile components has been described by Bowen (1928, p. 293). During crystallization the residual liquor is progressively enriched in H_2O and other mineralizers, but there is no general agreement whether the mineralizers given off by the cooling igneous mass escape as a liquid or a vapor phase. It has been demonstrated that surface and near-surface lavas give off gases, and furthermore, that these gases are capable of transporting large quantities of magnetite and other ore materials (Zies, 1929). The mineralizers given off from igneous masses crystallizing at depth, however, where pressure can be maintained, may escape from the parent rock as a liquid phase (Ross, 1935, p. 48).

The magnetite deposits in the Dover district were derived from the granite magma that consolidated to form hornblende granite and alaskite. During the progressive crystallization of this magma a more mobile and highly volatile portion of the magma was concentrated adjacent to inclusions and in the crests of certain large anticlines. This magma, which consolidated to form alaskite, was split off prior to the crystallization of the pegmatites. Further differentiation of the alaskitic magma by progressive crystallization concentrated the volatiles still more and these ferriferous fluids escaped from the crystal system, migrated along the microbrecciated zones, and replaced the rocks within these zones to form magnetite bodies.

The field evidence indicates that the residual liquids of the crystallizing magma were continuously enriched in iron. On the other hand, the aqueo-igneous solutions that consolidated to form pegmatites contained very little iron as evidenced by the scanty amounts of magnetite in most pegmatites. The field evidence for the enrichment of iron in the residual liquid is supported by several other studies. It has been demonstrated by Wager and Deer (1939, p. 133) by means of chemical analyses that there is an increase in Fe in the residual liquid of a crystallizing magma up to the final liquid, until about 95 percent is crystallized. Fenner, furthermore, contends (1929, p. 242) that the residual liquid is highly ferriferous up to complete crystallization.

The present writer's conclusions regarding the origin of the magnetite deposits in the Dover district differ considerably from most of those presented previously. There has been no general agreement among earlier workers as to the origin of the magnetite deposits in the New Jersey-New York Highlands. Some have favored an igneous origin; others have favored an origin through metamorphism of sedimentary iron beds. A summary of most of these theories is given by Bayley (1910, pp. 156–182), and hence they are only briefly reviewed in this report.

Rogers was the first to discuss the origin of the ores, and he believed (1840, p. 22) that the deposits "are real veins of injection, and not true beds, contemporaneous with the adjoining gneiss * * *." He presumed that the deposits resulted from "a forcible injection of fluid ore" into steeply inclined beds (Rogers, 1840, p. 36). A few years later Kitchell (1857, pp. 11–13) concluded that the magnetite deposits are metamorphosed sedimentary iron beds, and this hypothesis was widely accepted by most geologists for the next half century.

The presence of the ore in layers essentially parallel to the gneissic structure of the wall rocks was probably the main factor that led many early workers to favor a sedimentary origin for the magnetite deposits. They also, of course, believed all the gneisses to be metamorphosed sedimentary rocks. Some geologists still hold that the deposits are metamorphosed sedimentary iron formations, but several arguments can be presented against this hypothesis: the magnetite ores occur in a wide variety of host rocks--gneiss, skarn, and granite; the ore bodies locally cut across the gneissic structure in the wall rocks; small veinlets of magnetite cut across the structure and replace the minerals of the wall rocks; quartz-banded ores, so typical of metamorphosed sedimentary iron deposits (Geijer, 1936, p. 153), are entirely absent.

In 1904 Spencer revived the hypothesis of igneous origin. His view differed from Rogers' in many respects, though. He states (1904, p. 301): "Instead of being bog ores or carbonates deposited in sedimentary rocks and later changed to magnetite by metamorphism, as formerly suggested, they [the magnetite deposits] apparently have been introduced as products of igenous activity." Bayley (1910, pp. 147–156) favored an origin for the deposits similar to that proposed by Spencer. He stated (Bayley, 1910, p. 149):

> In all cases the ores are regarded as being of magmatic origin—that is, the source of their material is thought to have been the deep-seated magmas, portions of which, upon being intruded into the overlying rocks, solidified as the various gneisses now constituting the principal rocks of the Highlands ridges. After the partial cooling of the gneisses these were in turn intruded by ferruginous portions of the same magma that gave them birth, and these intrusions were later enriched by iron-bearing solutions or vapors originating in the same subterranean source. In their transit to the surface these solutions or vapors deposited additional magnetite in the intruded ferruginous rocks and made the ore lenses that now comprise the ore bodies.

From a study of the relation of magnetite to the minerals in the pegmatites, Bayley concluded that there were two generations of magnetite. The first crystallized before any of the other constituents of the pegmatite; the second after all the pegmatite minerals had been formed (Bayley, 1910, p. 151). He believed that the earlier generation of magnetite was clearly a product of the crystallization of the magma that solidified as pegmatite, and that the later generation was introduced by hot aqueous solutions or vapors after the normal components of the pegmatite had crystallized (Bayley, 1910, p. 151). He noted that the late magnetite in some places replaced the silicate minerals. Bayley concluded also that the important ore bodies in "dark gneiss" were formed in a manner analogous to those in the pegmatite, except that very acid siliceous material was lacking in the first stage in ore production (Bayley, 1910, p. 152). In these "dark gneiss" deposits, which characteristically contain hornblende and pyroxene in addition to magnetite, he assumed that the magnetite crystallized from the same magma that consolidated to form the mafic layers (1910, p. 152). He recognized, though, that the stringers of nearly solid magnetite that connect the shoots in the plane of the foliation were formed "by solutions passing between the ore bodies" (Bayley, 1910, p. 153).

The present writer differs from Bayley in believing that all the magnetite in the ore bodies was introduced after the crystallization of the pegmatites, and that it metasomatically replaced the host rocks. There is no evidence that some of the magnetite crystallized from iron-rich portions of the granite pegmatites; many pegmatite bodies are nearly barren. Those pegmatites that do contain magnetite concentrations usually are closely associated with known ore bodies, and further there is evidence that the magnetite was introduced later and replaced the minerals of the pegmatite. In pegmatites the magnetite occurs as veinlets and bunches that irregularly penetrate and replace feldspar, and as veinlets that penetrate cleavage cracks in the feldspar (see fig. 65). Furthermore the pegmatitic feldspars within and

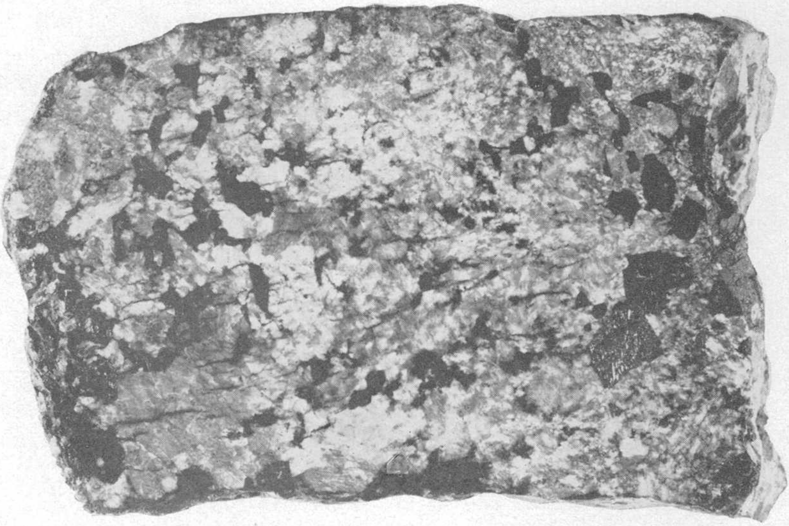

FIGURE 65.—Polished specimen from Mount Hope mine showing magnetite in granite pegmatite. Magnetite occurs as large subhedral grains, irregular veinlets that replace feldspar, and thin veinlets along cleavage planes of feldspar. The feldspar is bleached to green in part of the specimen. Specimen 11420, Princeton University collection.

adjacent to magnetite frequently are bleached from red or pink to green, indicating that the ore-forming solutions were not in equilibrium with the previously crystallized feldspar.

In the dark gneiss deposits of Bayley (those in skarn and amphibolitic rocks), the present writer has concluded that the mafic granules in the ore were not deposited by ore-forming solutions as Bayley held (1910, p. 152); but instead, they represent unreplaced fragments of the host rock. There is no evidence that hornblende or pyroxene was introduced during an early stage in the ore formation. Veinlets of this composition were not observed by the writer to cut across the foliation of the country rock as would be expected if the mafic minerals were deposited from vein-forming solutions.

HISTORY AND PRODUCTION

The Dover district is one of the oldest mining districts in the United States, and its history dates back at least to 1710 when both the Mount Hope and Dickerson mines are reported to have been in operation. Since that time mining has been carried on in the district more or less continuously, and the district has contributed about 70 percent of New Jersey's iron-ore production. A comprehensive history of mining in the Dover district, as well as in the State, to about 1908 is recorded by Bayley (1910, pp. 1–18). Additional historical information of interest is recorded by Roche and Stoddard (1915), Cook (1868), and Roche (1937).

During the early period the iron ore mined in the Highlands was treated by local forges and furnaces which converted the iron ore into bar iron. The first forge was built at Tinton Falls in 1682 (Roche and Stoddard, 1915, p. 171), even before mining activity was reported from the district. A large number of forges were built later, including the John Jackson forge at Dover (1710) and the Job Allen forge at Rockaway (1730). For an interesting history and description of the early forges and furnaces in the State the reader is referred to Boyer (1931).

During the Revolutionary War, mines from the Dover district supplied the local forges with iron ore to make shot and cannon for the army of George Washington. Production during that period was not great, though. In 1821 only 2,500 tons of iron was manufactured in New Jersey, and ten years later the production still was only 4,670 tons annually. All the ore, of course, was reduced by charcoal.

With the advent of anthracite furnaces iron production increased greatly, and there was a marked increase also in ore production. In 1855 Kitchell estimated that 100,000 tons of iron ore was mined in northern New Jersey (Bayley, 1910, p. 8); by 1867 the production reached 275,000 tons. Most of this ore was produced from mines in the Dover district. There continued to be a general increase in production, except for the depression year of 1873, through 1882, when New Jersey produced 932,762 gross tons of iron ore. In that year the iron ore production from New Jersey ranked second to that of Michigan in the United States. Following this peak production there was a general decrease in output, and also in the number of producing mines, and by 1885 only 350,000 tons of iron ore was produced in the State. Undoubtedly the major cause of this decrease was the rapid advance made in the uses of steel rather than iron, for which the magnetic ores are particularly well suited. The replacement of iron by steel was due largely to the utilization of the Lake Superior hematite ores which are so well adapted to steel making. At this time also many of the older and larger mines in the Dover district were closed either because they had attained a depth too great for commercial operation, or because they were too far from railroad sidings to be able to ship ore at the lower market prices.

In 1886 production in the State again increased to 500,501 tons (Bayley, 1910, p. 13), because of a rise in the price of iron ore. The yield during the next several years varied directly with general economic conditions, being high in prosperous years and low in depression years. During this period there was, however, a gradual decrease in the number of producing mines, and in 1905 only 16 mines were active in the State, 10 of which were in the Dover district. During the decade from 1920 to 1930 the production of iron ore in New Jersey was 2,262,718 gross tons (Roche, 1937, p. 74). During the next 10-year period the iron production was much lower, however, and during the worst years of the depression all the mines were closed. In 1939 there was a revival of production to meet the increased demand for iron ore during World War II, and since that time the district has produced about 500,000 long tons of iron ore annually. This production has come from three mines, the Scrub Oaks, Richard, and Mount Hope, all of which are now active, and is about 10 percent of the aggregate production of magnetite in the East.

It is estimated that about 26 million long tons of iron ore that has an estimated value of about $100 million has been produced from the Dover district. This is about 70 percent of the total production from the State. Production for the period before 1870 is based upon estimates recorded in various publications of the New Jersey Geological Survey. Where estimates are not given, the writer has estimated approximate production tonnages from the extent of the individual mine workings, as given by Bayley (1910). The amount of iron produced since 1870 is known more accurately as the yield for each mine has been recorded for the most part in publications of the New Jersey Geological Survey. Five mines in the district have produced more than 1 million tons each. They are in order of their yield: Mount Hope, Richard, Hibernia, Scrub Oaks, and Dickerson mines.

EXTRACTION AND BENEFICIATION OF ORE

Before 1912 the ore bodies were mined principally by underhand stoping (Roche and Crockett, 1933a, p. 162). Considerable tonnages were extracted by this method from open pits because of the relatively long "outcrops" and the generally low rake of the deposits. Underground stoping, though, was dangerous and expensive. It was necessary to leave substantial pillars and the percentage of ore extraction was low, consequently only about 30 to 40 percent of the ore was recovered (Roche and Crockett, 1933a, p. 163).

Shrinkage stoping without timbering or filling was first used in

1912 at Mount Hope mine, and later this method was adopted at the other operating mines in the district. The height, thickness, shape, and generally steep dip of the ore bodies all favor shrinkage stoping. Sublevel stoping was begun at Mount Hope mine in 1949 to mine the Richard ore body, and this method of extraction is now being compared with the more widely used shrinkage stoping.

The ore from each of the mines is concentrated by means of magnetic separation, and this process of beneficiation has been used exclusively since 1916. The phosphorus content of the ore is reduced by grinding and magnetic concentration; as the sulfur content is low or absent it is not necessary to sinter the ore.

The Richard and Mount Hope mines produce two shipping products—lump ore and fine concentrate. The lump ore at both mines averages about 60 percent iron and 0.6 to 0.8 percent phosphorus, whereas the concentrate averages about 65.5 percent iron and 0.10 to 0.35 percent phosphorus. In 1949 the concentration ratio at Richard mine was about 1.4 to 1; at Mount Hope mine it was about 1.6 to 1. The lump ore is in demand for open-hearth steel furnaces; the concentrate is sintered at the furnaces and used as a blast furnace charge. The milling procedure at Richard mine has been described by Roche (1923) and at Mount Hope mine by Davenport (1945).

The Scrub Oaks mine produces only concentrate (Roche and Crockett, 1933b). Because of the presence of several percent of nonmagnetic iron (hematite) the ore requires a dual treatment. It is first passed over wet-magnetic separators and then passed through gravity separation machines to recover the nonmagnetic fraction (Roche and Crockett, 1933c, p. 274). The concentration ratio at Scrub Oaks mine is about 2.5 to 1.

FUTURE OF DISTRICT

The Dover district has a promising future. Although the district is an old one, and many of the deposits have been worked for over 200 years, the reserves are adequate to provide iron ore for many generations at the present rate of exploitation. Because the district has been thoroughly prospected it is unlikely, however, that any new discoveries will be made, except possibly in the region mantled by thick moraine or in areas covered by lakes and swamps. There is no evidence that the deposits in the district diminish in size or tenor as depth increases. On the contrary, mining has demonstrated that the deposits are remarkably uniform along the pitch length and that they persist to considerable depths. Probably under favorable economic conditions the known deposits can be exploited to depths of at least 3,000 feet. The principal problem in the extraction of the ore is faulting, which may cut up the ore bodies so much that they are locally unprofitable to mine.

The most favorable deposits for future exploitation are those now being mined, that is, the deposits in the Mount Hope, Richard, and Scrub Oaks mines. Possibly, the Scrub Oaks and Mount Hope mines will be able also to mine a few deposits that are situated close to present underground workings, but which are not now being worked. Deposits distant from existing mine plants are less promising as producers. Of these, the Hibernia deposit is most likely to be a large producer again. Possibly this ore body, which contains large reserves of high-grade ore, can be reopened through No. 12 shaft, which is situated at the northeast end of the mine (see pl. 26), or through workings extended from the Mount Hope mine.

The Hibernia Reservoir deposit, a low-grade deposit that contains large reserves that possibly can be exploited by open-cut mining methods, is a favorable prospect that could become a large producer. The existing knowledge concerning this deposit is insufficient, however, and much exploratory work should be done to determine the size and tenor of the deposit before any mining is attempted. The exploratory work should include detailed magnetic exploration.

Probably few, if any, of the abandoned mines that formerly contributed large amounts of iron ore will ever again be important producers, except under the stimulus of much higher market prices. The reopening of most of these mines would be dangerous and costly. Also, most of the deposits in the larger mines of this group were mined to considerable depths, and deep shafts would have to be sunk to reach the deposits.

PRINCIPAL MINES AND PROSPECTS

Eighty mines and prospects were examined during the present survey, and their locations and the locations of the principal shafts are shown in plate 24. About 50 of the mines have produced some shipping ore; only 3, however, the Scrub Oaks, Richard, and Mount Hope, are now active.

Mining activity was most widespread during the past century and, except during economically depressed years, a large number of mines in the district were in operation until about 1890. In 1867, for example, 57 mines in the district were reported to have shipped some ore (Cook, 1868, pp. 540–542). Since about 1890, though, there has been a steady decrease in the number of operating mines, but there has been no appreciable change in the total iron ore production.

A description of most of the mines in the Dover district has been given by Bayley (1910). In the section that follows only five of the more important mines and prospects are discussed. These are described briefly because of their importance and because of the new data obtained during this survey. The numbers that follow the mine name in the text refer to the locations on plate 24.

MOUNT HOPE MINE (12)

The Mount Hope mine, owned and operated by Warren Foundry and Pipe Corp. of Phillipsburg, Pa., is at Mount Hope village, 3 miles north of Dover. The mine is said to be the oldest operating iron mine in the United States, and its production history dates back to about 1710 (Roche and Stoddard, 1915, p. 171). It has yielded more than 5½ million long tons of iron ore and ranks as the largest producing mine in the State. Since 1915 the mine has produced more than 100,000 tons of iron ore annually, except for the economically depressed years during the 1930's when the mine was closed.

Eleven separate ore deposits have been mined at Mount Hope mine. During the early years of the mine the individual deposits were worked to shallow depths as separate mines, and the deposits take their names from the old mines from which they were exploited. In 1901, when the Brown (inclined) shaft was completed, most of the separate mines were integrated into a single operation, and between 1901 and 1944 nearly all the ore was hoisted through the Brown shaft. Mining was carried on largely from the 300 and 400 levels and from inclines driven along the bottom rock of the Taylor, Leonard, and Elizabeth ore bodies (Sweet, 1932).

Since 1944 the ore has been hoisted through the New Leonard shaft (see pls. 24 and 25), a three-compartment shaft 2,694 feet deep, that connects with the 1,000, 1,700, 2,100, 2,300, and 2,500 levels. Most of the mine openings above the 1,000 level, as well as the Brown shaft, were inaccessible in 1949. In 1949 mining was being carried on principally on the 1,700 level, although the Teabo deposit was being worked also from the 1,000 level. On the 2,100 level a drift was being driven southwest from the New Leonard shaft to develop the Teabo and Richard deposits.

The principal rock exposed in Mount Hope mine is oligoclase-quartz-biotite gneiss, which is enclosed within alaskite, as shown in plate 25. Together these rocks constitute the limbs of an isoclinal syncline, herein named the Mount Hope syncline. A synclinal phacolith of alaskite occupies the axial area of the syncline between the Finley and Leonard ore deposits. The Mount Hope syncline trends about N. 45° E. and plunges 15°–18° NE.; the axial plane dips about 70° SE. Folds that may be drag folds are common on the limbs of the syncline.

The Mount Hope fault, a transverse break whose trace is in the small valley north of the New Leonard shaft (see pl. 24) separates the mine workings at Mount Hope mine into a northern and southern segment. The fault is a normal fault that dips 60° SW. and that has a net slip of about 300 feet. (See pl. 25.)

Several longitudinal faults have been encountered during mining and these constitute serious mining problems locally. Most of these are high-angle reverse faults, and they have vertical displacements ranging from a few inches to about 50 feet. A reverse fault that dips 30°–45° N., herein named the Taylor fault, was encountered in the North Taylor mine workings. This fault causes a 40- to 60-foot separation of the Taylor ore body on the 1,700 level. (See pl. 27.)

Of the 11 deposits that have been mined at Mount Hope mine only the Taylor, Leonard, Elizabeth, Teabo, Richard, and Finley have yielded large tonnages of ore. The other deposits, the Carlton, Spencer, Hawkins, Brennan, and "Gold Diggings" were worked to shallow depths from the surface but were too thin or too low in grade to be mined underground.

The magnetite deposits are tabular or lath-shaped bodies that trend about N. 45° E. and plunge gently northeast, parallel to the prevailing linear structures. The deposits are confined to a zone about 800 feet wide. (See pl. 24.)

The Richard, Teabo, Elizabeth, Leonard, and Finley deposits are replacements of oligoclase-quartz-biotite gneiss; the Taylor and Carlton deposits are replacements of hornblende skarn. The ore in each gneiss deposit is similar and is predominantly blocky magnetite with 1 to 2 percent apatite. Locally, though, the ore is "shot ore" and in places contains considerable biotite. Figure 61 is typical of the ore from gneiss deposits.

The Taylor ore body has been the principal source of ore at Mount Hope mine. It has been mined from its outcrop, where it was reported to form a ledge 100 feet high, to a depth of about 2,000 feet. The pitch length of the workings is about 8,500 feet. The Taylor deposit is on the northwest limb of the Mount Hope syncline. (See pl. 25.) It strikes N. 45° E., dips 50°–80° SE., and on the north side of Mount Hope fault rakes 15° NE. The deposit is a tabular body that averages about 20 feet in width, has a mining height (breadth) of 450 feet, and a stope length of about 1,500 feet. Between the 1,700 and 1,900 levels (see pls. 25 and 27) the deposit has a mining height of only 200 to 275 feet because the upper part of the ore body has been offset by the Taylor fault, and this faulted segment cannot be extracted profitably at present market prices.

The ore in the Taylor deposit is in part massive blocky magnetite and in part laminated. The laminated ore consists of alternating layers of massive magnetite and skarn minerals—hornblende, pyroxene, and biotite. Figure 62 shows the relationship of the magnetite to the skarn in a specimen of low-grade ore.

The Carlton, like the Taylor ore body, is a replacement of hornblende skarn. The deposit, however, is too irregular and variable in grade and thickness to be mined at present market prices. The Carlton deposit is on the southeast limb of Mount Hope syncline, 475 feet southeast of and essentially parallel to the Elizabeth ore body. (See pl. 25.)

The Richard ore body, in 1949, was being mined on the 1,700 level, near the southwest end of the Mount Hope mine. The Richard deposit is not present on the upper levels at Mount Hope mine, but it has been the largest producer at Richard mine, which adjoins Mount Hope mine on the southwest. Where opened in R3, R4, and R5 stopes on the 1,700 level, the deposit averages about 12 feet in thickness and dips about 50° SE. The Richard ore body is described under the Richard mine and is, therefore, not discussed at length here.

The Teabo ore body was worked at the surface from the Teabo mine (Bayley, 1910, pp. 406–407; also see pl. 24, this report), and has been mined in Mount Hope mine on the 1,000 and 1,700 levels. The Teabo deposit lies in the same plane as the Richard vein, and is separated from it by a pinch, as shown in plate 25. Together the two deposits have a breadth of about 1,000 feet, but the pinch that separates the deposits is not minable in most places.

The Teabo ore body strikes N. 45° E., dips 55° SE. (average), and rakes about 20° NE. It is a tabular body that ranges from a few feet to about 35 feet in thickness. The mining height of the deposit in stopes on the 1,000 level is about 250 feet. On the 1,700 level, however, the mining height is approximately 475 feet, to judge from mapping on the level. On the 1,000 and 2,100 levels the Teabo is a single tabular ore body, but in nos. 6, 7, and 8 stopes, above the 1,700 level in the southwest part of the mine, the deposit consists of two nearly parallel ore bodies that are separated by about 20 feet of mineralized amphibolite. The relation of the two ore bodies in this part of the mine to the rest of the deposit is not clear and cannot be ascertained until further exploration or mining is done.

The Elizabeth ore body is in the same plane as the Teabo, and above it, as shown in plate 25. The deposit strikes N. 45° E. and dips 70° or more southeast. The Elizabeth is a tabular deposit that has a mining height of 225 to 275 feet and a stope length of about 950 feet. The average thickness is 6 to 8 feet; the maximum known thickness is about 20 feet. Pinches in the deposit are common, and consequently the deposit in some places is not more than 4 feet thick. The hanging wall of the deposit is marked by faults in many places in the stopes on the north side of Mount Hope fault, and as a result the hanging wall tends to slab off during mining resulting in dilution of the ore.

The Leonard ore body cropped out on Mount Hope hill, southwest of Mount Hope fault, and was mined continuously from the surface to its intersection with the Mount Hope fault. Northeast of the fault it has been mined to the 1,700 level. The Leonard deposit is on the southeast limb of Mount Hope syncline, opposite the Finley deposit, and joins with the Finley in the axial area. (See pl. 25.) The deposit trends N. 45° E., dips near the vertical, and plunges about 17° NE. The stope length is about 800 feet; the mining height is approximately 250 feet. The ore ranges from about 4 to 25 feet in thickness. The general form of the deposit is repeated from level to level, as can be seen in plate 25.

The Finley deposit was extensively mined at the surface prior to 1868, and was worked underground in Mount Hope mine southwest of Mount Hope fault. Northeast of the fault, though, the deposit has been opened only by a small stope on the 400 level where it was found to be too narrow for profitable exploitation. The Finley deposit is on the northwest limb of Mount Hope syncline (see pl. 25); it unites with the Leonard deposit in the axial area of the syncline. The junction of the two deposits can be seen in the North Leonard drift on the 1,000 level.

The Finley deposit is a tabular body that ranges from about 1 to 10 feet in thickness; the average is 6 feet or less. Moderate pinches and swells can be seen in the open cuts at the surface. To judge from dip-needle data the deposit consists of two ore shoots.

The Brennan, or Brannin, deposit was opened prior to 1868 on Mount Hope hill where it was exploited along a distance of about 700 feet by four or five shafts sunk to depths of 35 to 40 feet (Bayley, 1910, p. 410). The deposit proved to be quite variable in width and tenor—in places it was as much as 17 feet wide, in others it was less than 4 feet thick. The Brennan was explored underground on the 400 level (456 drift), on the north side of Mount Hope fault, and it was cut on the 1,000 level in 1,019 cross-cut. (See pl. 25.) In 1,019 cross-cut the deposit is an irregular mineralized zone about 25 feet wide that is too low in grade to be commercial.

The Hawkins deposit is a remarkably continuous mineralized zone that extends throughout the mine. It lies near the contact between oligoclase-quartz-biotite gneiss and alaskite on the northwest limb of Mount Hope syncline. It probably correlates with the Middle vein at Richard mine. The Hawkins is thin, generally less than 5 feet thick, and low in grade. The magnetite occurs as streaks, disseminations, and less commonly as massive layers 1 to 4 feet thick. The deposit has not been mined.

The "Gold Diggings" deposit crops out on Hickory Hill, 2,600 feet north-northeast of the Brown shaft and 1,100 feet northwest of the Taylor ore body. The deposit has been prospected to shallow depths along a distance of 600 feet by several small pits and a shaft reported to be 50 feet deep. In 1919 Empire Steel and Iron Co. put down four diamond drill holes to test the deposit at depth, and the cores indicated that the deposit is thin and also low in grade. The magnetite replaces medium- to coarse-grained hornblende skarn. It is associated with abundant apatite, and locally apatite constitutes as much as 30 percent of the mineralized rock. The deposit has not been mined underground at Mount Hope mine.

The Spencer deposit crops out one-half mile northeast of the New Leonard shaft. (See pl. 24.) It has been worked to shallow depths along a distance of 1,000 feet, but it has not been mined from the main Mount Hope mine workings. The Spencer deposit trends about N. 45° E. near the Spencer shaft, but southwest of the shaft the trend is about N. 15° E. (See pl. 24.) It dips 60° SE. To judge from exposures in surface pits and from cores of drill holes, the deposit consists of a variably mineralized zone approximately 5 to 20 feet thick that contains alternating thin layers of massive magnetite and oligoclase-quartz-biotite gneiss with disseminated magnetite. The deposit is not commercially important at present market prices.

RICHARD MINE (18)

The Richard mine is 2 miles north of Dover, and immediately southwest of the Mount Hope mine. It is owned by Colorado Fuel and Iron Corp.

The Richard mine has been worked nearly continuously since 1856 and has yielded about 5½ million tons of iron ore. It ranks as the second largest producer in the district. The entire production has come from two ore bodies—the Mount Pleasant (North) and the Richard (South).

The principal mine workings are a vertical shaft and five operating levels about 200 feet apart vertically. The main shaft (Sweetser shaft) is a four-compartment opening, 1,244 feet deep, that is situated at the base of the hill, about 500 feet southeast of the "outcrop" of the Richard vein (see pl. 24). The shaft connects with the 700, 900, and 1,100 levels; all the levels above these are inaccessible. The Sweetser shaft intersects the Richard ore body at the 800 intermediate level (now inaccessible), and the Mount Pleasant ore body a short distance above the 1,100 level. The two ore bodies are connected on each level by one or more cross-cuts about 300 feet long. A 25° incline that trends nearly parallel to the plunge of the ore bodies extends from the 1,100 level to the 1,300 and 1,500 levels. The 1,300 level is connected to the 1,700 level of the Mount Hope mine by a 50-foot raise. In 1949 most of the mining was being done on the 1,100 and 1,300 levels—the Mount Pleasant deposit was being developed on the 1,300 and 1,500 level; the Richard deposit was being developed on the 1,500 level. The acquisition of a lease in 1949 on the Baker property, which lies southwest of the Richard mine, will permit the Richard mine to exploit the Mount Pleasant (North) deposit beneath the old workings in the Baker mine.

The position of the old shafts, and a brief description of the mine workings at Richard mine are recorded by Bayley (1910, pp. 400–403).

The principal rock type exposed in the mine is oligoclase-quartz-biotite gneiss, which forms the host rock, as well as the country rock, for the Richard and Middle deposits. Minor amounts of amphibolite, pyroxene gneiss, migmatite, hornblende skarn, and alaskite lie northwest of the gneiss.

The rocks in Richard mine trend N. 40°–45° E. and generally dip 40°–60° SE. The linear structures plunge gently northeast. The rocks constitute the northwest limb and the axial area of the Mount Hope syncline. The Richard deposit is near the axial plane of the syncline; the Mount Pleasant deposit is on the northwest limb.

Faults that produce notable offsets of the ore bodies are abundant, and constitute a considerable problem in mining. Two prominent transverse faults have been encountered—no. 4 fault, a nearly vertical fault whose surface trace is 525 feet southwest of the no. 2 shaft (Bayley, 1910, p. 400), and no. 1 fault whose surface trace is near the Teabo no. 3 shaft (see pl. 24). No. 4 fault was not observed by the present writer as it is now inaccessible, but no. 1 fault was mapped on the 900, 1,100, and 1,300 levels. Another transverse fault, the Allen, was reported (Bayley, 1910, p. 400) to lie 335 feet northeast of the Richard no. 3 shaft. It was encountered in the upper levels of the Richard mine (M. T. Hoster, personal communication), but has not been recognized below the 700 level.

Several longitudinal and oblique faults have been encountered in the Richard mine workings. These faults, which generally dip 40°–85° NW., mostly show reverse movements and cut across the ore bodies at small to moderate angles. Vertical displacements range from less than a foot to about 80 feet on individual faults, and generally are less than 20 feet. Two zones of faulting known as the August and September faults extend throughout the length of the accessible workings; other fault zones, as yet unnamed, for the most part seem to be less continuous.

Three deposits are known in Richard mine. They are from southeast to northwest: the Richard (or South) vein, the Middle vein, and the Mount Pleasant (or North) vein. The Richard and Mount Pleasant ore bodies have yielded all the ore; the former is the more important. The Middle vein has not been mined as it is thin and low in grade.

The Richard (South) deposit has an outcrop length of 2,600 feet.

The bottom rock is truncated at the surface southwest of the Baker mine by a gravel-filled channel; the top rock, which is marked by a pinch, lies near the Richard no. 3 shaft. About 300 feet farther to the northeast the deposit widens again to form the Allen deposit. The Richard deposit, therefore, is a well-developed ore shoot within a much larger deposit that includes the Allen and Teabo deposits.

The Richard deposit is a tabular body that trends N. 40° E., dips 30°–50° SE., and plunges 7°–15° NE. It ranges in thickness from about 5 to 35 feet, the average being about 15 feet, and has a mining height of about 550 feet. The deposit consists of high-grade massive magnetite. The ore is in part blocky and in part "shot ore"; locally it contains thin layers of biotite schist.

The Middle vein, which is 75 feet southeast of the Mount Pleasant deposit, is a remarkably persistent mineralized zone that is present throughout the mine; a deposit at the same "stratigraphic" position was reported in the Mount Pleasant mine (Bayley, 1910, p. 396), and was mapped by the present writer in the Mount Hope mine. The deposit is narrow, ranging from 1 to 4 feet in thickness, and low in grade. The deposit occurs in oligoclase-quartz-biotite gneiss close to the contact of this gneiss and amphibolitic rocks.

The Mount Pleasant (North) ore body is 300 feet northwest of the Richard (South) deposit, and nearly parallel to it. The deposit is known to have a surface length of about 8,800 feet. The bottom rock intersects the surface southwest of the Harvey mine in Wharton; the top rock is 600 feet northeast of no. 6 shaft at the Richard mine (see pl. 24). In addition to being mined at the Richard mine the Mount Pleasant deposit has been exploited in the Hubbard, North River, Harvey, Hurd, West Mount Pleasant, Mount Pleasant, and Baker mines, where it was the principal source of ore.

The Mount Pleasant deposit is an irregular tabular body that has an aggregate mining height of at least 1,900 feet. In the Richard mine it consists of three well-defined shoots that from top to bottom are the Kearney, Major, and Baker (or New) shoots. The shoots are separated by pinches. The ore shoots and the pinches plunge about 15° NE. The deposit generally dips between 40° and 60° SE., the dip being gentler in the lower part.

The Kearney (or upper) shoot probably has yielded most of the ore obtained from the deposit. This shoot averages about 8 feet in thickness, and has a mining height of about 500 feet. The ore consists principally of massive blocky magnetite.

The Kearney shoot is separated from the underlying Major shoot by a marked pinch that has a breadth of about 600 feet and which is represented by a thin stringer, or locally by two or more seams of massive magnetite. Where pegmatite occurs in the zone of pinch the magnetite is irregularly distributed through the pegmatite as small discontinuous veinlets and bunches.

The Major shoot, which has a mining height of about 400 feet, also has been mined extensively. It is more irregular and somewhat lower in grade than the Kearney shoot, particularly in the lower part, where the hanging wall portion of the deposit contains much unreplaced hornblende skarn.

The pinch that separates the Major from the underlying New (or Baker) shoot is not prominent everywhere; it is marked by a slight decrease in the thickness of massive ore. On the 1,100 level numerous faults occur in this part of the deposit.

The Baker (or New) shoot has not been mined in the Richard mine as extensively as the Major and Kearney shoots. It was, however, the principal source of ore in the Baker mine. In the Richard mine the shoot is 5 to 12 feet thick and has a mining height of at least 600 feet. Like the lower part of the Major shoot, the hanging wall of the shoot is low in grade and contains much hornblende skarn that is interlayered with the magnetite.

SCRUB OAKS MINE (33)

The Scrub Oaks mine, owned and operated by Alan Wood Steel Co. of Conshohocken, Pa., is 2 miles west of Dover. (See pl. 24.) The mine was formerly known as the Replogle or Dell mine.

The Scrub Oaks mine has been a large producer of iron ore since 1934 and during World War II its output exceeded that of any other mine in the State. In 1949 it yielded 597,031 tons of crude ore and 206,444 tons of concentrate.

The mine was opened in 1856 (Roche and Crockett, 1933a, p. 161), but it was not worked extensively until World War I when it was acquired by Alan Wood Steel Co. Bayley (1910, p. 365) estimates that the mine shipped 58,500 tons between 1856 and 1905.

The mine workings consist principally of a four-compartment shaft (no. 1 or Ross shaft), inclined 55° southeast, and six working levels 250 feet vertically apart. The levels, which average about 5,000 feet in length, are connected by several inclined raises; sublevels are driven about 30 feet above the main haulage levels. A detailed description of the mine and the mining method is recorded by Roche and Crockett (1933a, pp. 161–164, 197–200).

The Scrub Oaks deposit is 1,500 feet northwest of the Corwin and Sterling deposits (see pl. 24), and in the same mineralized zone as the Baker (at the base of the hill), Huff, and Dolan mines. The Scrub Oaks ore body does not crop out as it is covered to variable depths by glacial deposits. The deposit is known, however, from dip-needle surveys and from underground workings, to be about 5,500 feet long and to average about 25 feet thick. The mining height (breadth) is approximately 1,650 feet.

Two prominent transverse faults, the McNeil and Erb, cut the ore body (see pls. 24 and 28). The ore on the north side of the Erb fault was known to the early miners as the Erb deposit (Bayley, 1910, p. 365), but mining has definitely proved this ore to be a faulted segment of the Scrub Oaks ore body.

On the average, the Scrub Oaks ore body and the surrounding country rock trend N. 33° E. and dip 55° SE. The deposit plunges 28° N. 52° E., parallel to the lineation in the country rock.

The prevailing trend of the rocks is interrupted by several small rolls that are distinguished by local changes in strike to a more northerly direction, and by a flattening in dip (see pl. 28). Some of the rolls are large enough to be reflected by prominent bends in the mining drifts, which are driven near the footwall of the deposit.

The deposit is an irregular tabular body that consists of several shoots separated by mineralized rock or sub-ore (see pl. 28). The ore occurs mostly as veinlets, streaks and disseminations; massive layers are rarely present. The contacts between ore and country rock are relatively sharp, but considerable rock is necessarily mined along with the ore.

The ore shoots occupy granulated and partly recrystallized zones in the albite-oligoclase granite host rock. Granulation was most intense along the axes of the small rolls, hence the ore is thicker in these places.

Magnetite is the chief ore mineral; primary crystalline hematite constitutes about 15 percent of the ore, but ranges from about 1 percent to at least 30 percent locally. The hematite is abundant in 1,586 and 1,587 stopes (no. 5 level), where it forms about 50 percent of the ore; and at the head of 70 manway raise on no. 4 level. Elsewhere in the mine hematite generally constitutes less than 5 percent of the ore. To judge from its distribution the hematite-rich ore seems to be closely related to the axis of a prominent roll.

The nonmagnetic iron ore is locally referred to as martite. There is no evidence, however, either megascopically or microscropically, that this ore is martite; instead, the nonmagnetic ore is hematite. Polished sections of hematite ore indicate that the hematite forms distinct coarse granules that exhibit marked twinning. In part hematite forms rims around magnetite; it is seen also to form veins in magnetite.

The gangue minerals, which constitute an integral part of the ore, are chiefly albite and quartz, unreplaced remnants of the granite host rock. Several other minerals are present in the ore, however, that are not found in the country rock. These are apatite, rutile, tourmaline, calcite, muscovite, and pumpellyite. With the exception of apatite these accessory minerals are later than the magnetite.

The run-of-the-mine ore has an average iron content of about 27 percent and a phosphorus content of about 0.075 percent. The concentrate is of Bessemer grade.

A new complete analysis of the ore is given in table 2. The high silica content is attributed to quartz and albite principally. The titanium oxide is present as rutile (TiO_2); ilmenite is not known to be present. The phosphorus is derived from apatite, and the CO_2 from calcite.

HIBERNIA MINE (64)

The Hibernia mine is north of Hibernia village, and is owned by Warren Foundry and Pipe Corporation. The mine comprises the Lower Wood, Glendon, Scott, De Camp, Upper Wood, Willis (or Wharton), and Joseph Wharton mines of the early New Jersey Geological Survey reports (See pl. 26; also Bayley, 1910, p. 452.).

The mine is now inaccessible and has been abandoned since 1916. Nevertheless, it ranks as the third largest producer in the district with an estimated production of more than 5 million tons of ore that averaged more than 50 percent iron. Large reserves of recoverable ore remain below the abandoned mine workings.

The history and mine workings have been described by Bayley (1910, pp. 452–457).

The "outcrop" of the Hibernia deposit is 7,000 feet long. The deposit trends N. 40°–60° E. and dips steeply southeast to steeply northwest (see pl. 26). The deposit is tabular and ranges from 2 to 30 feet in thickness, the average being about 9 feet. According to Bayley definite shoot structures are lacking, but pinches occur that are simply portions of the deposit that are thinner than elsewhere.

The toprock of the deposit plunges 25° NE., as measured between no. 10 and no. 12 shafts (see pl. 26). The exact location of the bottom rock, and its angle of plunge, is not known, but the inferred position of the bottom rock is shown in plate 26. The angle of plunge of the bottom rock is estimated from lineation measurements (rolls and mineral lineation) in the walls of the deposit in open cuts near the southwest end of the mine workings to be 23° NE. Evidently the pinches in the ore body plunge at the same angle.

Faults that intersect the deposit are not common. In the Lower Wood mine two transverse fractures that dip steeply southwest were reported, but only one of these produced a separation that exceeded the width of the ore body.

The ore is composed of coarsely granular massive magnetite that in part contains several percent of dark-green hornblende and minor amounts of quartz, feldspar, and biotite. To judge from the rock dumps much of the ore is layered, and is similar in appearance to some of the ore from the Taylor deposit at Mount Hope mine and the Mount Pleasant deposit. Fluorite was reported to be present locally in the ore (Cook, 1868), but was not observed by the present writer. The host rock is principally hornblende skarn. Amphibolite and albite-oligoclase granite form the wall rocks.

Polished surfaces of the ore indicate that ilmenite is the only metallic mineral associated with the magnetite. Two complete analyses of ore from the Hibernia mine are given in table 2. The ore averages about 57 percent Fe and 0.4 to 1.0 percent P.

HIBERNIA POND ANOMALY (63)

The Hibernia Pond anomaly is the name here given to a belt of strong magnetic attraction about 1¼ miles long that extends from Telemark settlement, near Hibernia, southwestward 1 mile distant from Hibernia Pond. (See pl. 24.)

The mineralized zone represented by the magnetic anomaly was tested near Hibernia Pond by a few small prospect pits. The extent of the mineralized zone was not known, however, until 1938 when Hans Lundberg, Lt., conducted a ground magnetometer survey of the deposit for Warren Foundry and Pipe Corp., present owners of the tract. In 1938 Warren Foundry and Pipe Corp. cored three diamond drill holes to test the southwestern part of the anomaly. Two of the holes penetrated thick zones of low-grade magnetite ore; one hole cored 172 feet (true thickness is 85 feet) that assayed 22.52 percent Fe.

The magnetometer survey suggests that the mineralized zone is rather uniform in width. The drill cores indicate, though, that the deposit probably varies considerably in tenor, but generally is low in grade.

The Hibernia Pond deposit trends N. 40° E., and judging from exposures of country rock on the north side of Hibernia Pond, it dips about 60° SE. and rakes 16°–26° NE. The deposit is not exposed at the surface; south of Hibernia Pond it is covered by about 25 to 50 feet of unconsolidated surficial deposits; north of the pond the cover is thinner.

The magnetite forms disseminated grains and veinlets in migmatitic amphibole-biotite-pyroxene-feldspar gneiss. The deposit occupies a linear zone of strong granulation formed by pre-ore cataclastic deformation. The hanging wall and footwall of the deposit are not well defined; instead, they are determined by assay boundaries. The hanging wall is contaminated albite-oligoclase granite; the footwall is albite granite or plagioclase-hornblende-pyroxene gneiss, a modified facies of amphibolite.

The gangue minerals are chiefly amphibole, biotite, pyroxene, and feldspar. Apatite constitutes 1 to 2 percent of the ore.

The deposit is a potential large source of low-grade ore. Because of its proximity to the surface and its long "outcrop," the deposit is favorable for open-pit mining. Additional exploratory work, particularly diamond drilling, is needed first, however, to determine the extent and average grade of the deposit.

REFERENCES CITED

Adams, F. D., 1909, On the origin of the amphibolites of the Laurentian area of Canada: Jour. Geology, vol. 17, pp. 1–18.

Alling, H. L., 1938, Plutonic perthites: Jour. Geology, vol. 46, pp. 142–165.

Appleby, A. N., 1942, A study of joint patterns in highly folded and crystalline rocks, with particular reference to northern New Jersey, 30 pp., New York University, (privately published).

Barrell, Joseph, 1907, Geology of the Marysville Mining district, Montana: U. S. Geol. Survey Prof. Paper 57.

Barth, T. F. W., 1928, Zur genesis der pegmatite im Urgebirge: Chemie der Erde, Band 4, pp. 95–136.

Bayley, W. S., 1910, Iron mines and mining in New Jersey: New Jersey Geol. Survey, Final report ser., vol. 7.

——— 1941, Pre-Cambrian geology and mineral resources of the Delaware Water Gap and Easton quadrangles, New Jersey and Pennsylvania: U. S. Geol. Survey Bull. 920.

Bayley, W. S., and others, 1908, U. S. Geol. Survey, Geol. Atlas, Passaic folio (no. 157).

Bayley, W. S., and others, 1914, U. S. Geol. Survey Geol. Atlas, Raritan folio (no. 191).

Bowen, N. L., 1928, The evolution of the igneous rocks, Princeton Univ. Press.

Boyer, C. S., 1931, Early forges and furnaces in New Jersey, Univ. Pennsylvania Press.

Broughton, J. G., 1940, Comparison of pre-Cambrian and Paleozoic structures in northwestern New Jersey, Doc. Dissert, Johns Hopkins Univ.

Buddington, A. F., 1948, Origin of granitic rocks of the northwest Adirondacks: *in* Gilluly, James, chrm., Origin of granite: Geol. Soc. America Mem. 28, pp. 21–43.

Bugge, J., 1940, Geological and petrographical investigations in the Arendal district: Norsk geol. tidsskr., Bind 20, pp. 71–109.

Cook, G. H., 1868, Geology of New Jersey, Newark.

Davenport, Harry, 1945, New magnetic concentrator treats Mt. Hope iron ore: Eng. and Min. Jour., pp. 85–89.

Engel, A. E. J., 1949, Studies of cleavage in the metasedimentary rocks of the Northwest Adirondack Mountains, New York: Am. Geophys. Union Trans., vol. 30, pp. 767–784.

Eskola, P., 1914, On the petrology of the Orijärvi region in southwestern Finland: Comm. géol. Finlande Bull. 40.

Fenner, C. N., 1914, The mode of formation of certain gneisses in the Highlands of New Jersey: Jour. Geology, vol. 22, pp. 594–612; 694–702.

——— 1929, The crystallization of basalts: Am. Jour. Sci., 4th series, vol. 18, pp. 225–253.

Foye, W. G., 1916, Are the "batholiths" of the Halliburton-Bancroft area, Ontario, correctly named?: Jour. Geology, vol. 24, pp. 783–791.

Geijer, Per., 1936, Norbergs berggrund och malmfyndigheter: Sveriges geol. undersökning, ser. Ca, no. 24 (English summary, pp. 152–158).

Goldschmidt, V. M., 1922, Stammestypen der eruptivgesteine: Vidensk-selsk., Kristiania Skrifter, I kl.

Hess, H. H., 1949, Chemical composition and optical properties of common clinopyroxenes, part I: Am. Mineralogist, vol. 34, pp. 621–666.

Hotz, P. E., 1953, Geology and magnetite deposits of the Sterling Lake and Ringwood districts, New York and New Jersey: U. S. Geol. Survey Bull. 982-F.

Kitchell, W., 1856, New Jersey Geol. Survey 2d Ann. Rept. for 1855, pp. 111–248, Trenton.

——— 1857, New Jersey Geol. Survey, Ann. Rept. of Superintendent and State Geologist for 1856, pp. 5–38.

Kümmel, H. B., and Weller, Stuart, 1902, The rocks of the Green Pond Mountain region: New Jersey Geol. Survey, Ann. Rept. State Geologist for 1901, pp. 3–51.

Leonard, B. F., 1953, Magnetite deposits and magnetic anomalies at Spruce Mountain, St. Lawrence County, N. Y.: U. S. Geol. Survey, Mineral Inv. field studies map no. 10.

Lindgren, Waldemar, 1933, Mineral deposits, McGraw Hill.

Lowe, K. E., 1950, Storm King granite at Bear Mountain, New York: Geol. Soc. America Bull., vol. 61, pp. 137–190.

MacClintock, Paul, 1940, Weathering of the Jerseyan till: Geol. Soc. America Bull., vol. 51, pp. 103–116.

Nason, F. L., 1889, Geological studies of the Archaean rocks: New Jersey Geol. Survey, Ann. Rept. State Geologist for 1889, pp. 12–72.

Postel, A. W., 1952, Geology of the Clinton County magnetite district, New York: U. S. Geol. Survey Prof. Paper 237.

Putnam, B. T., 1886, Notes on the samples of iron ore collected in New Jersey, *in* Pumpelly, Raphael, Report on the Mining Industries of the United States (exclusive of the precious metals): U. S. 10th Census, vol. 15, pp. 145–177.

Read, H. H., 1931, The geology of central Sutherland: Scotland Geol. Survey Mem.

Roche, H. M., 1923, New magnetic concentrating mill at the Richard iron mine, N. J.: Eng. and Min. Jour.-Press, vol. 115, pp. 923, 971.

——— 1937, The iron ores of New Jersey: The Iron Age, vol. 139, no. 5, pp. 74–80.

Roche, H. M., and Crockett, R. E., 1933a, Iron-ore mining and milling at Scrub Oak: Eng. and Min. Jour., vol. 134, pp. 161–164, 197–200.

——— 1933b, Evolution of magnetic milling at Scrub Oak: Eng. and Min. Jour., vol. 134, pp. 241–244.

——— 1933c, Magnetic separation: Eng. and Min. Jour., vol. 134, pp. 273–277.

Roche, H. M., and Stoddard, J. C., 1915, Develop nation's oldest iron mine: The Iron Trade Review, pp. 171–177, July 22.

Rogers, H. D. 1836, Report on the Geological Survey of the State of New Jersey, pp. 132–144, Philadelphia.

——— 1840, Final report on the geology of the State of New Jersey, pp. 12–22, 36, Philadelphia.

Ross, C. S., 1935, Origin of the copper deposits of the Ducktown type in the southern Appalachian region: U. S. Geol. Survey Prof. Paper 179.

Salisbury, R. D., 1902, The glacial geology of New Jersey: New Jersey Geol. Survey, Final Report Ser., vol. 5.

Sander, B., 1930, Gefügekunde der Gesteine, Wien, Julius Springer.

Shand, S. J., 1947, The genesis of intrusive magnetite and related ores: Econ. Geology, vol. 42, pp. 634–636.

Smith, L. L., 1933, Magnetite ores of northern New Jersey: Econ. Geology, vol. 28, pp. 658–677.

Spencer, A. C., 1904, Genesis of the magnetite deposits in Sussex County, N. J.: Mining Mag., vol. 10, pp. 377–381.

Spencer, A. C., and others, 1908, U. S. Geol. Survey Geol. Atlas, Franklin Furnace folio (no. 161).

Sweet, J. R., 1932, Mining methods and costs at the Mt. Hope mine of the Warren Foundry and Pipe Corp., Mt. Hope, N. J.: U. S. Bur. Mines, Inf. Circ. 6601.

Vogt, J. H. L., 1910, Norges jernmalmforekomster: Norges geol. undersökelse 51, pp. 138–162.

——— 1918, Jernmalm og jernvek: Norges geol. undersökelse 85, pp. 30–55.

Wager, L. R., and Deer, W. A., 1939, Petrology of the Skaergaard intrusion, Kangerdlugssuaf, East Greenland, Meddelelser om Grönland, Bd. 105.

Wolff, J. E., 1894, Geological structure in the vicinity of Hibernia, New Jersey and its relation to the ore deposits: New Jersey Geol. Survey Ann. Rept. State Geologist for 1893, pp. 359–369.

Zies, E. G., 1929, The fumarolic incrustations and their bearing on ore deposition: Nat. Geog. Soc. Contr. Tech. Papers, Katmai Series no. 3.

INDEX