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Geology of the Andover Mining District, Sussex County, New Jersey*

by

P. K. Sims and B. F. Leonard**

DIVISION OF PLANNING AND DEVELOPMENT

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COUNCIL OF THE
DIVISION OF PLANNING AND DEVELOPMENT

LETTER OF TRANSMITTAL

May 13, 1952

Mr. William T. Vanderlipp, *Director*
Division of Planning and Development

Sir:

I am transmitting with this letter, and recommend for publication, a report describing a detailed investigation of the complex ore occurrences near Andover, Sussex County. It has been made available to us by the authors with the approval of the Director, U. S. Geological Survey, and I am happy to acknowledge this indebtedness and to express my grateful appreciation.

Although the known iron ore deposits of the Andover district were mined many years ago, the presence of zinc, lead and copper sulfides in association with the iron ores, and the known extension of the ore belt for more than a mile, made this district an attractive one for prospecting. For that reason an investigation was started which was supplemented by core-drilling in World War II and later years. Although ore was not found in sufficient amount to be minable, the investigation demonstrated the important influence of the rock structures in the location of the ore deposits and this lesson should not be lost in the further search for economically valuable ore deposits in New Jersey.

Respectfully submitted,

MEREDITH E. JOHNSON,
State Geologist

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Geology of the Andover mining district, Sussex County, New Jersey

By

P. K. Sims and B. F. Leonard

ABSTRACT

The mines in the Andover mining district, Sussex County, New Jersey, have produced about 400,000 long tons of iron ore; but they have been abandoned for many years. The Andover mine, the largest hematite-producing mine in New Jersey, is now mined out. The Sulphur Hill mine was worked for magnetite, but it also contains local concentrations of other base metals.

The bedrock in the Andover mining district consists of metasediments and intercalated microcline granite gneiss and granite pegmatite of pre-Cambrian age. Diabase dikes inferred to be of Triassic age were emplaced along northeast-trending faults in these rocks at the Andover mine. The metasediments include pyroxene-feldspar gneiss, garnet skarn and related rocks, amphibolite and related rocks, and biotite-quartz-feldspar gneiss. These rocks have been profoundly reconstituted by composite contact and regional metamorphism and it is not possible to reconstruct the stratigraphic sequence. They were derived from the metamorphism of calcareous and quartzose sediments.

The pre-Cambrian rocks have a secondary foliation and lineation. The rock units and the foliation predominantly trend about N. 55° E. and dip northwest, but there is considerable variation; the lineation plunges 10° to 35° NE. The predominant trend is interrupted by several northeast-plunging folds which range from several hundred feet to less than a foot in width. The skarn bodies are much thickened in the axial areas of folds and greatly thinned on the limbs. The skarn that constitutes the host rock at the Sulphur Hill mine is a pod-shaped body whose longest dimension is parallel to the dominant lineation in the region. The body has a thickness of more than 100 feet and a maximum breadth of about 330 feet near the surface, but it pinches out to a featheredge about 1000 feet along its pitch length.

High-angle longitudinal faults that trend about N. 40° E. are exposed along the walls of the main pit at the Andover mine but were not recognized elsewhere.

The mineral deposits belong to two types. The deposits at the Sulphur Hill mine, and at the Tar Hill and Longcore mines, to the north, are magnetite-sulfide deposits, the deposits at the Andover mine are hématite-magnetite bodies. The magnetite-sulfide deposits are in garnet skarn. The "ore" minerals occur as disseminations, nests, clots, and layers that form disconnected pipelike or tabular bodies generally only a few feet wide in crumpled and sheared parts of the skarn. The "ore" shoots are in the crests of tight folds, and conform to the lineation in the country rocks. The magnetite is associated with sphalerite (variety marmatite), chalcopyrite, galena, pyrrhotite, pyrite, and sparse molybdenite and marcasite. The ore extracted from the Sulphur Hill mine contained from 32 to 46 percent Fe. The cores drilled by the U. S. Bureau of Mines during this investigation indicate that the base-metal content of the Sulphur Hill deposit is slight.

The hematite-magnetite deposits at the Andover mine are shallow, and the

deepest deposit extends only to a depth of about 85 feet. The ore is a complex mixture of magnetic and nonmagnetic ore and is composed of magnetite, specularite, martite, and earthy hematite. The principal gangue minerals are carbonate and jasperoid. The ore that was mined contained as much as 60 percent Fe.

The magnetite-sulfide deposits are pyrometasomatic replacements of pre-Cambrian age. The hematite deposits formed by intense supergene alteration of hypogene magnetite and perhaps other minerals in fault zones at the Andover mine. The supergene enrichment is inferred to have taken place during Triassic time or later.

INTRODUCTION

Purpose and scope of the report

The Andover mining district was studied by geologists of the U. S. Geological Survey in 1949, as part of a cooperative investigation by the U. S. Geological Survey and the U. S. Bureau of Mines. The geologic study was made by the writers at the request of the Bureau of Mines and preceded the latest drilling of the Sulphur Hill deposit.

The Sulphur Hill and Andover mines were at one time important producers of iron ore, and together they have yielded about 400,000 long tons of iron ore, but both mines have been abandoned for many years. During World War II the mines were core-drilled by the U. S. Bureau of Mines and by the Bethlehem Steel Co. The drilling indicated that the iron ores of each mine were nearly exhausted, but also it proved the presence of sphalerite of possible commercial value at Sulphur Hill mine. Consequently, it was proposed that this deposit be investigated further to determine the extent and tenor of the sphalerite. This report presents the results of the geologic investigation. The result of the Bureau of Mines work is to be described in a separate publication.

During October and November 1949 the writers carried on surface mapping in the mine areas. In addition to mapping the geology of the Sulphur Hill and Andover mine areas, they extended their survey to include the small deposits at the Tar Hill and Longcore mines. The study of this larger area provided a better understanding of the structure and extent of the mineral deposits in the district. An area about 6,000 feet long and 500 to 1,400 feet wide was mapped in detail. The geologic data were plotted on a base map on a scale of 100 feet to the inch that showed only the mine workings and roads. Surface exposures were located by pace and Brunton compass traverses. In regions of abnormal magnetic declination, structural readings were made by observations on the sun, using a pocket watch as a compass. The diamond drill holes were located by plane table and alidade; elevations along lines of structure sections were determined by a Paulin altimeter. To support the field studies, about 30 thin sections and 8 polished sections of ore were examined.

Core drilling at the Sulphur Hill mine was carried on by the Bureau of Mines between December 1949 and March 1950, and three holes were completed that totaled 1,550 feet in length. The drill core for the holes was logged by P. K. Sims immediately after each hole was completed. The core drilling indicated that the Sulphur Hill deposit is too low in grade to be of commercial importance.

Acknowledgements

The field work was done under the general supervision of A. F. Buddington. The writers are equally responsible for the field work and preparation of this report. The Swedish literature was translated by B. F. Leonard. G. S. Koch assisted in the field work, and W. H. Tonking, of Princeton University, assisted in the study of polished sections of the ores. The writers are indebted to G. H. Neumann, project engineer, and to McHenry Mosier, of the Bureau of Mines, for their full cooperation during the investigation; to A. W. Pinger, formerly chief geologist of New Jersey Zinc Co., for providing the base map of the area and for many helpful suggestions; and to Prof. E. Sampson, of Princeton University, for his help in the preparation of photomicrographs of the ores. Laboratory facilities and some of the thin sections were kindly supplied by the Geology Department at Princeton University.

Previous investigations

The most important geologic reports on the Sulphur Hill and Andover mines are by Cook (1868, pp. 640-658), Spencer (1908), and Bayley (1910, pp. 79-83; 220-224). Cook was able to examine the mines while they were active, and consequently his report contains much important information on the mineral deposits and the mine workings. The reports of Spencer (1908) and Bayley (1910) are largely summaries of the information given by Cook, but they also present some new interpretations of the geology of the region.

In 1941 geologists of the New Jersey Zinc Co.[1] mapped the region, but the results of their study have not been published. In 1942 the U. S. Bureau of Mines investigated the Andover and Sulphur Hill mines as part of the Intertior Department's Strategic Minerals Pro-

[1] A. W. Pinger, oral communication.

gram (Lynch, 1947). The Bureau of Mines cored six diamond drill holes that totaled 1,387 feet in length—four at Sulphur Hill mine and two at Andover mine—but did not find deposits of economic value. In 1944 the Bethlehem Steel Co. further explored the mines. They cored seven drill holes—six at Sulphur Hill mine and one at Andover mine—but the results of the exploration have not been released for publication. The casings for the drill holes were located in the field during the present survey, and their locations are shown on plate 1.

Location and topography

The Andover mining district is 1½ miles north of Andover, in Sussex County, New Jersey *(see fig 1)*. Franklin is 12 miles northeast and Dover is 15 miles southeast of the mines.

The region is in the New Jersey Highlands, an area underlain principally by crystaline rocks of older pre-Cambrian age, with a few down-faulted blocks of Paleozoic rocks (Spencer, 908). It lies within the Reading prong of the New England physiographic province. In the vicinity of the mines, as elsewhere in the New Jersey Highlands, the surface is characterized by northeast-trending ridges and valleys that were formed primarily by stream erosion controlled by the dominant structure of the bedrock. The local relief in the mapped area generally is less than 100 feet, but because the ridges are closely spaced the region is moderately rugged. Nearly all the area is heavily wooded.

ROCK UNITS

The mapped area is underlain by rocks of older pre-Cambrian age. These rocks are chiefly metasediments with intercalated granite gneiss and pegmatite. The pre-Cambrian rocks are overlain unconformably in the valley west of the mines by sedimentary rocks of early Paleozoic age (Spence, 1908) and are intruded locally by small diabase dikes, possibly Triassic in age. Unconsolidated glacial and stream deposits of the Quaternary period form a thin discontinuous mantle over the region and completely obscure the pre-Cambrian bedrock in the larger valleys.

The pre-Cambrian rocks in this area were mapped by Spencer (1908, p. 4) in the Franklin Furnace quadrangle as Pochuck gneiss. As used by Spencer, the term Pochuck gneiss includes "all the gneisses occurring in the Highlands region that contain hornblende, pyroxene or mica as principal mineral constitutents. Some of these rocks are probably of sedimentary origin, and others may be altered igneous rocks, but in general they are so completely metamorphosed that their original nature cannot be ascertained." More recently the U. S. Geological Survey (Wilmarth, 1938, p. 1686) has used the term Pochuck gabbro gneiss for the black gneiss of intrusive origin. The older dark gneisses of sedimentary origin that formerly were included in the Pochuck are now included in the Pickering gneiss (Wilmarth, 1938, p. 1653).

The present writers subdivided Spencer's Pochuck gneiss in the mapped area into several rock units that are extensive enough to be mappable *(see pl. 1)*. Because his Pochuck consists of a wide variety of rocks of both sedimentary and igneous origin, the name Pochuck is not adaptable to detailed structural and petrologic mapping and is therefore not used in this report. The metasedimentary rocks are

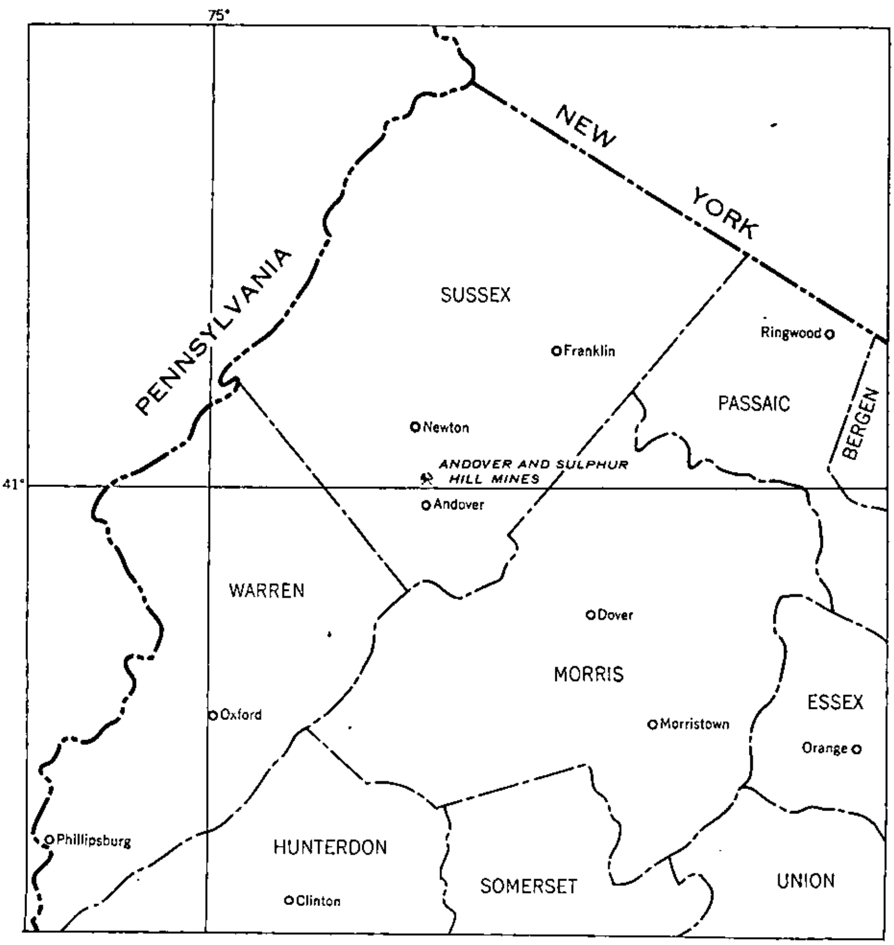


FIGURE 1—Index map showing the location of the Sulphur Hill and Andover Mines, Sussex County, New Jersey

principally derived from calcareous sediments; the igneous rocks are predominantly gneissic granites.

Metasediments

Metasediments underlie about 90 percent of the mapped area. These rocks include marble, skarn, pyroxene-feldspar gneiss, amphibolite, biotite-plagioclase gneiss, and biotite-quartz-feldspar gneiss.

The texture of all the rocks is granoblastic. Almost all of the grain outlines are polygonal, except where cataclastic deformation has produced mortar textures.

MARBLE

Marble constitutes only a small part of the rocks in the mapped area. It generally forms nodules and knots in skarn, but locally it forms homogeneous bodies several feet in diameter. The largest observed bodies of marble are exposed on the south slope of the hill at Sulphur Hill mine and on the floor of Andover pit a few feet south of the pond near the northeast end *(pl. 1)*.

The marble is a crystalline, medium- to coarse-grained, generally massive, white to gray, locally pink, rock. In a few places it contains some thin siliceous layers that represent quartzose beds of primary origin. The marble grades transitionally into garnet or pyroxene skarn, and only a few of the larger bodies are free from some disseminated pyroxene or garnet. The marble associated with the main Sulphur Hill ore body contains sparse disseminated sulfide minerals in a few places.

Marble is mapped with skarn and related rocks on plate 1 because it does not form discrete bodies of mappable size.

SKARN

Skarn, an old Swedish mining term for aggregates of dark silicate minerals rich in iron, magnesia, and lime (Holmes, 1920, p. 211), constitutes several percent of the bedrock in the region and is the host rock for the sulfide and magnetite deposits.

Skarn forms a relatively narrow belt, 300 feet or less in width, that extends from the vicinity of Andover mine northward to the Longcore mine, and probably beyond, a distance of more than a mile *(pls. 1 and 2)*. The skarn is not continuous throughout the belt; but instead, it forms several disconnected pods and layers of different sizes and shapes that together constitute a definite and traceable zone. The larger skarn masses are on the crests and noses of folds; the smaller masses are mostly on the flanks of folds. *(See fig. 2.)*

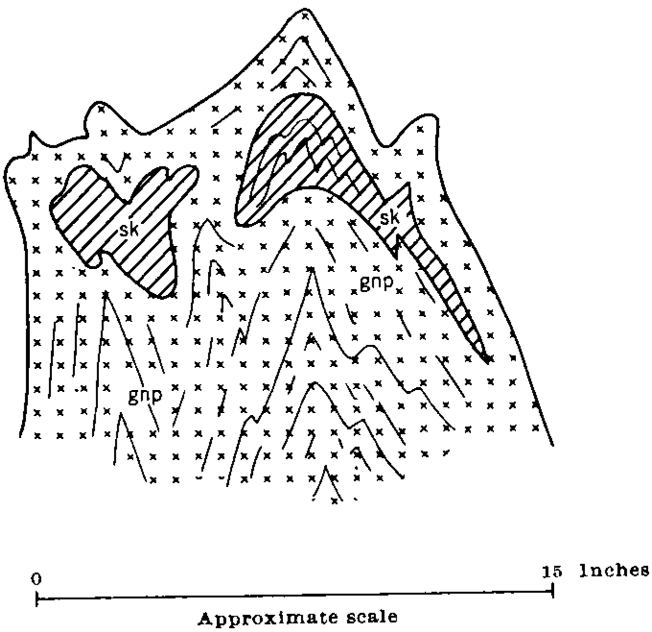


FIGURE 2—Sketch showing small skarn pods in crests of tight folds in pyroxene-feldspar gneiss, near Tar Hill mines. Note extreme thinning or absence of skarn on limbs of folds. sk, skarn; gnp, pyroxene gneiss

Natural exposures of skarn range from the large, bold outcrops between the Tar Hill and Longcore mines to the inconsequential rubble characteristic of much of the belt. This rubble of rough, angular, leached blocks can be detected only by close observation, but its recognition is essential to the mapping of the skarn belt.

The largest mass of skarn known in the region forms bold outcrops on the east side of the road, south of Tar Hill mine *(pl. 2)*. This mass, which occupies an area of at least 1,500 square feet, consists almost entirely of garnet and is barren of ore minerals.

Mineralogically the skarn can be divided into two main types—garnet skarn and pyroxene skarn. There are intermediate varieties between the two types and gradual transitions from one type to the other. The skarns contain variable amounts of calcite as irregular masses, knots, and disseminations. Calcite also forms veinlets that cut the skarn. Where observed, the garnet is later than the pyroxene and appears to replace it.

Garnet skarn, which constitutes more than 90 percent of the skarn, generally is fine- to very fine-grained and massive. Locally it has a good parting that cuts across several individual crystals. The garnet is nearly always dark reddish-brown and probably has the composition of andradite, the Ca-Fe garnet. Some pyroxene is usually associated with the garnet. Green to yellowish-green epidote and serpentine (?) are present in some skarn masses, particularly in the Tar Hill area. Actinolite was observed as a thin "layer" in garnet skarn in the middle Sulphur Hill pit. Scapolite, apatite, fluorite (?), and prehnite (?) are local sparse accessory minerals in some skarn bodies.

Pyroxene skarn is medium- to fine-grained, massive, and generally somewhat coarser than garnet skarn. It usually is coarse-grained adjacent to pegmatite. The pyroxene is a medium to dark green variety that probably has the composition of salite or ferrosalite.

PYROXENE-FELDSPAR GNEISS

Pyroxene gneiss is abundant in the mapped area. It is associated with skarn, amphibolite, biotite-quartz-feldspar gneiss, and marble.

A large mass of pyroxene gneiss that locally contains small skarn bodies crops out on the hill east of the Andover mine *(pl. 1)*. The gneiss typically is migmatitic and highly epidotized. Pyroxene gneiss that contains several bodies of amphibolite caps the hill west of the main Sulphur Hill pit. Locally the gneiss is crenulated and crumpled *(see pl. 3a)*, indicating that the rock has been strongly deformed and folded. A large irregular mass of pyroxene gneiss is well exposed in

PLATE 3A—Crumpled pyroxene-feldspar gneiss, 250 feet west of main pit, Sulphur Hill mine.

the area between the Sulphur Hill and Tar Hill mines *(see pl. 1)*. The gneiss contains a few isolated bodies of garnet skarn and grades transitionally into amphibolitic rocks.

In the Tar Hill and Longcore mine areas pyroxene gneiss forms an envelope of variable thickness around garnet skarn bodies *(see pl. 2)*. The contacts between pyroxene gneiss and skarn are generally sharp but in places are gradational and highly irregular.

Pyroxene gneiss is a green to light greenish-gray generally fine-grained rock consisting chiefly of sodic plagioclase and light-green diopsidic pyroxene. Locally the rock is calcareous. It generally has a distinct to rude layering due to differences in the proportion of diopside. Small knots, clots, and local sprays of pyroxene skarn are common in the gneiss. Felsic (granitic) varieties of pyroxene gneiss that contain abundant feldspar constitute much of the gneiss in some places. Scapolite takes the place of the plagiosclase locally; sphene and quartz are minor accessory minerals.

Pyroxene gneiss usually can be distinguished from amphibolite by the presence of stubby light-green diopsidic pyroxene crystals, by the almost complete absence of dark-green to black hornblende, and by its compositional layering; also pyroxene gneiss generally is much finer grained than amphibolite.

AMPHIBOLITE

Amphibolite, as used in this report, includes dark, medium-grained, equigranular rocks that consist of approximately equal amounts of intermediate plagioclase and one or more of the mafic minerals—hornblende, pyroxene, and biotite. Amphibolite is the most abundant rock type in the mapped area. It forms folded layers several hundred feet long and lenticular masses interlayered with pyroxene gneiss and locally with other metasediments. Because of its resistance to weathering, amphibolite forms many ridges and escarpments in the region.

A large irregular-shaped mass of amphibolite forms a part of the hanging wall of the Sulphur Hill deposit, between the Sulphur Hill and Tar Hills mine *(pl. 1)*. The amphibolite is well exposed on several hills near the road to the Tar Hill mines and was intersected in drill holes S-6 and S-7. The amphibolite in this mass grades transitionally into biotite-plagioclase gneiss and biotite-quartz-feldspar gneiss and is intimately associated with pyroxene gneiss.

Another large body of amphibolite forms the footwall of the Sulphur Hill deposit *(pl. 1)*. A steep escarpment about 30 feet in height marks the west contact of the amphibolite, which here is migmatized by the lit-par-lit injection of granite and pegmatite. The amphibolite layer was intersected in the drill holes that penetrated the skarn at Sulphur Hill mine, and it forms a useful marker for footwall rock *(see pl. 1, sec. A-A')*. A thin, complexly folded layer of amphibolite branches from the footwall layer to form the hanging wall of the Sulphur Hill deposit.

A large mass of relatively uniform amphibolite forms the crest of the hill east of the Tar Hill mine *(pl. 2)*. A nearly vertical escarpment, locally as much as 70 feet high, marks the east edge of the amphibolite mass.

Three varieties of amphibolite were recognized: (1) amphibolite, containing hornblende as the chief mafic mineral, (2) pyroxene amphibolite, in which pyroxene is more abundant than hornblende, and (3) biotite amphibolite, a variety containing several percent of biotite. All varieties of amphibolite are interlayered and grade into one another by a change in the proportions of the mafic minerals. Because of the difficulty of distinguishing different mineralogic varieties, all the amphibolitic rocks are mapped as a single unit on plates 1 and 2.

In drill hole S-7, amphibolite can be seen to grade transitionally into biotite-quartz-feldspar gneiss. The amphibolite, at depths of 53.7 to 111 feet, gradually becomes more biotitic as depth increases; between depths of 111 and 118 feet there is a gradual but rapid decrease in hornblende and an increase in biotite and quartz; and at a depth of 118 feet the rock is biotite-quartz-feldspar gneiss that contains only traces of hornblende. At a depth of 120 feet the hornblende is completely absent.

BIOTITE-PLAGIOCLASE GNEISS

Biotite-plagioclase gneiss constitutes several percent of the gneiss in the hanging wall of the Sulphur Hill deposit *(pl. 1)*, but it was not noted elsewhere in the region. The gneiss is well exposed near the road south of drill hole S-6.

Biotite-plagioclase gneiss is a dark gray, medium-grained, equigranular rock that consists chiefly of plagioclase and biotite, with subordinate amounts of hornblende. It grades into amphibolite, on the one hand, by an increase in the amount of hornblende, and into biotite-quartz-feldspar gneiss, on the other hand, by an increase in the amount of quartz. Because of its intimate association with amphibolite, the biotite-plagioclase gneiss was mapped with amphibolite *(pl. 1)*.

BIOTITE-QUARTZ-FELDSPAR GNEISS

The largest mass of biotite-quartz-feldspar gneiss is in the hanging wall of the Sulphur Hill skarn deposit *(see pl. 1)*. Here the gneiss generally is a medium-grained rock that has a poor to distinct foliation. In many surface exposures the biotite is greenish, as it is partly or completely altered to chlorite. Locally the gneiss is pinkish and distinctly granitic in appearance, both at the surface and in drill cores.

Biotite-quartz-feldspar gneiss is exposed on the hill east of the Andover mine, where it forms the hanging wall of the Andover deposit. The gneiss is distinctly layered by slight differences in the proportion of biotite in the rock, and generally is strongly deformed into tight isoclinal folds. This body of gneiss is inferred to be equivalent to the layer of biotite-quartz-feldspar gneiss exposed in the valley southwest of Sulphur Hill mine *(see pl. 1)*.

Small lenticular bodies of biotite-quartz-feldspar gneiss are intimately associated with microcline granite gneiss in the Tar Hill region, and in the area west of Andover mine. Sillimanite is a local accessory mineral in these rocks.

Biotite-quartz-feldspar gneiss is a light- to dark-gray, equigranular, generally fine-grained rock. The color depends largely upon the proportion of biotite present. The rock consists of sodic plagioclase and quartz, with variable but smaller amounts of biotite. The biotite is pleochroic, ranging from reddish brown to straw yellow; locally it is greenish where it is partly altered to chlorite. That chloritization is in part due to alteration by hydrothermal solution is indicated by the presence of chlorite adjacent to carbonate-epidote veinlets. Hornblende is a variable mafic that usually is segregated in thin seams. Microcline, always fresh and well-twinned (quadrille structure), constitutes as much as 5 percent of the rock. Sillimanite, magnetite, apatite, zircon, and allanite are minor accessory minerals.

Origin of metasediments

Nearly all the metasediments in this region have been profoundly reconstituted by composite contact and regional metamorphism, and it is not possible to reconstruct the stratigraphic sequence. The present writers interpret the marble, pyroxene-feldspar gneiss, skarn, and amphibolite to represent metamorphosed calcareous sediments for the most part; the biotite-quartz-feldspar gneiss represents metamorphosed aluminosiliceous sediments, perhaps tuff. The rocks are similar to the metasediments in the northwest Adirondacks (Buddington, 1939, pp. 11-17; Engel, 1949, pp. 767-784; Engel and Engel, 1950, p. 1457).

Marble, which now constitutes only a small proportion of the bedrock, formed by recrystallization of carbonate rocks. It is believed to be equivalent to the Franklin limestone (Spencer, 1908). Pyroxene-feldspar gneiss possibly represents metamorphosed impure carbonate-bearing sediments. There is strong evidence that the skarn formed by metasomatic alteration of carbonate rock. Field evidence indicates that the metasomatism was produced by solutions that moved ahead of a magma of granitic composition, for the skarn locally is disintegrated and injected by granite and pegmatite. The chemical change resulted mainly from an addition of iron, silica, and alumina; calcium and carbon dioxide, especially, were removed. The role of magnesia is difficult to assess, as the magnesia content of the pre-existing carbonate rocks is entirely unknown.

The intimate association of amphibolite with, and the gradation into, other rocks of metasedimentary origin strongly suggest a sedimentary origin for the amphibolite. Amphibolite grades into biotite-plagioclase gneiss, on one hand, and into biotite-quartz-feldspar gneiss, on the other hand. Field evidence suggests that the amphibolite was formed by the metamorphism of impure calcareous and magnesian sedimentary rocks. There is no evidence that the amphibolite is modified skarn.

Biotite-quartz-feldspar gneiss from the Dover magnetite district, N. J., has been described by Sims (U. S. Geol. Survey, Bull. 982-, in preparation) and from the Ringwood and Sterling districts, N. J.-N. Y., by Hotz (U. S. Geol. Survey, Bull. 982-, in preparation). The gneiss from the northwest Adirondack Mountains also has been described (Engel and Engel, 1950, p. 1457). Sims and Hotz agree that these rocks formed through metamorphism of alumino-quartzose sediments. Engel and Engel (1950, p. 1457) have suggested that the gneiss was derived from a siliceous sodic shale or tuff.

Igneous rocks

Igneous rocks, which constitute only about 10 percent of the rocks in the mapped area, consist predominantly of microcline granite gneiss and granite pegmatite of pre-Cambrian age, and a few small dikes of aphanitic diabase inferred to be of Triassic age.

MICROCLINE GRANITE GNEISS

The most prominent mass of microcline granite gneiss is a thin, folded sheet, generally not more than 150 feet wide, that extends for more than a mile along the northwest side of the mapped area *(see pls. 1 and 2)*. The granite is variable in composition, and locally forms migmatite, for it characteristically is interlayered with, and includes schlieren, wisps, and clots of biotite-quartz-feldspar gneiss and other metasediments.

One or more thin and intricately folded sheets of microcline granite gneiss are enclosed within the main mass of skarn at Sulphur Hill mine. Most of this granite gneiss is contaminated by small xenocrysts derived from the associated metasediments. A course-grained syenitic facies of the granite, which formed at the contact with carbonate rocks, was observed in drill hole S-5.

The microcline granite gneiss is composed chiefly of microline and quartz, with smaller but variable amounts of sodic plagioclase. The microcline is slightly perthitic locally, as in the mass west of the Pinkneyville-Andover road, shown on plate 1. The varietal minerals are biotite, sillimanite, hornblende, and pyroxene; zircon, magnetite, and apatite are minor accessories. The most common facies is biotite granite gneiss; hornblende and pyroxenic facies are less common. The granite gneiss is similar to the microcline granite from the Adirondack Mountains described by Buddington (1948, pp. 36-39). The microscope reveals that the plagioclase tends to be restricted to narrow seams and that in places it forms as much as 40 percent of the total feldspar. Within a single thin section there may be several plagioclase-rich and plagioclase-poor zones. Sillimanite occurs here and there in the biotite granite gneiss and it is always closely associated with plagioclase. It was not observed in the granites that contain hornblende or pyroxene.

The texture of the granite gneiss characteristically is granoblastic; grain outlines are typically polygonal. Cataclastic textures were observed in a specimen from the nose of the plunging anticline west of the Andover pit *(pl. 1)*.

PEGMATITE

Granite pegmatite, and locally syenite pegmatite, form small irregular masses intimately associated with skarn. Pegmatite also occurs locally in the granite gneiss and in the metasedimentary rocks.

The pegmatite is course-grained and consists almost entirely of quartz and feldspar. Locally it contains small inclusions of country rock. The pegmatite seems to be undeformed for the most part, but it is crackled in some exposures, and a few of the cracks are filled with late carbonate and epidote. Pegmatite is sheared and crushed, and is locally included as angular fragments in the fault zone along the northwest wall of the Andover mine *(pl. 1)*.

DIABASE

Dark, aphanitic diabase forms thin dikes in the fault zone along the northwest wall of the Andover pit *(see pl. 1)*. The diabase generally is sheared and highly chloritized, and in part resembles the chloritized mylonite that constitutes a large part of the fault zone *(See p. 20)*. The diabasic texture of the rock is evident in some thin sections, but the rock is so highly altered that the primary minerals are obscured.

A vertical dike of blue-gray, aphanitic diabase, which strikes N. 20° W., cuts amphibolite 65 feet south of the test pit that is 320 feet north-northeast of the north Sulphur Hill pit *(pl. 1)*.

The diabase is inferred to be Triassic age because it is similar to diabase of known Triassic age in New Jersey.

STRUCTURE

The dominant structural feature in the Andover mining district is the prevailing northeast trend of the rock units and the foliation *(pls. 1 and 2)*. This trend is characteristic of the pre-Cambrian rocks in the New Jersey-New York Highlands and has been known since Cook (1868, p. 51) first described the parallelism between structural trends and topographic features. It is not widely recognized, however, that the apparent simplicity of this pattern is only superficial and that the pre-Cambrian rocks are compressed into a series of folds which trend and plunge northeast.

The rocks in the Andover mining district have a prevailing trend of N. 55° E. and a prevailing dip to the northwest, but there is considerable variation. The fold axes and lineation plunge 10°-35° N. 50° E. In the Sulphur Hill mine area *(pl. 1)*, the most important structure is a sigmoid flexure that consists of a northeast-plunging syncline and anticline. The general structure of the Tar Hill-Longcore area is a series of northeast-plunging minor anticlines and synclines.

Steeply-dipping longitudinal faults, possible of Triassic age, that trend about N. 40° E. occur along the northwest and southeast wall of the main pit at the Andover mine.

As the garnet skarn contains the primary mineral deposits in the region, the writers mapped the structure of the skarn belt in more detail than other belts. A narrow strip of surrounding rocks also was mapped, however, as shown on plates 1 and 2.

Foliation and lineation

The rocks in the region are strongly deformed and have a secondary foliation and lineation. The foliation is marked by a fair to excellent lithologic layering and by the dimensional orientation of tabular and platy minerals in the rocks. The lithologic layering is principally the result of slight differences in composition or texture, or both. For the most part it reflects the bedding of the original sediments, but in part it reflects the lit-par-lit injection of igneous material along the structural planes of the matesedimentary rocks. Foliation generally is strong on the limbs of folds and obscure to faint in the axial areas of folds. The lineation becomes dominant on the noses and in the axial zones of folds.

The rocks have a strong lineation that is produced by several different elements. The linear structures are visible in outcrops, in hand specimens, and under the microscope. All the rocks have a mineral lineation that is produced by the subparallel alignment of elongate mineral grains or mineral aggregates. The development of this lineation differs, however, in the various rock types and is dependent primarily upon two factors—the proportion of elongate minerals or mineral aggregates in the rock and the degree of orientation of individual grains. In amphibolite, lineation is produced by elongate hornblende crystals; in pyroxene-feldspar gneiss it is produced by pyroxene skarn lenses; in biotite-quartz-feldspar gneiss it is produced by biotite streaking and "fins" or elongate bundles of small sillimanite needles. In many parts of the mapped area lineation is the result of crumples, crenulations, and rods formed by tight isoclinal folding *(see pl. 3a),* and boudinage.

The lineation is essentially parallel to the fold axes, and thus conforms to the direction of intermediate elongation of folding deformation, or the *b*-axis of the coordinate system (Sander, 1930, p. 119). Petrofabric diagrams of the rocks were not studied by the writers, but petrofabric diagrams of similar pre-Cambrian gneisses from the vicinity of 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.

The lineation is remarkably uniform throughout the mapped area. The average bearing of the lineation is N. 50° E.; the angle of plunge ranges from about 10° to 35° NE.

The long dimension of garnet skarn bodies in the region conforms to the dominant N. 50° E. lineation. The skarn body at Sulphur Hill mine is an elongated podlike mass whose maximum thickness is 135 feet; its breadth (measured along the dip at right angles to the plunge) is about 330 feet, and its pitch length (Lindgren, 1933, p. 192) about 900 feet. Core drilling indicates that the skarn pinches out to a feather edge along its rake. *(See pl. 1.)*

A notable departure from the nearly constant N. 50° E. lineation is shown within skarn at the middle Sulphur Hill pit *(see pl. 4)*. Here the dominant lineation, given by warp axes and pod structures is skarn and by mineral lineation in an included block of amphibolite, trends N. 70°-80° E. and plunges 20°-30° E. This local deviation is thought to be the result of differential movements in the limestone during deformation, perhaps controlled by the outline of the "horse" of amphibolite. It is conceivable that patterns produced by such local movements have determined, in some measure, what parts of the skarn could later be replaced by ore. However, the writers believe that the outlines of the skarn masses themselves were controlled by the prevailing N. 50° E. lineation and not by this anomalous lineation.

Drag folds

Minor folds of the type commonly called drag folds are conspicuous in parts of the area. The folds range in amplitude from a fraction of an inch to 100 feet or more. Small-scale asymmetric drag folds are best shown in thin-layered portions of the pyroxene gneiss, particularly in calcareous varieties. Those of large dimensions are shown by the pattern of the skarn masses. *(See pls. 1 and 2.)* Drag folds of intermediate size are mappable at places in all the metasediments. In addition, chevron folds and shear folds have been observed locally. Flowage folds that lack a regular pattern seem to be sparse.

In general, the axes of minor folds plunge parallel to the axes of folds of next higher order. The dip of the axial planes of drag folds is variable. Where the asymmetry of the drag folds is sufficiently pronounced, these minor structures are useful in working out the pattern of the larger folds.

Boudinage

At several places in the northern part of the mapped area *(pl. 2)*, boudinage structure of several types can be seen. Beads of garnet skarn, elliptical or crudely rectangular in cross section, are strung out in some outcrops of pyroxene amphibolite adjacent to the main skarn zone. One outcrop of garnet skarn shows small, contorted fragments of a once-continuous thin layer of pyroxene gneiss. These fragments are now isolated in the skarn matrix. Boudinage on a much larger scale is shown by the disruption of the skarn belt into contorted masses 50 to several hundred feet long *(see pl. 2)*. The various types of boudinage have resulted from differential yield of rock units during plastic deformation.

Fracture cleavage

A crude type of fracture cleavage, which is possibly much younger than the foliation and which consists of closely spaced, slightly curved shear surfaces, locally transects the foliation in the gneisses and also cuts quartz-rich pegmatite veins. It is well shown in outcrops just east of the south end of the Longcore drain *(pl. 2)*, where the shear surfaces are coated with fibrous yellow epidote and purple fluorite.

Metasediments and associated granite gneiss sheets

The metasediments form layers or belts that parallel the trend of the foliation. The layers tend to be lenticular *(see pls. 1 and 2)*; the lenticularity probably reflects lensing and intertonguing of the original sediments, plastic flowage, and shearing out of some units by cataclastic deformation. There is evidence that rocks of different competence have behaved differently. The more competent quartzose rocks seem to have retained a certain degree of rigidity during deformation, but the more mobile carbonate rocks flowed previous to their conversion to skarn, and consequently the silicated paragneisses intercalated with them were locally disrupted and floated apart.

The metasediments, with the exception of most of the garnet skarn, have a visible gneissic structure. Where the skarn is essentially monomineralic it normally shows no planar or linear elements; where it contains several minerals, however, a crude to distinct foliation or lineation is visible locally. The planar structure is produced by alternate layers of different mineral composition. Lineation is rarely visible in skarn, though some bodies in the northern part of the mapped area have a distinct streaking where epidote accompanies the garnet. The internal structure of the skarn probably is due to several factors—mimetic crystallization of previously deformed carbonate rock, selective replacement, crude diffusion banding, and post-skarn deformation.

The granite gneiss forms elongate folded sheets that are parallel to the gneissic structure of the metasedimentary rocks.

The Andover-Sulphur Hill area

The most important structure in the Andover-Sulphur Hill area is the sigmoid flexure that consists of a syncline and an anticline. *(See (pls. 1 and 4.)* Dips along the northwest flank of the flexure, north of Sulphur Hill mine, are generally near the vertical, and the prevailing trend of the lithologic units and foliation is about N. 55° E. In the axial area of the flexure the dips are much flatter and average about

25° NE. Along the southeast flank of the sigmoid flexure the rocks trend again northeast and dip steeply to the southeast. Linear structures in the rocks indicate that the folds plunge 15° to 25° approximately N. 50° E.

The skarn in the Sulphur Hill area is characterized by extreme thickening and thinning. On the northwest limb of the syncline at the Sulphur Hill mine the skarn consists of two essentially parallel layers that are thinned, constricted, and locally disrupted. *(See pls. 1 and 4.)* In the middle and north pits the inner skarn layer is intricately folded, and locally is swelled into moderately large "pods." In the axial area of the syncline both skarn layers converge to form a very much thickened podlike mass whose greatest dimension parallels the prevailing lineation *(see pl. 1, sec. CDEF)*. The surface geology and drill cores indicate that the maximum known thickness of the skarn mass is about 135 feet *(see pl. 1, sec. B-B')*, the breadth (measured along dip at right angles to plunge) is about 330 feet, and the pitch length (Lindgren, 1933, p. 192) about 900 feet. The deposit conforms to the lineation in the country rock. As can be seen on plate 1 *(sec. CDEF)*, the Sulphur Hill deposit plunges about 25° N. 50° E. at the surface, flattens to about 10° near hole S-5, then steepens again between drill holes S-5 and S-6. If the silicated marble penetrated in drill hole S-7 at a depth of 572 feet is equivalent to the garnet skarn in hole S-6, the apparent plunge of the deposit between holes S-6 and S-7 is about 33°. This steepening in the plunge is accompanied by a diminution in the size of the skarn body; also garnet skarn largely disappears.

The Sulphur Hill deposit is the largest known garnet skarn body in the New Jersey Highlands. The structure of the deposit is similar in many respects to the structure of the skarn bodies in the Kaveltorp field in central Sweden *(see p. 35)* and in the Forest of Dean mine in New York (Colony, 1923, p. 104).

The skarn in the main Sulphur Hill pit has a synclinal bottom sharply ridged by minor anticlines, and an inferred anticlinal top. *(See pl. 4.)* The internal structure of the skarn consists of intricate folds and associated crumples whose axes are generally only a few feet apart. The ore shoots are confined to crumpled and folded portions of the skarn. The mineralization is on the noses and, less commonly, the crests or troughs of minor folds in skarn. The thickest parts of the skarn tend to be barren, perhaps because these zones in the original limestone provided less vigorous differential movement than was possible where thin limestone zones moved past resistant gneiss walls.

The Tar Hill-Longcore area

The prevailing trend of the lithologic layering and foliation in the Tar Hill-Longcore area is N. 55° E., and the prevailing dip is northwest, but there is considerable variation, as shown by the rock units and the structure symbols on plate 2.

The general structure indicated by the skarn belt is the Tar Hill-Longcore area is a series of northeast-plunging minor anticlines and synclines. These minor folds are, in effect, drag folds on the limb of a major structure. Their asymmetry suggests that a major anticlinal axis lies southeast of the belt, and a major synclinal axis northwest. The relations would be reversed, of course, if the minor folds should prove to be flowage folds of the type described by Bain (1931), rather than drag folds. However, the almost complete absence of small-scale flowage folds scarcely supports this alternative. The major structures of this region have not been delineated fully because the mapping has been confined to a narrow strip.

The skarn belt is characterized by marked thickening and thinning *(see pl. 2)*. In several places, for example between pits 3 and 4, Longcore area, the skarn seems to have been pulled apart. Whether the belt consists of one skarn layer or two is uncertain. In the vicinity of the main Tar Hill pits, the evidence suggests two separate layers, unless there is a refolded fold.

The structural pattern in the region of the Tar Hill and Longcore mines seems consistent with the following interpretation: a series of calcareous shales and calcareous illitic sandstones with two (one?) relatively thin layers of limestone was deformed to the point of exceeding the elastic limit and the rocks failed by plastic flow. During deformation the limestone yielded more readily than the associated sediments and in places was even pulled part. Nevertheless, its comparative thinness allowed the enclosing sediments to exert considerable control, thereby preventing the limestone from billowing into the disordered structures found in some freely flowing limestone masses of considerable size, as in the northwest Adirondack Mountains (Engel, 1949).

Faults

Longitudinal faults that trend about N. 40° E. are exposed along the northwest and southeast walls of the main pit at Andover mine, and locally along the projection of these faults outside the pit *(see pl. 1)*. The faults are slightly discordant to the foliation; the dip is nearly vertical. The fault surfaces are marked by slickensides and mullion structures that rake near the vertical, as shown in plate 3b. The faults are closely spaced and constitute fault zones several feet thick. The rocks in the fault zones are so highly altered and fractured that their original identity is nearly or completely destroyed. For the most part the rocks have been ground into mylonite, but locally breccia that contains identifiable rock fragments is visible, particularly along

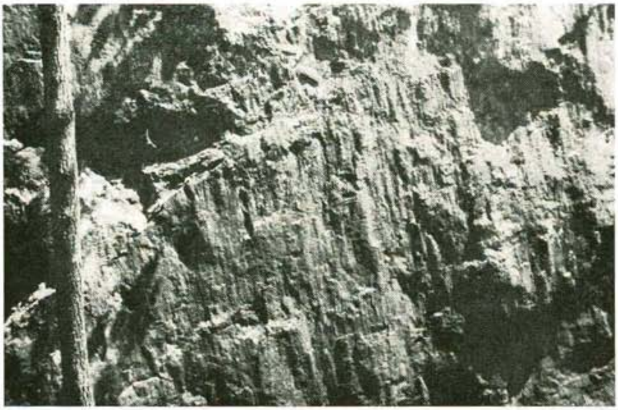


PLATE 3B—Fault along southeast wall of main pit, Andover mine.

the northwest wall of the main pit. The principal exposures of breccia are shown on plate 1.

In many places the breccia consists of white subangular quartz fragments an inch or less in diameter in a hematitic or limonitic matrix.. Another type of breccia, of local occurrence, consists of sparse angular fragments, as much as 6 inches in diameter, of biotite-quartz-plagioclase gneiss, altered garnet skarn, pegmatite, and diabase (?), in a chloritic mylonite matrix. On the east side of the most northeasterly underhand stope along the northwest wall of the main pit (see *pl. 1,* a breccia is exposed that consists of irregular-shaped magnetite fragments in a hematitic or a limonitic matrix. Similar magnetite breccia is exposed along the west wall of the main pit, 200 feet farther south. The mylonite typically is schistose and almost completely altered to chlorite.

The breccia and mylonite along the northwest side of the main pit were interpreted by Bayley (1910, p. 79) and Till (1932) to be quartzite conglomerate and indurated carbonate shales, but there is strong evidence that these rocks are tectonic in origin, as described above.

Aphanitic diabase dikes occur at numerous places in the fault zone along the northwest wall of the Andover pit, as shown in plate 1. The diabase is in part sheared and brecciated. Late quartz veins that have been reported (A. V. Heyl, oral communication) to contain sparse yellow sphalerite are also visible locally in the fault zones. The faulting cannot be dated exactly, but it is inferred to be of Triassic age. The diabase that occupies certain faults at the Andover mine is also inferred to be of Triassic age. The faulting, therefore, is pre-diabase and may be related to the period of Triassic faulting (Darton, 1908, p. 7; Bayley, 1914, p. 8). Subsequent to the emplacement of the diabase, movement in the fault zones was renewed, for the diabase generally is sheared.

MINERAL DEPOSITS

History and production

The history of the mines in the Andover mining district has been described by Bayley (1910), and only a summary is presented here. The Andover mine was worked extensively before the Revolutionary War and the ore was smelted in the Andover furnace, which was built in 1763. During the War the Continental Congress took possession of the mine to supply the army with iron and steel. After the War the mine was closed. In 1847 the mine was reopened by the Trenton Iron Company, which operated it until 1863, when it was finally abandoned.

The Sulphur Hill mine was opened sometime between 1855 and 1860. It was operated for a few years and then closed, probably in 1863. The mine was reopened in 1871 and worked for 2 years. It was worked again in 1879 and 1880; and during the census year 1879-1880 it produced 15,201 tons of ore. The mine apparently was abandoned because of the large quantity of sulfur in the ore.

The total production from the Andover and Sulphur Hill mines is estimated by Bayley (1910, p. 83) at 400,000 long tons of iron ore. About 120,000 long tons was mined between 1847 and 1854.

The Tar Hill and Longcore mines were opened before 1855. Between 1867 and 1873 the Tar Hill mines were in operation, but apparently they have been idle since 1873. Production from the Tar Hill and Longcore mines is not known, but it probably was small.

For a map showing the claim boundaries of the Sulphur Hill and Tar Hill tracts the reader is referred to Lynch (1947, fig. 2).

Types of ore deposits

The mineral deposits belong to two types—primary magnetite-sulfide deposits and secondary hematite deposits. The magnetite-sulfide, deposits are replacements of garnet skarn and constitute the deposits at Sulphur Hill *(pls. 1 and 4)*, Tar Hill, Longcore mines *(pl. 2)*. The hematite deposits at Sulphur Hill *(pls. 1 and 2)*, Tar Hill, and Longcore mines *(pl. 2)*. The hematite deposits resulted from intense supergene alteration of primary magnetite deposits and occur only at the Andover mine *(pl. 1)*.

MAGNETITE-SULFIDE DEPOSITS

General character and structure

The magnetite-sulfide deposits are replacements of garnet skarn. The ore minerals occur as disseminations, or less commonly, as layers, in structurally favorable portions of the skarn. In the Sulphur Hill deposit, the largest body of this type in the area, magnetite is closely associated with sphalerite, galena, chalcopyrite, pyrrhotite, and pyrite. The magnetite forms thin lenticular layers and streaks, and locally irregular veinlets and disseminations; the sulfide minerals are distributed as disseminations or as nests and clots. The sphalerite is difficult to distinguish from the andradite garnet because of its dark brown color.

The ore minerals are not scattered uniformly through the skarn; instead they form disconnected tabular or pipelike bodies. These shoots are small, generally being only a few feet wide, and occur in crumpled and sheared parts of the skarn. For the most part the shoots are in the crests of very tight folds. The shoots conform to the lineation and are elongated in the direction of the lineation.

The ore shoots are confined to garnet skarn, but small amounts of disseminated sulfides locally are distributed through pyroxene gneiss and marble associated with the garnet skarn. Sparse disseminated molybdenite was observed at the margins of the main sulfide concentrations in the cores of drill holes S-5 and S-6, but it apparently does not occur in the ore. In the Tar Hill and Longcore areas magnetite is the chief ore mineral, but it is associated with abundant pyrite. The magnetite forms thin layers, a maximum of 4 feet in thickness, in garnet skarn.

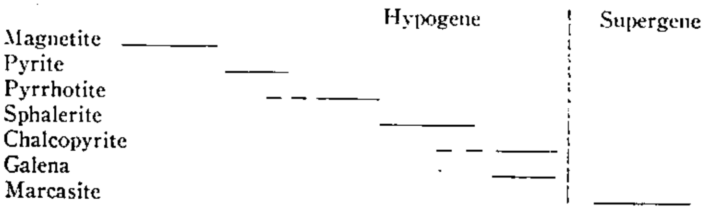
Mineralogy

The mineralogy of the magnetite-sulfide ore is relatively simple. The metallic minerals include magnetite, sphalerite (variety marmatite), chalcopyrite, pyrrhotite, pyrite, molybdenite, and marcasite. With the exception of marcasite, all these minerals are hypogene. Nearly all specimens of mineralized rock are magnetic to various degrees.

The paragenesis of the ore minerals is given in the following table. As the position of molybdenite in the paragenetic sequence is not known, it is not listed in table 1.

TABLE 1

Paragenesis of the ore minerals at Sulphur Hill mine[1]



Magnetite was deposited first. It replaces skarn and locally occupies small fractures in the host rock. Polished sections of the mineral indicate that the magnetite does not contain any exsolved constitutents.

Pyrite replaces magnetite and the host rock. At places remnants of pyrite are completely surrounded by pyrrhotite or chalcopyrite. Pyrite is abundant in the Tar Hill deposits but is sparse at the Sulphur Hill mine.

Pyrrhotite is the most abundant sulfide in the Sulphur Hill deposit. It replaces both magnetite and pyrite. Most grains are partly replaced by marcasite.

The sphalerite is marmatite, the dark-brown variety which contains several percent of Fe. It contains scattered minute blebs of exsolved chalcopyrite *(see pl. 5)*, and replaces pyrite pyrrhotite, and magnetite.

Chalcopyrite, in addition to being present as exsolved blebs in sphalerite, forms disseminations and discontinuous veinlets in fractures within the host rock. It is generally associated with galena.

Galena forms isolated grains in the host rock that are generally associated with chalcopyrite.

A brown micaceous mineral, tentatively identified as stilpnomelane, was observed to be intergrown with pyrrhotite, sphalerite, and chalcopyrite in two specimens from the Sulphur Hill mine. *(See pl. 5)*. Presumably stilpnomelane was the last hypogene mineral to be deposited.

Grade

Published analyses of ore from the Sulphur Hill and Tar Hill mines are given in table 2. For a complete analysis of a sample of cobbed ore *(No. 2 in table 2)* the reader is referred to Pumpelly (1886, p. 153). The analyses in table 2 represent specimens of iron ore, and probably indicate rather accurately the grade of the iron ore mined at

[1] By W. H. Tonking.

PLATE 5—Photomicrograph of a polished specimen of ore from the Sulphur Hill mine.

the Sulphur Hill and Tar Hill mines. The analyses indicate that the Fe content of the ore ranged from about 32 to 46 percent. They do not, however, indicate the base-metal content of the ore.

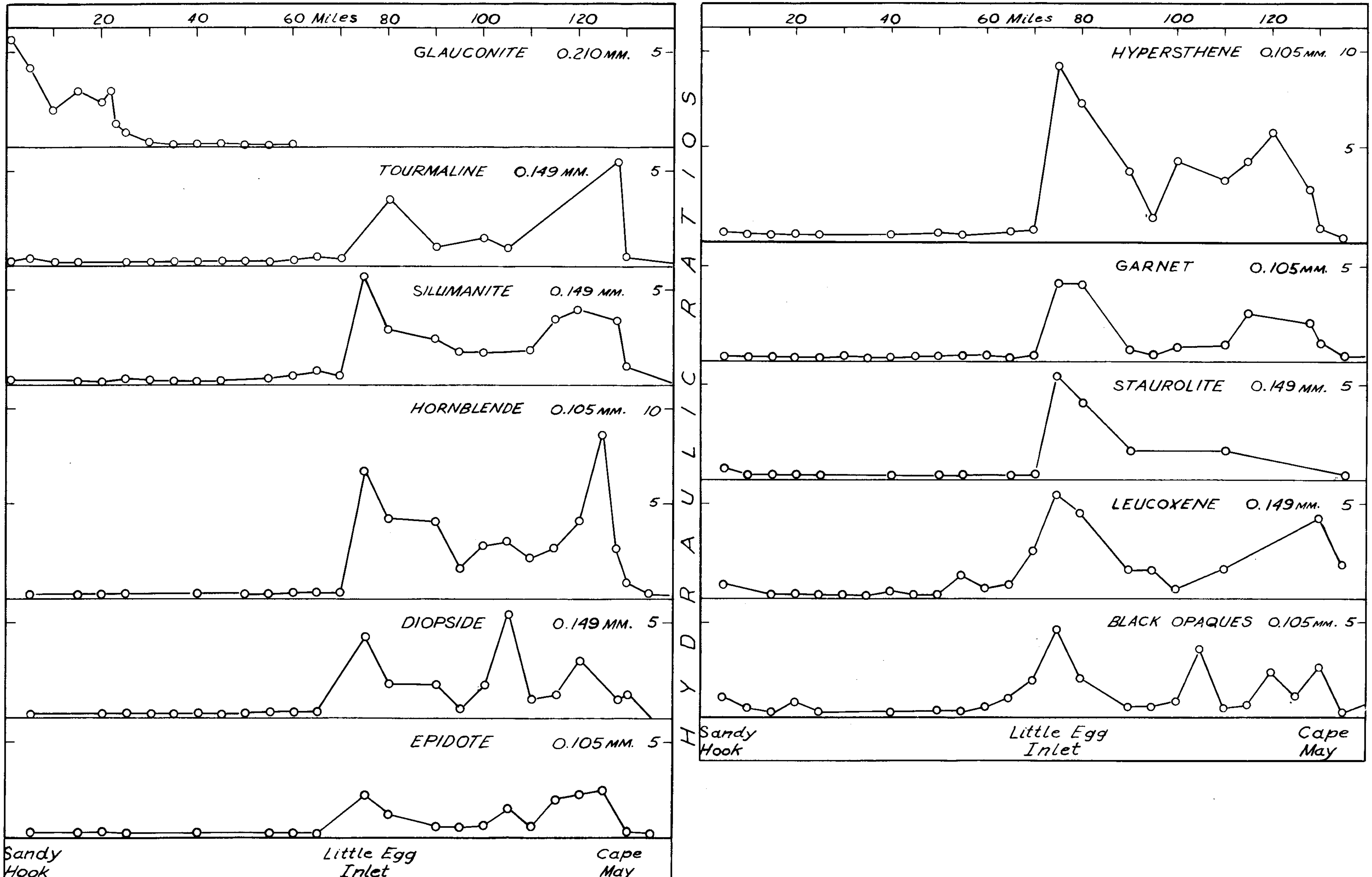


Figure 7 Hydraulic Ratios of Selected Heavy Minerals

TABLE 2

Partial analyses of ore from Sulphur Hill and Tar Hill mines

[Pumpelly, 1886, pp. 151 and 153; analyses 1-4. Cook, 1868, p. 658; analysis 5]

Sample	*Fe*	*S*	*P*	*SiO_2 and insol.*
1.	42.63	2.290	0.024	
2.	36.91	2.527	0.022	
3.	46.53	0.786	0.020	
4.	32.73	0.270	0.100	
5.	53.3*	1.1	trace	20.6

1. Chippings taken around north and west sides of Sulphur Hill mine. Contained garnet, pyrite, and pyrrhotite, in addition to magnetite.
2. From 80 tons cobbed ore on dock, Sulphur Hill mine.
3. Shipping ore after roasting, Sulphur Hill mine.
4. Stringers of brown ore in magnetite, probably produced by surface alteration of the magnetite, Sulphur Hill mine.
5. Magnetite ore, Tar Hill mine.

* Fe_3O_4, 73.6 percent.

Assays for base metals, as well as for iron, were made by the U. S. Bureau of Mines at Sulphur Hill mine. Samples from the face of the main Sulphur Hill pit (Lynch, 1947, p. 12) indicate local zinc concentrations; and one sample, 13.7 feet wide, assayed 3.00 percent Zn, 0.07 percent Cu, and a trace of Pb. Assays of core from drill hole S-2 *(see pl. 1)* indicate 43 feet (depth: 107-150 feet) of mineralized rock containing small amounts of Zn, Cu, Pb, and Ag (Lynch, 1947, p. 11). The magnetite content of the core is not known, for the Bureau of Mines assays indicate total iron and not recoverable magnetic iron. The iron given in the assays for drill hole S-2 can be accounted for largely in the iron-rich garnet skarn; the magnetite content is probably small, although the geologic log (Lynch, 1947, p. 9) indicates some magnetite at depths between 107 and 150 feet. Holes S-3 and S-4 intersected garnet skarn, but the skarn was barren (Lynch, 1947, p. 10).

Assays of cores from drill holes S-5 and S-6, drilled during the present investigation, together with visual observations of the core, indicate sparse zinc mineralization and local traces of lead ond copper. Magnetite is not present in these cores. Abbreviated geologic logs of these holes and of drill hole S-7 are to be included in the report by the U. S. Bureau of Mines.

Origin and age

The magnetite-sulfide deposits are pyrometasomatic replacements of garnet skarn and closely associated calcareous rocks. The ore minerals were deposited by hydrothermal and pneumatolytic solutions after the skarn had formed, for the minerals locally fill fractures in the skarn that resulted from post-skarn deformation. The deposits are pre-

Cambrian in age. The sphalerite in the deposits in marmatite, the ferroan variety of ZnS that is characteristic of many pre-Cambrian sulfide deposits in dark skarn.

An unusual feature of the deposits is the presence of magnetite in garnet skarn. In most deposits of similar type in Norway, Sweden, Finland, and the Adirondacks, magnetite preferentially replaces other types of skarn, particularly pyroxene skarn, and is absent or sparse in garnet skarn. Sulfides, on the other hand, characteristically occur in garnet skarn, as they do in this area.

The source of the ore is not known, but by analogy with the magnetite deposits in the Dover district, New Jersey (Sims, U. S. Geol. Survey Bull. 982, in preparation) it is inferred to be derived from an alaskitic magma.

HEMATITE-MAGNETITE DEPOSITS

The hematite-magnetite deposits are confined to the Andover mine area. The hematite was formed by supergene alteration of hypogene magnetite and perhaps other minerals along the fault zone at the Andover mine. The largest deposit was mined from the main pit at Andover mine; a few small deposits are on the hill slope northeast of the main pit *(see pl. 1)*.

To judge from published descriptions (Cook, 1868, pp. 647-650; Bayley, 1910, pp. 79-83) and from the limited observations by the writers, the hematite-magnetite deposit at the Andover mine was a generally high-grade ore body that consisted of specular hematite, earthy hematite, and variable quantities of magnetite. Most of the ore was magnetic, but in different degrees. The ore occurred in irregular-shaped basins. In the largest basin, at the northeast end of the Andover pit (see pl. 1), it contained a kernel, known to the miners as "blue ore," that was composed largely of magnetite. The kernel was surrounded by a thick shell of "red ore" that was predominantly hematite. Silica, in part amorphous or opaline, was associated with the "red ore," and this caused the mass to have a jaspery fracture (Bayley, 1910, p. 81). In the stopes at the northeast end of the open cut (known as the middle stopes) the ore was predominantly magnetite, presumably unaltered portions of the hypogene ore. In some of the smaller basins, particularly at the southwest end of the mine and to the west of the main pit, the ore was largely earthy hematite. This type of ore is nonmagnetic.

The hematite deposits are shallow—the deposit at the Andover mine bottomed at a maximum depth of 85 feet; the smaller deposits were even shallower. Laterally the deposits are confined within the fault zones that form the southeast and northwest walls of the Andover mine. The magnetite shoot that was mined in the stopes northeast of the main pit probably plunges northeast parallel to the lineation. Evidently, however, this shoot cannot be mined profitably below the bottom of the zone of supergene enrichment.

Mineralogy

The ore in the Andover mine is a complex mixture of magnetic and non-magnetic iron minerals, consisting principally of magnetite and hematite with variable, but generally small, quantities of limonite, jasperoid, and carbonate. The hematite is in part the crystalline variety, specularite, and in part the earthy variety. The crystalline variety of hematite forms pseudomorphs after magnetite, and is, therefore, martite. Sulphides minerals are not known to be present in the hematite ore.

The magnetite in the ore occurs as coarse aggregates that are altered to various degrees to martite. The writers did not observe any completely unaltered magnetite in the Andover mine.

Crystalline hematite, the most abundant constituent of the ore,

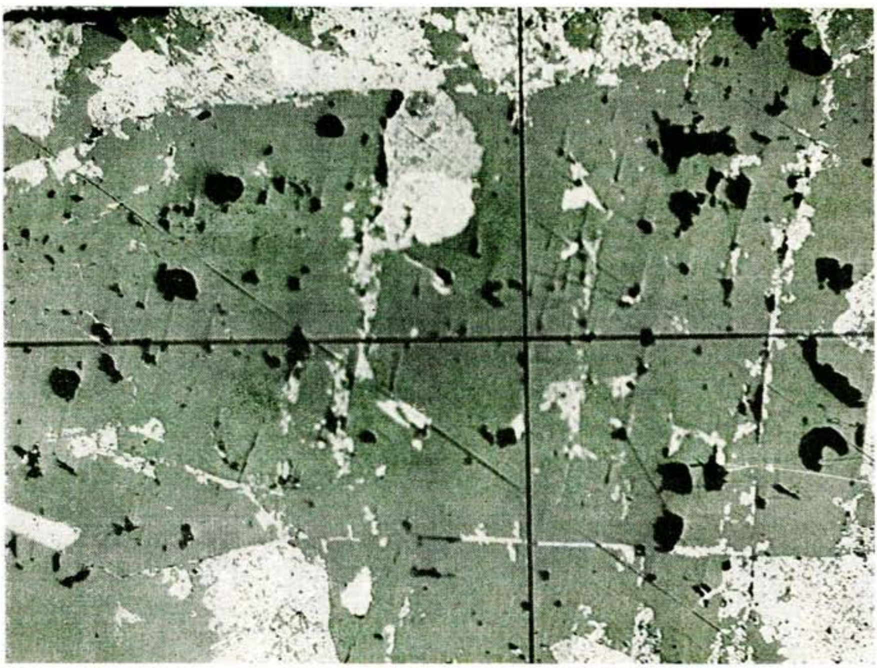


PLATE 6—Photomicrograph of a polished specimen from the Andover mine. X275.

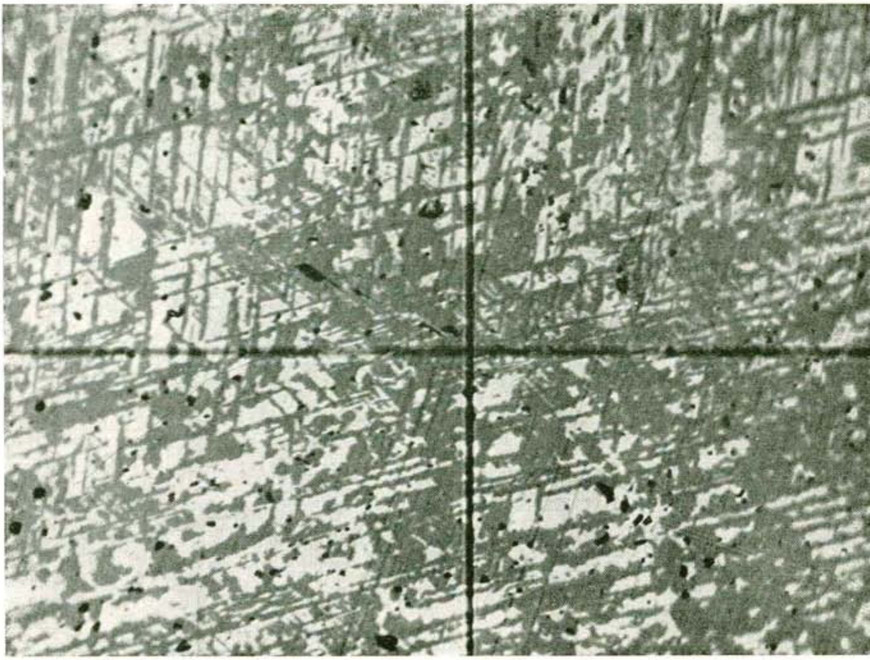


PLATE 7—Photomicrograph of a polished specimen from the Andover mine. X495.

always is closely associated with the magnetite. It embays and veins the magnetite and all stages in the martitization can be observed. So far as known hematite does not form single grains or aggregates of individual grains.

Under the microscope it can be seen that two contrasting textures have been developed by the alteration of the magnetite to martite. In some specimens hematite has replaced the magnetite irregularly, leaving pin-point blebs and islands of the host *(pl. 6)*. In this type of ore the alteration did not proceed from the grain boundaries inward, as would be expected, but it pervasively penetrated the host. In other specimens the replacement was controlled to a large extent by the crystallographic directions of the host *(pl. 7)*. The hematite forms ragged blades and lamellae, leaving patchy areas, islands, and films of the host. The hematite has three directions of extinction, indicating that it has three orientations.

Earthy hematite, which is thought to have replaced the gangue, commonly is associated with the martite and in many specimens encloses the crystalline material. A little limonite was observed here and there in the ore.

The gangue minerals observed by the writers are principally carbonate and jasperoid. It has been reported (Bayley, 1910, p. 82) that the "blue ore" (magnetite) contained garnet and sparse sphalerite, but as this ore has been mined out the writers were not able to verify their presence.

Grade

The ore at the Andover mine generally was high in grade, as shown by the analyses in table 3. To judge from the analyses the strongly magnetic ore averaged 40 to 50 percent Fe, and the supergene hematite ore averaged 55 to 60 percent. The analyses also indicate that some of the magnetite ore contained several percent of MnO. One analysis *(No. 5, table 3)* shows 19.85 percent MnO. Analyses of pig iron from the Andover ore also show appreciable manganese, and Bayley (1910, p. 82) gave an analysis that had 5.75 percent manganese. The source of the manganese presents a considerable problem. According to Cook (1868, p. 65) the manganese occurred in the form of sesquioxide or deuteroxide, or both, and was found only in the magnetic "blue ore." It may be that the manganese was in the crystal lattice of the magnetite, or that it was derived from a manganese-bearing olivine in the skarn, but the writers have been unable to verify the presence of olivine in unaltered skarn. The sulfur and phosphorus content of the iron ore was generally low.

TABLE 3

Partial analyses of ores from Andover mine

[Cook, 1868, p. 653]

	Percent				
Sample No.	*Fe*	*MnO*	*S*	*P_2O_5*	*Insoluble*
1.	56.85	0.45	tr	tr	5.80
2.	58.12	0.45	0.0	0.30	6.20
3.	40.75	tr	0.0	tr	11.30
4.	44.51	0.20	0.0	0.51	11.30
5.	46.80	19.85	0.0	tr	6.90
6.	64.65	0.40	tr	0.19	2.75

1. Hematite from southwest opening.
2. Hematite with a little magnetite forming the upper part of the deposit in large mine [main pit].
3. Hematite with magnetite from northwest side of deposit in large mine [main pit].
4. Magnetite with hematite from deepest part of large mine [main pit].
5. Polaric magnetite from central part of deposit in large mine ("blue ore").
6. Magnetite from extreme northeast end of mine.

Origin and age

The mineralogy of the ore and the shape and structure of the hematite deposits indicate that they formed by supergene alteration of hypogene magnetite and perhaps other minerals. Some of the specularite formed directly through the alteration of hypogene magnetite. The earthy hematite, however, probably resulted mainly from the alteration of sulfides and silicate gangue. The weathering of the sulfides was undoubtedly a factor in permitting oxidation of the magnetite. The hypogene ore, which was probably similar to that at the Sulphur Hill mine, was altered in a fault zone that provided channelways where percolating supergene solutions could migrate freely. The ore accumulated in relatively shallow basins within the fault zone. During the alteration the base metals in the hypogene ore were leached out.

The age of the supergene enrichment and the faulting is not known. The deposits must have formed later than the faulting at the Andover mine, and from the presence of sheared and altered diabase of possible Triassic age in the fault zone, the writers prefer to consider the deposits to be of Triassic or younger age. There is no indication that the hematite was formed on an ancient peneplain of pre-Hardyston (Cambrian) age, but additional study should be made of the Andover and other hematite deposits in New Jersey before this possibility is ruled out.

A summary of the stages in the formation of the Andover hematite deposits is given below:

1. Formation of a hypogene magnetite deposit by replacement of garnet skarn by high-temperature solutions during pre-Cambrian time.
2. Faulting. Age uncertain, but possibly Triassic.
3. Emplacement of diabase dikes along faults on the northwest side of the main open cut during Triassic (?) time.
4. Formation of mineralized quartz veins along some faults.
5. Renewal of fault movements, with intense local brecciation and mylonitization accompanied by and/or followed by pervasive supergene chloritization.
6. Long period of weathering, probably Triassic, or younger, during which supergene hematite formed in the fault zone.

Supergene alteration of magnetite deposits of skarn type in central Sweden has yielded "soft ores" similar to the hematite at Andover. The soft ores consist of limonite, martite, siderite, magnetite residuals, and a little quartz. In at least one mine (Stollberg, in the Väster-Silvberg belt) the alteration is definitely related to faults. The weathering process has involved both reduction and subsequent oxidation, perhaps of Mesozoic or younger age (Geijer and Magnusson, 1926, pp. 49-53). The soft ores have been remarkably enriched in manganese as a result of this weathering (Magnusson, 1940, p. 188; 1950, p. 376).

Results of drilling at Sulphur Hill mine

During this investigation three vertical drill holes were cored to test the Sulphur Hill deposit—holes S-5, S-6, and S-7. These drill holes, together with those cored by the U. S. Bureau of Mines and by the Bethlehem Steel Co. during World War II, are shown on plate 1.

From the earlier drilling and from the geology in the vicinity of the main Sulphur Hill pit, the writers concluded that the Sulphur Hill deposit plunges northeast parallel to the dominant lineation. Drill hole S-5 was located, therefore, 450 feet N. 50° E. from the face of the main Sulphur Hill pit. Hole S-5 penetrated mineralized garnet skarn between depths of 155 and 196 feet and nearly barren calcareous pyroxene-garnet skarn between 214 and 269.5 feet *(see pl. 1, sec. CDEF)*. Scattered grains of disseminated sphalerite, chalcopyrite, galena, and pyrite were noted in the mineralized skarn. Assays by the U. S. Bureau of Mines, however, indicate an average of only about 0.1 precent Zn in the skarn. Drill hole S-6 was placed 250 feet northeast of hole S-5. This hole penetrated skarn at depths between 292 and 339 feet *(see pl. 1, sec. CDEF)*. In addition to the skarn being thinner in hole S-6, it is much more variable in composition. The skarn zone is composed predominantly of calcareous pyroxene-garnet skarn, with variable amounts of marble. A 0.5-foot layer of massive sphalerite with scattered pyrite was cut at 294.6 feet. Drill hole S-7 was placed 350 feet northeast of hole S-6, and 1,000 feet from the face of the main Sulphur Hill pit. This hole did not cut garnet skarn, but at a depth of 572 feet it penetrated silicated marble that is interlayered with pyroxene-feldspar gneiss and feldspathic quartzite *(see pl. 1, sec. CDEF)*.

Future of the mines

Diamond-drill exploration together with detailed studies of the mines indicates that none of the deposits are in the Andover mining district are of commercial value under present economic conditions.

The supergene hematite ore at the Andover mine has been mined out, and there is little chance that additional ore will be found. Drill holes A-1 and A-2, cored by the U. S. Bureau of Mines during World War II *(see pl. 1)*, failed to cut ore beneath the main pit at the Andover mine, indicating that the supergene ore does not extend beneath the floor of the pit. A small pod of hypogene magnetite may possibly plunge northeastward beneath the surface from the northeast end of the open cut, but the magnetite body probably is not large enough to be mined. According to Bayley (1910, p. 81) some magnetite was mined from the underground workings at the northeast end of the main pit, but the magnetite probably pinched out or was too low in grade to mine profitably.

The Sulphur Hill deposit was mined for its magnetite content; the sulfides that are intimately associated with the magnetite were selectively removed from the ore during mining. The magnetite in the Sulphur Hill open cuts appears to have been almost entirely mined out at the surface *(pl. 4)*. Diamond drill cores further indicate that magnetite ore does not extend down the rake from the open cuts. Small quantities of magnetite were cut in drill hole S-2 (Lynch, 1947, p. 9) at depths between 100 and 150 feet but this magnetite is too low in grade to be minable. The drilling by the Bureau of Mines during the present investigation further indicated that the deposit does not contain base metals of commercial grade under present economic conditions.

The magnetite deposits at Tar Hill and Longcore mines are too small to be mined profitably. The thickest known deposit at the Tar Hill mines is 4 feet; also the deposits probably are lenticular along the rake. In addition, the magnetite is admixed with several percent of sulfides, principally pyrite.

REVIEW OF SIMILAR SWEDISH SULFIDE DEPOSITS

The deposits in the mapped area are strikingly similar to some sulfide deposits of central Sweden, described by Geijer (1917). These Swedish deposits fall into two principal classes (Geijer, 1917, p. 304); those in limestone or dolomite and accompanied by skarn silicates and those in quartzose rocks characterized by the presence of Mg-Fe-Al silicates (cordierite, anthophyllite). Deposits of the first class are abundant; but, as individuals, they are considerably smaller and economically less important than the great Falun ore body, the principal sulfide deposit of the district and a member of the second class. Many of the deposits in carbonate rocks are closely associated with minable bodies of magnetite, for which the central Swedish district is famous; and one group of Swedish geologists, headed by Geijer, maintains that the magnetite and sulfides are genetically related.

The geology of the area around Falun is representative of much of the district. Here the pre-Cambrian bedrock comprises the leptite formation:[1] several types of granite and granite gneiss, differing in age and degree of deformation; diorite; pegmatite; and subordinate dike rocks, including diabase (Geijer, 1917, p. 296). All the rocks except diabase, some granite, and some leptite have been highly deformed and recrystallized during metamorphism. They now constitute long parallel belts with superficially uniform structure. Foliation is parallel to primary structures, such as bedding and contacts in the metasediments, and the borders of granite masses conform to the outlines of the leptite formation. The "simplicity" of the structural pattern is deceptive, for at many places within the leptite formation one can see steeply plunging, complex folds whose axes trend nearly parallel to the regional strike of the units. The limestones alone, because of their high degree of plasticity during deformation, have assumed remarkably irregular forms within the leptite. At least one major transverse fault has cut the leptite and granite west of Falun (Geijer, 1917, pp. 18-20). Thus it is evident that the geologic setting of Falun is similar to that of the Andover and Sulphur Hill mines, and other parts of the New Jersey Highlands.

We may now consider the central Swedish sulfide deposits that occur as replacements of carbonate rock or its derivatives. Of the six types of deposits listed by Geijer (1917, p. 305), only two (his numbers 5 and 6) are characteristically found with garnet skarn. The ore of type 5 usually consists of sphalerite and galena. Some of the galena is argentiferous, containing 0.015 percent Ag at the Kallmora silver mine, Västmanland, according to Beck (Geijer, 1917, p. 238). Magnetite, chalcopyrite, and arsenopyrite are fairly common constituents, and the first two are true ore minerals locally. Pyrite and pyrrhotite are occasionally present. The sulfides are usually in garnet-hornblende-fluorite skarn, though they may also replace limestone directly. In type 6 either chalcopyrite or sphalerite predominates and is accompanied by andraditic garnet, hedenbergitic pyroxene, and fluorite (Geijar, 1917, pp. 225-242 and 305). At Yxjö, Västmanland, where chalcopyrite was formerly sought, scheelite and molybdenite are found locally. The scheelite has recently been mined on a modest scale (Magnusson, 1940, p. 171).

Though all the ore bodies are in skarn or limestone, minor amounts of disseminated sulfides (pyrite, chalcopyrite, sphalerite) are found in leptitic gneiss, quartzitic rocks, and associated rocks(Geijer, 1917).

[1] *Leptite* is a term used by Fennoscandian geologists for some widespread, very old, fine-grained rocks that they interpret to be metamorphosed "supracrustal" volcanics. These are the principal members of the *leptite formation*, which also cotais metamorphosed limestone and dolomite, skarn, amphibolite, quartzite, and biotite gneiss.

The sphalerites from central Swedish skarn deposits (Gabrielson, 1945, pp. 24-25, 30-31) are relatively high in Fe and low in Co, Ga, an In. The content of Mn and Cd is appreciable. Germanium is absent. Sphalerites from Fe-rich skarns (Geijer's types 5 and 6) have 11.6 to 19.5 percent Fe in contrast to the 8.0 to 8.3 percent Fe in sphalerites from light-colored skarns (Geijer's types 2 and 3). The Fe content of the analyzed sphalerites is due partly to slight contamination from associated or exsolved Fe-bearing minerals but also to substitution of Fe^{++} for Zn^{++} within the crystal lattice. The behavior of Mn is similar to that of Fe.

Additional mineralogical features of the central Swedish ores need not be discussed, except for the manganiferous magnetite in the northern part of the Väster-Silvberg belt, Dalarna. Weibull (1884, p. 108) states that the mines had long been known for their lead and silver ores but in 1884 were worked principally for the manganiferous iron ores. The magnetite, which occurs with quartz, manganiferous calcite, and finebelite (Mn-bearing olivine), contains 1.23 to 6.27 percent MnO (Weibull, 1884, p. 110). Its composition, if not its paragenesis, is therefore comparable to that of ore from the Andover mine (Bayley, 1910, p. 82).[1] Manganiferous skarn-iron ores are a common type in central Sweden, but not all of them are so closely associated with large sulfide deposits as they are at Väster-Silvberg.

One of the most important reasons for considering the central Swedish sulfide deposits is to find out something about their structure. This is doubly difficult for us, first, because Swedish geologists have not often been able to get all the needed structural information on these complex deposits; second, because specific structural details are presented in Swedish and are rarely summarized in English or German. In the following notes, an attempt is made to abstract some of the structural information, in the hope that it will be representative and helpful, if not complete.

1. Replacement breccia of sphalerite and galena with fluorite-garnet-hornblende skarn in limestone. Dammberg mine in the Väster-Silvberg belt, Norrbärke parish, Dalarna (Geijer, 1917, p. 229).
2. Streaks and elongate bodies of sphalerite with local pyrite, chalcopyrite, and galena in tremolite-actinolite skarn. Garpen-

[1] Analyses of Andover ore cited by Bayley show a trace of 0.45 percent MnO. The samples, of course, do not represent pure magnetite, but mixtures of hematite, magnetite, and gangue. The inference is that at least some of the Mn was in the magnetite. Kent's old analyses (Kitchell, 1855, p. 40) show considerably more Mn in the ore —3 to 15 percent MnO (?). Some of this Mn may indeed have been in the form of carbonates and silicates, as Kent supposed for one sample. Secondary oxides of manganese, and manganiferous magnetite, may also have been present in some samples.

berg, Garpenberg parish, Dalarna (Geijer, 1917, p. 233).[1]

3. Flattened lenses of zinc ore on the sides and at the top of a magnetite body in hornblende-diopside skarn. In depth, the quantity of zinc ore increased in relation to the iron ore [questionable translation]. Some intermixture of iron and zinc ores locally. Ryllshyttan, Garpenberg parish, Dalarna (Geijer, 1917, p. 233).
4. Deposits of magnetite and sphalerite, accompanied by hornblende skarn, in a limestone layer that forms a plunging V-shaped fold. Mässings and Silver mines, north of Ryllshyttan, Garpenberg parish, Dalarna (Geijer, 1917, p. 233).
5. Deposits of sphalerite, galena, chalcopyrite, and magnetite controlled by a dominant lineation. Kaveltorp field, Ljusnarsberg parish, Västmanland (Magnusson, 1940, pp. 105-110).[1]

The ore bodies in the Kaveltorp field have been studied in great detail, and the information on their structure is particularly illuminating. The ore, found in several types of skarn, replaces parts of four principal limestone layers within the folded leptite formation. Flowage of limestone during deformation has resulted in rupture of the more brittle leptite interlayers, in places bringing together limestone layers that were originally separate. Most of the deformation preceded the development of skarn and ore. A prominent lineation—apparently a pencil structure—prevails in the mines down to about the 100-meter level; it plunges 28° ESE. This lineation controls the pinching and swelling of the limestone, thereby determining the pattern of the ore bodies. Where the lineation is nearly parallel to the strike of the rocks, rolls ("steps" are developed. Rich ore is generally found on the steps or flat parts of the rolls [where the limestone is thickened?— sense uncertain to translator], whereas the steeply dipping parts are leaner. Where the trend of the lineation makes a large angle with the strike of the rocks, the limestone and ore form a series of thick, elongated bulges or pods between which the limestone is greatly thinned. Thus in both types of lineation the ore bodies plunge parallel to the lineation in the country rock. At about the 125-meter level, the limestone layers generally pinch out completely or become so thin that they are no longer minable. At about the same depth the lineation is known to flatten and then reverse its direction of plunge, a phenomenon that Magnusson considers evidence of late deformation and relates to the intrusion of younger granites. Though he does not specifically state that the pinching out of the limestone is concomitant with the reversal

[1] This example belongs to type 2 of Geijer (1917, p. 305) but is included here because of its significant structure.

of plunge, one strongly suspects that to be the case. Magnusson does not say how extensively the operators prospected for another limestone "swell" below the first one, in the direction of plunge, on the assumption that the lineation might reverse once more and resume its east-southeast plunge.

Concerning the size of the central Sweden sulfide deposits, little information is available to the writers. Geijer (1917) and Magnusson (1940; 1950) give the depths of several mines in skarn-sulfide deposits. Their figures range from about 100 feet to 750 feet or more, an average of six being 450* feet. What "vertical depth" means in terms of "length of ore shoot" depends on the structure of the ore body.

A few small sulfide deposits in skarn are known in the Orijärvi region, Finland (Eskola, 1914). Eskola gives no data on the depth of these deposits. The important sulfide bodies are in cordierite-anthophyllite quartzite, as at Falun, Sweden.

Bergshantering 1946 (1948), the official statistical review of the Swedish mining industry, gives recent production data for some of the mines discussed in our résumé of the deposits of the central Sweden district. In 1946, the Garpenberg mine handled 60,887 metric tons of Pb-Zn-Cu ore and rock, of which 48,388 metric tons was considered concentrating ore. This apparently represents the greatest production of base metal ore from any single mine of the skarn type in the central Sweden district. Individual mines of other skarn-ore fields listed in the compilation produced less than 25,000 metric tons of concentrating ore apiece. The grade of ore is not given.

Data on the production and grade of the ore from some central Sweden deposits are given by Magnusson (1950, pp. 371-379). The ore at Garpenberg mine averages 5.2 percent Zn, 3.5 percent Pb, and 0.3 percent Cu; at Saxberget mine it averages 4.5 percent Zn, 3 percent Pb, and 0.9 percent Cu.

MINE DESCRIPTIONS

Sulphur Hill mine

The Sulphur Hill group of openings comprises three pits (the north, middle, and south or main pits), a partly filled shaft, a shallow rock cut, and three small openings south of the main pit. These workings are shown in plates 1 and 4. The three pits at Sulphur Hill mine are marked on plate 4.

North pit.—The north pit, about 5 to 15 feet deep, was entirely dry in the fall of 1949. It must be the most recent opening in the Sulphur Hill group, as it does not appear on the map accompanying the 10th Census Reports (Pumpelly, 1886, p. 152). At the southeast corner *(see pl. 4)* is a lens of medium-grade magnetite ore with a little pyrite and pyrrhotite in garnet skarn. The lens has a maximum thickness of 2 feet and extends northward for 5 feet before pinching out. Locally beneath the ore is a zone, several inches wide, with abundant pyrrhotite, some pyrite, and a trace of chalcopyrite in pyroxenic garnet skarn. The rest of the pit walls, where exposed, are skarn of garnet, pyroxene, or both. The skarn carries sporadic disseminated sulfides, including sparse chalcopyrite. A few stringers and patches of magnetite are visible on the north and west wall. At the north end, a small pegmatite dike has coarsened the skarn. The contact between skarn and hanging-wall amphibolite follows along the east side of the pit at the surface.

Middle pit.—The middle pit is 10 to 20 feet deep and has a water-filled shaft (?) at the north end. It corresponds to the northwest pit mentioned by Bayley (1910, p. 221) and reported by him to be on the northwestern or "back" vein. The outline of the pit is so irregular, and the scale of mapping so small for the complicated geologic structure, that it is exceedingly difficult to describe and interpret what the pit shows.

The walls of the north part of the pit are not accessible for mapping. Though ore may have been encountered here, it is equally likely that this area contained nothing but disseminated iron sulfides in a swollen anticlinal mass of garnet skarn cut by granite pegmatite. Scattered exposures of ore are confined to the south-central part of the pit *(see pl. 4)*. Magnetite with a variable amount of sulfides replaces several types of skarn and some silicated limestone. On the promontory 50 feet northeast of the southwest end of the pit, a 3- to 4-foot layer of medium-grade ore forms a partial (?) envelope or sheath about a rod-like mass of silicated limestone. Farther south, interlayers of leached skarn and ore form gentle anticlinal and synclinal warps whose axes are only a few feet apart. Scattered exposures of magnetite in the pit floor and along the east wall can be projected up the dip to meet, approximately, the exposures already noted. Possibly all the principal exposures of magnetite belong to an elongate warped and twisted body, locally disrupted to form lenses parallel to the lineation, which trends about N. 75° E. and plunges 20° to 25° ENE. The under side of this body outlines two narrow synclines and an anticline; the shape of the upper surface is unknown. The thickness of the body is probably 4 feet or less, though this is difficult to estimate because of the intricate structure and the odd way in which it is now laid bare.

Sulfides disseminated through skarn and magnetite ore include pyrite, pyrrhotite, and chalcopyrite. A little black sphalerite is visible locally. Some of the magnetite ore contains as much as 15 percent pyrite and several percent chalcopyrite. The reaction from oxidation of sulfides and leaching of calcium carbonate has yielded crusts of minute gypsum crystals that coat a part of the pit walls.

A folded amphibolite layer is enclosed within garnet skarn on the prominence southeast of the water-filled shaft (?) *(see pl. 4)*. This amphibolite appears to be one fragment of a layer severed by flowage of limestone before the limestone was converted to skarn. Pegmatite is closely associated with the amphibolite in several places.

South (or main) pit.—The workings at the main pit include the central opening, whose maximum depth is about 80 feet, an inclined cut at the southwest end, a haulage way roughly parallel to the inclined cut, and a dry tunnel, 130 feet long, that enters the pit from the southeast *(see pl. 4)*.

The pit was opened in the largest known skarn "pod" in the area. The "pod" has a synclinal bottom sharply ridged by minor anticlines, and an inferred anticlinal top. The ore occupied the central part of this pod. One or more layers of pyroxene gneiss and granite are infolded with the skarn, and relics of partly silicated limestone can be seen in several places. The skarn is mostly garnet-rich, but other types are also present. Locally, granite pegmatite cuts the skarn as dikes and masses. Some of these are broken by small transverse faults.

The upper 80 feet of the magnetite ore body has been mined out rather cleanly, except for a small block at the southwest end of the pit floor *(see pl. 4)*. Plunging podlike remnants of ore along the southeast wall of the inclined cut confirm the present writers' opinion that the ore body was a plunging shoot. From the few remaining exposures along the walls of the pit and the sloping cut, it appears that in plan the ore body was an elongate oval, possibly with a maximum width of 50 feet, but with an average width closer to 20 or 30 feet. Not all of this was even medium-grade ore, as a 10-foot parting of barren skarn splits the ore body in the block at the southwest end of the pit. At the northeast end of the pit thin layers of magnetite in the skarn and small, contorted masses, a few feet long and about 2 feet thick, may be the truncated ends of folds that plunge about N. 50° E. The average grade of the mixture is low, and this "ore" was probably at or near the top of the shoot. Because much of the pit floor is covered with broken blocks of rock and ore, it is impossible to check this inference.

The distribution of sulfides is particularly interesting. At the northeast and southwest ends of the northwest wall of the pit floor, nests of sphalerite and galena are visible in pyroxenic garnet skarn *(see pl. 4)*. Pyrrhotite and pyrite, as well as sporadic chalcopyrite and magnetite, are also present. There is considerably more sphalerite than galena, and the material constitutes zinc ore of good grade. The two exposures are probably part of the same layer, which is about 4 feet thick at the northeast end and more than 3 feet thick at the southwest. The layer's southeast wall—pyroxenic garnet skarn with sparse magnetite and sporadic pyrite—projects far enough into the pit to give a false appearance of separating the two exposures. The counterpart of the zinc-bearing layer has not been found along the southeast wall of the pit. Whether the layer is absent, or mined out, or represented by specks of sphalerite with pyrite in pyroxene gneiss is uncertain. At the northeast end of the pit, several small pockets of sphalerite are present with the magnetite masses, and at one place in garnt skarn several inches of calcite rich in galena can be seen.

Structure in the pyroxene gneiss swings abruptly from northeast to south-southeast at the inner mouth of the tunnel.

Combining the foregoing evidence with the writers' knowledge of the structure of the area, the writers now attempt to reconstruct the ore body, as follows: at the core of a podlike mass of skarn lies an elongate body of magnetite, trending about N. 50° E. and plunging 20° to 25° NE. The sides of this shoot are apparently smooth, and they dip steeply eastward. Very likely the top and bottom are irregular, conforming to, but not meeting, the ridged synclinal bottom and anticlinal (?) top of the enclosing pod of skarn. Indeed, the skarn "parting" seen at the southwest end of the pit bottom may be only an up-pushed "ridge" of unreplaced skarn. The top of the magnetite body frays out into isolated, small, contorted masses of magnetite that have replaced favorable, crumpled, rodlike (?) zones within the skarn. Sheathing the magnetite body and its sporadic sulfides is a thin zone of garnet skarn with scattered magnetite and pyrite, as well as local marble relics. On at least part of the northwest side of this sheath is a skarn zone, 4 feet thick, carrying considerable sphalerite with galena, pyrrhotite, pyrite, and a little chalcopyrite. Perhaps this zone is also sheathlike but is discontinuous and in places merges into the magnetite body.

Other openings.—A partly filled shaft, now 15 feet deep, lies 65 feet northeast of the northeast corner of the main pit, as shown in plate 4. The exposed rock walls are pyroxenic amphibolite and biotite-quartz-feldspar gneiss. The shaft was bottomed in ore, according to the sketch map in the 10th Census Reports (Pumpelly, 1886, p. 152).

A shallow cut, 45 feet northeast of the northeast end of the main pit (pl. 4), was excavated long ago for a tramway to one of the dumps (map, Pumpelly, 1886, p. 152). The only bedrock exposed is biotite-quartz-feldspar gneiss; the large blocks of garnet skarn that line part of the walls are not in place.

Two small shallow pits and a cut 50 feet long are found south and southwest of the main pit. All are caved.

Tar Hill mines

Openings in the Tar Hill area include three main pits at the northeast end and several scattered shafts and test pits. The main pits are described in order, beginning with PitTH-1 at the northeast end *(see pl. 2)*. The dumps have not been examined.

Reconnaissance dip-needle traverses, spaced 150 to 300 feet apart and oriented perpendicular to the strike, showed significant magnetic anomalies centered at Pit TH-2 and over the group of small pits lying 120 feet southwest of the road fork west of Pit TH-3.

Pit 1.—Pit 1, which is dry, is 10 to 12 feet deep. No ore is visible in the pit walls, which consist of garnet skarn with local masses of granite pegmatite. However, the skarn shows sporadic traces of magnetite and pyrite. The pit conforms to the elliptical plan of the anticlinal skarn mass, from which a podlike (?) body of ore may have been removed.

Pit. 2.—Pit 2 is a shallow cut, from the narrowest part of which a water-filled stope runs back for 20 feet under the northeast third of the trench. The depth of the stope is unknown. A cross section at the portal shows, from northwest to southeast: contact, highly contaminated granite over skarn, dip 50° NW.; 9 inches of magnetite "ore"; garnet skarn, locally pyroxenic, dip 15° NW.; 1 foot of magnetite "ore"; footwall not exposed. The magnetite, with considerable pyrrhotite, occurs in pyroxene skarn. The flattening of the dip at the southeast side of the portal indicates either a roll or the approach toward an anticlinal axis—perhaps the same axis that runs through Pit 1. The rest of the cut, where not caved, shows only microcline granite gneiss, the hanging wall of the skarn layer.

Pit 3.—Pit 3 is long; it is generally 10 to 15 feet deep, is water-filled for much of its length, and the walls are thus inaccessible. The only visible skarn is at the northeast end of the pit, on what appears to be the nose of a minor anticline. A little "rotten" magnetite ore is enclosed in this pyroxene skarn. How far southwest the skarn and ore extended is not known, but the water-filled opening may have contained ore, or at least skarn, which was followed and removed.

However, the accessible tops of the pit walls show only biotite-quartz-feldspar gneiss along the edges of the water-filled area. The same rock, directly underlain by pyroxene-feldspar gneiss, is exposed in the southwest third of the cut. The footwall side of the whole cut is undulatory, owing to gentle warps in the foliation.

Other openings.—Several small shallow pits, most of which are in skarn, lie west of Pit 3, near the road. The pit on the west side of the road and 50 feet south of the road fork contains a 2-foot layer of massive magnetite that is nearly vertical. The magnetite was stoped out to an estimated depth of about 15 feet, where the layer appears to flatten. The other pits appear to be in nearly barren skarn, although some ore may have been removed from a few of them.

Longcore mines

Openings in the Longcore area include five pits and small trench in the skarn zone and two long cuts and two tests pits in the "gneiss" at either side. These openings are numbered L-1 to L-7 on plate 2, with L-1 the farthest northeast. The dumps of the pits have not been examined. There is no magnetite of commercial interest in the pits, and pyrite is the only sulfide noted. Reconnaissance dip-needle work in the area failed to detect any significant magnetic anomalies.

Pit 1.—This pit was not visited by the writers. According to a New Jersey Zinc Co. map, it shows some garnet skarn and "ferruginous" pyroxene skarn.

Pit 2.—The floor of pit L-2 is water-filled, except for a thin strip at the north and south ends; the depth to water is 10 to 15 feet. On the east and north sides, the pit is rimmed with amphibolite, below which lies a mass of skarn with several granite pegmatite bodies. A 1-foot layer of high-grade magnetite "ore" is visible in the skarn at the north end of the pit. At the southern end magnetite stringers are present in skarn and, very sparingly, in granite pegmatite. The footwall skarn, which is predominantly garnet-rich, carries as much as 50 percent pyrite locally. Structures in the west wall and in amphibolite southwest of the pit indicate that the skarn mass is generally synclinal, though possibly podlike. Small drag folds outline an anticlinal skarn "spur" in the trench at the northeast end of the pit.

Pit 3.—Pit L-3, which is about 10 feet deep, has a water-filled shaft near the northeast end. Two stringers of low-sulfur magnetite "ore" one-half to 1 foot thick are present in pyroxene skarn in the pit wall at the southeast side of the shaft. They are overlain by pyroxene gneiss and underlain by garnet skarn. The rest of the exposed pit walls show garnet skarn with large masses of granite pegmatite. Sparse patches and stringers of magnetite occur in the pegmatite and in pyroxene skarn adjacent to pegmatite borders. The garnet skarn, which carries some pyrite locally, is cut by many close-spaced joints—possibly late "shears"—that give the rock a prominent pseudo-foliation dipping 45° SE. The general structure of the skarn mass appears to be anticlinal.

Pit 4.—Pit L-4 is 8 to 10 feet deep to water level and shows a 9-foot sulfide zone in garnet skarn. The zone carries 10 to 20 percent pyrite but no magnetite. Some pyroxene skarn and scapolitic (?) garnet skarn are also present. A think dike of syenitic pegmatite cuts the skarn on the northwest side of the pit.

Pit 5 and shallow trench.—A small caved pit. 10 feet in diameter and 4 feet deep, lies between Pit L-4 and the end of the road. Fifty feet south, a caved shallow trench shows a few inches of barren garnet-pyroxene-epidote skarn along its southeast side.

Openings outside the skarn zone.—A long cut *(L-6 on pl. 2)* is 15 feet deep; it begins 250 feet north of Pit L-3 and curves northeastward and northward for 300 feet. The cut passes through granite gneiss, quartzose gneisses, and amphibolite but fails to show any sign of skarn or mineralization. A very shallow caved test pit lies 45 feet beyond the southwest end of the cut.

A large drainage cut lies near the bend in the road southeast of Pit L-3. Presumably the tunnel at the north end of the drain connects with the shaft in Pit L-3. It was not explored, owing to lack of time. Perhaps this tunnel corresponds to the tunnel mentioned by Bayley (1910, p. 224) as belonging to the 'Tar Hill" exploration.

Andover mine

The Andover mine is 600 feet south of the main Sulphur Hill pit and is separated from it by a flat-bottomed alluvial valley *(pl. 1)*. The mine workings consist of the main pit, a large open cut 650 feet long, 50 feet wide, and 20 to 75 feet deep; two pits southwest of the main pit; several small pits on the hill northeast and east of the main pit; and some underground workings that extend beneath the hill at the northeast end of the main open pit. These workings are shown on plate 1. The open pits were examined by the writers, but the underground workings were inaccessible in 1949.

The Andover deposit was worked out before 1880, and only a few small pockets of ore remain. The floor of the main pit is mostly covered with muck, large rock boulders, and vegetation, and the northeast and southeast walls are mostly inaccessible. It was not possible, therefore, for the writers to determine fully the character of the deposit, so the following description is based partly on information recorded by Cook (1868, pp. 648-650) and Bayley (1910, pp. 79-83).

Main pit.—According to Cook (1868, p. 648) the main pit was mostly filled with ore. The hematite-magnetite ore occurred in several irregular shaped basins, the largest of which was in the northeast part of the mine. This basin is 200 feet long, 65 feet wide, and 85 feet deep. Presumably the deepest part of this basin is now marked by the pond at the extreme northeast end of the main pit *(see pl. 1)*. None of the ore is exposed, but country rock is exposed at the west and southwest edges of the pond. Biotite-quartz-feldspar gneiss and sheared pegmatite, which strike N. 27° E. and dip 70° E., are exposed at the west edge of the pond. Silicated marble is interlayered with these rocks at the southwest edge of the pond. The writers presume that biotite-quartz-feldspar gneiss was the wall rock for the deposit that occupied this basin. The ore in the basin consisted of a mass of magnetite in garnet skarn (blue ore) which was completely surrounded by hematite (red ore) (Cook, 1868, fig. on p. 647; p. 648). This body of ore probably plunged northeastward beneath the floor of the pit, and the magnetite ore was mined to a depth of about 50 feet below the pit floor in the stopes at the northeast end of the mine (middle stopes). The southeast wall of the main pit in this part of the mine is about 70 feet high, is vertical, and is marked by a fault with prominent slickensides *(see pl. 3b)*. At the crest of the wall biotite-quartz-feldspar gneiss is exposed. The gneiss strikes N. 30°-40° E. and dips 75° E. to vertical; fluting and mineral lineation plunge 28° N. 42° E. At the northeast end of the main pit, at the surface, the biotite-quartz-feldspar gneiss is crumpled into tight folds that plunge 28° N. 45° E.

Cook (1868, p. 648) states that a longitudinal rock ridge separated the large ore basin described above from a smaller and shallower basin along the northwest side of the main pit. In the northwest basin high-grade black crystalline hematite ore is exposed locally along the floor and the northwest wall. On the east side of the small pond in this basin magnetite breccia is exposed. The breccia, which is composed of irregular fragments of magnetite in a chloritic and limonitic matrix, was formed by brecciation of magnetite ore.

The rocks along the northwest wall of the main pit in this part of the mine are sheared and highly altered, and locally are mylonites. In places a pink feldspathic rock is recognized that may be altered biotite-quartz-feldspar gneiss. To the southwest, the pit wall is predominantly mylonite with local breccia. Locally diabase dikes, generally less than 3 feet thick, are exposed. On the west side of the underhand stopes near the southwest end of the main pit *(see pl. 1)* coarse-grained white marble and calcareous pyroxene-garnet skarn were locally observed. The remnants of ore in these stopes are low- to medium-grade hematite.

Pits at southwest end of Andover mine.—The two pits at the southwest end of the Andover mine are about 20 feet deep and contain sparse remnants of nonmagnetic hematite ore. A thin diabase dike occupies the fault zone that separates the pits. A small body of brecciated, leached, and altered garnet skarn is exposed at the southwest end of the west pit.

Other openings.—There are several small openings on the hill slope northeast of the main Andover pit, as shown on plate 1.

The northeast-trending pit 250 feet northeast of the face of the main Andover pit is a shallow cut that exposes a thick breccia zone, probably the northeast continuation of the fault zone exposed along the northwest wall of the main pit *(p. 30)*. The rocks in the walls of the pit are completely altered. Sparse graphite is disseminated through the altered rock. Magnetite breccia is locally exposed.

A shallow northwest-trending pit is located 50 feet northeast of the pit described above, at the base of a nearly vertical slope about 30 feet high. Two small pyroxene skarn pods that contain sparse pyrite are exposed along the north wall of the pit. The westernmost skarn pod is enclosed by biotite-quartz-plagioclase gneiss; the eastern pod is in pyroxene-feldspar gneiss.

Two pits, 100 and 200 feet southwest of the above-described pit *(see pl. 1)*, were opened on small garnet-pyroxene skarn bodies that plunge northeast. Both skarn bodies contain thin seams of magnetite and sparse disseminated pyrite.

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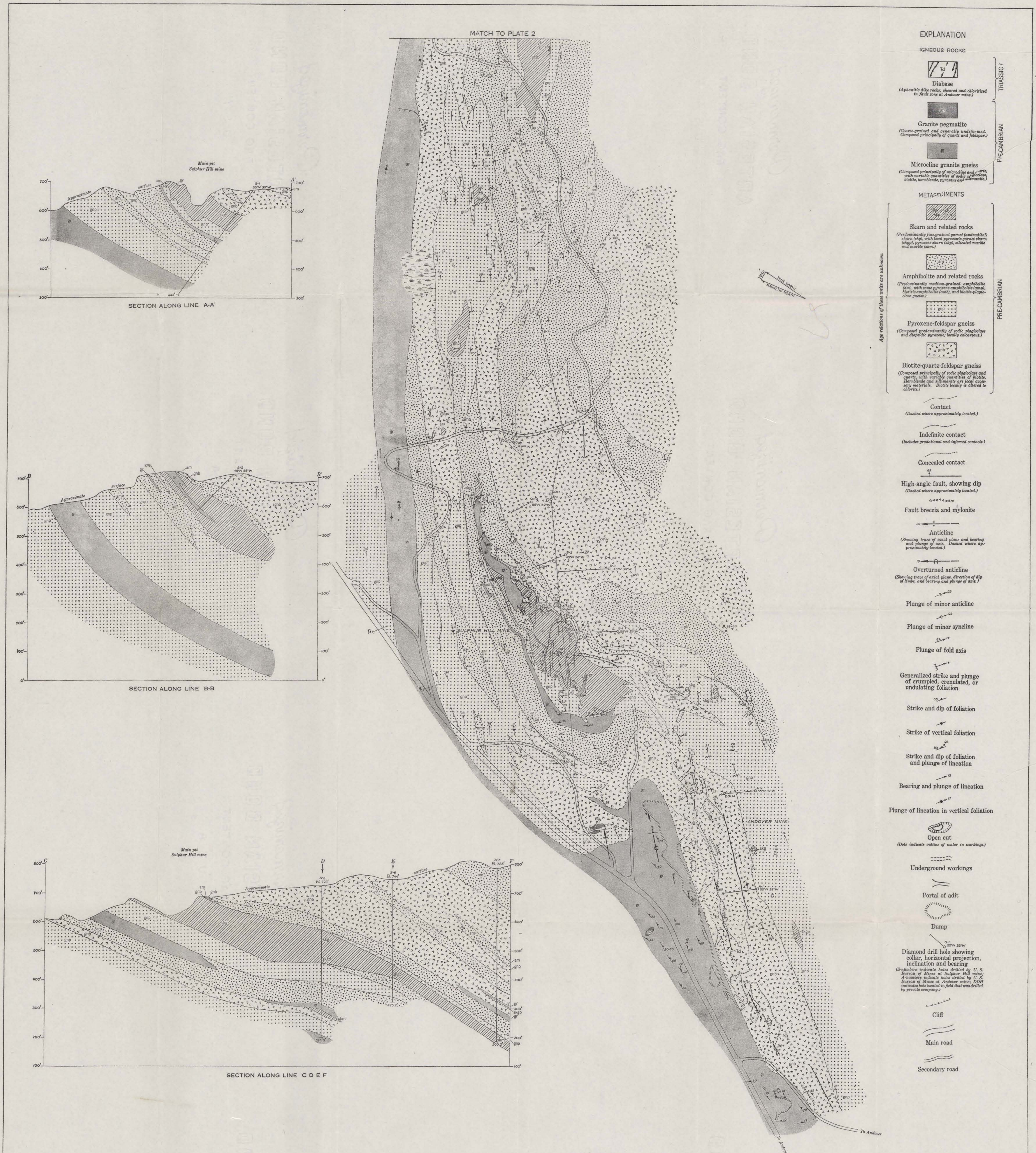

Base map by New Jersey Zinc Co. with additions by P. K. Sims

Geology by P. K. Sims and B. F. Leonard
U. S. Geological Survey-1949

PLATE 1.—GEOLOGIC MAP AND STRUCTURE SECTIONS OF SULPHUR HILL AND ANDOVER MINES, SUSSEX COUNTY, NEW JERSEY

Datum is assumed

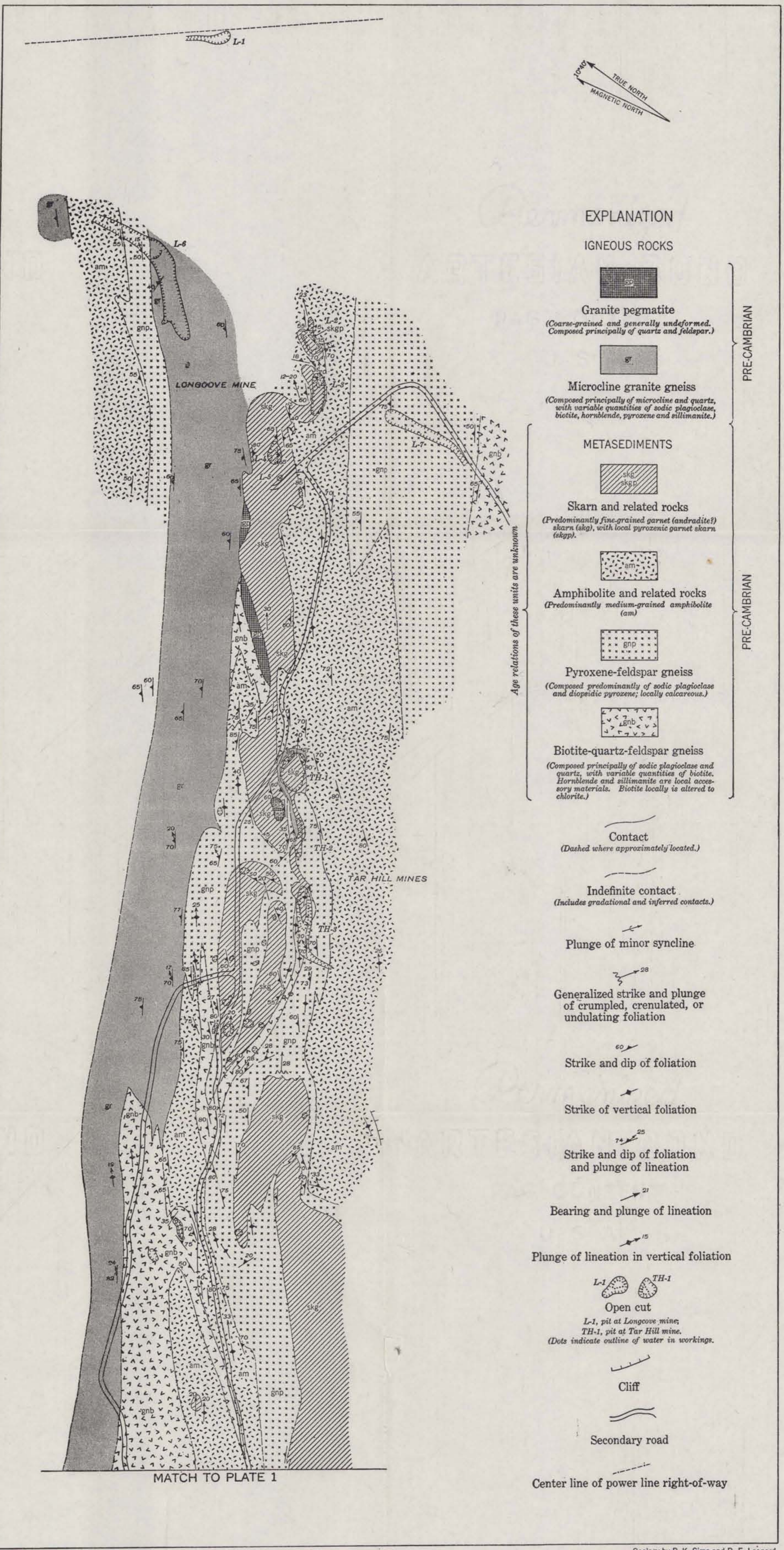

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PLATE 2.–GEOLOGIC MAP OF THE TAR HILL AND LONGCORE MINES, SUSSEX COUNTY, NEW JERSEY

100 50 0 100 200 300 400 Feet

Datum is assumed

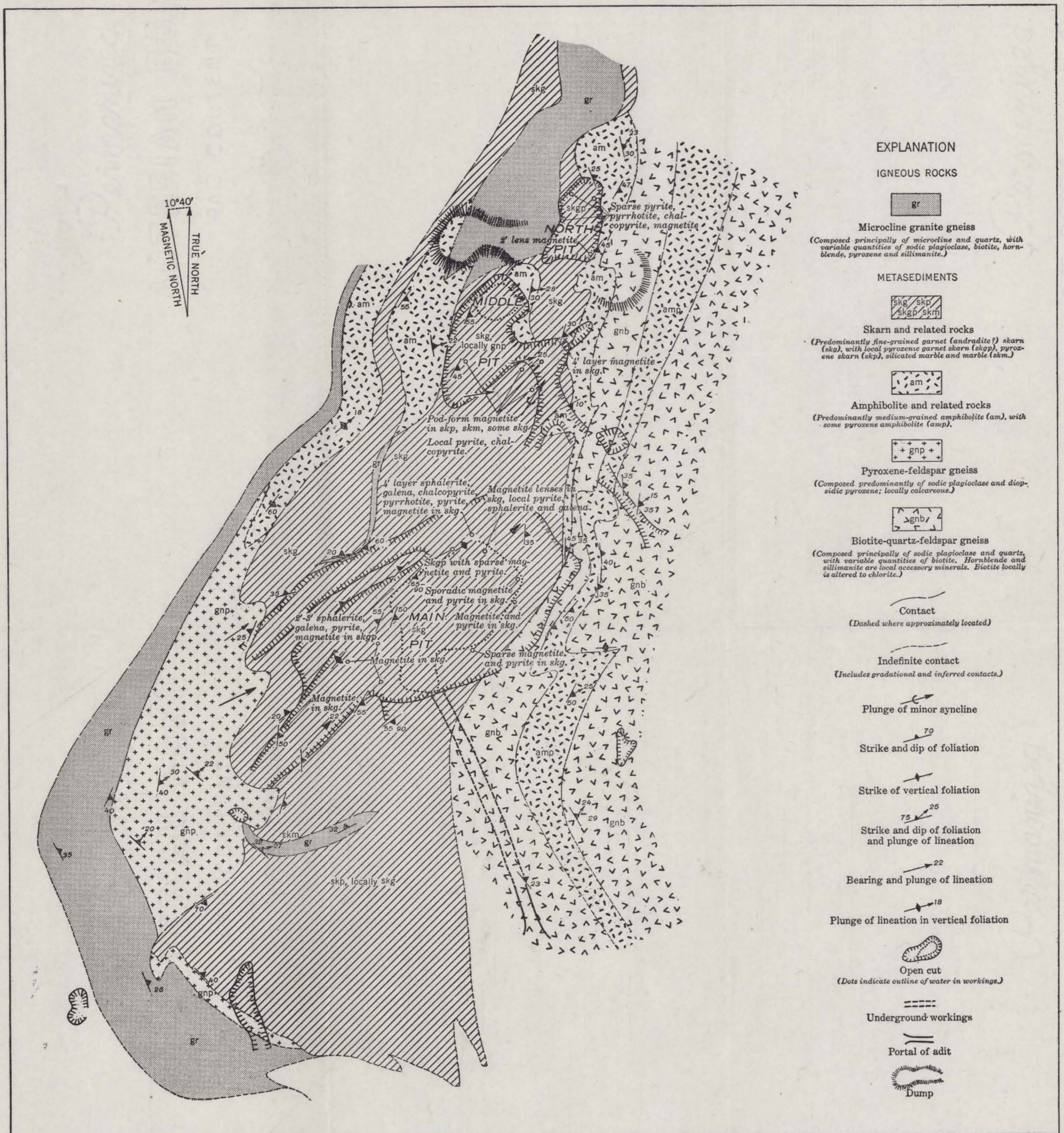

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PLATE 4—DETAILED GEOLOGIC MAP OF SULPHUR HILL MINE, SUSSEX COUNTY, NEW JERSEY

50 25 0 50 100 150 200 Feet

Datum is assumed