UNITED STATES DEPARTMENT OF THE INTERIOR
Oscar L. Chapman, Secretary

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W. E. Wrather, Director

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DRILL-HOLE CORRELATION AS AN AID IN EXPLORATION OF MAGNETITE DEPOSITS OF THE JERSEY HIGHLANDS NEW YORK AND NEW JERSEY

BY

H. E. HAWKES AND P. E. HOTZ

Contributions to economic geology, 1947
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DRILL-HOLE CORRELATION AS AN AID IN EXPLORATION OF MAGNETITE DEPOSITS OF THE JERSEY HIGHLANDS, NEW YORK AND NEW JERSEY

By H. E. Hawkes and P. E. Hotz

ABSTRACT

Detailed studies of diamond drill cores from four magnetite deposits in the pre-Cambrian gneisses of the Jersey Highlands, New York and New Jersey, show that the gneisses adjoining the ore-bearing zones comprise pseudostratigraphic units of differing composition. These units are recognized in field examination of drill cores by (1) the relative proportion of dark to light minerals and (2) the presence of indicative mineral species as a basis for setting up characteristic units. The logging of the core is facilitated by the use of a tabular chart. After the logging of the core and determination of true thickness of the layers by measurement of the angle between the core axis and the foliation or layering of the gneiss, a graphic log showing the distinctive units on a true-thickness scale is prepared. The graphic logs of adjoining drill holes are then compared to determine the correlation of stratigraphic sections. Detailed studies of the stratigraphy and structure as revealed by drill cores give a much more nearly complete picture of the mode of occurrence of the ore than is otherwise possible, and when used as a guide in exploration they may save a considerable footage of drilling that would otherwise be wasted.

INTRODUCTION

Renewed exploration of the magnetic deposits in the pre-Cambrian rocks of the Highlands of southeastern New York, New Jersey, and Pennsylvania has recently been stimulated by wartime demands for additional sources of iron ore and by changes in the status of grade and reserves of Lake Superior ores. Old properties that have been inactive for many years are again being explored, both as war projects by the Bureau of Mines, United States Department of the Interior, and as long-term potential sources of ore by some of the major steel companies. Under the national strategic minerals program, the Geological Survey has been reexamining the general geologic environment of the ore deposits with special emphasis on principles of structural control that might be applied to future exploration problems.

As work is still in progress, this report is of a preliminary nature only.

B. F. Leonard, of the Geological Survey, logged the core and made the geologic interpretations at the Red-back property. The program has been under the general supervision of A. F. Buddington.

The data used in the present report were compiled from detailed geologic logging of core representing a total of 14,398 feet of diamond drilling at the Croton Magnetic Iron mine, Putnam County, N. Y., the Red-back prospect of the Sterling Group, Orange County, N. Y., and the Turkey Hill and Swayze mines near West Portal, Hunterdon

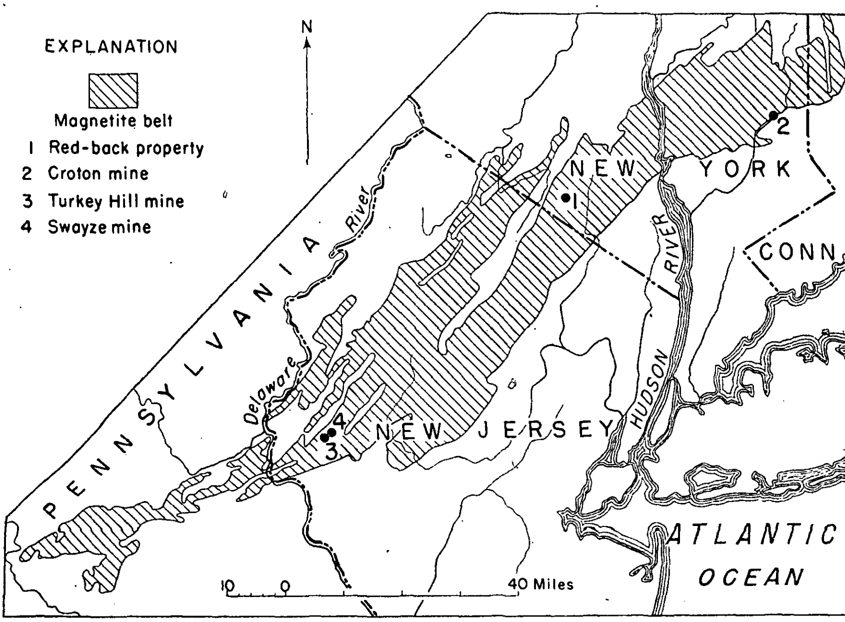

FIGURE 1.—Index map showing outline of pre-Cambrian magnetite belt in New Jersey and adjacent States.

County, N. J. (See fig. 1.) The Croton mine was drilled by the Bethlehem Steel Co., and the others by the Bureau of Mines.

ACKNOWLEDGMENTS

The writers wish to express acknowledgment to Mr. Hugh Park, of the Nipissing Mining Co., for permission to examine the Croton core and to publish the resulting data; and to the Bureau of Mines for permission to publish the results of the Red-back, Turkey Hill, and Swayze investigations.

PROBLEM

Most mining men familiar with the pre-Cambrian gneisses of the Jersey Highlands have recognized a general layered structure in the rocks. Not only are the ore bodies confined to fairly well defined tabular zones or "veins", but in many places the gneiss country rock also gives the appearance of inter-layered alternating zones of contrasting rock types. This feature is so conspicuous that the gneisses were regarded by early writers [1] as the product of metamorphism of a great series of stratified sedimentary rocks. This view has been opposed by more recent workers [2] who consider that the gneisses are largely igneous in orgin and that the stratiform appearance is the effect of deformation in injection. Because of the prevalence of the theory of igneous origin, the stratiform character of the gneisses and its possible application to exploration problems have in recent years been largely overlooked. However, regardless of its origin, a stratiform habit of the gneiss country rock, at least in some described areas, has been reported as an observed fact.[3]

Magnetite deposits in the Jersey Highlands commonly are restricted to more or less definite zones. If a succession of rocks adjoining the ore-bearing zone can be established in a given area, the exploration engineer can tell from an examination of the core already drilled how much farther he must drill to reach the ore-bearing zone and when to stop after passing through it. Also in faulted and folded areas, the development of a more accurate picture of the structure of the ore body will be facilitated. These and many other applications of stratigraphic methods would contribute toward a better understanding of the geology and consequently to a more efficient use of funds for exploration.

Before stratigraphic methods can be applied in the solution of exploration problems, the existence of a definite succession in the gneiss adjoining a magnetite deposit must first be demonstrated by careful and detailed mapping or by examination of cores from the first holes drilled. Then a practical and generally applicable method for identifying and correlating the successions must be developed.

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[1] Rogers, H. D., Description of the geology of the State of New Jersey, a final report, New Jersey Geol. Survey, p. 13, 1840. Kitchell, William, New Jersey Geol. Survey, 2d Ann. Rept., for 1855, p. 131, 1856. Cook, G. H., Geology of New Jersey, New Jersey Geol. Survey, p. 44, 1868. Britton, N. L., and Merrill, F. J. H., New Jersey Geol. Survey, Ann. Rept. for 1885, p. 36, 1886.

[2] Nason, F. L., New Jersey Geol. Survey, Ann. Rept. for 1889, pp. 54-56; questions sedimentary origin of gneisses but does not actively support igneous origin. Spencer, A. C., U. S. Geol. Survey Geol. Atlas, Franklin Furnace folio (no. 161) p. 8, 1908. Bayley, W. S., Iron mines and mining in New Jersey; New Jersey Geol. Survey, Final Rept. Ser., vol. 7, p. 126, 1910. Bayley, W. S., U. S. Geol. Survey Geol. Atlas, Passaic folio (no. 157) pp. 5-6, 1908. Berkey, C. P., and Rice, Marion, Geology of the West Point quadrangle, N. Y.: New York State Mus. Bull. 225-26, p. 110, 1921. Fraser, D. M., in Miller, B. L., Northampton County, Pa., Geology and Geography; Pennsylvania Geol. Survey, 4th Ser., Bull. C No. 48, p. 159, 1939.

[3] Wolff, J. E., The geological structure in the vicinity of Hibernia, New Jersey, and its relation to the ore deposits: New Jersey Geol. Survey, Ann. Rept. for 1893, pp. 359-69, with map, 1894. Westgate, L. G., The geology of the northern part of Jenny Jump Mountain in Warren County, New Jersey: New Jersey Geol. Survey, Ann. Rept. for 1895, pp. 21-61, with map, 1896. Bayley, W. S., U. S. Geol. Survey Geol. Atlas, Passaic folio (no. 157), p. 6, 1908.

GENERAL GEOLOGY

The belt of pre-Cambrian gneisses which underlies the Jersey Highlands extends in a northeasterly direction from eastern Pennsylvania through northern New Jersey into southeastern New York. (See fig. 1) The formations on the flanks of the gneiss belt are sedimentary rocks of Paleozoic and Mesozoic age. The pre-Cambrian complex includes medium-grained crystalline gneisses composed primarily of quartz, feldspar, hornblende, biotite, and pyroxene in varying proportions. Locally, marble and mafic mineral aggregates (skarn), interpreted as replacements of marble, are associated with the gneiss. The entire gneiss belt is characterized by layering and gneissic foliation which in general strikes uniformly northeast and dips southeast. Superimposed on this is a linear structure, indicated by the alignment of rod-shaped minerals and by axes of minor folds in foliation surfaces. The linear structure lies in the planar structure and is commonly inclined toward the northeast at gentle to moderate angles. The structural trends are amazingly uniform throughout the gneiss belt.

The stratiform character of the rocks appears very definite and undoubtedly reflects in some manner the past history of the gneisses—the primary composition and structure, and the type and degree of subsequent metamorphism.

The structure of the magnetite ore bodies that occur in the gneiss is intimately related to the structure of the adjoining country rock. The four deposits studied in detail for this report and, as far as can be inferred, most of the other deposits of the Highlands are localized within very definite layers or ore-bearing zones which are comformable with the structure of the country rock. Ore within the ore-bearing zones occurs as "shoots", which have the form of flattened and greatly elongated pods in which the short axis is normal to the plane of the ore-bearing zone and the long axis parallel to the linear structure of the enclosing gneiss. In some places the shoots may pinch down to negligible thickness or may terminate. Although these distinctive zones are the exclusive hosts for the ore shoots, magnetite is not always present in them, and the zones must then be identified by other lithologic or mineralogic features. (See fig. 2.)

Most of the local areas of mineralization in the Highlands apparently contain only one ore-bearing zone, though some of the larger mines have two parallel ore-bearing zones, each with its complex of individual shoots. In some areas the apparently random distribution of deposits has been interpreted as complex folding of a single ore-bearing zone.[4] One persistent pencil-shaped shoot is interpreted

[4] Nason, F. L., The geological structure of the Ringwood Iron mines, New Jersey: Am. Inst. Min. Eng. Trans. vol. 24, p. 509, 1895.

as a localization of ore on the axis of a fold.[5] The intimate relation of ore to certain definite layers of gneiss has been emphasized in almost all published descriptions.[6]

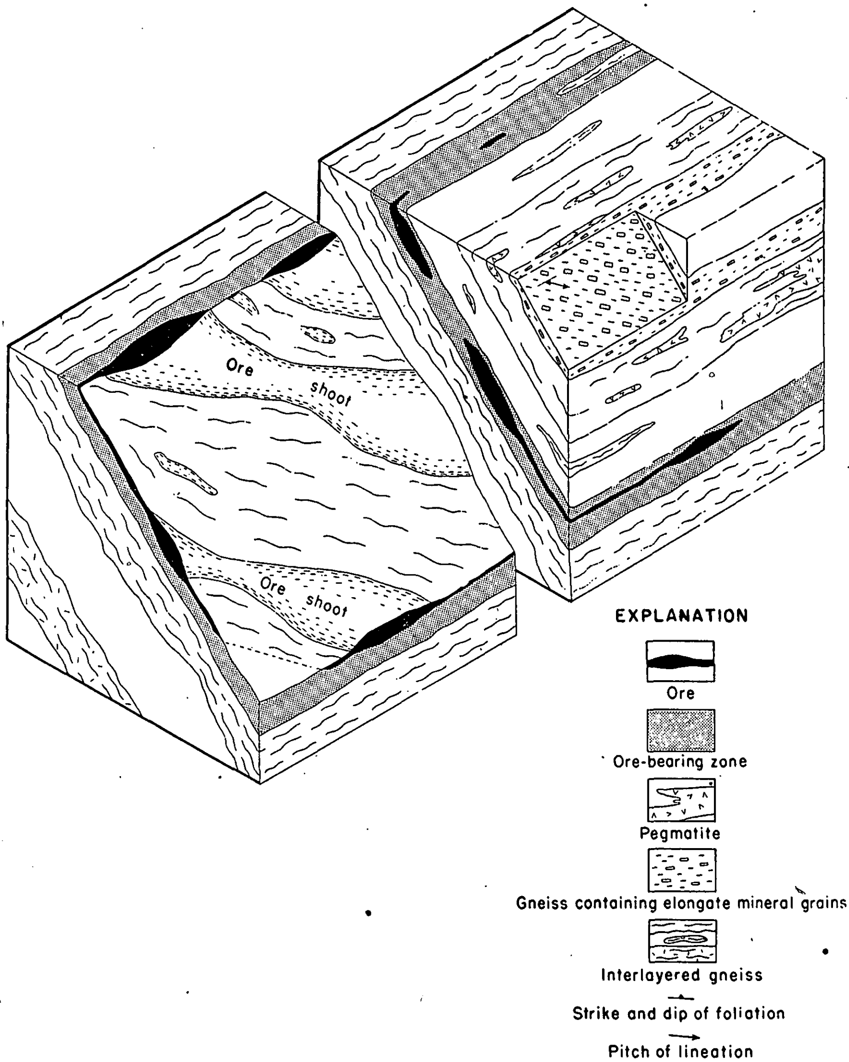


FIGURE 2.—Idealized block diagram showing structural relations of country rock to ore.

Little is known about the genesis of the iron ore. Modes of origin that have been advocated in the literature include metamorphism of bog ore, concentrations of magnetite sand, segregations of iron de-

[5] Colony, R. J., The magnetite iron deposits of southeastern New York; New York State Mus. Bull. 249–50, pp. 99–105, 1923.

[6] Colony, R. J., op. cit. Bayley, W. S., Iron mines and mining in New Jersey: New Jersey Geol. Survey, Final Report Ser., vol. 7, 1910.

rived from the metamorphism and subsequent redistribution of the components of basic igneous rocks, igneous injection of the ore as magma, and hydrothermal and pneumatolytic deposition.

ROCK CLASSIFICATION AND CORRELATION

Several widely divergent systems of classification for the Highlands gneisses have been proposed by workers in the field. The system that has received the widest acceptance is that sponsored by Spencer [7] and Bayley,[8] who divide the gneiss complex into three units depending on composition: (1) The potash-rich Byram gneiss, (2) the soda-rich Losee gneiss, and (3) the magnesia- and iron-rich Pochuck gneiss. The three gneisses, according to Bayley, are predominantly igneous, although the Pochuck may contain some metamorphosed sediments. The pre-Cambrian marble (Franklin limestone) is regarded as part of an older sedimentary series into which the gneisses were intruded.

Berkey and Rice [9] make somewhat similar division of the gneisses in their study of the gneiss belt in the West Point quadrangle, New York. Colony [10], in discussing the magnetite deposits of southeastern New York, accepts the classification of Berkey and Rice but points out the profound influence that the lithology and structure of the original sedimentary series had on the composition and structure of the later instrusions.

This system and classification—the threefold division of the gneisses and the separation of igneous and metamorphosed sedimentary rocks—is not well adapted to detailed geologic problems, such as drill-core logging and large-scale underground and surface mapping. A distinction between soda and potash feldspars in the field may be difficult and unreliable. A distinction between dark gneisses of igneous origin and rocks of similar appearance but of sedimentary origin is still more difficult. The most important objection to this classification is its failure to distinguish between certain variations in the mineral composition of the rocks that have proved to be reliable keys to the lithologic units.

The system which has been found most effective in logging drill cores is essentially a variation of Spencer's system in which some of his fundamental lithologic distinctions are retained, but where the use of rigid formational categories is avoided.

Two lithologic features have been found that are relatively persistent laterally and that can be used for identifying corresponding

[7] Spencer, A. C., op. cit., pp. 4–6.

[8] Bayley, W. S., U. S. Geol. Survey Geol. Atlas, Passaic folio (no. 157), pp. 4–6, 1908. Bayley, W. S., Iron mines and mining in New Jersey; New Jersey Geol. Survey, Final Rept. Ser., vol. 7, pp. 117–129, 1910. Bayley, W. S., U. S. Geol. Survey Geol. Atlas, Raritan folio (no. 191), pp. 7–9, 1914.

[9] Berkey, C. P., and Rice, Marion, op. cit., pp. 28–29.

[10] Colony, R. J., op. cit., pp. 39, 49–54.

layers in adjoining drill sections, namely, the relative proportion of dark to light minerals and the presence of indicative mineral species. The principal dark minerals rich in magnesia, iron, and lime are hornblende, biotite, and pyroxene, and the principal light minerals rich in silica, soda, potash, and alumina are quartz and feldspar. The diagnostic mineral species are diopside, garnet, and carbonates.

Correlations based upon a large number of other compositional and textural variations were tried and found to be unreliable, or at least inconclusive. A statistical study of the distribution and relative abundance of pegmatite in the drill core showed no correlation whatever with mineralization or with any particular rock type or unit. The presence of brown or black biotite, the ratio of hornblende to augite, and the presence of conspicuous sphene all failed to identify a given unit well enough to permit correlation between drill sections.

TECHNIQUE OF CORRELATION

The procedure given below for establishing unit correlation has been developed as a result of detailed geologic analyses of drill cores from the four properties studied. It will probably be subject to revisions, and the authors will welcome any suggestions for improvements.

The procedure may be outlined as follows:

1. Preparation of detailed geologic logs of the core.
2. Computation of the true thickness of the layers of the gneiss from the angles of foliation with respect to the drill core, whose inclination is known.
3. Preparation on separate strips of paper of a graphic log of the detailed geology of each hole, using a true-thickness scale.
4. Division of the graphic log into units that are characterized by some unique or predominant feature, such as distinctive rock type or mineral species.
5. Comparison of the graphic logs of adjoining holes to determine the correlation of stratigraphic sections.

GEOLOGIC CORE LOGGING

The descriptive system used in preparing the geologic logs involves only such features as can be seen with the naked eye. Although it lacks the precision of microscope analysis, it has the advantage of obtaining in the field practically all the information necessary for working out correlations. Features that can be determined adequately only with the microscope, such as the composition of the feldspars or the ratio of feldspars to quartz, are not used.

The task of core logging may be further simplified by the use of a tabular chart. (See chart, facing p. 8.) Longhand recording of detailed and complete geologic notes of drill cores is often exceedingly tedious. Without a constant reminder, such as is provided by the chart, some of the textural and compositional features that should be recorded in a complete description may readily be forgotten. Furthermore, significant changes in a rock sequence may be obscured in the confusion of a large number of notebook pages.

The chart, which may be prepared in mimeographed or printed form, contains spaces in which almost all the pertinent geologic data can be indicated by check marks or other simple forms of notation. Where longer descriptions are desirable, reference can be made to notes in the field book, although in actual practice this is rarely found necessary.

The descriptive terms and notation used in the chart are defined below in accordance with their usage in the present investigation. With some of the terms the special problems involved have made it desirable to diverge slightly from standard usage in the geologic literature. For example, "gneiss" is used for all nonpegmatitic silicate rocks containing less than 50 percent of dark minerals, regardless of whether the gneissic texture is well developed or not.

ROCK TYPE

The presence of a rock type is shown on the chart by a check mark. Where a given section is composed of thin layers of more than one rock type, figures inserted in the appropriate columns indicate the percentage of each type, the total percent being distributed over two or more columns.

Pegmatite.—Rock in which the minerals are coarse-grained, the grains frequently as much as an inch or more in diameter. Pegmatite in the Jersey Highlands is commonly composed of quartz and potash feldspar and minor amounts of dark minerals like those in the gneisses.

Light gneiss.—Rock that contains less than about 25 percent of dark minerals.

Dark gneiss.—Rock that contains more than about 25 percent of dark minerals, but less than 50 percent.

Mixed gneiss.—Rock showing alternating thin layers of more than one rock type. Where these rock types are markedly contrasting, individual descriptions of each component are recorded, and the percentage of that component rock type is entered in the proper column.

Amphibolites.—Typically a massive homogeneous hornblende-feldspar rock containing more than 50 percent and less than 85 percent of dark minerals.

Skarn.—Rock composed entirely or almost entirely of dark minerals, principally pyroxene but also to a lesser degree hornblende and biotite and locally garnet.

Marble.—Rock composed predominantly of calcite or dolomite.

Ore.—One of the above rock types that is estimated to contain magnetite in commercial quantities.

TEXTURE

Intermediate textures are indicated on the chart by checks in more than one column.

Pegmatitic.—Average diameter of crystals greater than 0.4 inch.

Coarse-grained.—Diameter between 0.15 and 0.4 inch.

PROPERTY Croton | HOLE 1 | LOCATION 18860 N. 17272 E. | BEARING N. 50° W. | LOGGED BY P.E.H.

PUTNAM COUNTY N.Y. | INCLINATION 60° | DATE 7/18/44

					Rock type								Texture: Grain size				Texture		Fabric and structure							Mineral content: Light		Mineral content: Dark												Mineral content: Secondary			Mineral content: Opaque					Remarks	Foliation	
Depth (in feet)	Feet drilled	Core recovered	Recovery (percent)	Rock unit	Pegmatite	Gneiss (light)	Gneiss (dark)	Gneiss (mixed)	Amphibolite	Skarn	Marble	Ore	Pegmatitic	Coarse-grained	Medium-grained	Fine-grained	Homogeneous	Inhomogeneous	Massive	Foliated	Lineated	Layered	Contorted	Schlieren	Sheared	Quartz	Feldspar	Calcite	Diopside	Hypersthene	Augite	Hornblende	Biotite (brown)	Biotite (black)	Garnet	Sphene	Apatite		Percent, dark minerals	Chlorite	Epidote	Weathering products	Magnetite	Pyrite	Pyrrhotite	Chalcopyrite	Notebook reference (No. and page)	Average foliation angle: 36° Computed dip: 84° SE.	Depth	Angle
132.0–136.0						✓							✓	✓			✓		✓							✓	✓				1	3				2			15						✓	✓			153	35
136.0–144.0				A			✓								✓		✓			✓	✓	✓	✓			T	✓				2		1						25				T	T	✓	✓		Lineation, parallel dip	156	30
144.0–146.0							✓								✓	✓	✓			✓	✓						✓				2		1						30										186	35
146.0–						40		✓						✓	✓			✓	✓							✓	✓									✓			3						T	T			192	40
–160.0							60	✓							✓		✓			✓						✓	✓		1				T			2			30						T	T		Pyroxene, dirty green	202	50
160.0–166.0										✓					✓		✓		✓								✓		1							2			85	?			T		✓	T	2-26	Pyroxene, dirty green	226	20
166.0–169.0		Core abridged: No data		B			✓							✓			✓		✓	(✓)							✓		1				T			✓			50						✓	✓			245	35
169.0–179.0							✓							✓	✓			✓	✓						✓		✓				✓		✓						40	✓				✓			2-26	Slickensided; seamed with chlorite	252	25
179.0–180.0						✓									(✓)		✓		✓							✓	✓							✓					8						✓				264	50
180.0–202.0							✓							✓	✓			✓	✓	(✓)		✓					✓		1				T			2			50	?					5					
202.0–204.0						✓									✓			✓		✓						✓	✓				1					2			3											
204.0–240.0						✓	✓								✓		✓		✓	(✓)		✓				✓	✓				1	2				3			20						T	T				
240.0–253.5				C			✓								✓		✓		✓	(✓)		(✓)				✓	✓				1	2				3			25				10			T				
253.5–255.0						✓							✓	✓	✓			✓	✓							✓	✓				2	3	1						3				T					Feldspars, pink		
255.0–266.0							✓								✓		✓		✓	(✓)						✓	✓				1	3	4			2			30				15							

HOLE 4: INCLINATION 75°, IN SAME CROSS SECTION AS HOLE 1

405.0–415.0							✓								✓	✓		✓	✓			✓	✓			✓	✓				2	1				3			20		✓		✓						420	45
415.0–438.0						✓	✓	✓							✓			✓	✓	✓						✓	✓				2	1				3			20										460	25
438.0–				A			50	✓								✓	✓			✓						✓	✓				2	1	✓			3			20		✓								488	15
					15			✓					✓				✓		✓							✓	✓								✓				T										522	50
–488.5						35		✓							✓		✓		✓							✓	✓				2	1				3			8									At 456', brown biotite instead of hornblende	560	25
488.5–501.0								✓							✓		✓			✓		✓				✓	✓				1	2				3			25						T	T			587	35
501.0–531.0							✓								✓		✓		✓	✓						✓	✓	✓	1			2				3			30	✓				T		T	2-28	Pyroxene, dirty green	595	0
531.0–540.0				B		✓									✓		✓		✓								✓	✓							✓				T	✓							2-28	Rock appears spongy because of leached calcite	600	60
540.0–565.0							✓								✓			✓	✓	(✓)							✓	(✓)	1			✓	✓			✓			35	✓				✓		T		Pyroxene, dirty green	610	15
565.0–613.0						✓	✓								✓		✓			✓		✓				✓	✓				1	2				3			25					✓		T			635	18
613.0–617.0							✓								✓	✓	✓			✓			✓				✓						1			✓			20					T				Pyrite in pyritohedrons	645	15
617.0–655.0				C		✓								✓	✓	✓		✓	✓	✓						✓	✓				1	2				3			15					T						
655.0–662.0							✓								✓		✓			✓							✓				1		2			✓			30					T	✓	T				

EXAMPLE OF DATA SHEET USED TO TABULATE CORE DATA, CROTON MAGNETITE MINE, PUTNAM COUNTY, N.Y.

(SEE TEXT FOR EXPLANATION)

735194 O - 47 (Face p. 8)

Medium-grained.—Diameter between 0.04 and 0.15 inch.

Fine-grained.—Diameter less than 0.04 inch.

Homogeneous.—Having uniform grain size.

Inhomogeneous.—Grain size varies locally within limits indicated in the grain-size columns.

FABRIC AND STRUCTURE

Fully developed features are indicated by simple check mark. Faintly developed feature of fabric or structure is indicated by a check mark enclosed in a circle.

Massive.—Showing little or no foliation or lineation.

Foliated.—Showing a planar fabric defined by planar orientation and distribution of dark minerals or by thin layers of different character.

Lineated.—Showing a linear fabric defined by orientation of elongate minerals, principally hornblende but to a lesser degree biotite.

Layered.—Composed of contrasting layers of half an inch or more in thickness.

Contorted.—Locally showing extreme changes in the attitude of the foliation or layering.

Schlieren.—Elongate masses containing conspicuous dark minerals in a lighter-colored matrix.

Sheared.—Cut by secondary schistose zones.

MINERAL CONTENT

The relative abundance of the various dark minerals is noted on the chart with numerals to indicate the order of abundance, the number 1 indicating the most abundant, the number 2 the next in abundance, and so on; accessory minerals are indicated by check marks, and minerals present only as a trace by "*T*". The following list of common minerals of the Highlands gneisses gives the features by which they may be most readily distinguished in hand specimens.

LIGHT-COLORED MINERALS

No attempt is made to indicate the relative abundance of quartz or feldspar; their presence is indicated by a check mark.

Quartz.—White to colorless, hard (scratches glass), distinguished from feldspar by lack of cleavage.

Feldspar.—Generally conspicuous cleavage; potash feldspar is white to salmon pink, soda-lime feldspar white to deep green or gray, and albite-twinning lamellae may be visible.

DARK-COLORED MINERALS

Calcite (including dolomite).—Soft; effervesces directly or in powdered form with dilute acid; commonly indicated by leached character of enclosing rock. Calcite is classified as a dark mineral because of its genetic relationship with diopside.

Diopside.—Color white, light gray, pale green, dirty green, or dull greenish gray; commonly occurs in rounded grains; distinguished from feldspar by "woody" appearance of cleavage surfaces and from augite by color. Color as a criterion for distinguishing diopside from augite is purely for convenience in field identification; microscope determination of some pyroxene here included with diopside shows that it should strictly be classed as augite.

Hypersthene.—Color tawny to brassy; otherwise similar in appearance to augite.

Augite.—Color uniformly deep green; distinguished from hornblende by its color and stubby crystal form, from chlorite by its greater hardness, and from diopside by color.

Hornblende.—Color commonly black; good cleavage; rodlike crystal form.

Biotite.—Easily distinguished from other dark minerals by its micaceous cleavage; both brown and black varieties apparently belong to the same continuous series, in which the shade of color is a reflection of variation in chemical composition.

Garnet.—Color pale pink to rose red; hard with rounded grain outlines; distinguished from sphene by absence of yellow or brownish color tinge and lack of diamond shape.

Sphene (titanite).—Color yellow to deep tan, in places shows diamond shape; distinguished from garnet by color and form.

Apatite.—In rounded to subrounded granules; clear, colorless to pale green; greasy fracture surfaces; distinguished from quartz and feldspar by greasy appearance.

Other dark minerals.—Rarely tourmaline (coal black; high luster; hard, brittle) and allanite (dark brown; commonly surrounded by alteration halos resulting from radioactive emanations) occur in pegmatites and quartz veins.

SECONDARY MINERALS

Chlorite.—Soft, deep green; flaky; commonly occurs in sheared zones and locally as an alteration product of augite or hornblende.

Epidote.—Occurs primarily as a secondary pistachio-green alteration in lime feldspars; also occurs in veinlets.

Weathering products (limonite, kaolin):—Indicated by brown staining, leaching, and softening of rocks in upper 100 feet of drill holes.

OPAQUE MINERALS

Where the mineral is present in significant quantities, the estimated percentage by volume is entered in the appropriate column; a check mark (√) indicates that it is present in minor quantities, and a *T* that it is present as a trace.

Magnetite.—Black, metallic luster; most readily identified by its magnetic properties.

Pyrite.—Color uniformly brassy; hard, brittle; nonmagnetic.

Pyrrhotite.—Color paler and more bronze-colored than pyrite; softer than pyrite; magnetic.

Chalcopyrite.—Color golden yellow with faint olive-green tinge; softer than pyrite.

DETERMINATION OF TRUE THICKNESS

The true thickness of the rocks penetrated in a drill hole can be determined, provided (1) that the strike and dip of the rocks are fairly uniform and (2) that the hole is straight or is one whose vertical deflection is known, and is directed normally to the strike.

In figure 3, if the dip of the rocks (*B*), as determined from measurements of the inclination of foliation or layering in local rock exposures, and the inclination (*A*) of the drill hole are known, the true thickness (*t*) of the section cut by the drill can be computed. The true thickness is the product of the drilled thickness (dt) and the sine of the angle

(C) that the foliation or layering makes with the axis of the core ($dt \sin C = t$). The angle may be determined by simple graphic construction, or, if two angles—dip of foliation and inclination of drill hole—are known, the unknown angle is 180° minus the sums of the known angles ($C = 180 - A - B$). This angle is referred to here as the "foliation angle".

In the absence of local rock exposures, however, the dip may not be accurately known and some alternative method of determining foliation angle must be sought.

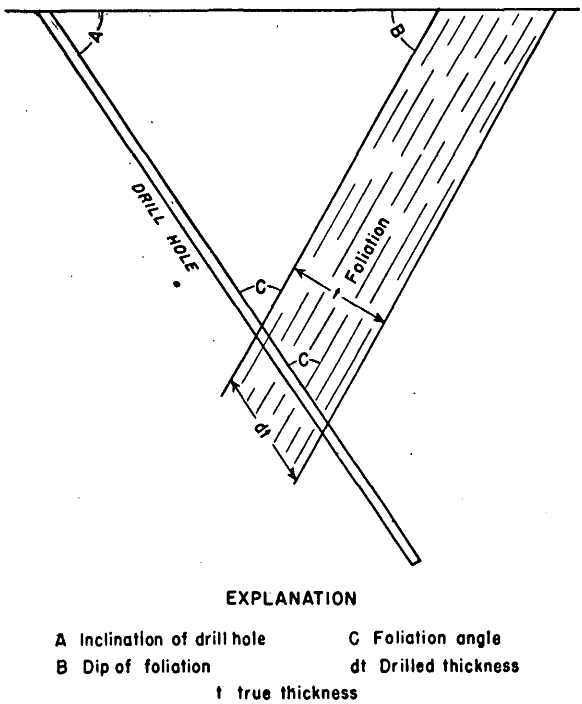


FIGURE 3.—Idealized vertical section showing relation between foliation angle in drill core and true thickness.

For that reason a special study of the Croton, Swayze, and Turkey Hill cores was made to determine whether direct measurements of the foliation angle with respect to the core axis in core specimens were reliable. This study showed that although individual observations varied widely, the arithmetic mean of a large number of dips computed from measurements of the core-foliation angle checked surprisingly well with the observed dips in rock exposures. With three exceptions the dip computed from directly measured foliation angles differed from the dip measured on rock exposures or on cross-sectional drill-hole diagrams by 10° or less. In most of the measurements the difference was less than 4°.

The following tables summarize these data:

Comparison of computed dip with observed dip of rocks in the Croton, Turkey Hill, and Swayze mines

Croton magnetic iron mine, Putnam County, N. Y.

Drill hole No.	Inclination of drill hole	Number of angles measured	Mean of measured angles	Computed dip
1	60° NW.	35	36°	84° SE.
2	45° NW.	32	55°	80° SE.
3	60° NW.	22	52°	68° SE.
4	75° NW.	48	29°	76° SE.
5	45° NW.	22	40°	85° SE.
6	45° NW.	22	50°	85° SE.
7	58° NW.	24	38°	84° SE.
8	60° NW.	27	39°	81° SE.
9	45° NW.	23	37°	82° NW.
10	65° NW.	67	33°	82° SE.
11	65° NW.	25	34°	81° SE.
Average of 15 dip observations in Theall Tunnel				82° SE.
Dip measured on diopside zone, section through drill holes 1 and 4				81° SE.
Dip measured on diopside zone, section through drill holes 7 and 10				85° SE.
Dip measured on diopside zone, section through drill holes 9 and 11				78° SE.

Turkey Hill property, Hunterdon County, N. J.

Drill hole No.	Inclination of drill hole	Number of angles measured	Mean of measured angles	Computed dip
8	90°	36	43°	47° SE.
9	90°	33	44°	46° SE.
10	60° NW.	33	70°	50° SE.
11	65° NW.	46	67°	48° SE.
Average of six dip observations on outcrops 3,000 feet southwest of drilled area				50° SE.
Dip measured on bottom of ore zone, section of drill holes 8 and 10				40° SE.

Swayze property, Hunterdon County, N. J.

Drill hole No.	Inclination of drill hole	Number of angles measured	Mean of measured angles	Computed dip
1	40° N.	57	47°	87° N.
2	45° N.	47	42°	87° N.
4	42° S.	8	53°	85° N.
5	60° S.	30	51°	69° N.
6	52° S.	28	48°	80° N.
Dip measured on north ore zone, section of drill holes 1 and 5				79° N.

PREPARATION OF GRAPHIC LOG

It may happen, as at the Croton and Red-back properties, that a grouping of layers into natural units will be directly observable from an examination of the tabular chart. This is illustrated by the sample tabular drill logs of drill holes 1 and 4 at the Croton mine where the limits of the diopside unit are indicated by the extent of diopside-bearing rocks.

In the Turkey Hill and Swayze drill cores, however, the identity of the various units was not immediately apparent from a cursory study of the geologic logs. Here, the details of the geology were plotted for each drill hole on individual strips of cross-section paper, using a true-thickness scale. Special symbols were used to indicate variations in the two diagnostic characteristics of the lithology—the relative proportion of dark to light minerals and the presence of diopside or garnet. The rock types tabulated at the Swayze and Turkey Hill mines were light gneiss and pegmatite, dark gneiss, and skarn, all of which could be conveniently represented by various symbols. Where individual members of the sequence were less than 2 or 3 feet thick, it was found impracticable to plot them separately, and a symbol for "mixed" gneiss was used. The presence of diopside was shown by a heavy line parallel to the lithologic section. Detailed graphic logs are illustrated in plate 1, A.

DIVISION INTO UNITS

In general, experience has shown that minor members of the gneiss sequence are not persistent laterally and cannot be positively identified in adjoining drill holes. The only exceptions were the 5-foot garnet-biotite gneiss layer, which appears in drill holes 1A, 2, and 3 at Red-back (pl. 2, A)—indicated lateral extent 1,500 feet—and the 4-foot marble bed below the ore zone at Red-back—indicated lateral extent 3,900 feet.

However, marker zones a few score to several hundred feet thick and composed of many minor layers occur at all the properties studied. In contrast to the component layers, these marker zones or units maintain fairly consistent thickness and lithology along the strike. The most persistent and reliable marker units contain either a diagnostic rock type, skarn or amphibolite, or a diagnostic mineral species, diopside or garnet. These units serve as keys to the rock succession and form the framework around which the rest of the sequence is built.

Once the key units have been delimited, the remainder of the section may be subdivided, if desirable. Further groupings may be made on the basis of variations in the relative proportion of light and dark gneiss. In many places a relatively sharp boundary may separate a section which is composed predominantly of dark gneiss from one that is predominantly light gneiss, and here the delimitation of the unit is relatively easy. Where the transition between dark and light gneiss is spread over an appreciable thickness, selection of the boundaries of the units is more difficult and to a certain extent arbitrary. Examples of both types of boundaries are represented on the Turkey Hill and Swayze diagrams. (See pl. 1. Upper boundaries of units B, E, and F, Turkey Hill sections.)

METHOD OF CORRELATION

Adjoining cores are now correlated by matching the graphic logs, with proper attention of course to the expected position of the various units inferred from geometric projections. Key units are first matched, and the adjoining units examined for similarities in thickness and lithology. If the correspondence is not good, a minor revision of the boundaries of the units or possibly a reexamination of the core may solve the difficulty. When this fails, the possibility of complication by faulting, folding, or lateral variation in metamorphic effects or original composition should be considered.

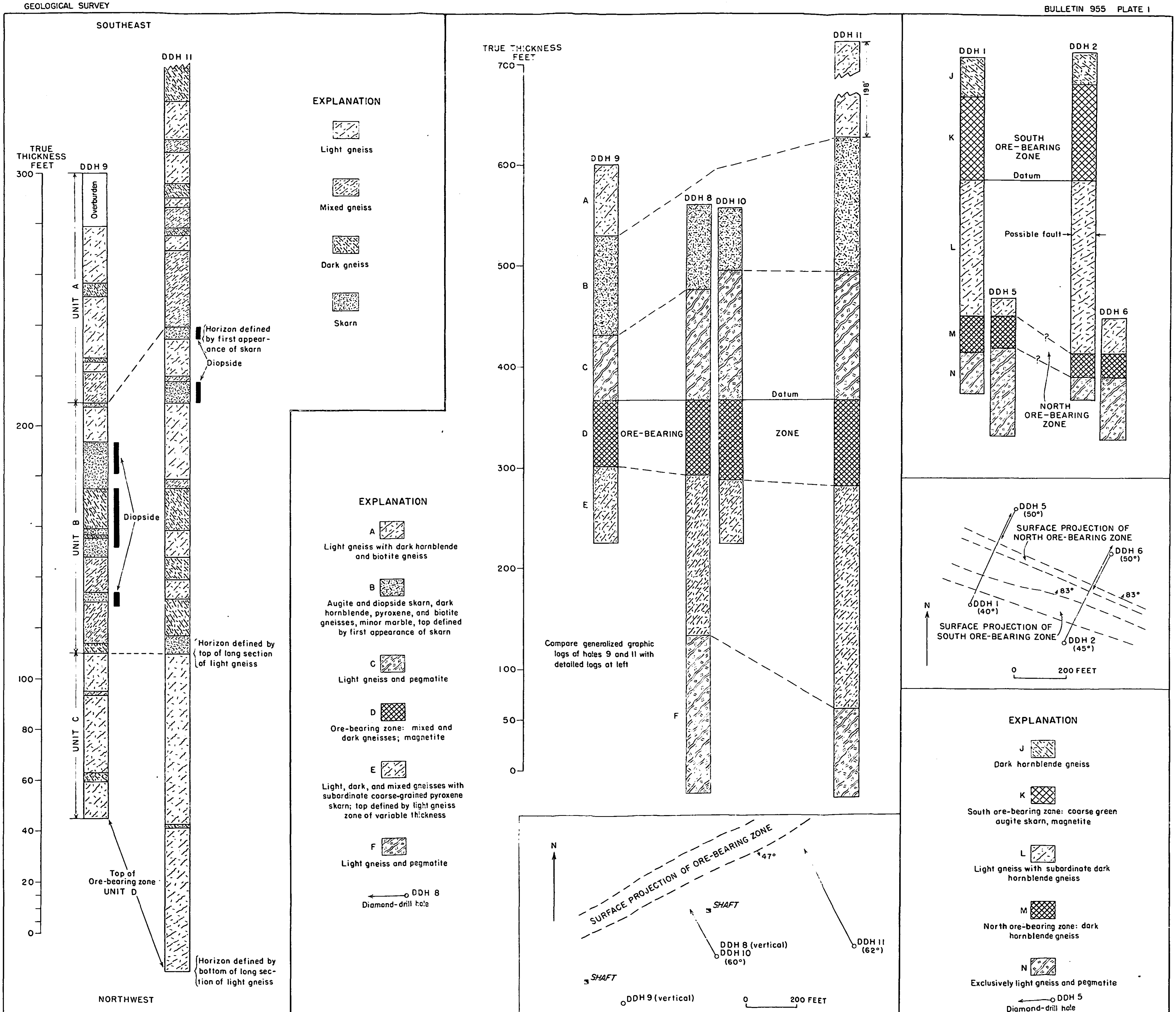
A forecast of the position of the ore zone in a hole where drilling is still in progress can be made if one contact of a key unit is identified and correlated with an adjoining drill section. This method was applicable at all four of the properties studied, as key horizons were penetrated above the ore zone in almost all the holes.

DETAILED DRILL-HOLE CORRELATION

The four properties studied do not, of course, represent all the types of gneissic structure and lithology which may be expected in the Jersey Highlands. In none of these areas is there much calcareous rock, and it is possible that a somewhat different structural environment will be found in the neighborhood of the magnetite deposits that occur in marble.

Sillimanite and graphite were not present in significant quantities in any of the cores examined. These minerals are known to be present in the rocks adjoining other magnetite ore bodies, and they may prove to be valuable, like garnet and diopside, as diagnostic minerals.

The four properties show certain notable contrasts. The Red-back area is the only one that contains garnet as a diagnostic mineral. Diopside may be found at both Croton and Turkey Hill as a diagnostic mineral, but is absent or nondiagnostic at Swayze and Red-back. The Croton section is composed predominantly of relatively dark gneiss, the Red-back section predominantly of light gneiss, and the Swayze and Turkey Hill sections of a complex interlayering of the two.



A. SAMPLE OF DETAILED LOGS, TURKEY HILL MINE

B. DRILL-HOLE CORRELATION, TURKEY HILL MINE

C. DRILL-HOLE CORRELATION, SWAYZE MINE

DETAILED LOGS AND DRILL-HOLE CORRELATIONS, HUNTERDON COUNTY, N. J.

Red-back magnetite property.—The geologic section at the Red-back property (pl. 2, A) differs from those of the other areas in the presence of "marker horizons," relatively thin layers in the sequence that can be identified in two or more drill holes. Conspicuous marker layers are a garnet-biotite gneiss layer (unit C) and a layer of marble beneath the ore zone (unit H). The other key units are characterized by garnet-bearing rocks (unit E), amphibolite (unit F) and skarn (the ore zone, unit G). The remainder of the sequence is built around this framework of marker layers and units.

The ore-bearing zone in all the drill holes contains local concentrations of magnetite, though in some of the sections only in negligible quantities. The ore apparently favors pyroxene skarn as a host, though some disseminated magnetite occurs in the marble.

Croton magnetite mine.—The principal key unit at the Croton property (pl. 2, B) is the diopside zone, unit B, which appears in the same position in all the holes for a strike length of 3,700 feet. Apparently the unit pinches or dies out south of drill hole 6, as it does not appear in drill holes 2, 3, and 5.

Unit D, predominantly light gneiss, adjoins the ore-bearing zone on the west side and provides a secondary key to the rock succession. In drill holes 2, 3, and 5, where the diopside zone is absent, the eastern boundary of unit D is the only distinctive horizon, as units A and C merge and are indistinguishable in the absence of the diopside zone.

The ore-bearing zone (unit C) is a thick zone of fairly uniform dark hornblende-pyroxene gneiss through which concentrations of magnetite are scattered without any system or control that could be determined. The barren parts of the zone are identical lithologically with unit A.

Turkey Hill mine.—Unit B, containing augite and diopside skarn with admixed dark and minor light gneiss, is the most distinctive unit of the Turkey Hill drill sections (pl. 1, B). Parts of this unit appearing in drill holes 8 and 10 have been subjected to intense secondary shearing and alteration, which have largely destroyed the original texture and appearance of the rock In drill hole 11 marble occurs with the diopside rock of unit B.

The top of the ore-bearing zone, unit D, is defined by a relatively abrupt change from the predominantly light gneiss of unit C to the predominantly dark gneiss of the ore-bearing zone. The bottom of the ore-bearing zone is marked by light gneiss of variable thickness separating it from unit E below. The separation is not well marked, as the general lithology of units D and E is somewhat similar. The contact of unit E with unit F is also indefinite, as it is marked only by a gradual transition from predominantly dark to predominantly light gneiss. The zone which contains the ore in drill holes 9 and 10 is barren however in drill holes 8 and 11, and would not have been recognized except for its appropriate position in the rock column.

Swayze mine.—Two ore-bearing zones may be found at the Swayze property (pl. 1, C). The south ore-bearing zone (unit K) is defined by an abundance of coarse-grained, deep-green augite skarn. The limits of the zone are well defined, as the adjoining units are devoid of this rock type. Small concentrations of magnetite occur in unit K in both holes.

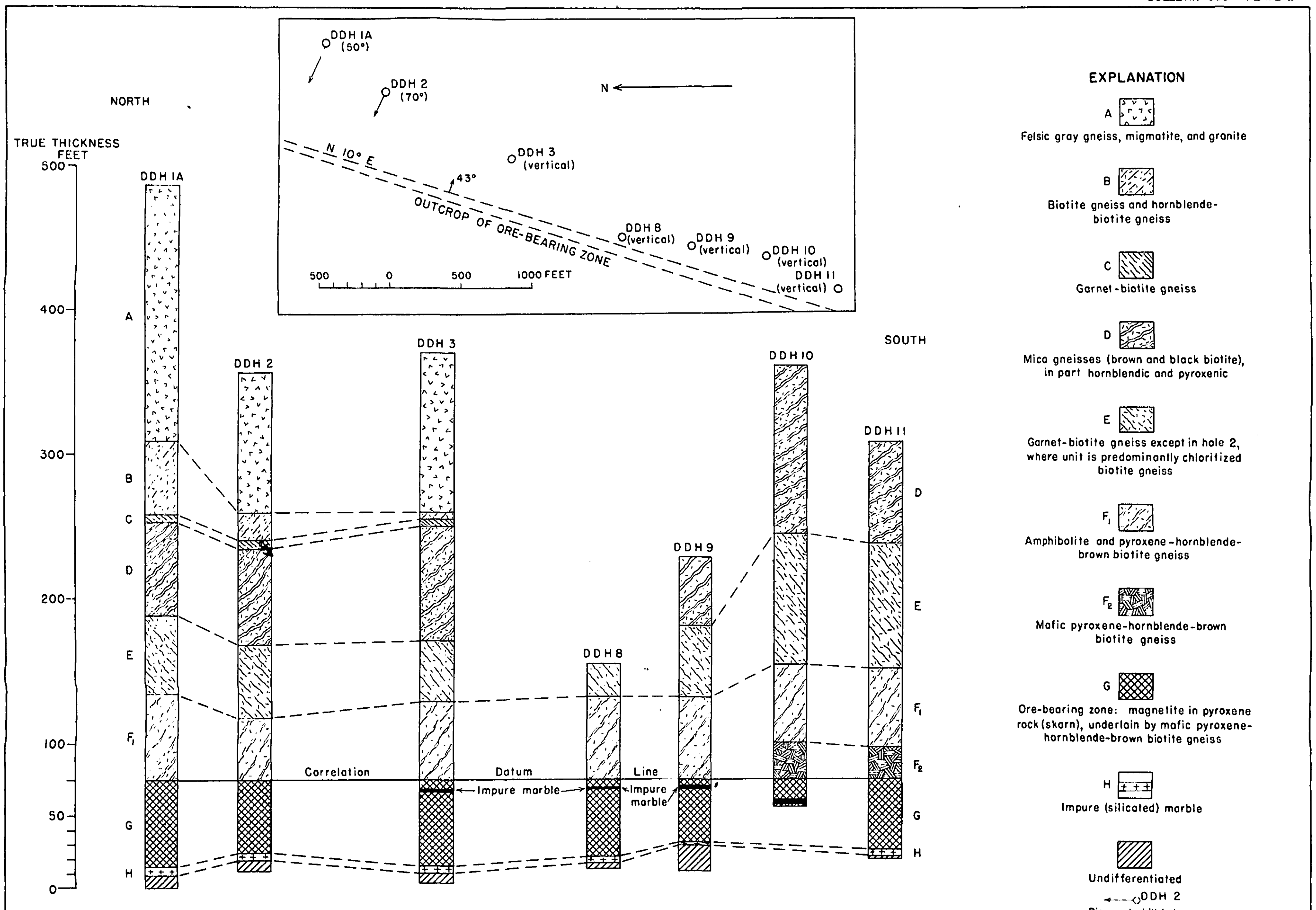
No ore was cut in unit M, but the identity of this unit with the north zone that contains the ore was inferred by its position with respect to the previously mined north ore body. It is not a distinctive unit, and the correlation shown in the diagram is highly speculative.

APPLICATION OF METHODS

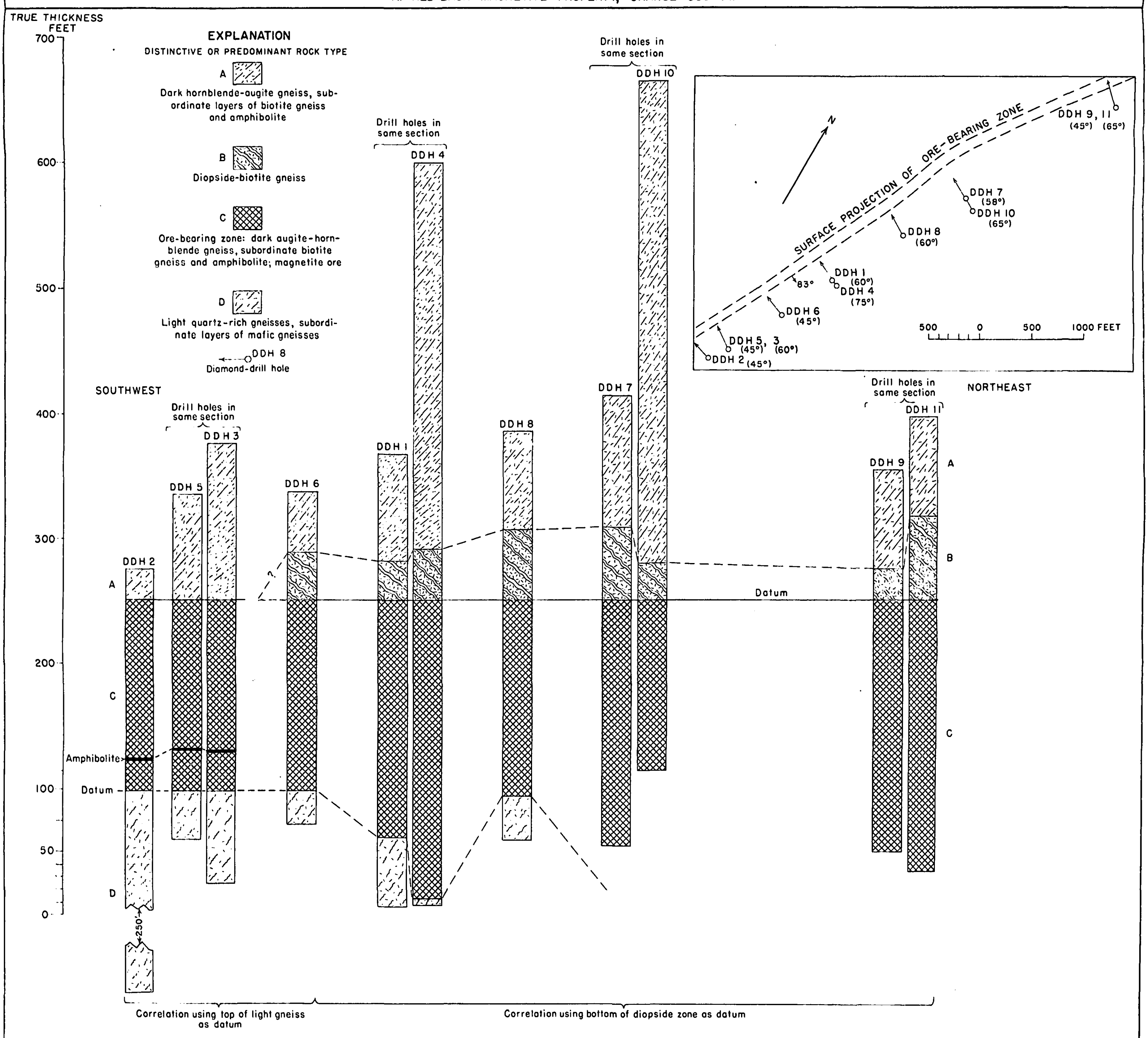
If the layered gneisses of the Jersey Highlands had few structural complexities and if local structural trends were completely known, the expected position of the ore-bearing zone could be accurately projected for any proposed diamond-drill hole. Unfortunately this is not generally possible. The application of stratigraphic methods has proved useful in more accurately predicting the position of the ore-bearing zone, as shown by the following examples.

When drilling at the Swayze property (pl. 1, C) began, there was considerable doubt as to the strike and dip of the ore structure. No bedrock is exposed within half a mile of the mine, and a determination of the strike of the ore by dip needle was not feasible because of artificial magnetic disturbances. The rocks exposed within a 5-mile radius uniformly strike northeast and dip 45° SE. Nevertheless, the old mine reports and the recollections of men who had worked in the mine indicated a northwest strike and a vertical to northeast dip. Holes 1 and 2 were drilled on the assumption of a northwest strike. Correlation of the distinctive lithology of unit K and compilation of foliation angles measured in the core specimens showed this assumption to be correct, barring the remote theoretical possibility of horizontal layering. As a result of the confirmation of the northeast dip by measurements of foliation angles in the core, subsequent drilling was laid out to approach the ore-bearing zone from the northeast rather than the southwest side.

At the Turkey Hill property (pl. 1, B), the badly sheared section in the upper parts of drill holes 8 and 10 suggested a cross fault. As the ore-bearing zone in drill hole 11 might be offset by the supposed fault, it was therefore desirable to ascertain from stratigraphic evidence where the position of the ore-bearing zone was to be expected. Identification of skarn-bearing unit B served to locate the relative position



A. RED-BACK MAGNETITE PROPERTY, ORANGE COUNTY.



B. CROTON MAGNETITE MINE, PUTNAM COUNTY

DRILL-HOLE CORRELATIONS, ORANGE AND PUTNAM COUNTIES, N.Y.

of the hole in the stratigraphic sequence, and the ore-bearing zone was penetrated in its normal position beneath unit B.

At the Red-back property (pl. 2, A) the expected position of the ore-bearing zone in drill hole 10 was determined by geometric projections from the surface and from adjoining drill hole 11. In the absence of a detailed analysis of the core, the drill hole was stopped a short distance below what was believed to be the bottom of the ore zone. Subsequent detailed geologic logging showed that the hole had not passed through the ore-bearing zone.

Stratigraphic logging is useful also in identifying the ore zone where it contains no magnetite to distinguish it from adjoining layers. Wasteful drilling in the barren footwall rock can be avoided when the ore-bearing zone is passed and no chance remains of finding more ore.

Naturally, every mineral deposit has a somewhat different environment and presents different geologic problems. However, an intelligent application of stratigraphic methods should help in solving many of those problems and in the long run save more than enough money to offset the time and trouble of making the correlations.

CONCLUSIONS

The following conclusions apply specifically to the four magnetite deposits that were studied in detail, but it may be reasonably inferred that similar conditions prevail at many other magnetite-bearing areas in the Jersey Highlands.

(1) The gneissic complex has a stratified character, and the magnetite deposits are restricted to certain layers.

(2) In general, the individual minor layers are not laterally persistent, but broader units comprising homogeneous groups of minor layers and containing a distinctive lithologic or mineralogic feature are persistent and can be used as stratigraphic horizon markers.

(3) In the absence of more reliable data and provided (a) the strike is known to be approximately normal to the drill section, (b) there is no complex folding, and (c) the course of the drill hole is known, a reasonably accurate determination of the dip of the gneissic foliation, layering, and ore structure can be obtained by taking closely spaced measurements of the foliation angle in core specimens and computing the dip from the average of those measurements in each hole.

(4) Detailed examinations of drill cores for systematic succession of lithologic units and for structure give a more nearly complete picture of the mode of occurrence of the ore than is otherwise possible, and when used as a guide in exploration may save a considerable footage of wasted drilling.

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