GEOLOGY OF THE ANORTHOSITE MASSIF IN CHESTER COUNTY, PENNSYLVANIA

Thesis by

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ABSTRACT

The major objectives of this study have been to distinguish any variation within the anorthosite and to determine its age relationship with the adjacent rocks.

Two distinct facies comprise the pre-Cambrian Honeybrook anorthosite: (1) a relatively pure anorthosite facies, and (2) a chilled border facies which is more mafic than the pure anorthosite facies.

Quartz-monzonite of pre-Cambrian age has enveloped and penetrated the Honeybrook anorthosite, causing severe alteration in the anorthosite and forming a hybrid rock.

The anorthosite is also intruded by a pre-Cambrian pegmatite dike. Metadiabase dikes of pre-Cambrian age cut both the anorthosite and quartz-monzonite.

The structure of the anorthosite is doubtful. The meager data suggests a possible domical body.

The primary magma yielding the anorthosite complex is assumed to have had the composition of gabbroic anorthosite. An upper chilled border of this composition developed. By gravity stratification during crystallization the mafic crystals settled to form gabbro and the plagioclase crystals remained suspended to form anorthosite.

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INTRODUCTION

Purpose

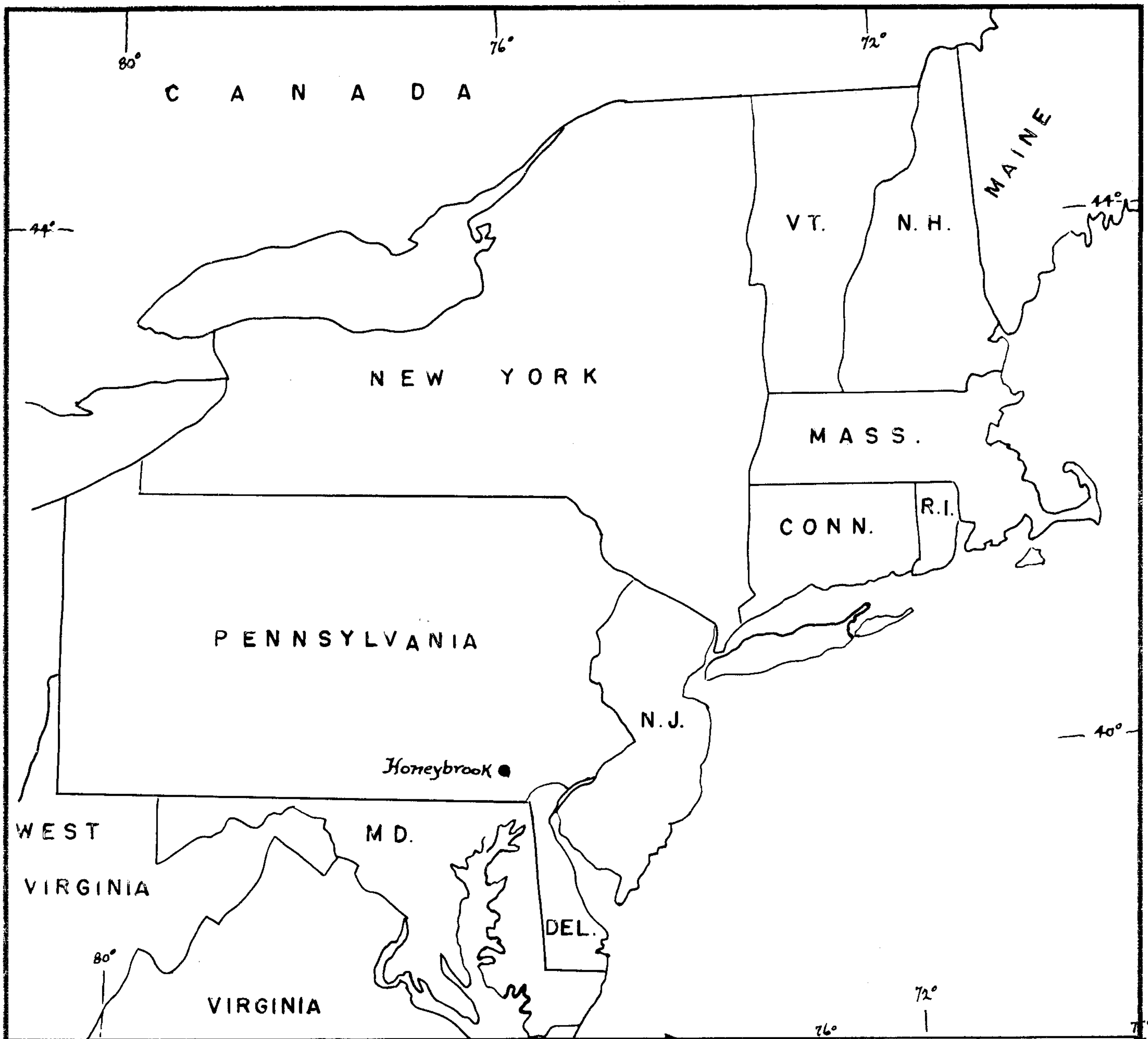
This report is based upon a geologic investigation of the anorthosite massif located in Chester County, Pennsylvania. The study of this massif was undertaken with three purposes in mind: (1) to obtain all the geologic data possible and to prepare an accurate geologic map of the area; (2) to determine whether variations exist within the anorthosite; (3) to establish the age relationship between the anorthosite and the quartz-monzonite.

Location

The anorthosite massif is located in the central-eastern portion of the Honeybrook quadrangle in Chester County, Pennsylvania, between north parallels 40°03' and 40°07' and west meridians 75°45' and 75°52', (fig.1). The area is two miles east of the town of Honeybrook and approximately 40 miles northwest of Philadelphia. Access to the area is by a network of good roads.

Present Work and Acknowledgements

From the latter part of July 1951 to the second week of September 1951 six weeks were spent mapping the anorthosite and the adjacent rocks. During the next six months the equivalent of five work-weeks were spent in



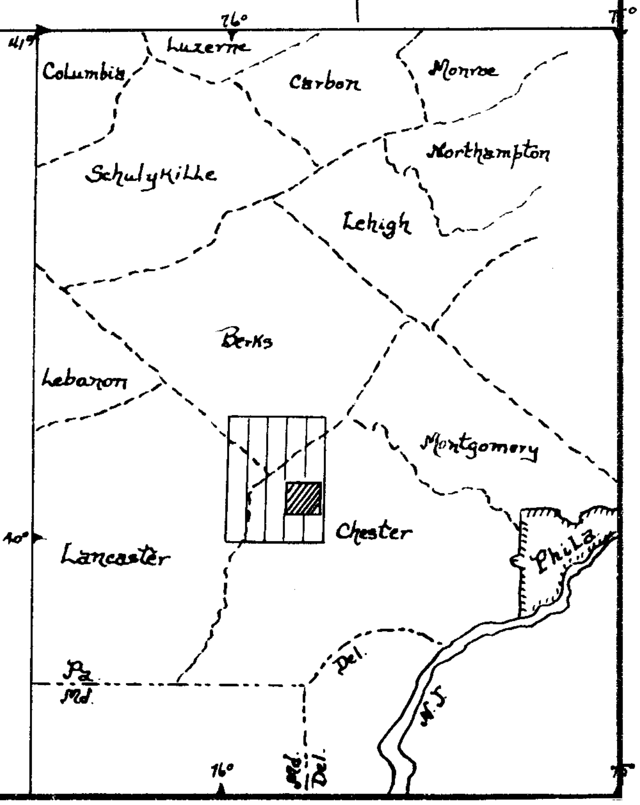


Figure 1 - Index maps showing location of the Honeybrook area. The map in the lower right hand corner shows the Honeybrook quadrangle by vertical ruling and the mapped area by diagonal ruling. Counties are shown and their boundaries indicated.

research, laboratory work, and in the preparation of this report.

Field mapping was done by the traverse method with the aid of aerial photographs and topographic maps. North-south traverses across the anorthosite massif were spaced approximately 300 feet apart to establish a satisfactory control. The borders of the anorthosite were carefully determined by walking out the contact.

Throughout the mapped area outcrops are rare and relations somewhat obscure. The recognition of float fragments and distinctive topography were used as a basis for field mapping. Locally, where varying types of float fragments are mixed, the predominant rock type was statistically established and used as a basis for mapping.

Sixteen thin-sections of anorthosite selected mainly along four north-south traverses in the west-central and central portions of the massif were examined for variation. In addition, one thin-section of diabase porphyry, one of quartz-monzonite and one of a hybrid rock type were examined.

The writer is indebted to Dr. Richard M. Foose for obtaining the aerial photographs and topographic maps and for his field check of the area with Dr. Jacob Freedman. The criticisms of Dr. Albert Engel and Dr. Richard H. Jahns were of great aid in the completion of this thesis. Mr. Albert Hoch prepared the thin-sections for the author. The interest of Dr. Ian Campbell has been inspiring.

Previous Work

Florence Bascom described the area in her report entitled The Piedmont District of Pennsylvania published in 1905. In 1922 Isabel F. Smith published her work on the Honeybrook anorthosite which was used as a partial fulfillment toward the Doctor of Philosophy degree at Bryn Mawr College. Florence Bascom and George W. Stose mapped the Honeybrook and Phoenixville quadrangles and published their results in the Geologic Survey Bulletin 891, dated 1938.

Geography and Geomorphology

The Honeybrook quadrangle lies within that portion of the Appalachian Highlands which is known as the Piedmont province. The Piedmont province is located at the foot of the Blue Ridge Mountains, extending northeastward to the New England upland and southwestward to the East Gulf Coastal Plain. The province parallels the Atlantic coast with a mean width of 60 miles and a maximum width in its central portion approximating 120 miles.

The Piedmont province includes two sections, the Piedmont uplands and the Piedmont lowlands. The anorthosite massif occurs in the Piedmont upland section which is characterized by deeper valleys and more abrupt hills when compared to the relatively level country of the Piedmont lowlands.

A series of dissected plateaus, extending as a broad upland to the southeast of the Appalachian Mountains, make up the Piedmont province. The summits of these plateaus are the remnants of successive peneplanes which have been traced throughout the Piedmont province. Bascom and Stose (1938, p.10) correlate the 700 foot level maintained by the quartz-monzonite and granodiorite in the Honeybrook area with the Harrisburg peneplane surface of upper Cretaceous age.

Drainage

The East and West Branches of Brandywine Creek, both perennial streams, and their tributaries drain the area. The parallel relationship of the present course of the East Branch of Brandywine Creek and the northern contact between the anorthosite and quartz-monzonite suggests strongly that prior to uplift this stream course was controlled by that contact. After uplift, presumably during Cretaceous time, accelerated downcutting by the stream and erosion shifted the contact between the anorthosite and quartz-monzonite to the north, away from the stream (fig. 2).

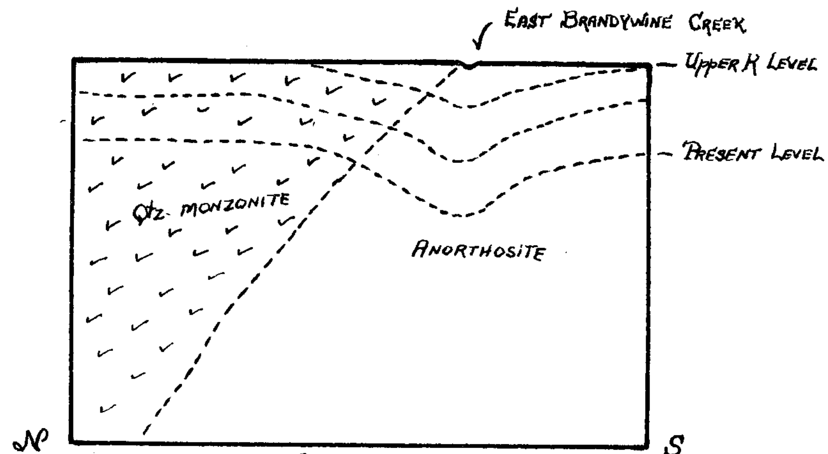


Figure 2
Relationship between Brandywine Manor Creek and the Anorthosite - Quartz - Monzonite contact. Sketch not drawn to scale. Taken after Isabel Smith (1922).

Climate

The climate in the Honeybrook area is clement without extremes of temperature, precipitation or wind velocity. At Coatesville, one mile south of the Honeybrook quadrangle, the mean annual temperature for a period exceeding 30 years was 51.9° and the mean annual rainfall about 45 inches.

ANORTHOSITE

Anorthosite Problems

Most plutonic or granular igneous rocks are represented in pre-Cambrian eruptions, as well as eruptions of post-Cambrian time. Most of the large anorthosite massifs, however, are generally believed to have eruptive dates confined to the pre-Cambrian. The only large bodies of anorthosite not assigned definitely to the pre-Cambrian are the Bergen masses of Norway. Kolderup (1914) assigned these Bergen masses to the Silurian. The confinement of the majority of these large anorthosite masses to the pre-Cambrian suggests somewhat peculiar conditions existing in pre-Paleozoic time.

A second point of contrast with other plutonic types is found in the lack of effusive equivalents of anorthosite. This negative result implies that anorthosite was never molten as such or that it lacked the power to reach the surface. Factors such as high viscosity or a minimal charge of the gaseous constituents necessary for continued volcanic action might account for such lack of power.

A third abnormality is the very coarse grain generally characteristic of anorthosite bodies. This large grain size may have been controlled by the existence of a thick cover which aided in the retention of volatiles and heat to further crystallization.

Most of the larger bodies show pronounced effects of strain. Protoclastic textures are commonly described and have been attributed to shearing during or after lithification. This phenomenon, however, is not universal, for the Norwegian, Minnesotan, Transvaal and Honeybrook bodies exhibit practically no strain.

Possibly the most difficult anorthosite problem is its simple mineral composition. Two contrasting hypotheses have been offered to account for the origin of this occurrence. One hypothesis is that the anorthosite was emplaced as a magma of approximately its own composition; the second hypothesis is that anorthosite is the result of the sorting and aggregation of plagioclase crystals by sinking, rising, flowage-clustering, or filter pressing from a more gabbroid magma. These two hypotheses are discussed in more detail on pages 27 and 28.

THE HONEYBROOK ANORTHOSITE

General Statement

The Honeybrook anorthosite makes an elliptical pattern, about 6 miles long and 3 1/3 miles wide, in the central-eastern part of the Honeybrook quadrangle (plate 1). The anorthosite massif is surrounded by quartz-monzonite except on the south and southeast where Cambrian quartzite is faulted against it. Metadiabase dikes and one pegmatite dike - all of pre-Cambrian age - have penetrated the anorthosite.

Two facies genetically related and belonging to the anorthosite series of rock comprise anorthosite and gabbroic anorthosite in the Honeybrook area. The plagioclase of the gabbroic anorthosite, also referred to in this report as the border facies, is near the boundary between andesine and labradorite. Because the plagioclase is commonly calcic andesine and the ferromagnesian mineral content of the rock ranges from 10 to 30 per cent, the term dioritic would be more strictly appropriate. The term gabbroic anorthosite will be retained, however, to conform with past usage in the literature.

Anorthosite Facies

The major portion of the Honeybrook anorthosite massif consists of typical anorthosite. This anorthosite is generally blue-gray in color but locally greenish-white, pink and purplish variations appear. The anorthosite is medium-to-coarse-grained with the grain sizes varying from 3 mm. to 8 mm., the average grain-size approximating 6 mm. The rock weathers into large spheroidal boulders with relatively smooth surfaces.

The composition of the plagioclase feldspar which constitutes over 90 per cent of the rock is commonly calcic andesine ($Ab_{52}An_{48}$). The feldspar crystals are subhedral and in thin-section the twinning lamellae only rarely appear bent. No zoning of the plagioclase was seen in the thin-sections examined. Subhedral to euhedral hornblende crystals occur as distinct grains in amounts up to 10 per cent of the rock. The hornblende is in colors of brown and green. Accessary minerals seen in thin-sections were apatite, magnetite and sphene. The approximate modes of 16 anorthosite specimens are given in Table 1. The Rosiwal method was used to determine the modes.

Alteration of the anorthosite varies from slight to severe (table 1). The division lines used to describe the degree of alteration is as follows: slight- 1-19 per cent; moderate- 20-59 per cent; severe- 60-100 per cent.

Table 1

Approximate modes of Honeybrook anorthosite

Slide Number*	Andesine-Labradorite	Hornblende	Augite	Magnetite	Sphene	Apatite	Alteration** Plagioclase	Alteration** Hornblende
S2A	94.8	5.2	--	--	--	--	slight	slight
S3	96.2	3.8	--	trace	--	--	slight	slight
S4	97.6	2.4	--	trace	--	--	severe	severe
S5B	98.2	1.8	--	--	--	--	severe	severe
S6	98.5	1.5	--	trace	--	--	moderate	moderate
H1	97.0	2.4	<1.0	--	trace	trace	moderate	moderate
H2	96.5	3.5	--	--	--	--	severe	severe
H3	98.2	1.2	<1.0	trace	--	--	moderate	moderate
H4	98.5	1.1	--	--	--	--	moderate	severe
H5	94.3	4.9	<1.0	--	trace	--	severe	severe
H6	95.4	4.5	--	trace	--	--	moderate	severe
H7	93.6	6.3	--	trace	--	--	moderate	moderate
H8	96.5	3.5	--	trace	--	--	moderate	severe
H9	94.2	5.8	--	trace	--	--	severe	severe
H10	90.3	9.7	--	--	--	--	moderate	severe
H11	92.2	7.8	--	trace	--	--	moderate	moderate

*Locality of the rock from which the thin-section was made is shown on Plate 1 by a number corresponding to the slide number.

**Alteration products of plagioclase are zoisite, clinozoisite, sericite and kaolin; alteration products of the ferromagnesian minerals are epidote, clinozoisite and minor amounts of calcite.

Most of the severe alteration of the anorthosite occurs in the central portion of the massif (plate 1) where heavy float concentrations of anorthosite and quartz-monzonite are intermixed. Thin-sections S4, S5B, H4, H5, H6, H8, H9 and H10 (table 1), all within this area, show severe alteration of the hornblende with moderate or severe alteration of the plagioclase.

Thin-sections S2A, S3, S6, H1, H3, H7 and H11 (table 1), all from localities outside the area of intermixed float fragments of quartz-monzonite and anorthosite, show only slight or moderate alteration of the hornblende and plagioclase. Only one thin-section, H2, indicates severe alteration outside the zone of intermixed anorthosite and quartz-monzonite. However, the boulder from which this thin-section was made might have been moved from its original location.

Alteration of the anorthosite shows a saussuritization of the plagioclase in which clinozoisite is a conspicuous mineral. Zoisite, sericite and a minor amount of kaolin are also found as alteration products of the plagioclase. Hornblende is altered to epidote, clinozoisite and a minor amount of carbonate. The saussuritization seems to be reasonably related in origin to late-stage thermal solutions yielded by the quartz-monzonite magma. The close spatial relationship between the degree of anorthosite alteration (table 1) and the occurrence of quartz-monzonite in the central part of the area (plate 1) is strong evidence to support this conclusion.

Protoclastic texture, common in many of the larger anorthositic massifs, is lacking in the Honeybrook anorthosite. Foliation within the anorthosite facies is not evident at all places, although locally a parallelism or subparallelism of the plagioclase can be seen.

An analysis and norm of the anorthosite half a mile west of Forrest, Pennsylvania, as determined by W. T. Schaller is shown below. It is taken from Geology and Mineral Resources of the Honeybrook and Phoenixville Quadrangles, Pennsylvania, by F. Gascom and G. W. Stose, Geological Survey Bulletin 891, published in 1938.

Analysis

SiO_2	52.86
Al_2O_3	26.68
Fe_2O_3	1.03
FeO	.74
MgO	.38
CaO	10.93
Na_2O	4.44
K_2O	.92
H_2O	.11
H_2O+	1.49
TiO_2	.25
ZrO_2	trace
CO_2	trace
S	.05
P_2O_5	.33
MnO	.02
BaO	.03
	100.26

Norms

Quartz	0.54
Orthoclase	5.56
Albite	37.73
Anorthite	50.04
Diopside	1.94
Hypersthene	.23
Magnetite	1.39
Ilmenite	.46
Apatite	.67
Water	1.60
S	.05
MnO	.02
BaO	.03
	100.26

Border Facies

The border facies is distinguished from the true anorthosite facies of the massif by its 10 to 30 per cent mafic mineral content. This change to a more gabbroid character is restricted to the periphery of the mass but it is not universal throughout the mass, as typical anorthosite is found up to the edge of the intrusion at places. Along with this change in the amount of ferromagnesian silicates, garnet also occurs in noticeable quantity, ranging from 1 to 2 per cent of the rock in places. The garnets appear euhedral with no evidence of shearing or deformation. The foliation in the border facies is much more prominent than the foliation in the anorthosite facies.

As in the anorthosite facies the plagioclase is of andesine-labradorite composition. Augite was found in thin-section but hornblende is the predominant ferromagnesian mineral. Alteration of the border facies is moderate with plagioclase altering to zoisite, clinozoisite, sericite and kaolin,and hornblende altering to epidote and clinozoisite.

The border facies varies in texture, ranging in grain size from 1 mm. to 8 mm. The fine-grained border facies, with grain sizes ranging from 1 to 3 mm., is found locally along the northern border of the massif; it is best developed north of Wyebrook near the Isabella Furnace (plate 1). In the entire border facies the rock is holocrystalline with subhedral plagioclase crystals and subhedral to euhedral augite and hornblende.

Evidence points toward the border facies being a relatively chilled zone. Direct evidence is the finer-grained variety found north of Wyebrooke near the Isabella Furnace (plate 1). The idea of a chilled zone is further strengthened because it is, in general, more mafic and less completely differentiated.

Hybrid Rock

Hybrid, as used in this report, is a product formed by an acid magma reacting with a basic magma that has already solidified. As originally defined by Bunsen, hybridism is attributed to the intermingling of two primitive magmas, one of "feldspathic" and one of "pyroxenic" composition. Since that original definition, the term hybrid has been used to cover both the intermingling of two liquids and also the contamination of liquid magma by reaction with the country rock. The writer uses the term hybrid to conform with the latter definition of the liquid magma reacting with the country rock.

The hybrid rock is found locally in the north-central portion of the massif, associated with the intermixed quartz-monzonite and anorthosite boulders and float fragments. The best outcrops of the hybrid rock occur one-tenth of a mile south of Forrest (plate 1), on the east side of the road leading from Rockville to Forrest. Large crystals of hornblende up to 8 inches long, commonly associated with blebs and lenses of quartz which reach dimensions of 6 inches in places, occur in what appears to be altered anorthosite. An interesting group of hornblende crystals (plate 2) resembling a "burst" appears in an outcrop.

Balk (1944, p. 300-304) has reported large crystals of pyroxene over 6 inches in length in anorthosite at the shore of Lake Champlain in the Adirondacks. He believes the appearance of such large crystals is suggestive of pneumatolytic processes, the volatiles entering either pore spaces or cross fractures of the rock where mafic minerals developed to impressive sizes.

An examination of one thin-section made from a boulder fragment south of Forrest in the Honeybrook area suggests that the quartz-monzonite magma reacted with anorthosite to form this hybrid rock. Two generations of hornblende appear. The older generation, presumably a relic from anorthosite, is severely altered to clinozoisite. The younger hornblende, however, is unaltered and is poikilitic with small enclosed fragments of feldspar in one place. Anhedral quartz grains appear in clusters and are definitely strained. The feldspar is antiperthite. The host feldspar of the antiperthite is albite-oligoclase as determined by its index of 1.536 in

Plate 2

Hornblende crystals in a coarse-grained hybrid rock. Note the group of hornblende crystals outlined in ink and marked Hb. East side of road leading from Rockville to Forrest, about one-tenth of a mile south of Forrest.

thin-section (the index of the oil in the slide was 1.536 and the host feldspar had no relief at all when compared to the oil). The relief of the feldspar within the host albite-oligoclase was much lower and presumably orthoclase. Vague plagioclase twinning was recognized in the antiperthite host. The antiperthite is suggestive of interaction between plagioclase feldspar and the liquids of quartz-monzonite. The release of calcium from andesine feldspar of anorthosite could be accounted for in the second generation of hornblende in the hybrid rock.

An approximate mode of the hybrid is as follows:

Antiperthite	----	30-35%
Quartz	----	20-25%
Hornblende (1st generation)	----	10-15%
Hornblende (2nd generation)	----	15-20%

The texture of the hybrid in the thin-section was holocrystalline and inequigranular with medium-to-coarse-grained crystals. Subhedral antiperthite crystals ranged from 4 to 6 mm. in size; subhedral to euhedral hornblende of both generations were approximately the same size, averaging between 3 and 4 mm. Anhedral quartz was slightly smaller, averaging less than 3 mm.

PRE-CAMBRIAN ROCKS

Quartz-Monzonite

The quartz-monzonite surrounds the anorthosite massif except on the south and southeast where the Brandywine Manor fault brings Cambrian quartzite against the anorthosite.

The texture of the quartz-monzonite is holocrystalline, medium-to coarse-grained, inequigranular and inequant. The grain size ranges from 3 mm. to 8 mm. The quartz-monzonite when fresh is tan to gray in color and appears for the most part massive. Where weathered it is a lighter yellow-gray in color and can be distinguished from the anorthosite by its rougher, pitted surfaces.

Feldspar, quartz, pyroxene, amphibole, and biotite can be distinguished megascopically. The feldspar is represented by microcline, orthoclase and microperthite with minor amounts of albite or oligoclase. The feldspar comprises from 60 to 85 per cent of the rock. Alteration of the feldspars is slight to moderate, the decomposition products being kaolin, sericite, muscovite and zoisite.

The percentage of quartz ranges from 10 to 25 per cent in the thin-sections studied. The chief ferromagnesian constituent is augite altered to hornblende and chlorite. Diopside and biotite occur in minor amounts.

Ilmenite was the only accessory mineral seen in thin-section but magnetite, zircon, apatite, pyrite, rutile, and garnet have been reported by Bascom and Stose (1938, p. 41).

An approximate mode of the quartz-monzonite one-half mile north of Barneston follows:

Microcline	---	43.5
Microperthite	---	19.2
Orthoclase	---	6.1
Albite-oligoclase	---	2.3
Quartz	---	21.8
Augite	---	6.3
Biotite	---	<1.0
Ilmenite	---	trace

Pegmatite

A post-anorthosite pegmatite dike, probably pre-Cambrian in age, occurs 1 1/2 miles east of Icedale (plate 1). Orthoclase and quartz are its chief constituents in approximately equal proportion with magnetite present in minor amounts. The orthoclase is kaolinized with the accompanying development of sericite and muscovite. No attitudes of the pegmatite dike were obtained because of lack of outcrops.

Metadiabase

Numerous metadiabase dikes cut the anorthosite and quartz-monzonite. These metadiabase dikes strike in a general northeast-southwest direction. Nowhere did the author find an outcrop of metadiabase dike; the only evidence of metadiabase dikes in the mapped area being in float fragments. The trace of metadiabase float fragments from each dike follows a linear pattern, suggesting a steep dip in each case.

Two distinct types of metadiabase dikes occur. One type is a fine-grained to aphanitic rock with ophitic texture andconsisting chiefly of subhedral labradorite and subhedral to euhedral augite. Labradorite is altered to aggregates of zoisite, albite and muscovite. The augite is altered peripherally to hornblende, biotite, chlorite and epidote. Ilmenite is altered to leucoxene.

The second type of metadiabase dike is porphyritic with thickly set phenocrysts of andesine-labradorite feldspar measuring up to one centimeter in length in some places. Augite, hornblende and ilmenite are also present but in lesser amounts than the feldspar. A thin-section from a porphyritic dike one-quarter of a mile southeast of Barneston gives the following mode:

Andesine	---	68.3
Augite	---	20.2
Hornblende	---	7.2
Ilmenite	---	4.3

The andesine crystals in the thin-section of porphyritic metadiabase measure to to 8 mm. long, the average size being about 4 mm.

Augite crystals average less than 1 mm. Hornblende occurs in close association with ilmenite. The plagioclase is altered to aggregates of zoisite grains with minor albite or muscovite. Augite is slightly altered peripherally to pale brown hornblende, chlorite and epidote.

Fresh metadiabase is difficult to distinguish from Triassic diabase dikes because of their unweathered appearance. The difference, however, can readily be distinguished in thin-section comparisons. Two thin-sections of Triassic diabase dikes from Lancaster County, Pennsylvania, were examined by the author. The difference in alteration between the pre-Cambrian metadiabase dikes of the Honeybrook anorthosite area and the Triassic dikes of Lancaster, Pennsylvania, leaves no doubt as to the difference in ages. The Triassic diabase rocks from the thin-sections examined show no alteration.

PALEOZOIC ROCKS

Chickies Quartzite

The Chickies quartzite, of Cambrian age, is faulted against the quartz-monzonite and anorthosite in the southern part of the area (plate 1). This formation is a pure quartzite and sericitic quartz schist so resistant to erosion that it forms prominent hills. The pure quartzite consists of light gray to blue-gray thick beds over 2 feet thick with bluish quartz grains apparent. The sericitic quartz schist is thin-bedded, the beds ranging in thickness from 2 inches to 8 inches in the area mapped by the author. The sericitic quartz schist disintegrates into a fine white siliceous clay.

STRUCTURE OF THE ANORTHOSITE

The lack of outcrops in the Honeybrook anorthosite area makes it impossible to reach a definite conclusion as to the present structure of the anorthosite massif. A total of five outcrops showing foliations were found in both facies of the anorthosite. The foliation dips away from the center of the massif in each case suggesting a domical body.

RELATIONSHIP OF QUARTZ-MONZONITE AND ANORTHOSITE

Evidence found by the author in the field and from the study of thin-sections indicates that the quartz-monzonite is definitely younger than the anorthosite.

One-half mile east-southeast of Barneston, in a field located northeast of the crossroads (plate 1), two boulders show quartz-monzonite dikes definitely penetrating anorthosite. These dikes measure 1 to 1 1/2 inches in width and appear unaltered. Coarse-grained feldspar crystals averaging 6 mm. in size, make approximately 60 to 70 per cent of the dikes. The feldspars are pink to gray in color and are commonly subhedral. Anhedral quartz makes up the remaining 30 to 40 per cent of the rock. No evidence of chilled margins in the dike was seen, suggesting a possibility that quartz-monzonite was injected into the anorthosite while the latter was still hot. The quartz-monzonite dikes, however, show no indication of being schistose or stretched nor do they coincide with the foliation present in the anorthosite. Such structures would indeed strengthen the possibility of quartz-monzonite invading a hot, unconsolidated anorthosite.

The evidence presented on page 16 indicates a younger quartz-monzonite magma invaded the anorthosite to form a hybrid rock.

Additional evidence discussed on page 12, shows that where quartz-monzonite and anorthosite are related spatially, the alteration of the anorthosite is pronounced.

It should also be noted that the border facies of the anorthosite does not border the massif. Could this irregularity be accounted for by an invading quartz-monzonite cutting out some of the border facies?

The field evidence and the evidence from the study of thin-sections definitely proves that the quartz-monzonite is later than and penetrates the anorthosite.

ORIGIN AND HISTORY OF THE HONEYBROOK ANORTHOSITE

The Honeybrook anorthosite was probably formed by the differentiation of a gabbroid magma, under deep-seated conditions during pre-Cambrian time. A relatively chilled border developed and as the gabbroid magma slowly cooled the pyroxene crystals sank leaving a viscous but still fluid plagioclase magma. Plagioclase crystals formed from the plagioclase magma and continually changed in composition as a result of interchanging of material between the liquid and crystals, the change being in the direction of the lower-melting component.

After solidification, the anorthositic body was intruded during pre-Cambrian by a quartz-monzonite magma which enveloped it and broke through the anorthosite in at least one place.

Other activity during pre-Cambrian time is recorded by the intrusion of a pegmatite dike and diabase dikes.

The only evidence of sedimentation of which there is a record in the mapped area took place during Cambrian time with the deposition of sand. The sand was consolidated into strata and metamorphosed into Chickies quartzite during Cambrian or post-Cambrian time. The only other record of structural disturbance is post-Chickies quartzite when the Brandywine Manor fault resulted in uplift of the Honeybrook anorthosite. Erosion has been active to an unknown extent since the Brandywine Manor fault occurred.

COMPARISON WITH OTHER REGIONS

Adirondack Mountains.—In the Adirondack Mountains of New York anorthosite occupies an almost unbroken area of 1,200 square miles, a smaller area of nearly 100 square miles, and various much smaller outlying areas.

Two rather clearly recognizable facies of the anorthosite have been reported by many Adirondack geologists. Miller and Alling (1919, p. 29) have described a coarse-grained, light to dark bluish-gray anorthosite consisting very largely of plagioclase varying from oligoclase to labradorite and a border facies which is usually a medium-grained, light-gray, moderately gneissoid rock consisting mainly of white labradorite feldspar together with 5-15 per cent of mafic minerals.

Two important hypotheses in regard to the Adirondack anorthosite have been advocated and discussed. Bowen, after a reconnaissance of the Adirondacks and the Norion district of Canada and study in the laboratory, proposed a radical departure from previous concepts. Bowen (1917, p. 209-243,500-72) postulated a laccolithic intrusion of a gabbroid magma from which developed an upper chilled gabbroid border facies. From the unlithified portion of the magma mafic crystals settle to form gabbro and peridotite while the plagioclase crystals remain suspended in the liquid magma. With slow cooling the plagioclase crystals continually change in composition as a result of interaction between liquid and crystals, this change being toward an enrichment from anorthite to labradorite. With the depletion of the ferromagnesian constituents the liquid becomes lighter than the plagioclase crystals and rises to form a syenitic magma between the anorthosite and the upper chilled border.

Miller and Alling (1919, pp. 32-33) argue that the syenite-granite in the Lake Placid quadrangle is "distinctly later and clearly intrudes the anorthosite." Cushing (1917, pp. 506-7) also maintains the conclusion that the syenite-granite series of the Adirondacks is distinctly younger than the anorthosite.

Balk (1930, p. 289), referring to the Adirondacks, states, ". . .gabbro, anorthosite and syenite series are considered closely related consanguineous members of a common parent magma. . . . . .Frictional forces seem to have played a dominant role in the differentiation of the parent magma. . . . .The magma is believed to have risen from the southern edge of the Canadian Shield obliquely to the south."

Buddington (1939, pp. 204-221) advocates the intrusion of a gabbroic anorthosite magma in the Adirondacks with the development of a chilled border of such composition. With partial settling of the mafic minerals during consolidation, an anorthosite mass concentrates above. A distinctly later, widespread intrusion of quartz syenitic magma follows.

A comparison of the anorthosite of the Honeybrook area with that of the Adirondack Mountains indicates the following:

(1) The exposed area of Adirondack anorthosite is much greater.

(2) Protoclastic texture is lacking in the Honeybrook anorthosite but present in the Adirondack anorthosite.

(3). Distinctly younger quartz-monzonite cuts the Honeybrook massif, whereas syenite-granite penetrates the Adirondack anorthosite.

(4) The plagioclase is predominantly andesine in the Honeybrook anorthosite and chiefly labradorite in the Adirondack anorthosite.

(5) Foliation exists within both massifs.

(6) A border facies is developed in both.

Pigeon Point, Minnesota.— Grout (1928, pp. 555-57) explains the anorthosite-gabbro at Pigeon Point, Minnesota, as follows:

The intrusion of basaltic magma in the form of a sill 500 feet thick with the development of a chilled diabasic border at both top and bottom of the sill. Phenocrysts rise from the main body of the magma to form a zone of gabbro grading into anorthosite-gabbro and small masses of true anorthosite. An appreciable amount of diabase-gabbro develops in the lower part of the sill (above the lower chilled border) by settling of crystals or some other process, leaving a much thinner zone of acidic magma above it. The acidic magma solidifies to form a relatively thin zone of granite grading downward through intermediate rock into the gabbro, and lying just below the anorthosite-gabbro.

The Honeybrook anorthosite cannot be explained by using Grout's hypothesis concerning the Pigeon Point massif because the Honeybrook anorthosite, including its border facies, does not appear to be in the form of a sill with chilled borders at the top and the bottom. Furthermore, there is no evidence of a zone of anorthosite-gabbro just under an upper chilled border, nor a zone of granite grading downward into gabbro in the lower part of the intrusive body.

Laramie Mountains, Wyoming.—Fowler (1930, pp. 305-315, 373-403) in a paper on the Laramie Mountains anorthosite describes the anorthosite as occupying an elongate area of several hundred miles. Evidence is presented to show that the anorthosite was intruded as a true magma into a series of highly folded pre-Cambrian schists in the form of a cone-shaped mass with thin edges in its upper portion. Xenoliths occur in the anorthosite. Gabbro masses, rich in magnetite, occur in the anorthosite and these grade into the anorthosite. These gabbro masses are regarded as differentiates of the anorthosite. Small lenses of titaniferous magnetite are also believed to be differentiates of the anorthosite. Granite surrounds the anorthosite and has clearly intruded the latter. Cataclastic textures occur near the margins of the anorthosite, and protoclastic textures well within it. Fowler (1930, p.403) states that "the anorthosite moved upwards as a deep-seated basic intrusive into the overlying rocks."

The Laramie Mountains anorthosite differs from the Honeybrook anorthosite in the following:

(1) The Laramie Mountains anorthosite is larger; (2) it has xenoliths occurring in the anorthosite; (3) gabbro masses and titaniferous magnetite lenses are evident in the Laramie Mountains; (4) granite, instead of quartz-monzonite, surrounds and intrudes the Laramie Mountains anorthosite; (5) cataclastic and protoclastic textures are evident in the Laramie Mountains anorthosite.

Los Angeles County, California.—Miller (1931, pp.335-338) in his report on the Los Angeles County anorthosite advocates an original gabbroid magma differentiating irregularly to form gabbroic and dioritic facies along with anorthosite. The anorthosite has inclusions of older schist and dikes of anorthosite cut into the older country rock. Generally little or no granulation occurs in the anorthosite, nor is foliation an evident structure. Miller believes the shape of the intrusive body is either a laccolith or a cone-shaped batholith because younger granodiorite dikes cut the outer portions of the anorthosite.

The principal crystalline rocks younger than the anorthosite are a massive quartz-diorite and a still later granodiorite, the latter probably of Jurassic age.

Similarities between the Los Angeles, California, anorthosite and the Honeybrook anorthosite are the lack of granulation, the predominant plagioclase being andesine, and the medium to coarse-grained textures shown in each massif.

The principal point of disagreement about anorthosite is in regards to the relation of the more acidic magma to the anorthosite of each region. Bowen, Balk, and Grout believe that the acidic magma was developed from a gabbroid magma after the intrusion of the latter; Cushing, Fowler, Miller, Buddington, and the writer support the point of view that the acidic magma is a later, separate intrusion in each of the regions studied.

Each of the five anorthosite bodies mentioned above have somewhat distinctive features. The possibility exists that each anorthosite massif was formed under more or less different conditions in the various regions which would account for some variations in the hypothesis advocated.

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