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PETROLOGY OF DIABASE SHEETS IN SOUTHEASTERN PENNSYLVANIA STUDIED

Director W. E. Wrather, Geological Survey, today announced that a report describing a recently investigated body of diabase rock, associated with iron ore deposits, in southeastern Pennsylvania has been placed in open file.

Diamond drill exploration of magnetite deposits near Dillsburg, Pa., revealed the body of diabase beneath the sedimentary rocks in which the deposits occur.

The report, titled "Petrology and habit of some diabase sheets in southeastern Pennsylvania", by Preston E. Hotz, is accompanied by geologic maps, sections, and other illustrations, and deals primarily with details of the chemical and mineralogic characteristics of the local rocks below the ore deposit. Copies of the report may be inspected in the Geological Survey Library, Room 1033, Federal Works Agency Building, Washington, D. C., and in the main library and Geology Department library, Princeton University, Princeton, N. J.

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PETROLOGY AND HABIT OF SOME DIABASE SHEETS IN SOUTHEASTERN PENNSYLVANIA

by

Preston E. Hotz

A Dissertation Presented to the Faculty of Princeton University in Candidacy for the Degree of Doctor of Philosophy

January 1949
Princeton, New Jersey

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ABSTRACT

Small masses of granophyre occur in the upper part of diabase intrusions in southeastern Pennsylvania. Diamond drill hole exploration of magnetite deposits near Dillsburg revealed a body of diabase beneath the sedimentary rocks in which the deposits occur. The drill core revealed a complete gradational sequence downward from a diabase chill zone through normal diabase, diabase pegmatite, transitional granophyric diabase into granophyre.

New data include the results of petrographic study of a series of specimens from the drill core and 10 new chemical analyses. The sequence, diabase to granophyre, shows progressive increase in alkalies and silica; iron increases into the transitional granophric diabase stage, then decreases in the granophyre. The chemical variations are accompanied by changes in mineralogy which are described in detail.

Field and petrographic studies of other granophyre masses were likewise made.

Possible origins of granophyre from diabase are considered, and it is concluded that crystal differentiation in a large sheetlike intrusion most satisfactorily explains the genesis of granophyre in this region. Prior to complete solidification a residual liquid rich in iron, alkalies, silica, and volatiles collected locally in the upper part of the diabase sheet. In some places fractures released volatile-rich iron-bearing solutions which deposited magnetite in the overlying sedimentary rocks; the remaining liquid crystallized to fine-grained granophyre. Elsewhere the volatiles were retained for a longer period; the resulting rock is coarse-grained with numerous miarolitic cavities.

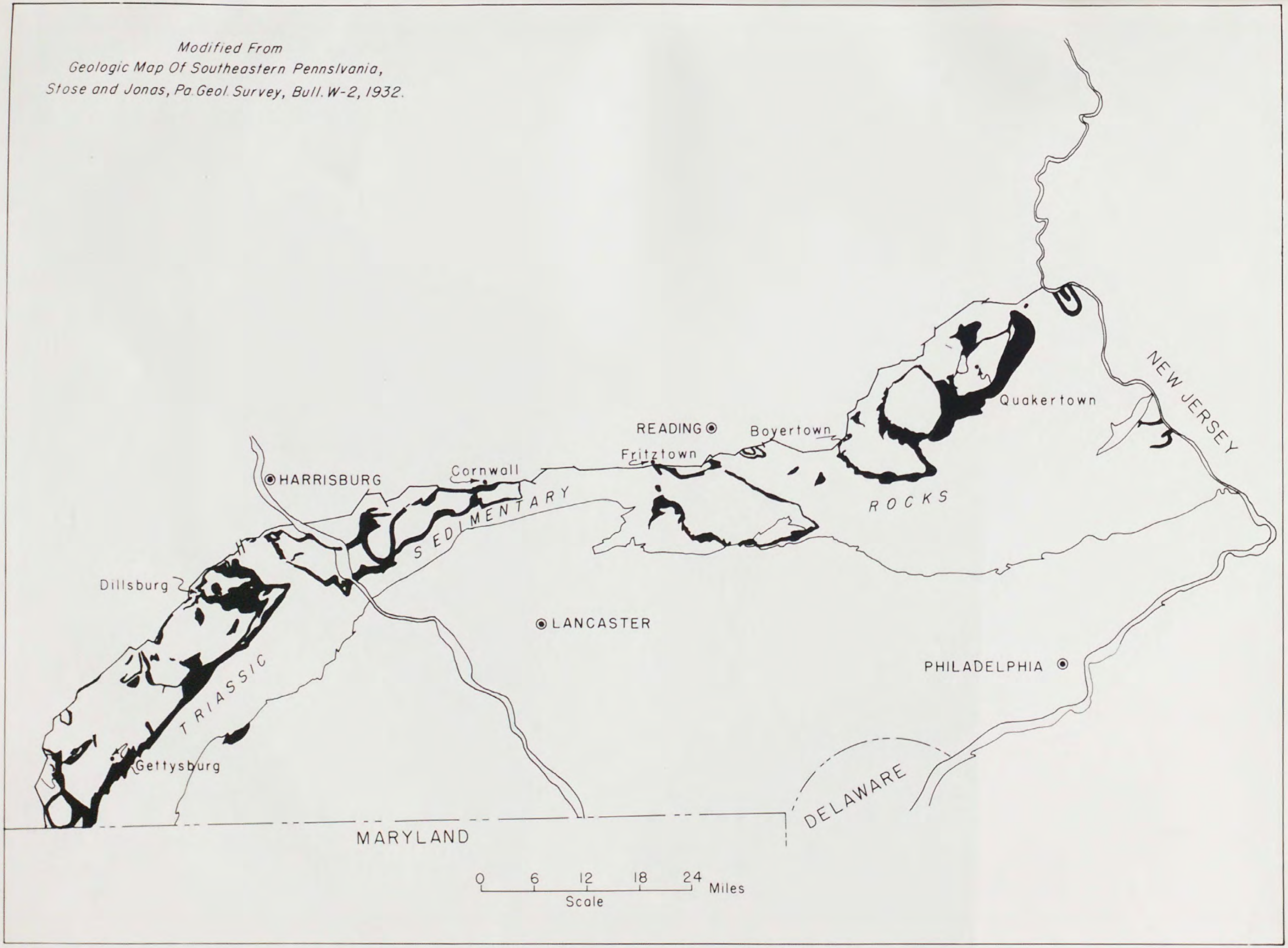
Ring-like outcrop patterns are characteristic of the diabase intrusions in southeastern Pennsylvania. Drill hole and geophysical data indicate that the diabase of these rings has the form of generally discordant curved sheets or basins. Pre-existing fractures or potential lines of weakness may have controlled the sheet-like form, or because of existing pressure conditions the diabase magma was forced to spread laterally rather than rise vertically.

INTRODUCTION

Terrestrial and lacustrine sedimentary rocks of Triassic age occupy several elongate trough-like basins in eastern North America extending with some interruptions from Nova Scotia to South Carolina. From bore hole records Triassic rocks are known as far south as Florida. The basins are narrow and elongate north and south. They range from 25 to over 300 miles in length and from 10 to 30 miles wide. The largest of these basins lies in southeastern Pennsylvania and southern New Jersey and extends from southeastern New York to northern Maryland. The northern part of this Triassic belt is usually referred to as the Newark Basin, the southern part is called the Gettysburg Basin. Toward the close of the Triassic period an enormous volume of magma invaded these sedimentary rocks, forming diabase intrusions and basalt flows. This paper is concerned with the diabase intrusions and their differentiates in the Gettysburg Basin and the southern half of the Newark Basin, southeastern Pennsylvania (Fig. 1). With one very minor exception, no surface flows are known in this part of the basin.

The undifferentiated magma which invaded these sedimentary basins is representative of a world-wide type, the tholeiitic magma type of Kennedy (1933, p. 240-242). In New Jersey and New York a thick sill of tholeiitic magma that forms the Palisades of the Hudson, cooled slowly enough to permit a considerable degree of differentiation. Lewis (1908b, p. 155-162) and Walker (1940, p. 1059-1105) have made detailed studies of the petrography, and in excellent accounts of the petrology have described the differentiation process which produced the well known olivine-rich layer near the bottom of the sill.

Figure 1. Map showing the distribution of diabase in Triassic rocks in southeastern Pennsylvania.


Modified From
Geologic Map Of Southeastern Pennslvania,
Stose and Jonas, Pa. Geol. Survey, Bull. W-2, 1932.
NEW JERSEY
Quakertown
READING
Boyertown
Fritztown
HARRISBURG
Cornwall
SEDIMENTARY
ROCKS
Dillsburg
LANCASTER
TRIASSIC
PHILADELPHIA
Gettysburg
DELAWARE
MARYLAND
0 6 12 18 24 Miles
Scale

Lewis and Stose (1916 p. 623-643) described the diabase in the vicinity of Gettysburg, and Stose and Jonas (1939, p. 126-130) described the Triassic intrusions in York County, where they noted small isolated masses of (sic) "pink diabase or diabase pegmatite" in the diabase, and recognized these bodies as differentiates of the diabase magma.

During exploration of some magnetite deposits which occur as replacement bodies in Triassic sedimentary rocks near Dillsburg, Pa., a diamond drill encountered a body of diabase beneath the sedimentary rocks containing the magnetite. In the upper part of this intrusion a zone of pink granophyre grades transitionally above and below into apparently normal diabase. An unequalled opportunity was thus afforded to make a detailed petrographic study of the diabase and granophyre.

Many of the diabase intrusions exhibit a ring-shaped outcrop pattern (fig. 1) due to their curved sheet-like habit. Drill hole and geophysical data indicate that a discordant sheet-like habit is typical of the diabase intrusions in southeastern Pennsylvania rather than concordance as exemplified by sill structures.

THE DILLSBURG DISTRICT

Dillsburg is a small village in northeastern York County, Pennsylvania, about 15 miles southwest of Harrisburg (Fig. 1). From about 1855 to the early part of this century the district produced a small amount of magnetite ore from underground workings and shallow open cuts. Since about 1915 there has been no active mining.

General Geology

The areal geology of the Dillsburg district has been more or less completely described in several earlier reports. The magnetite mines were first described by Frazer (1877). A later detailed report was made by Spencer (1908, p. 74-96). An important discussion of the origin and somewhat different interpretation of the structure of the Dillsburg ore deposits was made by Harder (1910). Stose and Jonas (1939) prepared an excellent map and report on the geology of York County which included the Dillsburg district. Two recent articles on the results of diamond drilling exploration of the magnetite deposits have been prepared by Neumann (1947) and the writer ⌋.

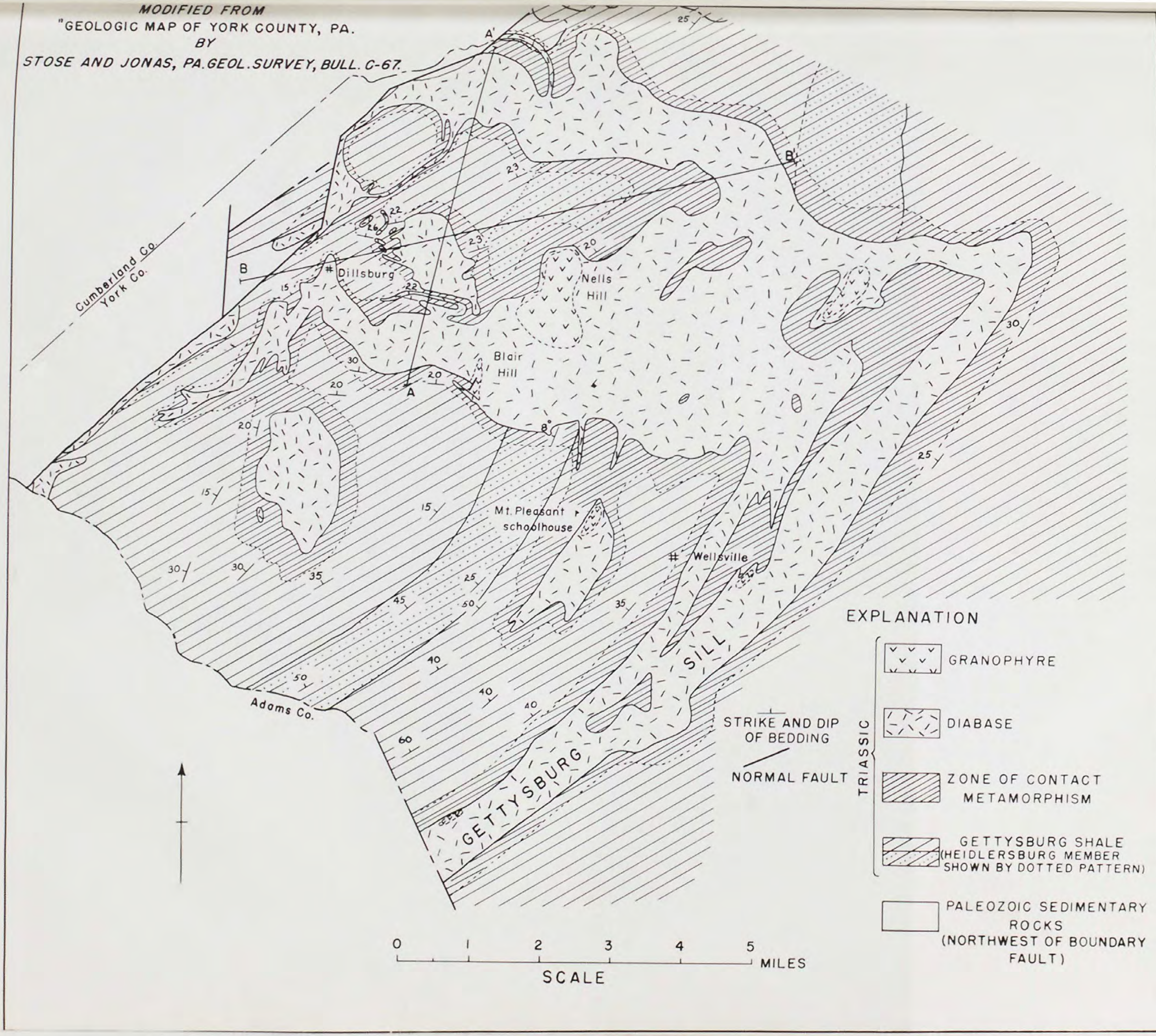
⌋ A report on the results of the diamond drill exploration of the Dillsburg deposits is in press at the U. S. Geological Survey.

The oldest rocks in the area, lower Paleozoic in age, lie northwest of Dillsburg and are in fault contact with the Triassic rocks (Fig. 2).

The sediments in this part of the Triassic basin are predominantly red shale and sandstone belonging to the Gettysburg shale. This formation is characterized by lenticular beds of limestone conglomerate whose constituent pebbles have been derived from the nearby Paleozoic rocks. The magnetite deposits occur as replacements of the limestone conglomerate. Within the formation there is also a belt of coarse arkosic sandstone and quartzose fanglomerate which has been mapped and described by Stose and Jonas as the Heidlersburg member of the Gettysburg shale. Adjacent to the intruded masses of diabase the normally red sedimentary rocks are bleached and metamorphosed to gray and buff hornstones and quartzites, and the limestone conglomerate is recrystallized to marble or replaced by silicates.

Figure 2 shows the distribution of diabase in the region surrounding Dillsburg. The main mass of diabase is continuous to the south with the 36 mile long, apparently conformable body known as the Gettysburg sill (Stose and Bascom, 1929, p. 11). Westward this large intrusive mass forms a ring almost completely enclosing the area of sedimentary rocks near Dillsburg. A small oval body of diabase intrudes the sedimentary rocks with the ring of diabase, as can be seen in the larger scale map of the Dillsburg district, figure 3.

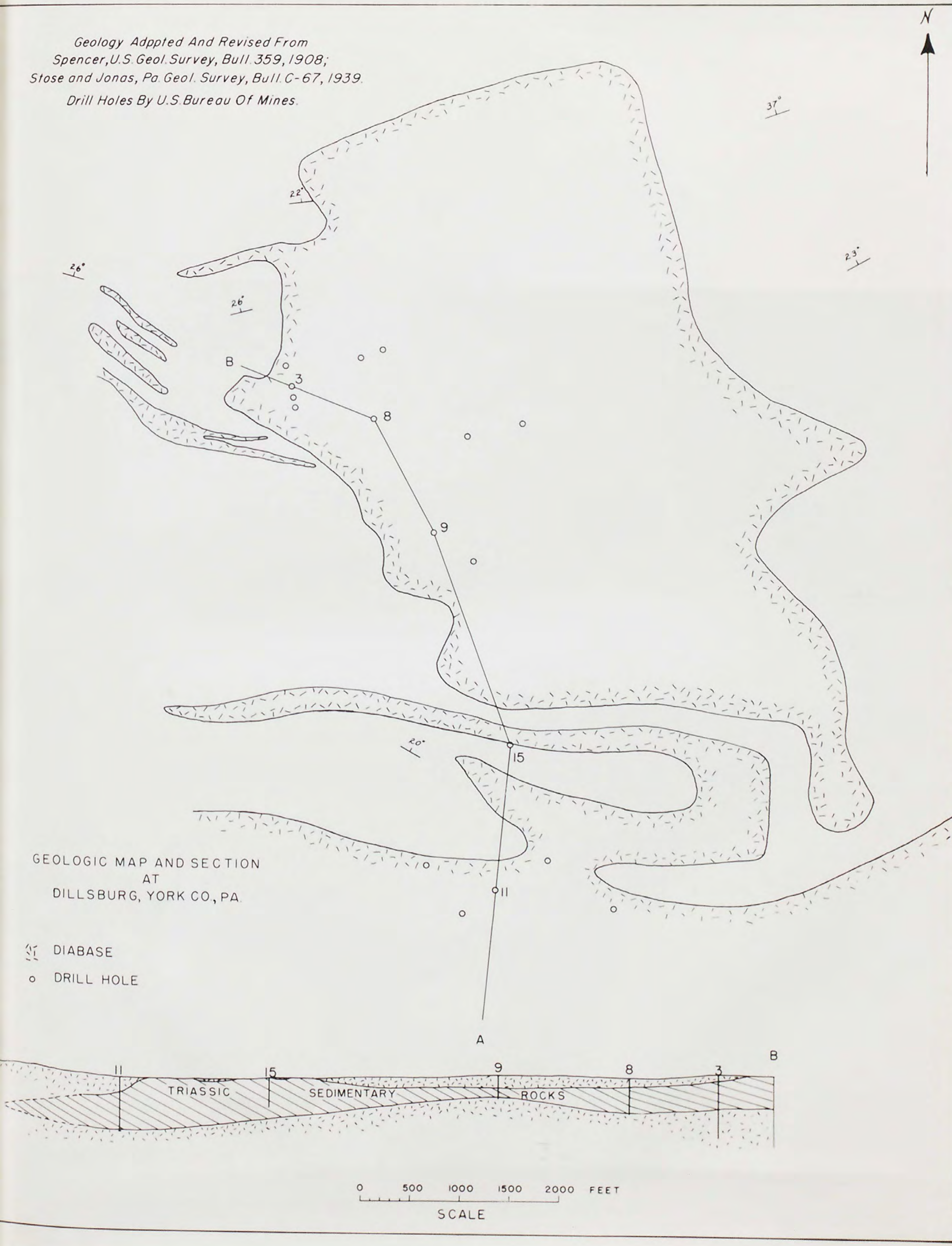
Figure 2. Geologic map of northwestern York County, Pennsylvania. See figure 16 for structure sections A-A', B-B'.



MODIFIED FROM
"GEOLOGIC MAP OF YORK COUNTY, PA.
BY
STOSE AND JONAS, PA. GEOL. SURVEY, BULL. C-67.
Cumberland Co.
York Co.
Adams Co.
Dillsburg
Nells Hill
Blair Hill
Mt. Pleasant schoolhouse
Wellsville
GETTYSBURG SILL
A
A'
B
B'
EXPLANATION
GRANOPHYRE
DIABASE
ZONE OF CONTACT METAMORPHISM
GETTYSBURG SHALE (HEIDLERSBURG MEMBER SHOWN BY DOTTED PATTERN)
TRIASSIC
PALEOZOIC SEDIMENTARY ROCKS (NORTHWEST OF BOUNDARY FAULT)
STRIKE AND DIP OF BEDDING
NORMAL FAULT
0 1 2 3 4 5 MILES
SCALE

Figure 3. Geologic map of the Dillsburg district,

York County, Pennsylvania



Geology Adppted And Revised From
Spencer, U.S. Geol. Survey, Bull. 359, 1908;
Stose and Jonas, Pa. Geol. Survey, Bull. C-67, 1939.
Drill Holes By U.S. Bureau Of Mines.
N
GEOLOGIC MAP AND SECTION
AT
DILLSBURG, YORK CO., PA.
DIABASE
DRILL HOLE
TRIASSIC
SEDIMENTARY
ROCKS
A
B
0
500
1000
1500
2000
FEET
SCALE

PETROGRAPHY OF THE DIABASE

Definition of Diabase

To avoid confusion it is desirable at the outset to clarify the use of the term diabase. As used here diabase includes hypabyssal rocks of basaltic composition having ophitic or subophitic texture commonly called dolerite by writers outside North America. Although the term now tends to be obsolete, European writers have reserved "diabase" for altered dolerites and pre-Tertiary rocks of basaltic composition whether hypabyssal or volcanic.

Field Character

Normal Diabase.- The normal diabase of the Triassic basins of the eastern United States is an exceptionally uniform rock type. It is commonly a gray, medium-grained rock of uniform texture. Fresh white feldspars laths intergrown with dark grayish green to black pyroxene, plus scattered black metallic granules of magnetite-ilmenite can usually be identified readily by the naked eye. The rock of the more quickly cooled smaller intrusion or the borders of large bodies is correspondingly larger, finer-grained and more dense.

Diabase Pegmatite.- Irregular masses of very coarse-grained diabase as much as several feet thick are scattered throughout the upper portions of the larger masses. From their appearance, occurrence, and genesis they are usually given the name diabase pegmatite. Walker (1940, p. 1065) writes of them as "pegmatite schlieren". Characteristically the pyroxene crystals are long and blade-like, attaining lengths up to three inches. The pyroxene usually has a bronzy luster and in many crystals twinning on (100) is visible. Some of the crystals are noticeably curved. The material between the pyroxene blades is chalky white feldspar, sometimes with some pinkish patches of orthoclase (?) and a little visible quartz. The third most conspicuous constituent is ilmenite-magnetite whose peculiar sketetal habit is visible with the aid of a hand lens.

Granophyre.- Granophyre is a less common rock type than the diabase pegmatite, but it is known at several localities. The occurrences of granophyre in the Dillsburg district are shown on the accompanying map (Fig 2). The masses are of irregular shape but tend to be elongate parallel to the long dimensions of the enclosing diabase body. As Stose and Jonas (1939, p. 27-130) have pointed out, they lie within but near the top of the diabase and under a cover of normal diabase.

In striking contrast to the gray diabase the granophyre is of a pale pink hue. The coloration is due to pink feldspar intergrown with quartz. Elongate green prisms of pyroxene and/or hornblende plus some black metallic grains are likewise plainly visible. The grain size ranges from fine to coarse. Miarolitic structure was observed in specimens of granophyre from some of the localities. The miarolitic cavities range in size from barely visible openings to spaces about an inch across. Projecting into the openings are crystals of feldspar and quartz, fibrous masses of hairlike amphibole, and small octahedra of magnetite. No miarolitic structure is present in any of the granophyre cut in the drill hole. The granophyre here is also somewhat finer-grained than that commonly seen at the surface.

Description of Relations in the Drill Hole✓

The units described in this section are summarized schematically in figure 4. The location of drill hole 3, the core of which furnished this detailed section through the granophyre, is shown in figure 3.

✓ All footages in the following descriptions are measured from the upper contact of the diabase.

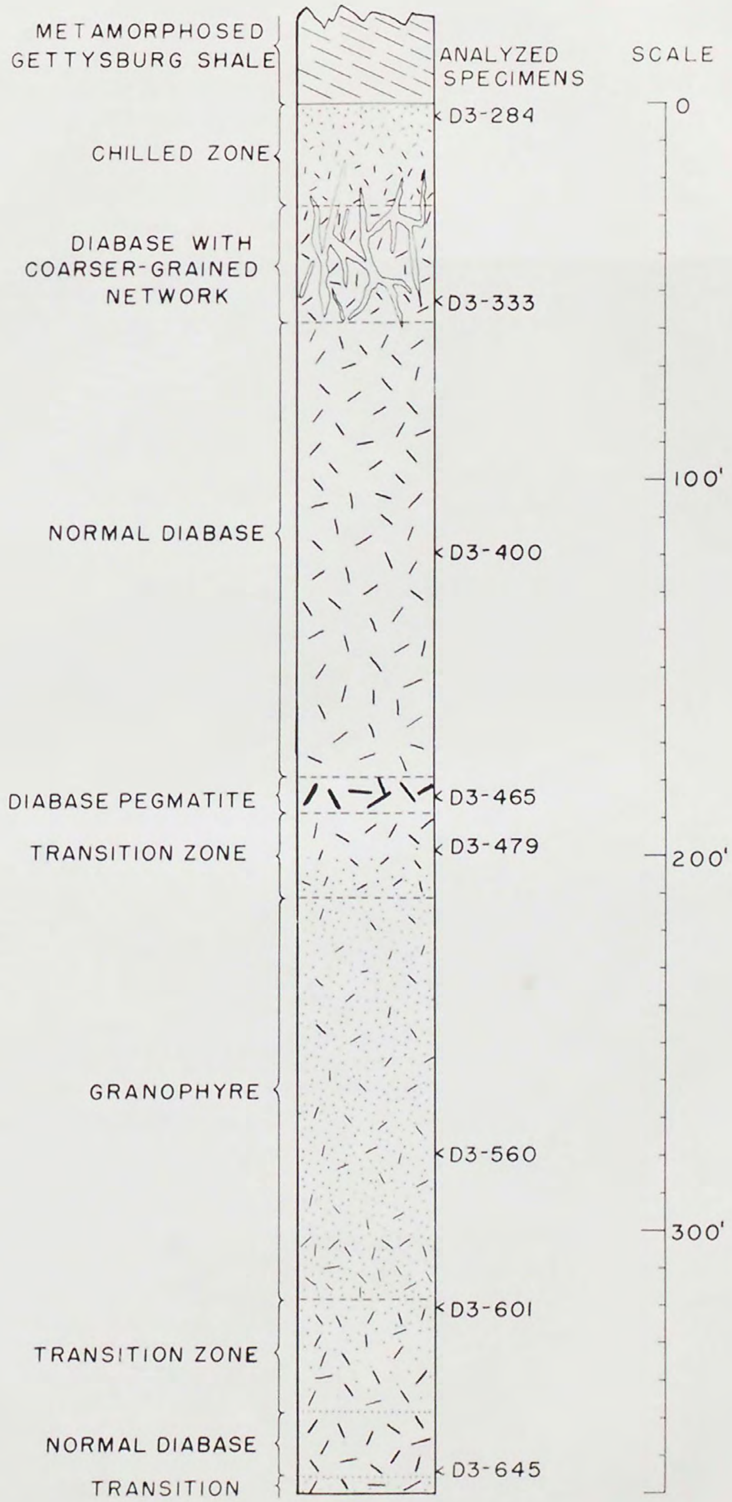
The top of the diabase in contact with the overlying metamorphosed sedimentary rocks is dark and very finely crystalline within a foot or so of the contact. The grain size gradually increases and the color lightens somewhat through a zone 25 to 30 feet from the contact. Compared to the rock in the rest of the drill core this zone constitutes the relatively fine-grained, rapidly-cooled upper chill facies. Within the lower part of this chilled zone and continuing down to about 58 feet below the upper contact the diabase has a somewhat heterogeneous texture with a meshwork of slightly coarse-grained material ramifying through the medium-grained rock. The coarser-grained material is also conspicuous because it has more feldspar and sketetal ilmenite-magnetite grains are confined to it. The coarse-grained meshwork gradually fades out in depth and the diabase is dominantly medium-grained.

From a depth of about 58 feet the diabase is uniform in appearance but gradually increases in grain size. Within the uniform rock there are occasional local coarse-grained layers 0.5 to 2 inches thick. The boundaries of the layers are not sharp but fade out by a decrease in grain size. Here and there the coarse layers show a tendency for crystal growth at right angles to the borders of the layers.

At a depth of about 179 feet a zone of very coarse, pegmatitic diabase 10 feet thick was encountered. In the lower 2 feet some distinctly pinkish feldspar is apparent.

Medium-grained granophyric diabase occurs below this pegmatite zone. It differs in appearance from the normal diabase in the presence of several percent of pale pink feldspar. This diabase changes downward gradually into pink granophyre. The top of the granophyre is taken somewhat arbitrarily about 211 feet below the upper contact of the intrusion.

Figure 4. Schematic representation of drill hole 3.


METAMORPHOSED GETTYSBURG SHALE
ANALYZED SPECIMENS
SCALE
D3-284
0
CHILLED ZONE
DIABASE WITH COARSER-GRAINED NETWORK
D3-333
100'
NORMAL DIABASE
D3-400
DIABASE PEGMATITE
D3-465
TRANSITION ZONE
D3-479
200'
GRANOPHYRE
D3-560
300'
D3-601
TRANSITION ZONE
NORMAL DIABASE
D3-645
TRANSITION

The granophyre is distinctly pale pink. It is considerably finer-grained than the overlying diabase and has a noticeably lower mafic mineral content. The megascopically visible mafics are light green pyroxene and black metallic grains, some of which on microscopic examination proved to be ilvaite. The pyroxene definitely tends toward prismatic development, and occasional long, plumose crystals are visible. The black "metallics" also tend to occur as elongate grains. The lower boundary is transitional and the lower limit of true granophyre was taken arbitrarily at a depth of 318 feet; the granophyre zone is thus about 107 feet thick.

Below the granophyre the diabase does not rapidly resume its normal aspect but over a distance of about 50 feet contains visible pink feldspar. Toward the very bottom of the drill hole the diabase is normal in appearance, but the last 5 feet drilled also showed some material with considerable pink feldspar. It is possible that more granophyre lies below the depth penetrated by drilling.

Petrography

Chilled Contact Facies.- The rock of the chill zone is holocrystalline throughout. Even that immediately at the contact contains recognizable crystalline phases, with no visible interstitial glass. Colorless to faintly greenish pyroxene is intergrown with laths of plagioclase in typical diabasic or subophitic texture. ✓

✓ True ophitic textures in which augite is in excess and occurs in large plates inclosing laths of plagioclase are practically nonexistent in these rocks. Most have a subophitic (Krökstrom, 1933a) or diabasic texture where the augite fills the interstices between lath-shaped crystals of plagioclase (Johannsen, 1939, p. 207).

Opaque "ore" occurs as tiny angular to subangular granules scattered uniformly through the rock and included in the plagioclase and pyroxene. A small amount of quartz occupies the interstices between earlier crystallizing constituents. A few microphenocrysts of pyroxene are visible as well as roundish masses of felted colorless amphibole and granules of magnetite which probably are secondary after olivine. Pale-green actinolitic amphibole replaces some of the pyroxene, and a few scattered flakes of biotite are present.

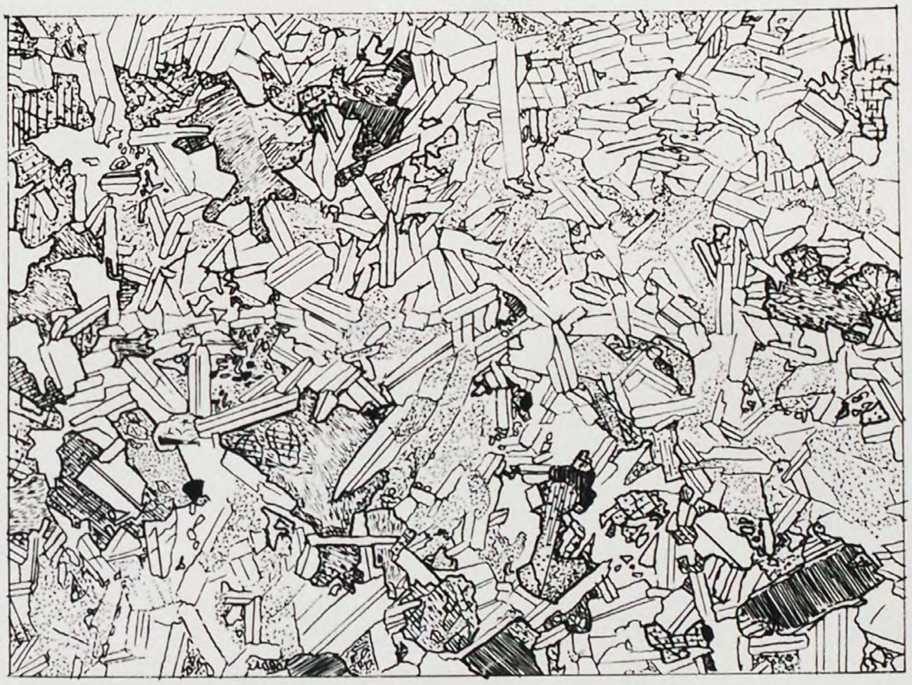
The average grain size of the rock of the chill zone at the contact is about 0.1 mm. Three feet from the contact the grain size increases to an average of 0.3 mm. and 15 feet from the contact the grain size reaches an average of 0.5mm.

Some thin sections from the lower part of the chill zone show that the diabase has undergone slight hydrothermal alteration; the pyroxene is partly clouded with flaky sericite and unidentified submicroscopic material of low birefringence. The rock is transected by occasional thin veinlets of chlorite, and scaly chloritic material occurs as a late-crystallizing mineral interstitial to the earlier plagioclase and pyroxene.

Diabase With Coarser Matrix.- The heterogeneous texture seen megascopically in the drill core specimens is also apparent in thin sections under the microscope (Fig. 6). The grain size on the average is about 0.2mm. The granularity of the coarser material shows more variation from section to section, the general range in grain size being from about 3.0 to 4.0 mm. Crystals of the coarse areas and finer-grained matrix interlock across the otherwise abrupt boundary. In no case does the coarse-grained diabase appear to be filling definite fractures in a finer rock. Both the matrix and coarser material possesses well-developed diabasic texture.

Figure 5. Normal diabase, 128 feet below upper contact, drill hole 3. Plagioclase, P; pyroxene, px; titanomagnetite, black. Sketched from photomicrograph. Ordinary light.

Figure 6. Pegmatitic area in fine-grained diabase. Note absence of well-defined boundary between diabase and pegmatite. From zone with coarse-grained network in fine-grained diabase, 46 feet below upper contact, drill hole 3. Plagioclase, P; pyroxene, Px; micropegmatite, m; chlorite, cl; titanomagnetite, black. Sketched from photomicrograph. Ordinary light.



1 mm.

1 mm.

Characteristically the plagioclase in this zone all shows more or less alteration, especially in some of the coarser-grained areas. In addition some micropegmatitic intergrowths of quartz and turbid alkalic feldspar make their appearance in the coarser material interstitial to the plagioclase and pyroxene. The pyroxene has a faint brownish tinge which it does not possess in the overlying chill zone, and many crystals have a patchy development of (001) parting. Two kinds of pyroxene, augite and pigeonite, are present. Augite shows some replacement by uralitic amphibole, and some interstitial green chlorite is also present.

Opaque ores are scattered through the rock and are especially prominent in the coarse material. They form large skeletal or grid-like crystals interstitial to the plagioclase and pyroxene and in part intergrown with the pyroxene.

Normal Diabase.- The normal diabase is very uniform in texture throughout the entire section cut by the diamond drill. Its grain size is very constant, averaging about 1 mm., with a tendency toward an increase in the lower part of the section. Pyroxene (augite and pigeonite) and plagioclase are intergrown in typical diabasic texture and there is some interstitial micropegmatite. (Fig. 5). The plagioclase is mostly fresh but every section examined showed at least some turbid alteration of parts of some crystals. Brownish augite with a characteristic fine parting parallel to (001) is intergrown polysomatically, the individual crystal members of the mosaic having different optical orientations. Besides the brownish augite there is colorless pigeonite which in part has inverted to grayish-green hypersthene. Skeletal magnetite-ilmenite crystals are in all cases present as a minor constituent.

The downward transition from normal diabase to diabase pegmatite is heralded by an increase in the amount of interstitial micropegmatite, severe alteration of the plagioclase, and development of rims of hornblende about the augite. The texture remains the same and the coarse pegmatite comes in abruptly with little or no real gradation from the normal diabase.

Diabase Pegmatite.- The diabase pegmatite differs from normal diabase in its much coarser grain, hypidiomorphic texture, and alteration of the primary minerals plus a larger amount of interstitial micropegmatite and coarse, skeletal crystals of ilmenite-magnetite (Fig. 7).

Purplish-brown augite which tends to form elongate crystals averaging over 3mm. in length and reaching a maximum in excess of 7.5mm. is the principal pyroxene; less than 5 percent of original pigeonite is present. The crystals are mostly single individuals rather than polysomatic groups. Many are twinned on (100), all have a well-developed (001) parting. The pyroxene has reaction rims of brown hornblende where it is in contact with the interstitial micropegmatite.

The original large plagioclase crystals (average length, 4mm.) are now mostly turbid with gray alteration products; only the central portions of the largest crystals are still clear and fresh.

Opaque ore is abundant in large skeletal crystals some of which are intergrown with and molded on plaglioclase and pyroxene. Usually it is accompanied by green to brownish-green stilpnomelane (?). Besides the primary skeletal ore there are blebby grains of magnetite associated with the hornblende reaction rims around pyroxene.

Apatite is abundant as long, acicular prisms.

Figure 7. Diabase pegmatite, 184 feet below upper contact, drill hole 3. (Thin section is from same specimen as analysis 465.) Plagioclase, p; pyroxene, px; hornblende, hb; micropegmatite, m; titanomagnetite, black. Sketched from photomicrograph. Ordinary light.

Figure 8. Transitional granophyric diabase. Note abundance of quartz (clear, irregular areas) as individual grains and in micropegmatite, and generally altered character of the feldspar. Chlorite veinlet in upper half, clear veinlet of albite in southwest quadrant. From lower transition zone 337 feet below upper contact, drill hole 3. Plagioclase, p; pyroxene, px; hornblende, hb; micropegmatite, m; quartz, q; chlorite, cl; stilpmomelane, st; titanomagnetite and ilvaite, black. Sketched from photomicrograph. Ordinary light.

1mm.

1mm.

Transitional Granophyric Diabase.- (Fig. 8) The rocks from the transition zones above and below the granophyre bear a closer resemblance to diabase than granophyre. Texturally they are similar to the normal diabase. They are composed of purplish-brown clinopyroxene intergrown with plagioclase, but contain no pigeonite. Interstitial micropegmatite is abundant and increases in volume toward the granophyre.

The plagioclase is invariably gray and turbid with alteration products, but the outlines of the original large crystals are clearly visible. Reaction rims of brown and green hornblende border much of the pyroxene and locally wholly replace it. The pyroxene shows partial bleaching to pale green and an absence of the prominent (001) parting adjacent to the hornblende. Near the granophyre small amounts of darker green pyroxene (hedenbergite) occur as elongate, ragged crystals in the micropegmatite. These appear to be the same as the pyroxene which characterizes the granophyre.

Illmenite-magnetite in irregular, skeletal grains is plentiful. Acicular apatite is an abundant minor accessory. Substantial amounts of stilpnomelane (?) and other chloritic materials occur in irregular masses interstitial to the other minerals.

The change to true granophyre from a rock with many of the characteristics of diabase yet with features also possessed by the granophyre takes place abruptly, that is, within a distance of some 4 feet. The rapid change is more apparent in thin section than megascopically. The amount of pyroxene rapidly diminishes, the brownish variety with the (001) parting disappears and gives way to the pale-green hedenbergitic pyroxene which characterizes the granophyre. One of the most important changes, of course, is the great increase of micropegmatite.

Granophyre.- As the name implies the texture of this rock is granophyric, that is, the euhedral to subhedral feldspar and pyroxene are set in a matrix of micrographically intergrown quartz and feldspar. (Fig. 9). Some of the quartz is not micrographically intergrown with feldspar but occurs as individual anhedral grains. The crystallinity is more variable than in the normal diabase, ranging from about 0.20 mm. in the finest-grained rock to nearly 0.40 mm. average grain size. The granophyre is finer-grained in general in the upper than in the lower part of the layer.

Feldspar, quartz, and hedenbergitic pyroxene are the principal mineral constituents. The euhedral plagioclase is gray and turbid due to alteration. In many instances it is in optical continuity with the feldspar of the micropegmatite, which often completely surrounds a lath of plagioclase. The pyroxene is much less plentiful than in the diabase, amounting to only about 5 percent. It tends strongly toward an elongate or plumose development, and some crystals have lengths a score or so times their width. Most are unaltered except for local replacement by hornblende or finely crystalline scaly green stilpnomelane (?) along their borders. Usually they enclose some granules of magnetite.

Opaque iron ore in irregular skeletal grains is the most prominent minor accessory. Associated with it is the hydrous calcium iron silicate, ilvaite. Scaly greenish masses of stilpnomelane (?) are also common, occurring in part with the interstitial micropegmatite and often with the ilmenite-magnetite.

Besides these mineral accessories there are ubiquitous but small amounts of acicular apatite and occasional grains of epidote. Calcite, interstitial to all the other minerals, is occasionally seen. A few grains of colorless zircon have been recognized.

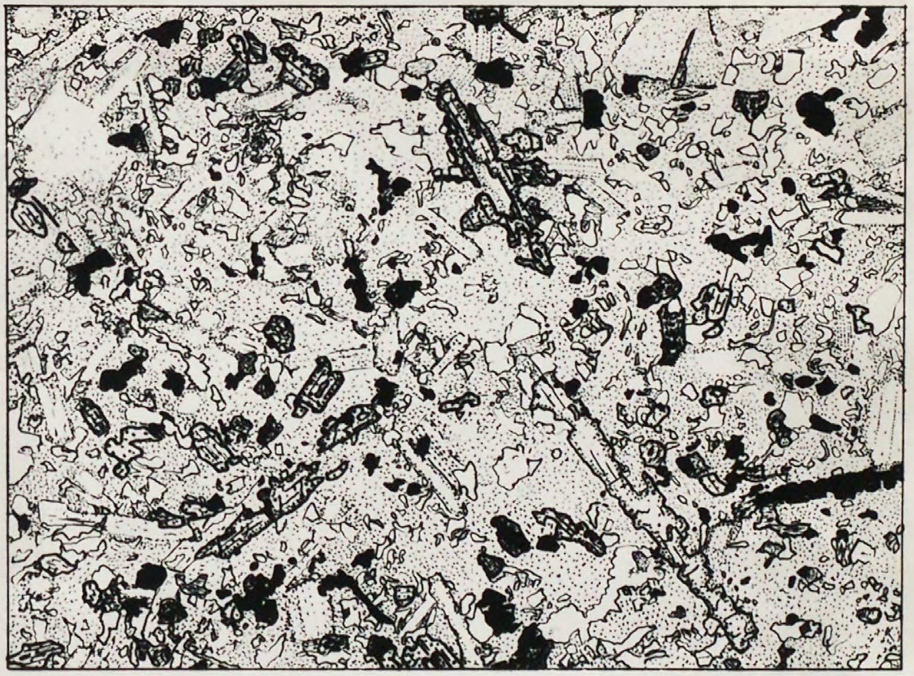


Figure 9. Granophyre. Note abundant quartz, generally clouded character of the feldspar, and peculiar form of the pyroxene. The elongate opaque grain in the lower right corner is mostly ilvaite. From granophyre zone, 299 feet below upper contact, drill hole 3. Plagioclase, p; pyroxene, px; quartz, Q; titanomagnetite and ilvaite, black.

MINERALOGY

Olivine

Olivine occurs only in the chilled border facies of the diabase. It is present in the quickly cooled contact zones of the diabase masses, such as the sheet overlying the sedimentary rocks at Dillsburg and on the contacts of the main intrusive. No concentration of olivine has been reported toward the bottom of the Gettysburg sill like that near the base of the Palisades sill in New Jersey.

Alteration has completely destroyed the original olivines in the upper chill zone of the main diabase. However specimens from the chilled lower border of the main Gettysburg sill and the base of the offshoot from the main sill near Rossville have relatively fresh olivine. It is reasonable to assume that the composition of these olivine crystals is the same as the altered olivines which crystallized early and were trapped in the upper chilled zone of the lower diabase.

The "fresh" olivine granules form irregular or rounded microphenocrysts having an average diameter of about 0.3mm. and ranging from 0.1 mm. to 0.5 mm. in diameter. They are colorless and unzoned. All show at least slight alteration to magnetite, chlorite material, and serpentine. Because of the scanty amounts and the small size of they crystals, the olivine was not separated for refractive index determinations. The optic angle is negative and is very constant at 87^{o} $\pm 2^{o}$. According to Wager and Deer's diagram showing variations in composition and optical properties of the olivine series (Wager and Deer, 1939), its composition is close to Fo_{80} Fa_{20}, the same as the olivine occuring in the chilled zone at the bottom of the Palisades sill, (Walker 1940).

Feldspar

Plagioclase accounts for about 47 percent by volume in the chilled border facies, from 45 to 50 percent in the normal diabase, and about 18 percent in the granophyre.[/]

[/] If the plagioclase intergrown with quartz in micropegmatite were included the amount would be considerable higher. However, the micropegmatite intergrowths are considered as an individual mineral constituent in itself.

The plagioclase 2 feet from the contact shows slight zoning of the normal type with an average composition of about An_{65} (labradorite); the most calcic plagioclase measured is about An_{70}. In the zone of fine diabase with coarser-grained network, the plagioclase of the finer-grained portion is labradorite (composition An_{60-65}); the plagioclase of the coarser network shows more pronounced normal zoning with a range of from An_{55} in the cores to about An_{30} for the rims. The composition of the plagioclase is relatively constant throughout the normal diabase; it is labradorite (An_{58} to An_{67}) averaging about An_{62} and exhibits normal zoning.

Although the plagioclase in the diabase pegmatite is largely altered, there is a central area of clear feldspar in the larger individuals with the composition of labradorite (ca. An_{55}), the same as that in the coarser network in the heterogeneous diabase just below the upper chill zone.

Much of the feldspar in the rocks from the transitional granophyric diabase is so completely sericitized and kaolinized it is difficult to determine. However, some of it is fresh and optical data indicate that it is andesine (An_{45-47}). Normal zoning is obvious in the larger crystals, with cores about An_{45}, the outer parts An_{35}.

All the feldspar in the granophyre is turbid and many grains are conspicuously zoned with gray cores surrounded by a rim of somewhat darker brownish feldspar containing an abundance of almost submicroscopic hematite. Albite twinning and combined carlsbad-albite twinning are common, but the albite twinning is not as clearly developed as in the diabase. The rims are optically continuous with the brownish feldspar which forms micrographic intergrowths with quartz. This brownish feldspar usually shows fine chessboard or gridiron twinning. From optical data the plagioclase was determined to be albite to oligoclase (An_5 to An_{15}).

Micropegmatite

In the normal diabase interstitial micrographic intergrowths constitute a small part of the rock. Micropegmatite disappears in the upper chilled zone and is present only in the coarser-grained material forming the network in fine-grained diabase in the rock below the chilled contact zone and overlying the normal diabase. Quartz and micropegmatite are more abundant in rock from the transition zones and diabase pegmatite than in normal diabase, and in the granophyre they assume the role of essential constituents.

The micropegmatite occurs in the interstices between the earlier-crystallized components of the diabase, plagioclase and pyroxene. Some of the quartz occurs alone but micrographic intergrowths with feldspar are the rule. The exact composition of the feldspar is not known because it is so fine-grained and clouded with submicroscopic inclusions that it is difficult to obtain accurate optical data. With crossed nicols patchy, discontinuous albite twinning and some pericline twinning can be seen. This and the fact that in many places the feldspar is in optical continuity with earlier plagioclase crystals indicates that it is probably a sodic plagioclase. Analyses (Table 5) of the normal diabase and diabase pegmatite (which has an abundance of micropegmatite) show that soda is clearly dominant over potash, suggesting that the feldspar is sodic plagioclase containing a high content of the potash feldspar molecule.

In the granophyre there is much micropegmatite which is so abundant that in many instances it completely surrounds earlier feldspar crystals in such a way that the earlier crystals stand as euhedral islands surrounded by a "sea" of micropegmatite. The feldspar of the micropegmatite in such instances is optically continuous with that of the "islands". The quartz of the micrographic intergrowths is also optically continuous over wide areas, and in some cases has the same orientation as quartz which may be intergrown with the feldspar cores. Not all the quartz is confined to intergrowths with feldspar. Much of it occurs in larger discrete grains each having a different orientation, and is more abundant than the feldspar which lies between the grains. In the granophyre the quartz and micropegmatite are of later crystallization than the pyroxene and plagioclase.

Measurements of thin sections show that the ratio of quartz to feldspar in the micropegmatite intergrowths is very constant throughout the drill-hole section, whether the intergrowth is in diabase or granophyre. In general, as Table 1 shows, the proportion is about 4 quartz to 6 feldspar.

Table 1

Quartz-feldspar ratios in micropegmatite

Specimen	Percent Quartz (volume)	Percent Feldspar (volume)	Rock
333	45.5	54.5	Diabase with coarser network
409	44.8	55.2	Diabase
465	42.2	57.8	Pegmatite
479	39.0	61.0	Transitional granophyric diabase
645	39.7	60.3	
560	39.3	60.7	Granophyre
601	40.3	59.7	
Average (volume)	40.9	59.7	
(weight)	41.4	58.6	

Pyroxene

Pyroxene of the Upper Chilled Zone.- The single variety of pyroxene in the uppermost microcrystalline chilled-contact facies of the diabase is colorless augite. The optical data are given in Table 2. Pigeonite, the low-lime clinopyroxene is first recognized in the lower part of the chilled zone. It is colorless and characterized by a very small optic angle. Both augite and pigeonite are colorless and intimately intergrown so that a grain which under ordinary light appears to be a single crystal of augite may be made up of both augite and pigeonite. Augite is the more abundant variety.

Table 2

Optical Properties of Pyroxenes From the Diabase-Granophyre Sequence

	Chill Zone		Normal Diabase		Skaer-gaard #VI	Pegma-tite		Transition Zones		Granophyre		Skaer-gaard #V
No.	1	2	3	4		5	Dil.-3	6	7	8	9	
Specimen	D-9-46	D3-296	D3-400	D3-440		D3-465		D3-645	D3-479	D3-601	D3-560	
α	1.681	1.683	1.684	1.687	1.684	1.692	1.697	1.702	1.711	1.721	1.722	1.721
β	1.685	1.687	1.690	1.693	1.692	1.699	1.701	1.707	1.720	1.728	1.729	1.728
γ	1.705	1.709	1.711	1.715	1.712	1.720	1.723	1.729	1.740	1.750	1.751	1.749
γ - α	0.024	0.026	0.027	0.028	0.028	0.028	0.026	0.027	0.029	0.029	0.029	0.028
Dispersion	r > v	r > v	r > v	r > v	r > v	r > v	r > v	r > v	r > v	r > v	r > v	r > v
z c	42°	43-½°	nd	nd	39°	47°	44-½°	nd	47°	45-½°	49°	39°
2V (+)	48°	49°	56° (zoned, 45° to 60°)	52° (zoned; core, 45-½° rim 59°)	46°	59°	43-½°	62°	61°	60°	61°	44°
Molecular % Wo	41	41	46½	43	39	50	34-½	50	50	48	48	46
Em	49	47	43-½	43	47	33	37	27-½	17	7-½	7	3
Fs	10	12	10	14	14	17	28-½	22-½	33	44-½	45	51

Skaergaard VI, Wager and Deer (1939), p. 152

Skaergarrd V, Wager and Deer (1939), p. 77

Pyroxene of the Normal Diabase.- The most abundant variety is augite which has a distinctly purplish-brown hue, suggesting a small amount of titanium in its composition. Finely-spaced parting parallel to (001) is a characteristic feature. Using the oil immersion lens it can be seen that there are minute grains and plates of a black to dark-brown mineral, possibly rutile or ilmenite, lying along these partings. "Hour-glass" zoning is rare. In some cases the augite is twinned on (100). The optical data for the augite are listed in Table 2.

Pigeonite as such is scanty in the normal diabase beneath the chill zone. Its former presence is indicated by irregular greenish-gray, finely striated masses intergrown with the brownish augite. Under ordinary light these masses appear to be composed of a greenish alteration product. However, they show sharp, smooth, though irregular boundaries against the augite and under crossed nicols fine lamallae can usually be seen. Using high magnification, one sees that the lamallae, though still very narrow, all have the same optical orientation and are usually optically continuous with the enclosing augite. They also have the same birefringence as the augite. The greenish-gray material between the lamellae is optically continuous but has a different orientation than the lamellae and a considerably lower birefringence. Unfortunately the lamellae and intervening areas of host mineral are too closely spaced and too narrow themselves to enable interference figures to be obtained from them. A few of these greenish-gray masses have some clear unaltered pigeonite in them. Apparently these altered-appearing patches were originally pigeonite which crystallized with the augite. Their low-birefringent host is probably hypersthene. During cooling of the intrusive the clino-pyroxene lamellae were exsolved from pigeonite and the pigeonite subsequently inverted to hypersthene (Hess 1941, p. 580-581).

Because of the scarcity of fresh pigeonite no index data were obtained for it. Measurements of its optic angle show it to be small, but larger than that from the chilled facies; 2V is variable but averages about 18°. The optic plane is perpendicular to (010).

Some replacement of augite by hornblende has taken place, especially along the edges of the crystals. The replacement is invariably accompanied by bleaching of the augite giving irregular, patchy areas of colorless to very pale green pyroxene flecked with small plates of pale-green hornblende and devoid of the close-spaced (001) parting. The colorless augite is optically continuous with the purplish pyroxene, and apparently has the same index of refraction and optic angle.

<u>Pyroxene of the Pegmatite</u>.- Most of the pegmatite pyroxene is a distinctly purplish-brown augite, while there appears to have been only about 5 percent or less original pigeonite.

The augite is intergrown with the plagioclase in large euhedral crystals many of which are elongated parallel to "c", with length several times their width. The elongate crystals are commonly twinned on (100) which, together with well-developed (001) parting gives them a distinctive "herringbone" structure. The original pigeonite which crystallized with the augite has inverted to hypersthene with exsolved lamellae of clinopyroxene. It appears as small greenish-gray areas within the brown augite.

Hornblende partly or sometimes wholly replaces the augite and occurs as a reaction rim between the pyroxene and interstitial micropegmatite.

Pyroxene of the Transition Zones.- Throughout most of the transition zone only one species of pyroxene is found. It is a purplish-brown clinopyroxene (salite to ferrosalite in composition) similar in general appearance and habit to that of the normal diabase. No pigeonite was found and no relics which might be interpreted as having once been pigeonite were seen. However, in the granophyric diabase a few feet from the granophyre there are, besides the purplish-brown pyroxene, a few small, scattered, crystals of relatively late crystallization which are clear, greenish and look like the hedenbergitic pyroxene in the granophyre.

Unlike the augite of the normal diabase, many continuous areas of pyroxene in the transition-zone rocks are actually made up of several individuals of differing orientation. This structure, which has been called polysomatic by other writers, is more common in the lower part of the transition zone. Occasionally a crystal of pyroxene is markedly curved; the bending took place during growth because there is no evidence of deformation of the surrounding fabric.

Most of the pyroxene crystallized more or less simultaneously with the plagioclase, but some of it continued to grow after the feldspar had ceased to crystallize, so that it projects into the interstices in which micropegmatite crystallized subsequently. Similarly, most of the augite finished its crystallization before the magnetite-ilmenite began, but there was some overlap so that a little of the pyroxene is partly intergrown with the metallics. Much of the pyroxene is partly replaced by hornblende and is locally bleached from brown to nearly colorless.

There is no evidence that the clear green hedenbergitic pyroxene which appears in the transition-zone rock near the granophyre has any genetic relationship to the brownish pyroxene. The hedenbergite comes in abruptly and shows no intergrowth with the brown pyroxene, but appears to have crystallized somewhat later.

Pyroxene of the Granophyre.- Even in hand specimens it is apparent that the pyroxene of the granophyre is different from the augite of the diabase and diabase pegmatite. In thin section the pyroxene is a pale-green, faintly pleochroic to nearly colorless hedenbergite. An elongate to plumose development is characteristic. Many of the crystals are elongate, highly irregular, and poikilitically enclose earlier minerals. (See Fig. 9). Some consist of several relatively small individual grains in optical continuity.

Throughout most of the section of granophyre the pyroxene is remarkably fresh and clear except for some small inclusions of opaque ore. In some cases there is replacement by hornblende and to a minor extent biotite, but it is not until the lowermost part of the zone is reached that alteration to hornblende becomes important. Here there is partial replacement by emerald-green hornblende.

Composition of the Pyroxenes.- The approximate compositions of the pyroxenes expressed in molecular proportions of wollastonite ($CaSiO_3$), enstatite ($MgSiO_3$), and ferrosilite ($FeSiO_3$) have been determined from their optical properties. The refractive indices were determined by the immersion method using monochromatic light from a sodium vapor lamp. The size of the optic angle was measured with the universal stage. Unpublished data by H. H. Hess correlating composition with optical properties were used to arrive at the approximate composition. The index of B, which is perhaps the most easily and accurately determined optic property, was plotted against 2V. It is known that the optic angle is affected somewhat by the presence of minor constituents such as Al_2O_3, therefore the compositions as plotted are only approximate but they are suitable for comparative purposes.

The optical data are summarized in Table 2 and the compositions are plotted on a triangular diagram, figure 10.

The pyroxene from the upper chill zone is a relatively magnesian augite (No. 2). This may be compared with the pyroxene from a specimen taken a short distance above the basal contact of the Gettysburg sill (No. 1). The composition of the latter is somewhat higher in En than that from the upper chilled border.

The composition of augites (Nos. 3, 4) in specimens from the normal diabase zone fall in the same general position on the diagram as the pyroxenes from the chill zone, except that the pyroxene (No. 4) from the lower part of the normal diabase zone is slightly richer in iron. The optic angles of these and other augites from the normal diabase are a little large and noticeably variable even in a single crystal, yet there is no visible zoning. Values range from 45° to 60° and average between 52° and 56°, the interior of the crystals having a smaller 2V than the outer part. This variation may be due in part to Al_2O_3 or TiO_2, which are known to affect 2V. The pyroxene has a definitely purplish-brown color which is characteristic of titaniferous augites.

For comparison an analyzed pyroxene from the Skaergaard intrusive (Wager and Deer, 1939, p. 152, Skaergaard VI) with the same general optical properties as the augite from the normal diabase and chill zone is listed in Table 2 and plotted on figure 10.

Because of the scarcity of fresh pigeonite no index data were obtained for it. Its optic angle is small and variable but averages about 18°. Hess has noted (1941, p. 585) that "...if a line joining the two pyroxenes of a given specimen be extended upwards to the En-Wo composition line it will intersect that line at approximately En_{25}-Wo_{75}..." and "...it may be used to predict the composition of one pyroxene...if the other pyroxene be known from chemical analysis or by determination from optical properties..." If we apply this rule of thumb, the approximate composition of the pigeonite accompanying the augite is obtained. (See Fig. 10).

Table 3

Chemical Analyses of Pyroxenes

	Skaergaard VI				Skaergaard V					Dil. 3 _/				
	Wt. %	Mol. ratios	Atomic ratio to 6(O,OH)		Wt. %	Mol. ratios	Atomic ratio to 6(O,OH)			Wt. %	Mol. ratios	Atomic ratio to 6(O,OH)		
SiO_2	50.39	0.8387	1.836		46.54	0.7749	1.867			50.64	0.844	1.94		
Al_2O_3	3.54	0.0347	0.152	1.99	5.77	0.0575	0.287	0.133	2.00	2.12	0.021	0.096	.073	2.01
TiO_2	0.87	0.0109	0.024		1.22	0.0153	0.037	0.145		0.75	0.009	0.021	.023	
Fe_2O_3	1.95	0.0122	0.053		1.88	0.0118	0.057			0.83	0.005	0.023		
FeO	8.47	0.1179	0.258		24.65	0.3431	0.827			17.39	0.241	0.554		
MnO	0.19	0.0027	0.006	1.98	0.74	0.0104	0.025		1.96	.37	0.005	0.011		1.97
MgO	15.82	0.3923	0.859		0.79	0.0197	0.048			12.86	0.321	0.738		
CaO	18.41	0.3283	0.719		17.70	0.3156	0.761			14.34	0.256	0.588		
Na_2O	0.70	0.0113	0.049		0.62	0.0100	0.048			0.20	0.003	0.014		
K_2O	0.14	0.0015	0.008		0.15	0.0016	0.008			0.00				
H_2O+	0.11				0.39					0.22				
H_2O-	0.04				0.18					0.08				
	100.63				100.53					99.80				

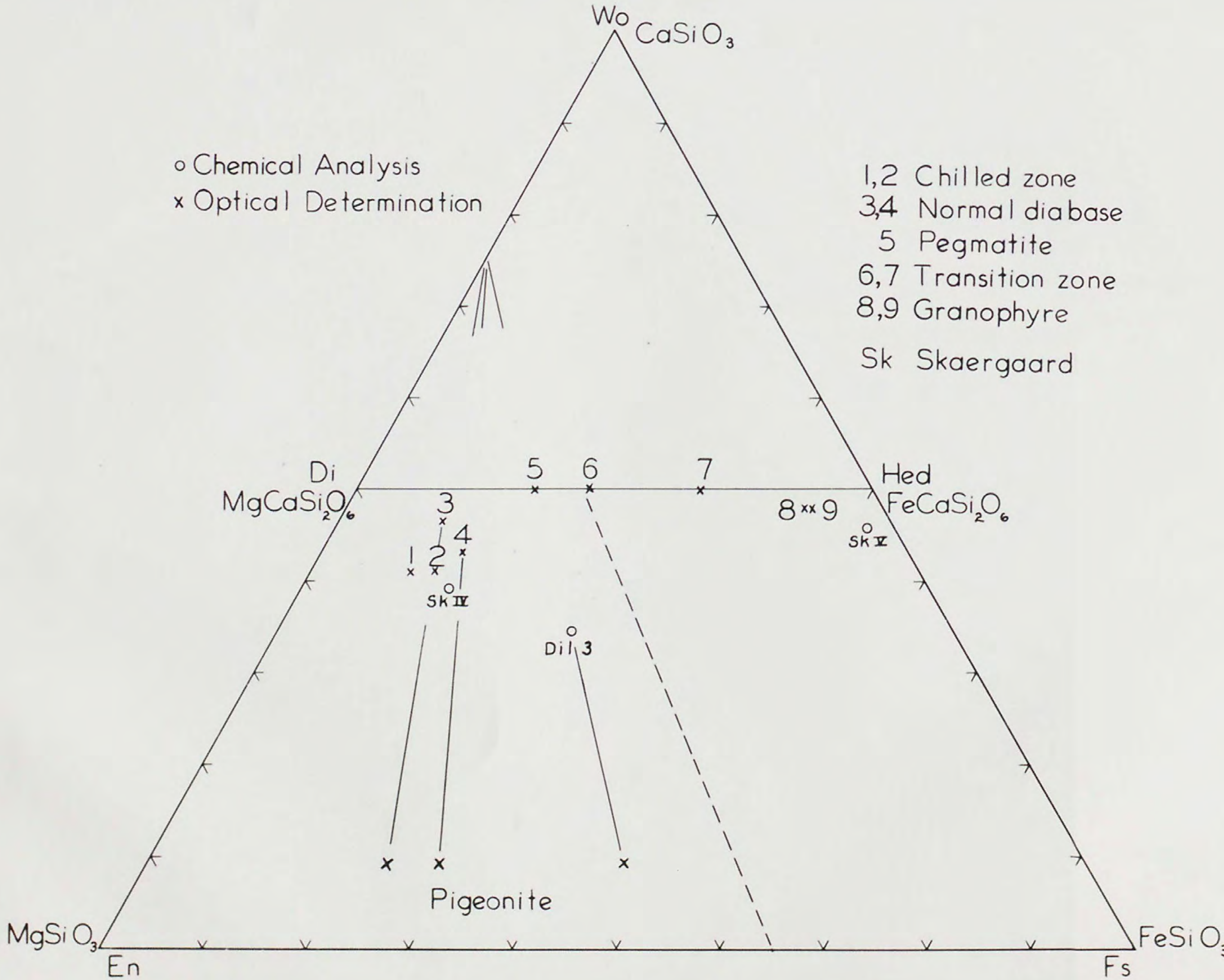
Analyst W. A. Deer — W. A. Deer — L. C. Peck

Skaergaard V, Wager and Deer (1939), p. 78

Skaergaard VI, Wager and Deer (1939), p. 152

_/ Contains a small amount of pigeonite as impurity.

Figure 10. Triangular diagram showing composition of the pyroxenes in molecular percent of wollastonite ($CaSiO_3$), enstatite ($MgSiO_3$), and ferrosilite ($FeSiO_3$).


Wo CaSiO3
o Chemical Analysis
x Optical Determination
1,2 Chilled zone
3,4 Normal diabase
5 Pegmatite
6,7 Transition zone
8,9 Granophyre
Sk Skaergaard
Di MgCaSi2O6
Hed FeCaSi2O6
5
6
7
3
4
1
2
8
9
Sk IV
Sk V
Dil 3
Pigeonite
MgSiO3 En
FeSiO3 Fs

The optic angle of the pyroxene from the drill hole pegmatite (no. 5) is large (2V - 59°), which places it on the diopside-hedenbergite join (salite). It is higher in lime and iron than the pyroxene of the normal diabase but lower in iron than similar-appearing pyroxene from the transition zone. Although the refractive indices are similar to those of an analyzed pyroxene (Dil-3) from a coarse-grained diabase dike from the Dillsburg district, the 2V is larger. The analysed mineral (Dil-3) with 2V = 43-½° is augite lying on or near the augite curve of Hess. (See Fig. 10).

On the basis of their optical properties the pyroxenes from the transition zones are ferrosalite and salite (Nos. 6 and 7). They consistently have optic angles in the neighborhood of 60°. They are also richer in the ferrosilite molecule than are pyroxenes from normal diabase and its chill zone.

The pyroxene from the granophyre (Nos. 8 and 9) is relatively rich in iron, low in magnesia, but high in lime. Like the pyroxene from the transition zones, 2V is large (60°) which, with the index of refraction, indicates a composition near the end member hedenbergite. For comparison the optical properties of an analyzed pyroxene from some of the later-stage crystallization products of the Skaergaard intrusion (Wager and Deer, 1939, p. 77, Skaergaard V) is included in Table 2 and its composition plotted on the diagram, figure 10. The indices of refraction are similar to those of the granophyre pyroxene but the optic angle as given by Wager and Deer is much smaller, though according to its composition it should have a 2V of near 60°. Wager and Deer (1939, p. 111) have postulated that the hedenbergite was formed by inversion from β-wollastonite of the solid solution series $CaSiO_3$-$FeSiO_3$. Bowen, Schairer and Posnjak (1933) have shown that β-wollastonite separates from melts in the system CaO-FeO-SiO_2 and inverts to hedenbergite at temperature between 940° and 980°C.

Ilmenite-magnetite.- Ilmenite and magnetite are, of course, present throughout the diabase and granophyre but their abundance as well as the nature of their development vary in the different zones. In thin section both are opaque to transmitted light and cannot be distinguished and so are listed as ore minerals, opaques, or ilmenite-magnetite. Polished surfaces of specimens from each of the principal zones of the diabase and granophyre were examined in reflected polarized light with a metallographic microscope. This and the use of concentrated hydrochloric acid etch tests made possible to distinguish magnetite from ilmenite.

In the upper chilled zone the metallic grains are very small and more or less evenly distributed through the rock. Individual anhedral grains of magnetite and ilmenite can be recognized but because of their small size it is not possible to tell whether the magnetite is pure or has exsolution lamallae of ilmenite. No ilmenite lamallae in magnetite were observed, but a few of the larger grains consist of intergrown ilmenite and magnetite.

In the normal diabase the size of the metallic grains increases. Ilmenite occurs in two forms: as individual anhedral grains intergrown with titanomagnetite, and as very fine, exsolved lamallae and rods within titanomagnetite. There appear to be about equal amounts of ilmenite and titanomagnetite. Most of the grains occur as local aggregates of intergrown ilmenite and titanomagnetite, but occassionaly as individual grains. The ilmenite and titanomagnetite are roughly equal in amount; the total intergrown ilmenite plus exsolved ilmenite is in excess of magnetite. The grains are anhedral and occupy an interstitial position to the silicates though occasionally they are intergrown with and partly enclosed by the outermost part of some of the pyroxene. They are usually associated with late, interstitial chlorite with which the ilmenite may have a dactylitic or sub-graphic intergrowth.

Titanomagnetite and ilmenite are most abundant in the diabase pegmatite and transition zones. They occur intimately intergrown with each other as large anhedral and typical skeletal bodies interstitial to and molded on pyroxene and plagioclase, but in part intergrown and enclosed by them. Most of the ore is partly intergrown with late-stage silicates and partly with micropegmatite; it occurs on the edges of the large interstitial micropegmatite areas suggesting that the bulk of the micropegmatite finished crystallizing after most of the ore had been formed. The ilmenite is pure and free from any exsolution product; characteristically it shows graphic intergrowth with the late-stage silicates. The titanomagnetite has an abundance of exsolved ilmenite as well-developed, fairly coarse lamallae. The proportion of ilmenite (intergrown) is somewhat greater than titanomagnetite (about 60:40); the total ilmenite is considerably in excess of magnetite. In some of the lower transition zone ilmenite is present almost to the exclusion of magnetite. Patches of skeletal or grid-like ilmenite are associated with dark-green stilpnomelane (?). The ilmenite bodies are usually separate from one another but show optical continuity in reflected light. These bodies of skeletal ilmenite may represent original ilmenite-magnetite intergrowths from which the magnetite has been removed by hydrothermal solutions.

In the granophyre the ores are considerably less abundant than in the diabase or the transition zones. Ilmenite appears to be in excess of titanomagnetite with which it is intergrown in part; much of the ilmenite occurs as small individual blades. The titanomagnetite has but a few very fine lamallae and spicules of exsolved ilmenite.

In contrast to the normal diabase the ores show a longer period of crystallization with respect to the silicates of the granophyre. A good many grains are completely enclosed in the hedenbergite crystals, many occupy an interstitial position and are associated with late crystallizing silicates (ilvaite, stilpnomelane (?), and other chlorite), and some of the bodies of ilmenite-magnetite occur in the micropegmatite which was the last component to crystallize.

Minor Constituents

Amphibole.- Most of the amphibole is hornblende which occurs as a marginal growth on the clinopyroxene and appears to be the result of late magmatic or hydrothermal reaction. A light-brown variety is commonest but green to bluish-green hornblende is also plentiful. The brown hornblende is frequently bordered by green hornblende, and the two are optically continuous and have the same extinction angle. In addition to the hornblende rims on pyroxene small patches of brown hornblende are found within the pyroxene where it is accompanied by bleaching of the pyroxene. Less commonly a pale-green to nearly colorless, fibrous, actinolitic amphibole is seen developed at the edge of the pyroxene and oriented parallel to the cleavage.

The amount of hornblende in the diabase is a function of the amount of interstitial micropegmatite. In the diabase pegmatite and upper heterogeneous zone where micropegmatite is more abundant than in the zone of normal diabase, more hornblende is present as a reaction product with pyroxene and is more abundant on pyroxene adjacent to the interstitial micropegmatite. It is somewhat more plentiful in the intermediate zone than in normal diabase.

In addition to amphibole derived from pyroxene there is a small amount of acicular pale-green interstitial actinolite ~~and~~ with micropegmatite which probably is of late magmatic origin.

In the granophyre proper, hornblende is relatively scarce, though it is more plentiful in the lower part of the zone approaching the lower transition zone. Most of it is a blue-green variety which occurs as small patches and blades in the hedenbergite, but larger crystals pseudomorphous after the pyroxene are likewise seen. Irregular, interstitial, felted masses of fibrous blue-green actinolitic hornblende represent some of the latest crystallized material in the granophyre.

<u>Chlorite</u>.- Chlorite is present throughout the diabase and granophyre, derived in part by hydrothermal alteration of the earlier ferromagnesian minerals but also occuring interstitially to the pyroxene and feldspar and frequently in association with magnetite-ilmenite.

In the normal diabase chlorite occurs with the hornblende formed by hydrothermal or magmatic reaction with the pyroxene. It likewise occupies interstitial positions with respect to the earlier silicates and probably formed in the last stages of crystallization of the rock. The optical properties of the chlorite in normal diabase as determined in thin section are:

color: light green (-) $2V = 15^{\circ}$ (estimated)

pleochroism: X, yellow; Z, light green; birefringence: moderate, ca. .022

Chloritic material of another variety is present in considerable abundance in the diabase pegmatite, the diabase from the transition zones adjacent to the granophyre, and to a lesser extent in the granophyre itself. It is interstitial to the silicates and usually is associated with magnetite-ilmenite and ilvaite. The skeletal ilmenite is intergrown with the chloritic material which replaces the magnetite originally intergrown with ilmenite. This "chlorite" occurs in irregular compact masses which are made up of a multitude of small scales or plates. Many of the plates have a hexagonal outline and show fine color zoning in shades of green. The mineral has one good cleavage and a parting at right angles to it. It shows the following optical properties determined in thin section and immersion liquids:

Color:	dark green	(-) 2V	= 0
		γ and β =	1.655 ± .002
Pleochroism:	X, brownish yellow;	α =	1.605 ± .002
	Z, dark green	$\gamma - \alpha$ =	.050 ± .002

The optical properties are similar to those for stilpnomelane given by Winchell (1927), though the birefringence is somewhat lower. The appearance and general optical properties agree well with Shannon's (1920) description of stilpnomelane from diabase in New Jersey. Stilpnomelane from granophyre has been described by Wager and Deer (1939, p. 189) but the indices and birefringence are considerably higher than in the Dillsburg material. However, Hutton (1938; 1945) has shown that the optical properties of the stilpnomelane group may vary considerably with changes in composition.

Ilvaite.- The composition of ilvaite given by Dana (p. 541) is $HCaFe''_2 Fe'''Si_2O_9$. It is recognizable in thin section only by its barely translucent character and marked pleochroism from dark brown to black and so can be easily mistaken for one of the opaque oxides. In polished specimens the ilvaite is easily recognized by its pronounced pleochroism and anisotropism which gives interference colors from blue or bluish-gray to rose or dark red in polarized light. It has a negative reaction to the usual reagents, and its reflectivity is lower than most metallics but somewhat higher than the silicates.

Ilvaite is essentially restricted to the granophyre though a small amount was observed in specimens from the transition zones above and below the granophyre. In the granophyre ilvaite is plentiful and almost equal to the amount of opaque oxides. Usually several grains of different orientation are intergrown. The grains and masses are anhedral though there is a tendency for the ilvaite to crystallize as blades.

Small, irregular replacements of some of the ilvaite by apparently secondary hematite can be seen in polished specimens. The hematite tends to be concentrated as a border just inside the outer edge of a body of ilvaite.

Ilvaite is interstitial to the earlier silicates and much of it is associated with late-stage stilpnomelane; only a few grains are intergrown with ilmenite or titanomagnetite. Most of the ilvaite appears to have crystallized after the metallic oxides.

The author is not aware of any previous published account of ilvaite occuring as an accessory mineral in granophyre. However, it is very possible that it is present under similar circumstances elsewhere but has been mistaken for an opaque ore in thin section as well as megascopically. Ordinarily it occurs in contact-metamorphic zones in limestone, from which it has been reported by Shannon (1918) and Sorenson (1927, p. 18-20) in Idaho, Spencer and Paige (1935, p. 67) at Santa Rita, N.M., and Prescott (1908) at Porter Creek, Shasta Co., California, as well as from several localities in Europe. Dana also lists it as occurring in granite in Tyrol and sodalite-syenite in Greenland.

Accessory Minerals

Apatite.- Apatite is an ever-present minor constituent which seldom amounts to more than about ½ percent. Usually it occurs as long slender needles. Apparently it did not commence to crystallize as early as much of the plagioclase and pyroxene because many of the needles are confined to interstitial positions where they are enclosed in micropegmatite and, in some places, later interstitial mafic minerals.

Biotite.- Reddish-brown biotite is never present in amounts greater than about 1 percent, but a few flakes are seen in almost every thin section. It usually occurs in irregular small flakes molded against pyroxene and associated with hornblende or sometimes with the ores.

Pyrite and Chalcopyrite.- Study of polished specimens with the metallographic microscope shows that the sulfides pyrite and chalcopyrite are present in the diabase and granophyre. They are much less abundant in the granophyre and transition zones than in the diabase.

Both sulfides occur as minute grains interstitial to the silicates; rarely do they approach in size that of the smaller grains of ilmenite-magnetite. A few are enclosed in ilmenite and titano-magnetite and apparently are as late in their time of crystallization as the oxides.

Other Accessory Minerals.- The granophyre contains small quantities of minerals not found in the other rocks. Their occurrence and association show them to be among the final products of crystallization.

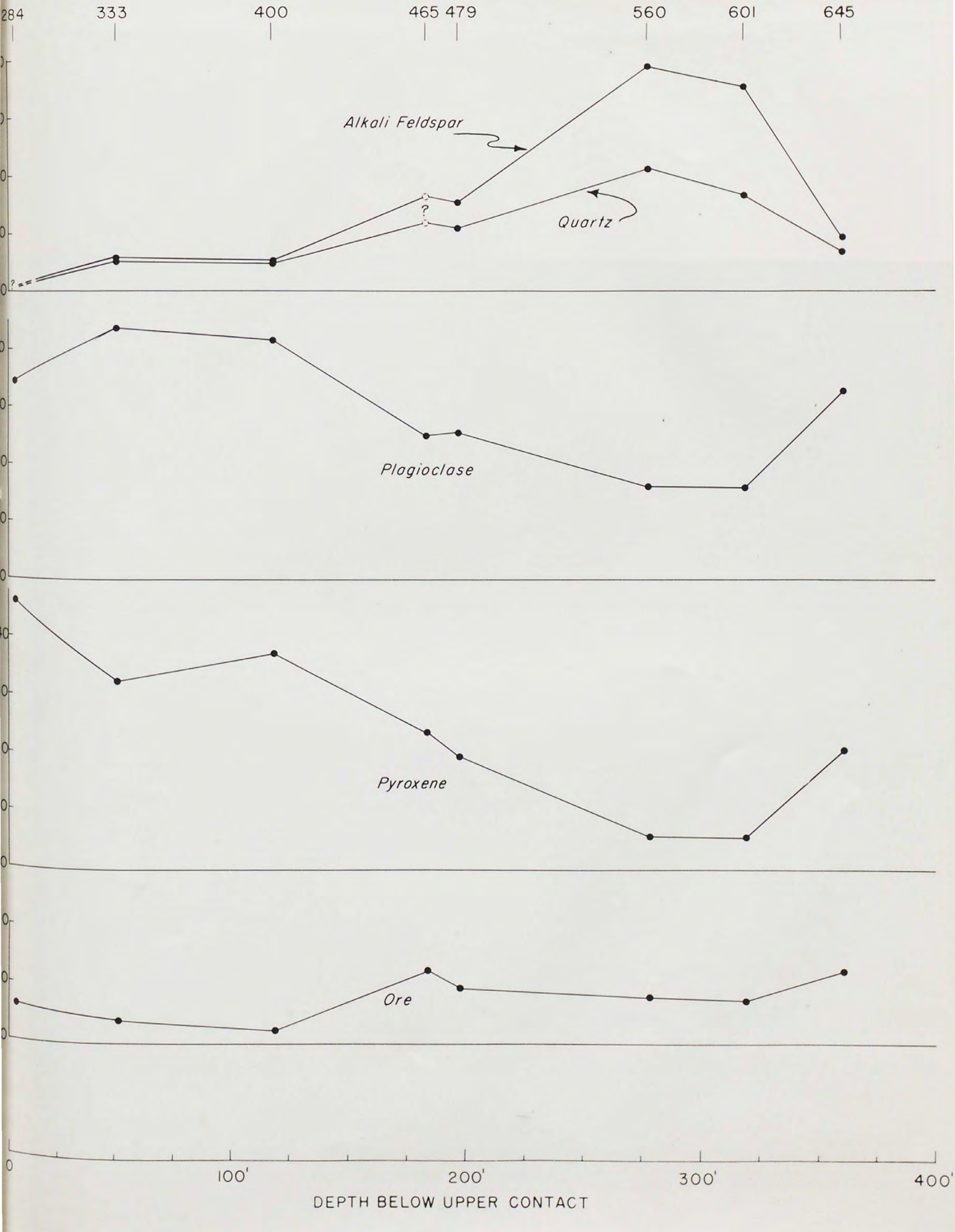
Epidote is probably the most plentiful accessory mineral in the granophyre, usually occurring with interstitial stilpnomelane (?). Small grains of a mineral pleochroic in brown occasionally accompany the epidote and chlorite. From incomplete optical data on a few crystals it is believed to be allanite, a variety of the epidote group containing rare earths.

Some pale-brownish to nearly colorless grains of sphene have been recognized accompanying the opaque ores and ilvaite.

In a few thin sections there are some small colorless grains of high relief having a stubby prismatic habit with a square cross section. Their high birefringence and positive uniaxial character suggest that they are zircons. They are surrounded by brown pleochroic haloes where they are embedded in scaly stilpnomelane (?). _/

_/ Recent work by Hutton (1947) has shown that in New Zealand granites, the nuclei of pleochroic haloes are not zircon but one of the other rare-earth minerals, xenotime or monazite.

Figure 11. Diagram showing the variation in modal minerals of the diabase-granophyre sequence in drill hole 3.



284
333
400
465
479
560
601
645
Alkali Feldspar
Quartz
?
Plagioclase
Pyroxene
Ore
0
100'
200'
300'
400'
DEPTH BELOW UPPER CONTACT

Table 4

Zone	Plagioclase Variation	Plagioclase Average	Micropegmatite Percent by Volume	Pyroxene	Ores
Chilled Zone	Most calcic observed = An_{70}	An_{65}	0-5	Augite only in uppermost part. Augite and pigeonite occur together beginning c.a. 20 feet below contact.	Small amounts of magnetite and ilmenite as small grains.
Diabase with Coarser Network	Fine-grained matrix. An_{60}-An_{65}	An62	0-10	Augite and pigeonite. (Pigeonite largely inverted to hypersthene with clinopyroxene lamellae.)	Magnetite with ilmenite lamellae; pure ilmenite.
	Coarse-grained material An_{30}-An_{55}		12-20		
Normal Diabase	An_{58}-An_{67}	An62	12-15	Purplish brown augite and pigeonite (mostly inverted.)	Ilmenite as irregular inte[r]growths with titanomagnetite. Roughly equal amounts of ilmenite and titanomagnetite.
Diabase Pegmatite		An_{55}	20-30	Purplish brown clinopyroxene (large 2V, salite?) Inverted pigeonite.	Abundant ilmenite and titanomagnetite. Ilmenite in excess of titanomagnetite (c.a. 60:40)
Transition Zones	An_{35-47}	An_{45}	Av. c.a. 33-1/2	Purplish brown clinopyroxene (ferro-salite?) No pigeonite or inverted pigeonite.	Similar to occurrence in pegmatite. In some of lower transition zone, ilmenite occurs almost exclusively. Ilvaite present
Granophyre	An_{5-15}		Av. quartz = 23	Pale green hedenbergite	Ilmenite and titanomagnetite less abundant. Ilmenite predominant. Ilvaite common.

A little calcite was observed as interstital bodies and also as thin veinlets traversing the granophyre.

Mineral Variation

The variation of the principal mineral constituents in the different zones of the diabase-granophyre sequence is shown in Figure 11 and presented in Table 4.

CHEMICAL DATA

For the present investigation ten new rock analyses were made in the University of Minnesota laboratory by Mr. James Kerr and Miss Eileen H. Kane. The analyses, norms and modes are presented in Table 5. Eight of the analyzed specimens were taken from the core recovered from the drill hole which penetrated the "lower" or main diabase. The other two, 14 and 21 are, respectively from the chilled bottom contact of the "upper" diabase at Dillsburg, and the chilled contact facies at the bottom of the Gettysburg sill. The specimens from the drill core were chosen as representative of the principal varieties of diabase and granophyre. The modes, computed in weight percent from Rosiwal analyses of thin sections of the analyzed specimens, generally show good agreement with the norm.

Composition of the Diabase Magma.- In Table 6 the chemical composition of the diabase at Dillsburg is compared with that of the Gettysburg sill and other Triassic diabases from the eastern United States. Analyses of diabase intrusives of similar composition are also included for comparison. All analyses are of specimens from the fine-grained, chilled contact of intrusions and hence represent as closely as possible the composition of the original undifferentiated magma. All the analyses listed are of the saturated or tholeiitic magma type of Kennedy (1933).

Table 5

Chemical Analyses

	Diabase: Chilled Facies			Diabase: With Coarse Network	Diabase: Normal	Diabase Pegmatite	Transitional Granophyric Diabase		Granophyre	
Analysis #	1	2	3	4	5	6	7	8	9	10
Specimen #	14	21	284	333	400	465	479	645	601	560
SiO_2	51.26	52.05	51.33	52.59	52.89	52.56	54.14	53.28	61.69	66.04
Al_2O_3	15.28	14.51	14.79	15.17	15.79	12.77	11.86	12.31	12.61	12.72
Fe_2O_3	1.66	1.37	1.85	2.22	1.71	4.78	3.08	3.43	2.98	2.48
FeO	8.98	9.00	8.32	7.85	9.19	10.18	12.57	12.27	8.32	6.55
MgO	7.31	7.30	7.23	5.21	4.33	2.69	1.92	2.61	0.77	0.54
CaO	10.18	10.61	10.51	8.85	9.78	7.21	5.69	6.91	4.04	2.65
Na_2O	2.06	1.91	1.94	2.74	2.49	3.65	3.21	2.88	5.71	4.62
K_2O	0.71	0.62	0.57	1.43	0.64	1.03	1.74	1.40	0.57	2.26
H_2O+	0.92	0.79	1.49	1.59	1.02	1.22	1.52	0.93	0.83	0.84
H_2O-	0.21	0.10	0.46	0.49	0.28	0.30	0.23	0.25	0.15	0.19
TiO_2	0.83	1.19	1.16	1.35	1.44	2.91	3.08	2.83	1.46	1.03
P_2O_5	0.10	0.14	0.14	0.17	0.18	0.27	0.37	0.31	0.50	0.22
MnO	0.21	0.18	0.17	0.15	0.18	0.20	0.24	0.22	0.15	0.11
S	0.08	0.03	nd	nd	nd	nd	nd	nd	nd	nd
Less O for S	0.04	0.01	--	--	--	--	--	--	--	--
Total	99.75	99.79	99.96	99.81	99.92	99.77	99.65	99.63	99.78	100.25
S. G.	2.97	2.98	2.94	2.93	2.94	2.99	2.89	2.95	2.80	2.72
Total Fe as FeO	10.47	10.23	9.98	9.85	10.73	14.48	15.34	15.36	11.00	8.78
FeO:MgO	1.23	1.23	1.15	1.50	2.12	3.78	6.54	4.70	10.80	12.13

Norms

	Diabase: Chilled Facies			Diabase: With Coarse Network	Diabase: Normal	Diabase Pegmatite	Transitional Granophyric Diabase		Granophyre	
Analysis #	1	2	3	4	5	6	7	8	9	10
Specimen #	14	21	284	333	400	465	479	645	601	560
Quartz	2.08	4.02	4.02	4.20	6.84	8.00	10.35	9.65	15.23	21.69
Orthoclase	3.89	3.34	3.34	8.34	3.34	6.05	10.30	8.29	3.34	13.34
Albite	17.29	16.24	16.24	23.06	20.96	30.82	27.25	24.35	48.21	39.00
Anorthite	30.58	29.19	30.02	25.02	30.30	15.39	12.65	16.60	7.23	7.36
Diopside. $CaSiO_3$	8.00	9.40	8.93	7.54	7.31	8.85	5.51	6.63	3.95	1.67
Diopside. $MgSiO_3$	4.30	5.20	5.10	4.00	3.24	3.13	1.36	2.04	0.65	0.31
Diopside. $FeSiO_3$	3.43	3.83	3.43	3.30	4.04	4.80	4.47	4.85	3.64	2.31
Hypersthene $MgSiO_3$	14.00	13.10	13.00	9.00	7.56	4.16	3.44	4.49	1.27	1.04
Hypersthene $FeSiO_3$	10.82	9.90	8.71	7.26	9.42	5.48	11.38	10.63	7.04	6.48
Magnetite	2.32	1.97	2.55	3.25	2.55	6.91	4.41	4.87	4.31	3.60
Ilmenite	1.52	2.28	2.13	2.58	2.74	5.53	5.93	5.38	2.74	1.98
Apatite	0.34	0.34	0.34	0.34	0.34	0.64	1.01	0.74	1.34	0.34
Water	1.13	0.89	1.95	2.08	1.30	1.52	1.75	1.18	0.98	1.03
Total	99.70	99.70	99.76	99.97	99.94	101.28	99.81	99.70	99.93	100.15
Normative Plagioclase	An_{64}	An_{64}	An_{65}	An_{52}	An_{59}	An_{32}	An_{32}	An_{40}	An_{13}	An_{16}
Ab:An	.565	.557	.541	.921	.691	2.00	2.15	1.47	6.67	5.30
$CaSiO_3$	19.7	22.7	22.8	24.2	23.5	33.5	21.0	23.2	23.9	14.1
$MgSiO_3$	45.1	44.2	46.2	41.8	34.2	27.6	18.4	22.8	11.6	11.4
$FeSiO_3$	35.2	33.1	31.0	34.0	42.6	38.9	60.6	54.0	64.5	74.5

Modes (in weight percent)

	Diabase: Chilled Facies			Diabase: With Coarse Network	Diabase: Normal	Diabase Pegmatite	Transitional Granophyric Diabase		Granophyre	
Analysis #	1	2	3	4	5	6	7	8	9	10
Specimen #	14	21	284	333	400	465	479	645	601	560
Quartz	—	—	0.9 (Quartz + Alkali feldspar)	5.1	4.8	28.1 (Quartz + Alkali feldspar)	10.9	6.9	16.5	21.0
Alkali feldspar		—		5.9	5.2		15.2	9.3	35.2	38.8
Plagioclase		30.0	34.4	43.7	41.5	25.0	25.6	32.8	16.0	16.2
Pyroxene		57.5	46.1	32.6	37.4	23.9	19.7	20.8	5.8	6.0
Olivine		2.0	—	—	—	—	—	—	—	—
Ore		7.0	6.2	4.1	2.5	12.9	9.9	12.6	7.6	8.2
Minor accessory mafics		3.2	12.4	8.3	8.4	9.8	18.1	16.9	18.2	9.5
Apatite		—	—	0.1	0.2	0.1	0.6	0.7	0.7	0.3
Sphene		—	tr.	—	—	0.2	—	—	—	tr.

1. Chilled diabase at lower contact of upper diabase sheet.

   Core from drill hole 14, Dillsburg, Pa., Eileen H. Kane, analyst.

2. Chilled diabase within 1 foot of lower contact of Gettysburg sill, Beaver Creek, 0.4 miles from Conewago Creek, York County, Pa., Eileen H. Kane, analyst.

Note: The following specimens are from core recovered from diamond drill hole 3, Dillsburg, Pa., analyses by James Kerr.

3. Chilled diabase 3 feet from upper contact of lower diabase.
4. Fine-grained diabase with coarser-grained network 52 feet below upper contact.
5. Normal diabase 119 feet below upper contact.
6. Diabase pegmatite, 184 feet below upper contact.
7. Transitional granophyric diabase above granophyre 198 feet below upper contact.
8. Transitional granophyric diabase beneath granophyre 364 feet below upper contact.
9. Granophyre near lower transition zone 320 feet below upper contact.
10. Granophyre from central part of granophyre zone 279 feet below upper contact.

Table 6

Comparison of Dillsburg diabase with rocks of similar magma type

	Dillsburg		Gettysburg sill	Palisades sill (av. of 6)		Whin sill	Average Karoo	Downes Mountain	Average Tasmanian dolerite
	1	2	3	4	5	6	7	8	9
SiO_2	51.33	51.26	52.05	52.12	51.82	50.72	52.25	53.21	52.65
Al_2O_3	14.79	15.28	14.51	14.33	14.76	13.76	14.60	13.95	16.23
Fe_2O_3	1.85	1.66	1.37	1.34	1.22	3.87	0.84	1.24	0.51
FeO	8.32	8.98	9.00	8.86	9.24	8.50	9.89	8.93	8.21
MgO	7.23	7.31	7.30	7.76	7.32	5.42	6.95	7.19	6.64
CaO	10.51	10.18	10.61	10.55	10.02	9.09	9.71	8.95	11.34
Na_2O	1.94	2.06	1.91	2.01	2.06	2.42	2.21	2.65	1.58
K_2O	0.57	0.71	0.62	0.78	0.82	0.96	0.96	1.13	0.90
H_2O+	1.49	0.92	0.79	0.75	0.84	1.51	0.71	0.49	0.48
H_2O-	0.46	0.21	0.10	0.16	0.14	0.76	0.32	0.22	0.85
TiO_2	1.16	0.83	1.19	1.14	1.34	2.39	1.10	1.73	0.58
P_2O_5	0.14	0.10	0.14	0.14	0.12	0.26	0.22	0.21	0.01
MnO	0.17	0.21	0.18	0.18	0.12	0.16	0.45	0.23	0.15
S	.....	0.08	0.03	.....	.....	.....	.....	.....	.....
less O for S	.....	0.04	0.01	.....	.....	.....	.....	.....	.....
	99.96	99.75	99.79	100.10	99.82	100.31	100.21	100.13	100.13

1. Three feet below upper contact of "lower" diabase; core from drill hole 3, Dillsburg, Pa., James Kerr, analyst.
2. Chilled facies at bottom of "upper" diabase sheet; core from drill hole 14, Dillsburg, Pa., Eileen H. Kane, analyst.
3. Chilled facies within one foot of lower contact of Gettysburg sill, Beaver Creek, 0.4 miles from Conewago Creek, York County, Pa., Eileen H. Kane, analyst.
4. Average of 6 analyses of chilled border facies of diabase, Palisades sill, New Jersey. (H.H. Hess, unpublished data)
5. One foot above lower contact, Palisades sill, New Jersey, F.A. Gonyer, Analyst (Walker, 1940, p. 1080).
6. Whin Sill (average of 6). Harwood, analyst. (Holmes and Harwood, 1928, p. 539).
7. Average Karoo dolerite, South Africa. (Daly and Barth, 1930, p. 101.)
8. Downes Mountain dolerite, Calvinia, South Africa. A.J. Hall, analyst. (Walker and Poldervaart, 1941, p. 171.)
9. Average undifferentiated Tasmanian dolerite (six analyses). A.B. Edwards, analyst. (Edwards, 1942, p. 465.)

The close general similarity in composition of these representatives of a magma type having world-wide distribution is remarkable. The uniformity of composition between the diabase of the Dillsburg and Gettysburg areas and the diabase which forms the Palisades is also striking, though no more so than might be expected for both groups are members of the same province and are identical in age and mode of occurrence.

Composition of the Granophyre.- In Table 7 the chemical composition of the granophyre from the drill hole is compared with granophyres of similar composition from other localities. There is some variation in the oxides but all have one feature in common, the Na_2O content is in excess of K_2O.

Chemical Variation

Figure 12 illustrates the variation in chemical composition of the diabase-granophyre sequence at Dillsburg. This method of plotting the components using depth below the upper contact as the abscissa was found to be more satisfactory than the usual method where silica is used as the base. The corresponding changes in weight percent of the modal minerals are shown in figure 11.

A slight difference in chemical composition between the chilled contact facies and the underlying normal diabase is apparent. The normal diabase is a bit more silicic because of a somewhat longer cooling period of the diabase magma beneath the chill zone which permitted slight fractionation. The discrepancy between modal ore content and total iron in the chilled zone is largely due to the difficulty of measuring the volume of the opaque ores in this very fine-grained rock. Many of the grains have a smaller diameter than the thickness of the section and are not necessarily all in one plane and so are measured in excess of their amount relative to the other mineral grains which extend completely through the thickness of the section. Alumina reaches a maximum in the normal diabase, suggesting a

Table 7

Composition of the Dillsburg granophyre
compared with other granophyres

	Dillsburg 560	A	B	C	D
SiO_2	66.04	65.20	64.13	58.81	63.33
Al_2O_3	12.72	13.72	13.15	12.02	12.99
Fe_2O_3	2.48	3.63	1.08	5.77	2.87
FeO	6.55	3.72	6.31	9.38	5.12
MgO	0.54	1.01	1.08	0.72	2.21
CaO	2.65	2.79	3.62	5.03	2.05
Na_2O	4.62	5.22	3.64	3.91	3.97
K_2O	2.62	2.17	2.32	2.39	3.52
H_2O+	0.84	1.27	2.71	0.21	1.25
H_2O-	0.19	0.72	0.36	0.19	0.58
TiO_2	1.03	0.39	1.19	1.26	1.55
P_2O_5	0.22	0.38	0.31	0.71	0.37
MnO	0.11	....	0.27	0.21	0.16
BaO	....	....	0.09	.....	....
Total	100.15	100.22	100.26	100.61	99.97

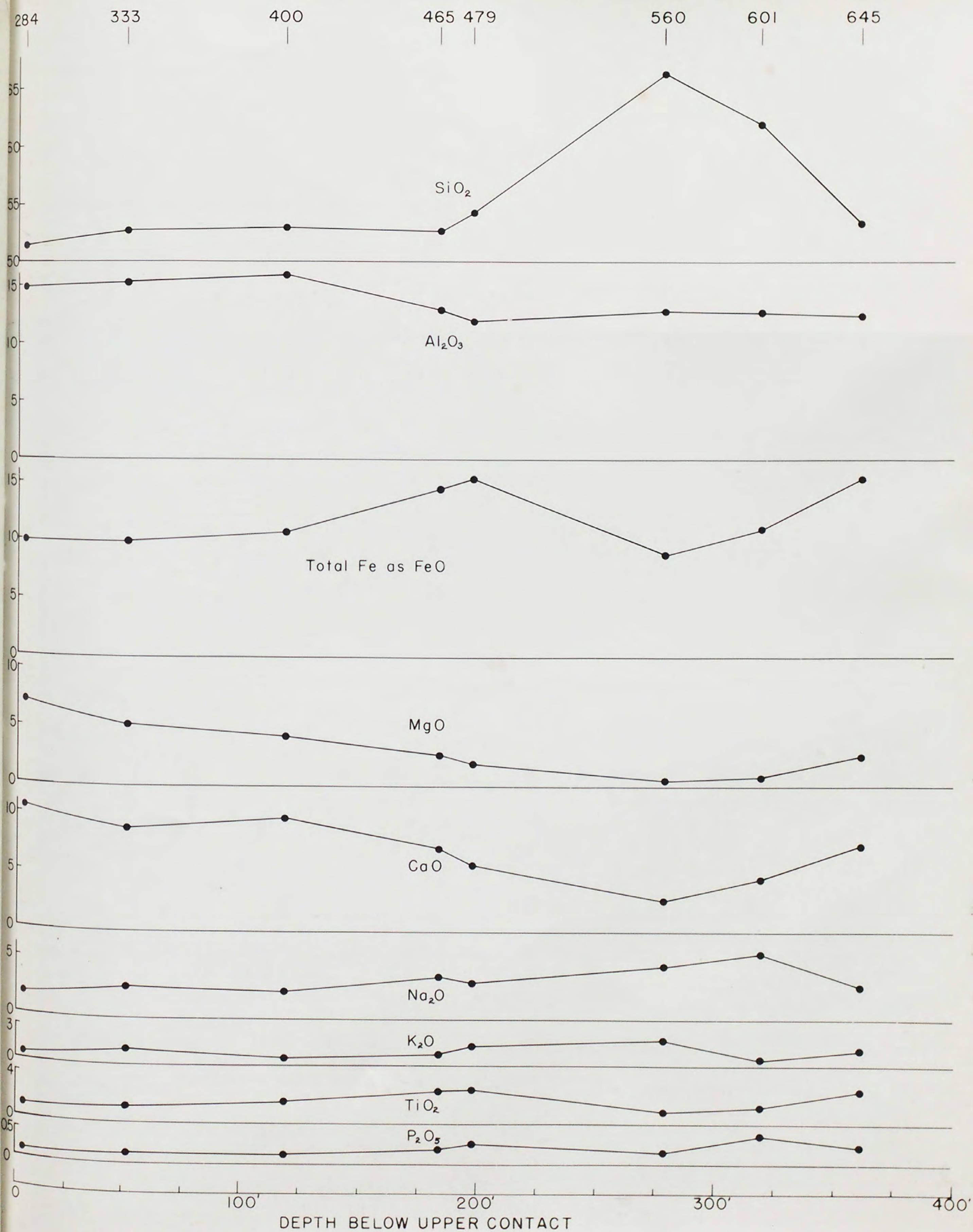
A. "Red veinlet" in Whin Sill. Tomkeieff (1929), Analysis III

B. Inninmorite pitchstone. Bayley et.al., Mull Memoir, p. 19

C. Hedenbergite granophyre 3047, Skaergaard intrusive. Wager and Deer (1939), p. 210

D. Red rock, Northland Sill, Duluth. Schwartz and Sandberg (1940), p. 1144.

Figure 12. Diagram showing the variation in chemical constituents of the diabase-granophyre sequence in drill hole 3.



284
333
400
465
479
560
601
645
SiO2
Al2O3
Total Fe as FeO
MgO
CaO
Na2O
K2O
TiO2
P2O5
0
100'
200'
300'
400'
DEPTH BELOW UPPER CONTACT

slight relative enrichment in plagioclase resulting from some sinking and removal of pyroxene in the beginning stages of crystallization. This assumption is consistent with the mode, which has a relatively high plagioclase content.

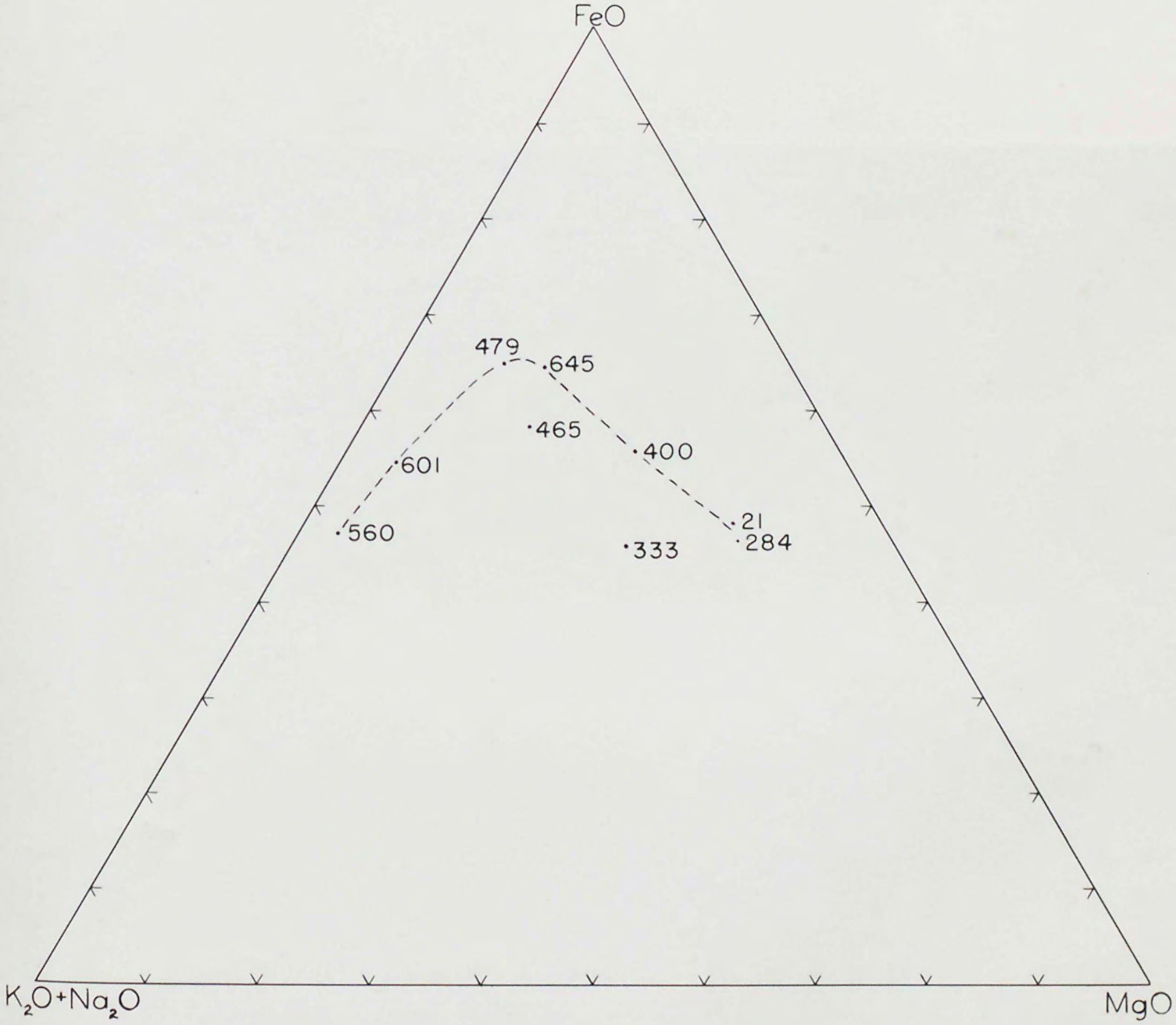
A slight break in the curves between the chilled zone and normal diabase is produced by the diabase with the coarser-grained network in fine-grained matrix. This is due to the coarser pegmatitic material with its sericitized, somewhat more sodic plagioclase and abundant interstitial micropegmatite, which produces a lower total CaO and Al_2O_3 content but raises the amount of alkalies and silica.

A major break in the curves in the diabase pegmatite and transition zones which occupy an intermediate position but are more like the diabase than the granophyre chemically and mineralogically. Silica increases abruptly and rises considerably in relative amount in the granophyre, as would be expected from the increase of quartz in the mode. In the transition zones and granophyre Al_2O_3 falls considerably below its amount in the normal diabase, again reflected in the mode by a corresponding change in the plagioclase content.

MgO decreases steadily from the chilled diabase toward the granophyre, which has but a small amount of low-magnesia pyroxene. The decrease of CaO in the same direction reflects the increasingly sodic character of the feldspar.

Analyses of the intermediate rocks reveal a high content of total Fe accompanied by a similar enrichment in TiO_2. In the norms there is a concomitant increase of magnetite and ilmenite corroborated by an abundance of opaque ores in modes. In the granophyre total iron is relatively very low. There is an absolute enrichment in iron in the transition zones and an increase in the FeO:mgO ratio, but in the granophyre, which shows a great increase in FeO:MgO, there is actually a marked decrease in absolute iron. If the granophyre is a differentiate from the diabase magma, an important point in petrogenesis over which there has been much controversey is demonstrated, namely, iron is concentrated in the magma at a late

Figure 13. Triangular diagram showing the variation in weight percent of FeO, MgO and K_2O + Na_2O in the diabase-granophyre sequence, drill hole 3.



FeO
479
645
465
400
601
21
560
284
333
K_2O+Na_2O
MgO

stage in its crystallization history, but not in the final residual product. Figure 13 clearly illustrates this variation.

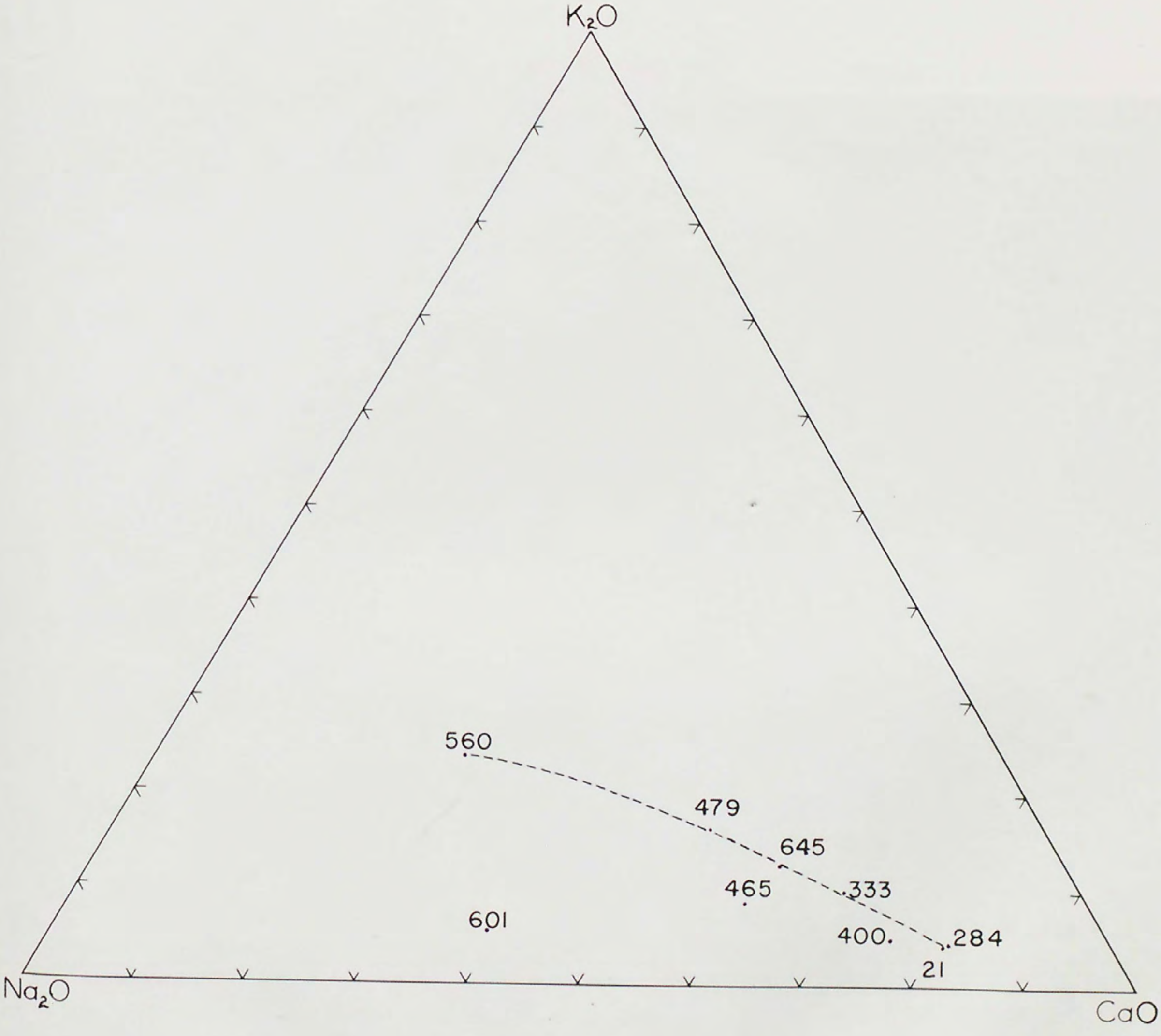
Figure 12, and more clearly figure 14, illustrates the change from high lime and low potash in the chilled facies and normal diabase to rock containing more alkalies and less CaO in the granophyre. It is interesting to note (table 5) that although the proportion of K_2O increases in the granophyre, it does not exceed the Na_2O content. This is in accordance with Bowen's conclusion that with limited reaction (strong fractionation) in the plagioclase feldspar series the soda content increases in the residual liquid and remains high ih the final stage so that although potash likewise increases it does not attain or exceed the amount of Na_2O.

The Na_2O:K_2O ratios of 21 analyzed granophyres including the granophyre near Dillsburg are listed in Table 8 and plotted in figure 15. A general correlation between the size of the granophyre mass and soda-potash ratio is apparent from the table._/ Of the 10 analyses listed having Na_2O in excess of K_2O, 6 are definitely small bodies, while 9 of the 11 masses with K_2O greater than Na_2O are known to be large. Exceptions to this general relationship can be found, as in the case of the analyses of the Carrok Fell granophyre (F) and the Knock Ring dike (J) in which Na_2O exceeds K_2O, or the small micropegmatite dike in the Karoo (S) where K_2O is greater than Na_2O.

In figure 15 the analyses with K_2O in excess of Na_2O occupy a relatively restricted field whereas the granophyres with Na_2O greater are rather scattered. The two fields are gradational with no clear gap separating them. The data on size of the masses is inadequate to enable one to show whether or not there is a

_/ It is difficult to obtain accurate data on thickness and extent of most of the granophyre masses for which analyses are given. By "small" is meant masses ranging from veins and dikes a few inches wide to bodies 100 feet or so thick. "Large" masses include those from around 100 feet to several hundred feet thick and usually with a considerable horizontal extent.

Figure 14. Triangular diagram showing the variation in weight percent of CaO, K_2O, Na_2O in the diabase-granophyre sequence, drill hole 3.



K₂O
Na₂O
CaO
560
479
645
465
333
601
400
284
21

Table 8

Alkalies in granophyres, and comparisons between size of bodies and soda-potash ratio

		% Na_2O	% K_2O	Ratio $Na_2O:K_2O$	Size	Location
Na_2O greater than K_2O	A	4.62	2.26	2.04	Small	Dillsburg, No. 560 (this paper).
	B	5.22	2.17	2.40	Small	Red veinlet in Whin Sill. Tomkeieff (1929).
	C	3.91	2.39	1.64	Small	Hedenbergite granophyre 3047, Skaergaard intrusive. Wager and Deer (1939), p. 210.
	D	4.24	3.85	1.10	Small	Acid granophyre 3058, Skaergaard intrusive. Wager and Deer (1939), p. 208.
	E	4.27	3.06	1.40	Small	Quartz-porphyry, Rum. Harker, 1908, quoted in Wager and Deer (1939), p. 208.
	F	5.55	3.53	1.57	Large	Augite-granophyre, Carrock Fell, Cumberland. Harker, 1895, quoted by Wager and Deer (1939), p. 208.
	G	3.97	3.52	1.13	Small (?)	Red-rock, Northland sill, Duluth. Schwartz and Sandberg (1940), p. 1144.
	H	2.48	2.37	1.05	Small	Acid rock, Moyie Sills, British Columbia. Daly (1905).
	I	5.12	4.08	1.25	?	Augite-granophyre, major intrusion, center 2, Ardnamurchan. Richey and Thomas (1930), p. 84.
	J	3.92	2.34	1.67	Large (?)	Augite-granophyre, Knock Ring dike, Mull, Bailey, Thomas et al., 1924, quoted by Wager and Deer, 1939, p. 208.
K_2O greater than Na_2O	K	3.90	4.67	0.83	Large	Granophyre, Beinn a' Ghraig ring dike, Mull. Bailey et al. (1924) p. 20.
	L	3.61	4.90	0.74	Large	Hornblende-granophyre, Skye. Harker, 1904, quoted by Wager and Deer (1939) p. 208.
	M	4.24	4.52	0.94	Large (Separate intrusion?)	Granophyre, Brevan dolerite dike. Krőkstrom, (1932), p. 305.
	N	3.40	4.10	0.83	Large	Red-rock, Endion Sill, Duluth. Schwartz and Sandberg (1940), p. 1144.
	O	2.82	4.07	0.69	Large	Red-rock, Lester River Sill, Duluth. Schwartz and Sandberg (1940), p. 1144.
	P	3.45	3.98	0.87	Large	Red-rock, Duluth gabbro. Grout (1918) p. 65.

Table 8 (Continued)

	% Na_2O	% K_2O	Ratio $Na_2O:K_2O$	Size	Location
Q	3.39	3.82	0.89	Large	Average Sudbury micropegmatite. Collins (1934).
R	2.40	5.20	0.46	Large	Granophyric granite, Bushveld. Hall (1932), p. 375.
S	4.29	5.58	0.77	Small	Microgranitic dike, Insizwa. Scholtz (1937). p. 143.
T	3.44	4.97	0.69	Large (?)	Red rock, Pigeon Point. Minn. Grout (1918) p. 653.
U	4.15	4.47	0.93	Large (?)	Granophyre, Glen More ring dike, Mull. Bailey et al. (1924), p. 29.

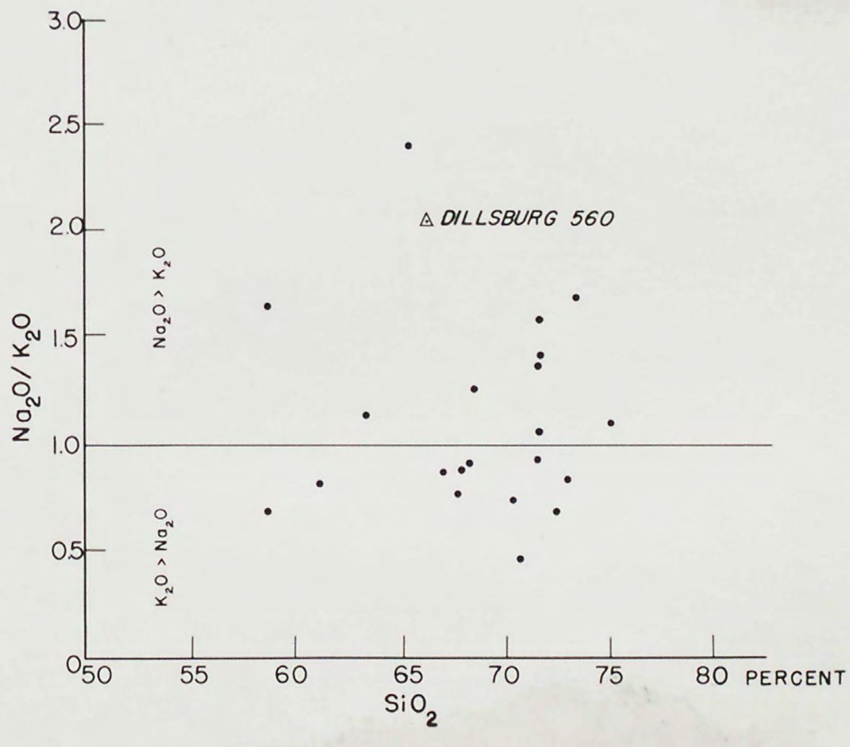


Figure 15. Ratio $Na_2O:K_2O$ of 31 analyzed granophyres.

similar gradation in size of the masses from small with K_2O less than Na_2O, through bodies of intermediate size with Na_2O and K_2O nearly equal, to large, K_2O-rich bodies.

OTHER GRANOPHYRE BEARING DIABASES IN SOUTHEASTERN PENNSYLVANIA

General Statement

Several exposures of granophyre associated with the Triassic diabase intrusions are known in southeastern Pennsylvania. At least six granophyre bodies are known in the Gettysburg sill and its offshoots near Dillsburg. Most of these are shown by Stose and Jonas on the geologic map of York County (Stose and Jonas, 1939, Pl. I). The writer has examined these occurrences and mapped another not shown by Stose and Jonas. The granophyre masses exposed near Dillsburg are shown in figure 2. A small body of granophyre is also known to occur in the diabase intrusion near Bechtelsville northeast of Boyertown, Pennsylvania. At Safe Harbor, Pennsylvania a small amount of granophyre occurs in conjunction with a diabase dike. Stose and Jonas have noted granophyre bodies also to the southwest near Gettysburg and at Saint Peters, Chester Co., Pennsylvania.

All the masses of granophyre are small relative to the size of the diabase mass enclosing them. They lie in the upper part of the intrusive sheet or sill beneath a cover of normal diabase. The bodies are lens-like with their longer axes oriented more or less parallel to the sill contacts.

York County

In general the York County granophyre masses are coarser-grained than the granophyre in the drill hole. The coarsest-grained rock seen anywhere in the region is that exposed near Mt. Pleasant school. The texture might almost be called pegmatitic because of its large pink euhedral feldspar crystals half an inch and more in length and the prisms and blades of hornblende of similar size. Miarolitic structure was not seen in any of the granophyre from the drill hole, but with the exception of that exposed west of Nells Hill, such cavities occur in granophyre from the other localities in the Dillsburg district as well as that at Safe Harbor.

The miarolites range in size from openings of microscopic dimensions to cavities almost an inch in diameter. The coarser-grained rocks possess the largest miarolitic cavities. Stubby terminated prisms of quartz and crystals of pink feldspar project into the cavities, as does an occasional octahedron of magnetite. Fibrous masses and needles of green amphibole extend into, across, and may partly fill a good many of the openings. Botryoidal opal lines the walls of some of the cavities in the granophyre at Mt. Pleasant school. The cavities in the granophyre at Safe Harbor are due to the leaching out of calcite which normally fills them in the unweathered rock.

Hornblende rather than pyroxene is the mafic mineral in most of the granophyres. The hornblende is dark green and appears to be of primary crystallization. The following optical properties were measured on typical amphibole from the Mt. Pleasant school granophyre:

$\beta = 1.673 \pm .001$

Pleochroism: X, yellow; Y, greenish yellow; Z, green

$\gamma \wedge c = 17\text{-}\frac{1}{2}^{\circ}$

$(-)\ 2V = 65^{\circ}$ (measured)

Some biotite is usually present, and secondary chlorite after hornblende is often seen. They only other granophyre besides the one cut by drill hole containing pyroxene instead of hornblende occurs west of Nells Hill and as float at the western foot of Blair Hill. The pyroxene closely resembles the light-green hedenbergite of the drill-hole granophyre.

The granophyre which was found as float west of Blair Hill occurs very close to the upper contact of the diabase and is fine-grained with small miarolitic cavities; it may represent an offshoot from a larger mass, possibly the granophyre body of Blair Hill.

On the York County geologic map a large area of granophyre is shown west and southwest of Nells Hill. Actually only a small part of this area is true granophyre. That in the northwestern third of the area is a fine-grained, pink, pyroxene-bearing rock like that found in the drill hole. The rock south of this smaller area is more of a transitional type between diabase and granophyre containing considerable alkalic feldspar and quartz but also some moderately calcic plagioclase. Hornblende rather than pyroxene is abundant in the upper (stratigraphically) part. The rock grades abruptly downward into normal diabase.

An area of granophryic rock not shown by Stose and Jonas occurs on Blair Hill near the southwestern boundary of the diabase (see Figure 2). It is a medium-grained, pinkish to brownish-red rock devoid of miarolitic cavities. The western (upper) and southern contacts of the granophyre are mapped with relative certainity, but the eastern (lower) limit is more difficult to locate, partly because of inadequate exposures but mostly because of its apparently transitional character downward into normal diabase. In this section the unquestioned granophyre can be seen to consist of abundant turbid alkalic feldspar and quartz in large individuals as well as in micrographic intergrowth with feldspar. Green hornblende is the mafic mineral but is not very abundant. The rock judged in the field to be transitional between granophyre and diabase contains abundant interstitial micropegmatite and large euhedral laths of altered plagioclase approximating medium andesine in composition. Hornblende is the essential mafic mineral here also and masses of late-stage fibrous green amphibole are plentiful. The rock appears to have been considerably affected by hydrothermal solutions and possibly the hornblende is secondary after pyroxene, though no pyroxene relics were observed.

The other areas of granophyre shown on the map (figure 2) have been visited and typical specimens collected. Some thin sections of these specimens were examined but no detailed petrographic studies have been made of them. Stose and Jonas (1939, pp. 127-130) have presented an adequate description of these rocks. All are composed of sericitized alkalic feldspar and quartz as individual crystals and in micrographic intergrowth with the potassic feldspar. Green hornblende is the important mafic mineral and the usual accessories, apatite and ilmenite-magnetite, are present. Allanite is reported by Stose and Jonas (1939) in the rock from one area and epidote from another.

Granophyre Near Boyertown

A small granophyric zone in diabase is exposed on the south slope of a low hill 2 miles northeast of Boyertwon, Pennsylvania. It lies near the upper contact of a sill-like body of diabase which intruded Triassic sedimentary rocks. The granophyric portion is thin (±100 ft.), lenticular, and oriented northwest-southeast more or less parallel to the contact. South of and supposedly below the granophyre is coarse-grained diabase with interstitial micropegmatite, sericitized euhedral plagioclase, purplish-brown augite, and abundant hornblende as reaction rims on augite. The rock lying below is normal, medium-grained diabase consisting of fresh plagioclase and augite, little or no hornblende and sparse interstitial micropegmatite.

The granophyre is a medium-grained rock with a definitely pinkish hue. No miarolitic cavities were observed. Under the microcope it is seen to consist of completely turbid sericitized plagioclase and orthoclase (?), abundant interstitial micropegmatite, and some individual quartz crystals. Green hornblende is intergrown in elongate prismatic forms with the feldspar. Pyroxene is apparently completely absent. Some of the hornblende is partly replaced by a reddish-brown mineral identified tentatively as iddingsite, which was formed as a late-stage magmatic alteration product of the amphibole. The occurrence is somewhat unusual as iddingsite normally occurs in more basic rocks where it originates from the alteration of divine and is in almost all cases limited to lava flows. The properties of the iddingsite (?) are:

Color: reddish brown. Slightly pleochroic; x, yellowish brown; y, brown; z, clear reddish brown.

(-) 2V, large (80° ?) Average R.I.: variable, estimate 1.68

Dispersion: $r > v$, distinct. Hardness: 3

Granophyre Occurrence at Safe Harbor, Pennsylvania

The granophyre occurrence at Safe Harbor, Pennsylvania was briefly described by Tomlinson (1945, p. 528-529). A. F. Buddington and the writer visited the locality and studied the geologic relationships. A large rock quarry exposes part of a diabase dike which is shown on the geologic map of Pennsylvania (Stose and Ljungstedt, 1931) as a continuous intrusion nearly 20 miles long. Most of the diabase has been removed and crushed for aggregate but at the north end of the quarry the nearly vertical dike, about 60 feet wide striking N.30°E., transects folded and contorted Antietam schist, (Cloos and Hietanen, 1941, p. 23).

The central part of the dike is a uniformly medium-grained, normal diabase. On the east side is a microcrystalline chilled border about 5 feet wide. The west contact is faulted and no chilled zone can be seen; over a distance of about 30 feet the diabase is badly fractured and deeply weathered to a buff-colored rock. There is a sheet of pink, fine-to medium-grained, miarolitic granophyre about 10 feet thick on the east side between the chilled zone of the diabase and the schist. On the other side of the diabase, west of the fault, there is a zone

25 feet thick, more or less, where miarolitic granophyre and white quartz penetrate the mica schist lit par lit.

Dikelets of granophyre intrude the chilled border zone of the diabase at the eastern contact, proving without question that the granophyre was emplaced subsequent to the intrusion, cooling, and solidification of the diabase. One granophyre dikelet extends out into the diabase for at least 1 foot from the diabase-granophyre contact. Elsewhere along this contact the granophyre contains fragments of the schist. There is likewise older granite pegmatite and white quartz veinlets and lit-par-lit injections in the schist. Tomlinson (1945, p. 528-529) interprets some of the granophyre as being generated out of the granite pegmatite "in situ" here, and implies that the "basaltic intrusion" had a similar effect on the granite at depth. However, granophyre veinlets can be seen transecting some of the milky quartz associated with the pegmatite, and specimens were found showing brecciated quartz and pegmatite cut by granophyre. The writer's interpretation is that the granophyre was intruded in a brecciated zone along the contact between diabase and schist.

Petrography.- The granophyre is fine-grained and has a xenomorphic equigranular or aplitic texture and is composed of orthoclase, quartz and micropegmatite. Small irregular miarolitic cavities are filled with calcite, and crystals of orthoclase and quartz project into them. Some of the cavities are almost completely closed by the projecting quartz crystals. Chlorite, some biotite and considerable sphene constitute the principal accessory minerals. There is a trace of apatite.

The granophyre dikelets in diabase have a very fine-grained chill facies a few millimeters wide at the contact. Under the microscope the boundary between granophyre and diabase is not clean-cut but gradational because of mutual reaction between the granophyre magma and solid diabase. On the granophyre side biotite and chlorite are abundant and granules of sphene and magnetite are plentiful. On the diabase side chlorite develops replacing pyroxene. Larger blades of chlorite cross the boundary and extend into the granophyre, the blades having a preferred orientation with their long direction perpendicular to the boundary. Iron and magnesia have been extracted from a narrow zone ih the diabase and migrated into the granophyre; water has been added to the diabase from the granophyre. The granophyre has been enriched in TiO_2.

Pinkish, fine-grained aplitic material resembling the granophyre is associated with the older pegmatite folia in the schist. According to Tomlinson this "granophyric aplite" is derived by the breakdown and remobilization of the pegmatite within the metamorphic aureole of the diabase dike. The writer believes that this aplitic material is really genetically related to the pegmatite. In thin section it is seen to penetrate the schist ahead of the pegmatite and quartz veinlets which ih turn disintegrate and absorb the aplite.

<u>Inclusion</u>.- In the middle of the dike, halfway up the north cliff, the writer found an irregular inclusion about 5 inches across. The center of the inclusion is a fine-grained gray rock with visible feldspar, interstitial chloritic material, conspicuous flakes of distinctly brown biotite, and grains of pyrite. Surrounding this is a rim of chloritic-looking material one-fourth to one inch wide which grades outward through medium-grained mafic diabase to the normal diabase. Tomlinson (p. 529) mentions having found specimens "containing rounded, partially dissolved, fragments of granophyre in diabase. These fragments were rising through the 'basaltic magma' and left a well-marked trail in the form of a pipe. A

section across the granophyre-diabase contact shows granophyre, then a zone of hybrid rock in which cordierite is abundantly developed, then diabase. Sections across the pipe below the inclusion show a highly granophyric diabase in which the basic minerals have been altered by hydration..." The writer found no pipe-like trails of granophyre through the diabase, but presumably the inclusion is similar to the "fragments" referred to by Tomlinson.

The core of the inclusion has a fine-grained, xenomorphic equigranular (aplitic) texture and is composed essentially of turbid orthoclase, lesser amounts of plagioclase (albite?) and some quartz. Brown biotite is the chief accessory. There are also granules of sphene, a little magnetite, a few large crystals of pyrite, and a little chlorite.

This core is succeeded by a hybrid zone consisting of two parts. The boundary between the intermediate zone and the core is abrupt. Next to the core the intermediate zone has an equigranular texture and consists mostly of turbid potash feldspar, lesser amounts of quartz and a little micropegmatite. Chlorite is very abundant and there are also scattered flakes of biotite. Magnetite and pyrite are present. In a direction away from the core the texture becomes progressively coarser and has a hypidiomorphic granular texture. Turbid potash felspar and a very little plagioclase are surrounded by abundant micropegmatite. Chlorite is plentiful and magnetite and pyrite are present as small grains.

Outside the intermediate zone the rock texture is definitely diabasic. The contact between the intermediate and outer zones is abrupt but highly irregular and interfingering. This boundary is judged to be approximately the original boundary between inclusion and host modified by interaction between the diabase and inclusion, though in hand specimen it appears as if the lighter-colored core was the original inclusion. In the outer zone the plagioclase laths have been completely sericitized. A small amount of micropegmatite is visible interstitially. Some augite and colorless non-pleochroic rhombic pyroxene are both present. The rhombic pyroxene occurs as relict cores surrounded by bastite, which is more plentiful closer to the hybrid zone. Some chlorite and a little biotite are visible. Magnetite granules and a trace of pyrite are present.

The core of the inclusion is judged to be more or less representative of the original rock caught up in the diabase. It may have been granite aplite, or possibly a fragment of Antietam schist which was recrystallized. Mutual reaction between the inclusion and the diabase magma produced the intermediate hybrid zone and effected some changes in the diabase adjacent to the inclusion. There is no increase in the amount of quartz and alkalic feldspar in the diabase. Instead, adjacent to the inclusion the diabase had an abundance of rhombic pyroxene and was more mafic than normal. This illustrates Bowen's principal of reactive precipitation wherein an inclusion of acid material in basic magma causes the crystallization of constituents with which the magma is already saturated, in this case rhombic pyroxene.

PETROLOGY

General Statement

The granophyre bodies in southeastern Pennsylvania have generally been considered to be differentiates of a mafic magma which solidified largely as diabase. The association of granophyre with diabase or gabbro is world wide and, because of the important bearing of the diabase-granophyre problem on questions of petrogenesis, numerous theories have been advanced to explain the associatich. The present writer subscribes to the theory of derivation of the granophyre in southeastern Pennsylvania by differentiation of tholeiitc magma. It is, however, desirable to examine some of the alternative modes of origin of granophyre which have been suggested by workers in other districts. Such modes of origin include:

1. Separate intrusion of granophyre.

2. Syntexis, or the assimilation of acidic material by the diabase magma, followed by differentiation.

3. Formation of granophyre by hydrothermal alteration of solidified diabase.

4. Liquid immiscibility.

Separate Intrusion.- In southeastern Pennsylvania the granophyric masses occur exclusively within the diabase. No bodies of granophyre are known ih the Triassic or older rocks outside the diabase. If the granophyre were a separate, later intrusion one would expect to find it elsewhere, especially as many of the older rocks would afford more favorable loci for the emplacement of magma than the massive, relatively homogeneous diabase. One would also expect to find granophyre dikes cutting diabase at random; instead the granophyre masses are restricted to the upper part of the diabase intrusions. The small volume of granophyre and its discontinuous distribution in a few small lens-shaped bodies is not what one would expect of a separately intruded magma.

Contact relations between diabase and granophyre are not well exposed at the surface, but the Dillsburg drill core affords a perfect cross section revealing the boundaries between the contrasted rock types. In the drill core there are none of the features which usually accompany intrusive contacts. The boundary between diabase and granophyre is not sharp and clean cut but is gradational through a transition zone. There is no evidence that the transition zone is the result of reaction between molten granophyre and solid diabase. The chemical and mineralogical data which have been presented show a gradation between the acid and basic facies suggesting a genetic relationship.

An important exception to the above statement is found in the quarry at Safe Harbor where granophyre is intruded along a contact between diabase and Antietam schist, and dikelets of granophyre intrude the chilled border of the diabase dike. The relations have been described in detail in a preceding section. The granophyre veinlets have a narrow, fine-grained, chilled selvage against the diabase ahd there is a narrow reaction zone between the granophyre and diabase. There is no question that here the granophyre is a later, separate intrusion, but this is not conclusive evidence that all granophyre masses in diabase are separate intrusions. Rather, on the basis of what is known of the occurrence of granophyre elsewhere, the relationships at Safe Harbor suggest that a larger concealed body of diabase magma, of which the dike is but an offshoot, cooled and differentiated at depth, producing a granophyric residuum which was tapped later and intruded along the faulted and brecciated boundary. Edwards (1942, pp. 604-605) has stressed the importance of the concept of dikes as subjacent chambers in which differentiation can take place.

Syntexis, or Assimilation.- The derivation of granophyre by assimilation and later differentiation, that is by syntectic differentiation, has been proposed by Daly (1905; 1917) for the gabbroic sills of British Columbia and the Pigeon Point sill, Minnesota. Tomlinson (1945) suggested that the diabase magma of the Pennsylvania Triassic is "a mixed solution of 'basaltic magma' and assimilated 'acid magma'". According to him the assimilated acidic material was responsible for the interstitial granophyre in diabase and the bodies of diabase pegmatite found in the upper zones of diabase masses. As Schwartz and Sandberg (1940, p. 1165) pointed out in discussing the possibility of the formation of the red rock of the diabase sills at Duluth by syntexis, it is difficult to obtain positive evidence for or against syntectic origin because if assimilation was active there might be almost no trace of the rock which was assimilated (in their case rhyolite, in Tomlinson's case a concealed older granite). Undoubtedly some granophyres have been formed by reaction between basic magma and xenolithic material of acidic composition. Wager and Deer (1939a, p. 185-194) have shown that besides transgressive granophyre veins, which they regard as late differentiates of the Skaergaard magma, there are also granophyre inclusions representing blocks of recrystallized acid gneiss. In South Africa "reaction granophyres" produced by metasomatism of siltstone blocks included in Kaoo dolerite have been described by Walker and Poldervaart (1941). In both these instances, however, the inclusions and granophyre derived therefrom are small, measuring a few feet to a few tens of feet at most, and the nature of the original xenoliths could be established. The Pennsylvania granophyres are relatively large and no evidence of their having been formed from blocks of Triassic sedimentary rocks submerged in dikes has been found.

Walker (1940, p. 1096-1098) studied the Palisades sill, which has numerous large inclusions of arkose, and concluded that there is no evidence for syntexis or introduction of silica into the sill. In the eastern part of the Dillsburg district there are some isolated areas of Triassic sediments enclosed in diabase, but these are unaffected beyond the bleaching and contact metamorphism normally shown by sedimentary rocks adjacent to diabase elsewhere in the region. No inclusions such as those in the Palisades sill are known here. In the diabase at Safe Harbor, however, the writer found an inclusion of acidic material of aplitic character which is probably similar to the inclusions of "aplitic granite" described by Tomlinson (1945, p.529). Thus one is forced to admit that, at least locally, the basic magma may have picked up and possibly incorporated some granitic material.

Tomlinson suggests that the diabase magma was able to derive an acid magma from granitic rock which it intruded at depth and cites the occurrence of the granophyre adjacent to the diabase dike as evidence of the effectiveness of this process. As pointed out above in the section on the granophyre at Safe Harbor, the writer cannot agree with Tomlinson's conclusions.

An hypothesis of local assimilation of acidic material by the diabase magma does not simplify the problem of origin of the small bodies of granophyre. According to Bowen (1928, p. 214) "there is no theoretical objection to the belief that a certain amount of...inclusions could be incorporated, (but)... once incorporated it requires, to produce acid differentiates, the same conditions of crystallization as would have produced an acid differentiate from the uncontaminated magma." Furthermore, analyses show that the magma was a saturated type which would give a siliceous residuum if crystallized under equilibrium conditions, with any differentiation which might take place serving to increase the amount of this final residue. If we consider the total volume of acid material it is unnecessary to invoke assimilation to explain their occurrence. One need only find some mechanism whereby the final siliceous magma can be moved out from the diabase and concentrated.

Tomlinson (1945, p. 527) attributes ..."such variations as occur in the diabases...to assimilation of various rock types (by 'basaltic magma')_/ along the

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_/ Author's insertion, Tomlinson's quotes.

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journey upward. If acid types such as granites were assimilated, the composition of the 'basaltic magma' would be changed to that of the diabase magma." The writer does not propose to enter a discussion here on the origin of magma types, but may state again that the magma which solidified as diabase in these Triassic intrusions was of the tholeiitic variety which has world-wide distribution. Kennedy (1933) regards it as a primary magma. Holmes and Harwood (1928) called it the Whin Sill type and believed it to be derived from an olivine basalt parent by differentiation, a proposition subscribed to by H.H. Thomas (1930, p. 98), in Mull and Ardnamurchan and endorsed by Bowen (1928, p. 78). Holmes (1932, p. 549) hints that a saturated basaltic magma may be produced by the admixture of acid material with basaltic magma, and Barth (1936) believes that the magmas of the "Thulean province" being in contact with the salic crust, are more acid than the olivine basalts of the Oceanic Islands, where the salic crust is absent. Tomlinson's idea is somewhat akin to Barth's theory but one gets the impression that Tomlinson pictures the local variations in the diabase as consequent on variations in the degree of assimilation of the immediately underlying basement rocks, a view which has little if any supporting evidence and, in fact, is in opposition to the observed uniformity of composition of the chill facies of the diabase. Tomlinson then calls on immiscibility (1945, p. 530) to explain the separation of the siliceous residue.

Formation of Granophyre by Hydrothermal Alteration.- If the granophyre had formed by hydrothermal alteration of already solidified diabase one would expect to find in its texture and mineralogy some remainder of the original rock. This is not the case, for the minerals and their relationships are such that they could only have formed by primary crystallization. There is no relict diabasic texture.

Fenner (1926, p. 753) contends that the micropegmatite in the interstices of diabase is of secondary origin and attributes it..."to processes of endomorphic transformation active in igneous bodies during the later stages of cooling." Bowen has effectively supported his belief in the primary nature of these quartz and feldspar intergrowths by demonstrating the complementary nature of olivine and quartz in the Palisades sill. The writer has shown that the ratio of quartz to feldspar in the micropegmatite is essentially constant throughout the diabase-granophyre series at Dillsburg. It is doubtful that this constancy of ratio would hold if the micropegmatite in the diabase is of secondary origin. The micropegmatite in the transitional granophyric diabase and the granophyre is likewise probably primary, particularly as the quartz-feldspar ratio is essentially constant throughout.

It is not denied that alteration due to hydrothermal activity has been important locally, particularly in the closing stages of the cooling history of the magma. But there is no evidence in the mineralogy or texture that the granophyre or the transitional granophyric diabase have been derived by hydrothermal alteration of diabase.

Immiscibility.- Seeking to explain the abrupt gradation from gabbro to granophyre without intermediate types in the Duluth gabbro lopolith, Grout (1918) proposed an immiscible separation of the granophyre liquid from the gabbro before solidification was complete. Immiscible separation of an "intermediate" magma into a noritic fraction and a fraction which solidified as micropegmatite was suggested by Collins (1934) for the norite-transition zone-micropegmatite sequence ih the Sudbury intrusive. Tomlinson (1945, p. 530) believes that the diabase magma in Pennsylvania "...split into two separate magmas which (solidified) more or less independently of each other..." where the original "basaltic magma" assimilated "acid magma" in excessive amounts (more than 6 percent).

Bowen (1928, p. 7-19) has clearly discussed the conditions under which immiscibility in silicate melts takes place and has effectively shown that unmixing of two liquids is a valid concept only under certain restricted physical and chemical conditions. However, the requirements under which such separation can take place are so exceptional that the hypothesis of immiscibility seems to have no value in explaining the origin of small granophyre bodies such as those in Pennsylvania from basic magmas.

An interesting reexamination of the immiscibility theory has recently been made by Fenner (1948) in which he contends that some of the fundamentals on which Bowen based his argument have been misinterpreted. Fenner believes that immiscibility of two silicate liquids is possible. The occurrence of large bodies of "red rock" according to him is a phenomenon of the separation of a comparatively large mass of liquid by immiscibility. Fenner derives support from the fact that in some systems immiscibility gradually ceases as the temperature is lowered and applies this to silicate liquids. Thus small amounts of immiscible segregate tend to recombine with the conjugate liquid before or at the time of crystallization, and a criterion which Bowen says should be found if immiscibility exists in silicate melts (trapped globules of an immiscible fraction) is not expected. The writer finds this a weak argument because somewhere cooling should have been rapid enough to prevent the resolution of the unmixed globules.

Differentiation

General Statement.- The magma which rose into openings in the crust and solidified as diabase or poured out on the surface as basalt flows in southeastern Pennsylvania and elsewhere in the Triassic areas of the eastern United States was unquestionably a true primary magma. This is indicated by the widespread distribution and enormous volume represented, the uniform composition of its chilled phase, and the occurrence of basalt and diabase without complementary igneous rocks. The magma must have risen essentially simultaneously throughout the region and moved rapidly into place, for the uniformity of composition of its chilled facies everywhere means that it was emplaced while still in an almost wholly liquid state without having had time to differentiate. As it solidified, certain processes of differentiation operating within this primary magma were effective in producing a small volume of late-stage rock types differing markedly in character from the rock which crystallized first and approximated the composition of the molten material.

There can hardly be any doubt that the diabase-granophyre association exposed by the drill hole at Dillsburg is a consanguineous series brought into existence by differentiation of the diabase magma. But when we come to consider the way in which the differentiation has been brought about, we find that there have been almost as many mechanisms proposed for the differentiation of a mafic magma by fractional crystallization as there have been explanations for the origin of the gabbro-granophyre association by other means. The process involved in differentiating an intrusive body of magma to give rise to a contrasted suite is complex, and several different forces and reactions may be operative simultaneously or successively, the end product(s) being the result of the total effect exerted over the entire cooling period of the magma. Our concern here is to determine which processes have been operative in producing the association found at Dillsburg.

Differentiation Mechanisms.- Bowen has emphasized the importance of separation of early-formed olivine, thus preventing its reaction to form pyroxene and enhancing the amount of silica in the magma. However, as pointed out above, the magma of these intrusions was saturated and the relative volume of granophyre is so small that the amount of quartz could have been formed by crystallization differentiation without the necessity of removal of early olivine. But crystal settling is of importance beyond its being a process by which the magma is enriched in silica. Accumulation of heavier constituents such as pyroxene in the lower parts of a magma chamber leaves the upper parts still liquid. This residual liquid is being constantly enriched in the less refractory "volatile" constituents and when it finally crystallizes it gives a rock richer in alkalies and silica than the original magma.

The Palisades diabase sill has for a long time been cited as an excellent example of gravitational differentiation through the settling of early-formed olivine crystals followed at a later stage by pyroxene. This led to an accumulation of the heavier solid phases in the lower parts of the sill while the upper parts remained fluid and became enriched in the volatile constituents (Walker, 1940, p. 1092). Edwards (1940) also argued the effectiveness of crystal settling in bringing about the differentiation of the magma of the Tasmanian dolerite sills. It has not been possible to study the lower parts of the Dillsburg intrusive to determine the extent to which crystal settling has controlled the differentiation of the magma. However, no concentration of olivine such as occurs at the bottom of the Palisades sill has ever been reported from the bottom of the Gettysburg sill or any of the other diabase intrusives in southeastern Pennsylvania. But Stose and Lewis (1916) describe olivine-rich diabase from the Gettysburg area which must, from what we know of the chemical composition of the magma, represent some sort of accumulation of early-crystallized olivine. The writer has seen plentiful microphenocrysts of augite in the fine-grained diabase near the bottom of the Gettysburg sill. These must have crystallized early and may also have settled through the fluid magma. Unfortunately, exposures in southeastern Pennsylvania are inadequate to enable a detailed study of the concentrations of the mafic mineral to be carried out. It is safe to assume, however, that in an intrusion of this size there was some downward movement of mafic minerals in the earlier period of cooling, though the settling may have been of brief duration due to the rapid development of an interlocking mesh of pyroxene and feldspar. It is unlikely that there was any complementary rising of plagioclase crystals in the magma. Walker (1940, p. 1088) has calculated the specific gravity of the Palisades diabase magma to be 2.64 at the time of emplacement (temperature 1100°C). The specific gravity of the early plagioclase at this temperature, according to Walker, would be 2.65, which is actually slightly higher than the magma.

A variation on the gravitational differentiation theme has been proposed by Koomans and Kuenen (1938) for the Glen More ring dike. They picture the sinking of olivine and pyroxene, but contrary to the idea of an upward migration of the acid residue by streaming or floating owing to its being light, they suggest that the acid magma is generated by abstraction. They say, "...while the basic magma is formed by the addition of material from a large part of the reservoir, the acid magma is generated by abstraction and no new material is added to it. It has undergone cleansing by precipitation. We do not need to suppose that first 90 percent of the magma crystallized to a meshwork from which the mesostasis was ejected. But the concentration of the acid material is gradual, starting from the time the first crystals begin to sink."

Incomplete reaction between crystals and liquid can also be brought about without the removal of either phase. Armoring of early-formed olivine by pyroxene "takes it out of circulation." There is no petrographic evidence that this process was operative at Dillsburg. Probably an equally effective mechanism bringing about incomplete reaction, however, is the slow rate of diffusion between the liquid and solid phases in a magma. Of this we have abundant evidence at Dillsburg in the zoning of crystals of plagioclase and, to a lesser extent, pyroxene.

The erratic distribution of the lens-shaped masses of granophyre at once suggests that the residual liquid collected in pockets. All the masses of granophyre including the one in the drill hole are near the top of the diabase and separated from the sedimentary rocks by a roof of diabase. Possibly these lay beneath high spots on the generally smooth but undulating roof of the diabase. Scholtz (1936) described such an occurrence in the Karoo dolerite of East Griqualand and Pondoland, South Africa, where granitic rocks are thickest under the upward bulges and the heavier differentiates (picrites) concentrated in the troughs. In order to account for the arrangement he postulated an upward migration of acid material.

Holmes has raised an objection to the gravitative concentration of the acid magma. According to him the amount of granophyre developed by crystallization and fractionation is so small that the separation of the granophyric substance by a simple gravitational filtration is mechanically impossible. In this he probably has a valid argument, for the acid fraction was probably not available until the crystallization of the magma was at least 75 percent completed. At this stage the interlocking meshwork of crystals would constitute an effectively solid mass. The small force arising from the difference in density between interstitial liquid and crystalline material would be insufficient to displace the liquid.

Circulation of liquid and crystals brought about by the combined effects of thermal convection and gravity has apparently been an important differentiation mechanism in some magma bodies. Grout (1918) proposed a "two phase convection" to explain the phenomenon of layering on the sides as well as the lower part of a magma chamber. One of the best demonstrated examples of the effectiveness of convection in aiding differentiation is the Skaergaard intrusive (Wager and Deer, 1939). Cornwall (1947) has recently suggested convective circulation as the process which brought about the layering in the lavas of the Keweenaw Peninsula, Michigan.

It is possible that convection was active at Dillsburg and produced local segregations of the siliceous residual fluid which crystallized as granophyre. To prove that circulation was active, it would be necessary to find fluxion structures in the rocks. No oriented fabrics have been observed anywhere in the district. Walker does not report any evidences of flow structure in the Palisades intrusion, which is much better exposed than any part of the Dillsburg diabase bodies. The drill hole at Dillsburg gives an excellent section but being restricted to the upper parts of the intrusion it did not penetrate the deeper parts where layering and flow structures would most likely be found. Of course it is perfectly possible that the conditions under which the mass crystallized were unfavorable to the development of important circulation; for example, if a meshwork of crystals formed fairly soon, movement of crystals or magma would be hindered.

Filter pressing or differentiation by deformation has been advocated, especially by Bowen, as the most effective way of removing the residual magma from the crystal mesh in which it is entrapped. The process conceived by him would undoubtedly be most effective, but no evidence of its having been operative in the Dillsburg district is forthcoming. One would expect to find fracturing of the earlier-formed crystals, or a packing together of the grains as a result of pressure exerted on the crystal mush. Furthermore, one would have considerable difficulty in defining the deformative force; aside from the faulting and tilting of the basin during deposition of the sedimentary beds there has been no deformation of the rocks enclosing the diabase intrusions.

Emmons (1940) has argued for the "dilatancy principle" as an important process in separating the acid liquid..."from more basic crystals." Deformation of partly solidified magma which disturbs..."the crystal arrangement results in a less closely packed condition," and residual liquid flows into these zones of deformation. The principle is probably valid enough under certain circumstances, but, as Emmons says, the scale on which it operates is unknown. Dilatation could have been operative to some extent at Dillsburg, but there is no evidence in the texture of the rocks that they have been deformed prior to complete solidification.

Origin of the Diabase-Granophyre Series

The mode of differentiation of the diabase magma at Dillsburg, culminating in the crystallization of granophyre, is visualized by the writer as follows:

According to Bowen (1928, p. 72) and Kennedy (1933) magma of the composition of the Triassic diabase, though showing silica in the norm, is not so siliceous that it cannot precipitate out olivine as an early phase. The composition is such that it lies very near the clinopyroxene-forsterite boundary but within the forsterite field of the investigated system anorthite-forsterite-silica (Bowen, 1928, p. 42, 72). Thus in the chilled contact facies of the diabase we find some microphenocrysts of olivine which formed in the magma due to slight cooling as it was intruded and were trapped by freezing of the liquid at the contact.

Crystallization of plagioclase and pyroxene commenced soon after the olivine. The petrographic data are inconclusive as to whether pyroxene or plagioclase was the first to crystallize. But in the chilled zone at the bottom of the Gettysburg sill microphenocrysts of augite, some of them enclosing one or two small plagioclase laths, are frozen in the fine-grained groundmass of the plagioclase and intergranular augite. Apparently a few plagioclase crystals developed intratellurically and were followed almost immediately by pyroxene which sank and was trapped in the quickly chilled contact facies.

Because heat was lost more rapidly from the upper part of the mass, a relatively fine-grained roof of diabase was formed. Complete solidification took place in the upper part before the plagioclase and pyroxene could change much in composition; so we find a relatively fine-grained uniform diabase with relatively magnesia-rich pyroxenes and zoned plagioclase of a composition not much more sodic than that which formed at the outset of crystallization. In the deeper parts of the intrusion which were still fluid, crystallization was proceeding in a more leisurely manner and we may suppose that, by analogy with other similar intrusions, there was a certain amount of gravitative settling of pyroxene and some early olivine.

By the time crystallization had progressed to the "intermediate" stage, there remained a residual liquid, part of which occupied crystal interstices and was concentrated locally in the upper part of the body as pockets of liquid. The writer is not prepared to specify what mechanism was operative in bringing about the local concentration of these pockets of residual liquid. Crystallization from the top and bottom of the intrusion, leaving a residual liquid between essentially solidified diabase, was possibly the dominant process of concentration, though other factors, including gravity and convection, have contributed in part. The concentration of iron and titania, alkalies, silica, and water in the remaining liquid was high, while magnesia and lime had been depleted. Correspondingly we find the plagioclase more sodic and the pyroxene relatively rich in iron with an abundance of alkali feldspar and quartz as micropegmatite between the pyroxene and plagioclase crystals. A good deal of the iron and titania combined to form titaniferous magnetite and ilmenite. The lower temperatures and high water content were favorable for the development of some hornblende, which formed by reaction between the pyroxene and the magma. A little biotite also crystallized. The formation of hornblende and biotite released still more silica to the remaining liquid.

Mineralization.- The intermediate stage was a critical one so far as the Dillsburg district was concerned, for now the magma, rich in iron was at the same time charged with volatiles. Here was a potential mineralizing agent with hydrothermal solutions rich in iron which could enter the country rocks, metamorphose them and deposit iron as magnetite. Release of the mineralizing solutions would increase the viscosity of the magma and prevent further differentiation. The writer believes this is essentially what happened at Dillsburg. The residual magma of the intermediate stage had collected in volume below the solid, impervious cover of diabase. Fractures were produced in the cover, perhaps by movements in the underlying partly fluid, partly solid, body due to surges of fresh magma in depth, perhaps because of the high internal pressures being developed by crystallization, or perhaps merely by cooling of the cover and formation of tension cracks. Some of these openings reached into the portion in which crystallization was fairly well advanced. Under pressure the volatile-rich solutions escaped, taking with them some of the oxides, particularly iron. These became the hydrothermal solutions which passed through the overlying sedimentary rocks, altered and developed new minerals ih them and, finding the layers of limestone conglomerate, replaced the calcium carbonate with new minerals, among these magnetite and calcium-iron silicates.

Diabase Pegmatite.- The diabase pegmatite represents magmatic liquid entrapped in essentially solidified but possibly still mushy diabase at a stage when crystallization of much of the diabase had enriched the liquid in viscosity-reducing volatiles as well as alkalies and iron. From this liquid plagioclase and pyroxene continued to crystallize with coarser grain than in the surrounding, essentially solidified, diabase.

With continued crystallization the remaining liquid changed in composition and toward the end was no longer in equilibrium with the solid phase. Thus the plagioclase is strongly zoned and shows continuous growth into the alkali feldspar intergrown micrographically with quartz; the final solution altered the earlier formed plagioclase. Likewise, the changing solutions reacted with the pyroxene and developed rims of hornblende and some biotite. The removal of iron as magnetite rather than in combination with silica as pyroxene, and the development of hornblende and biotite, augmented the amount of silica in the remaining liquid and thereby increased the quartz in the final interstitial material.

The heterogeneous diabase with its coarser-grained patches and streaks which lies just below the upper chilled zone had an origin similar to the diabase pegmatite. The network of coarser-grained diabase, whose mineralogical composition is more like that of the diabase pegmatite than the finer-grained diabase of the matrix, represents volatile-rich streaks in nearly solidified but still mushy magma. Because of their volatile-rich character these patches developed a coarser grain than the surrounding material. The mode of accumulation of these volatile rich streaks below the chilled roof is not entirely clear. Possibly crystallization of the roof downwards forced out volatiles into the partly liquid magma below, or bubbles of volatiles from lower down in the body moved upward and accumulated in streaks and layers beneath the solid, chilled roof.

The diabase pegmatite belongs to a late stage in the crystallization history of the diabase, possibly overlapping both the intermediate and final magmatic stages.

Granophyre.- The granophyre represents the latest stage differentiation product of the diabase. The residual liquid, now much depleted in volatiles and most of the mafic constituents crystallized more rapidly to granophyre, a rock composed principally of alkali feldspar, quartz, and a little pyroxene relatively rich in iron. Thus we have an abrupt transition from relatively coarse-grained granophyric diabase to fine-grained granophyre. Quite possibly the release of pressure attending the escape of the hydrothermal solutions started a movement of residual magma under pressure from elsewhere in the diabase body toward the point(s) of lower pressure, thus augmenting the supply of dwindling magma.

The development of granophyre from the diabase magma illustrates an important principle previously emphasized by Larsen (1938, p. 248), and Wager and Deer (1939, p. 230-231), namely, that the maximum change of composition due to differentiation of a basaltic magma is brought about only after crystallization of 75 to 80 percent of its volume. The effect is to give an abrupt change in rock types, a contrasted suite such as we have here.

The explanation for the coarse-grained, miarolitic granophyre masses which are different from the fine-grained hedenbergitic granophyre may be that they were able to retain their hydrothermal solutions for a longer time. This would permit the development of larger crystals, and would also explain the predominance of hornblende over pyroxene. When the high internal pressures were relieved or overcome the external pressure, the magma began to vesiculate, but the loss of mineralizers rapidly increased the viscosity and the magma froze, trapping some of the bubbles which later yielded miarolitic cavities.

Temperature.- For reasons discussed above it is certain that at the time of its intrusion the magma was almost entirely liquid. Sosman and Merwin (1913) determined the temperature of the liquid magma of the Palisades sill at the time of intrusion to be less than 1150°C. Hess (1941, p. 582-583) pointed out the value of pyroxene as geologic thermometers and estimated a temperature of 1120° ± 10°C for the Palisades. Hess's method makes use of the inversion temperature of pigeonite to hypersthene. The diabase beneath the upper chilled zone at Dillsburg has pigeonite which is mostly inverted to orthopyroxene, indicating that the temperature at which it crystallized was at or slightly above the inversion temperature, slightly more than 1100°C at this MgO:FeO ratio.

If, as the author is inclined to believe, the hedenbergite in the granophyre is an inverted β-wollastonite solid similar to that described by Wager and Deer for the Skaergaard intrusion, we can also approximate the temperature toward the end of the crystallization period, the stage at which the granophyre crystallized. This inversion takes place around 955°C.

The difference in temperature, then, between the time of intrusion or start of crystallization and its virtual completion is on the order of 195°C.

FORM OF SOME DIABASE SHEET IN SOUTHEASTERN PENNSYLVANIA

General Statement

Oval and elliptical outcrop patterns are characteristic of the diabase bodies in southeastern Pennsylvania. The Geologic Map of Pennsylvania (Stose and Ljungstedt, 1931), from which figure 1 was taken, shows several elliptical diabase rings occurring in a belt in the northwestern part of the Triassic basin beginning south of Reading and extending northeast to the Delaware River. Another series of smaller and less well-defined rings of diabase extends southwest from Cornwall to Dillsburg. A single, small, almost circular ring of diabase is found just north of the Pennsylvania-Maryland border southwest of Gettysburg.

As long ago as 1908 Spencer (1908, p. 44-45) suggested that the ring-like chain of diabase intrusions in the northeastern part of the belt was the surface expression of a "practically unbroken sheet." In the southeastern part of the Fairfield quadrangle Stose and Bascom (1929) show sheet-like diabase masses which owe their form to their position of intrusion along and a short distance above the contact between Paleozoic rocks and flat-lying overlapping Triassic sediments. Most of the intrusions, however, have been interpreted as conventional sills and and steeply-dipping, dike-like discordant bodies with concordant sill- and basin-like off-shoots.

Spencer's conclusions have been confirmed by drill-hole explorations at Dillsburg and elsewhere and by a gravity survey near Quakertown. It now seems that a sheet-like habit is characteristic of most of the diabase masses which exhibit oval or ring-like outcrop patterns.

Structural History of the Triassic Basin

The Triassic belt of southeastern Pennsylvania represents a continental basin in which terrestrial sediments were deposited. During deposition of the sedimentary rocks the basin was gradually sinking due to downward flexing or faulting along its northwest edge (Stose and Jonas, 1939, p. 107-108, 119). The northwest border is now marked by a fault boundary in many places, whereas the southeast limit is usually an unconformable depositional contact on the older rocks. Fracturing of the basin provided vents for the upward movement of magma, which was intruded into the sedimentary rocks and solidified as diabase. The sedimentary rocks were metamorphosed to quartzites and hornstone in the vicinity of the diabase intrusions.

The Triassic sedimentary rocks are not much disturbed except for normal faulting and general tilting to the northwest. The predominant trend of the strata is east-northeast and the dip averages about 30 degrees to the northwest. In places the rocks are gently flexed but the regional structure is generally homoclinal with a gentle northwest dip. Diastrophic activity virtually ceased in the Triassic basin before or at the time of diabase intrusion.

Structural Geology of the Dillsburg District

Structure of the Sedimentary Rocks.- The predominant strike of the Triassic sediments in this region is northeast with a uniformly gentle northwest dip at angles ranging from 15 to 30 degree. Studies by Stose and Jonas (1939,

p. 115-120), the general relations in the drill holes, and the character of the sedimentary rocks indicate that the beds are highly lenticular.

Most workers agree that the sedimentary rocks occupy a basin which is tilted to the west and terminates against a steep normal fault on the northwest border. The structure of the basin at Dillsburg conforms to this general structural pattern.

Form of the Diabase Intrusions.- Stose and Jonas, and Stose and Lewis have emphasized the concept of a sill-like structure for much of the diabase in York County (Stose and Jonas, 1939, p. 125) and elsewhere in eastern Pennsylvania (Stose and Lewis, 1916,; Stose and Jonas, 1933, p. 42). Where the relations are apparently discordant at the surface a steeply-dipping dike-like body has usually been postulated. Part of the large diabase body east of Dillsburg has apparent conformity with the bedding in the sedimentary rocks, (Fig. 2). However, the ring of diabase surrounding the Dillsburg area is discordant with the structure of the sediments on all but its south side, where the beds have a northerly dip.

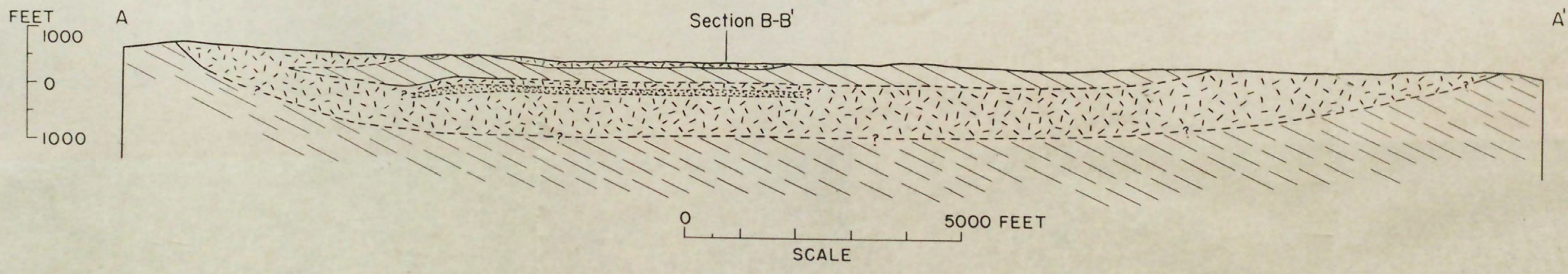
Spencer interpreted the body of diabase occupying an oval area and overlying the magnetite deposits in the Dillsburg ore field to be in part discordant, though in his description of the mines he assumed concordant relations to exist in most places (1908, p. 71-72).

Harder (1910, p. 601) interpreted the diabase overlying the magnetite deposits as a sheet which "...apparently lies on the sediments with a rolling uneven contact, while the outlying smaller masses appear to be erosion remnants lying in troughs on the surface of the sediments. The sediments underneath the diabase are continuous with those surrounding them and have the same prevailing dip...".

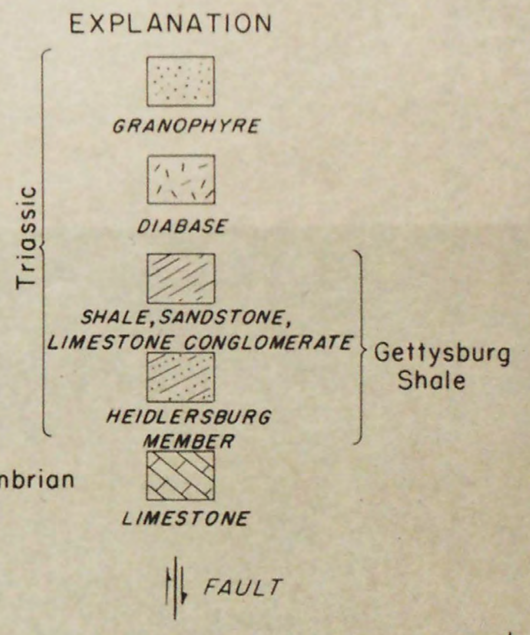
Diamond drilling has proved Harder's concept of the structure of the upper diabase body to be correct. In each drill hole a cap of diabase 60 to more than 100 feet thick was penetrated above the metamorphosed sedimentary rocks. From the structure section through the drill holes (Fig. 3) it is evident that the contact of the diabase with the underlying sediments is discordant and essentially a flat surface. Several drill holes encountered a second mass of diabase below the sediments in the magnetite-bearing areas. This underlying intrusive body was not known prior to the drill hole exploration. Its upper surface, at least within the drilled area, is a discordant, gently undulating surface. In one drill hole a mass of granophyre was disclosed beneath the upper chilled zone of the diabase. Similar masses of granophyre are known to occupy the higher parts of other thick diabase masses in York County and elsewhere in Pennsylvania. It is inferred that this diabase beneath the ore deposits is a thick body (1,000 feet ±).

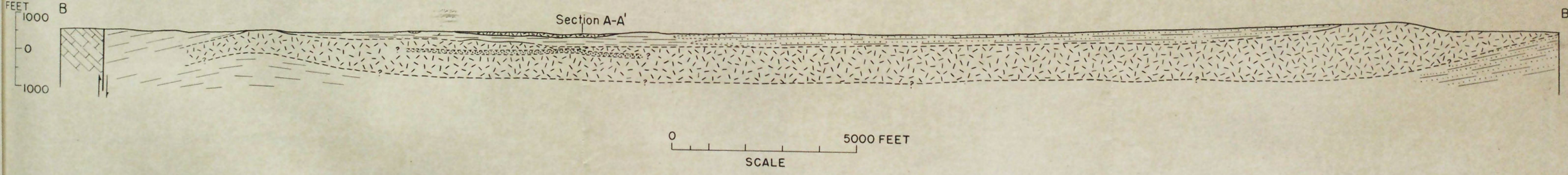
The "upper" diabase sheet is almost continuous at the south with the main mass of diabase except for two narrow strips where it has been removed by erosion (Fig. 3). The diabase sheet overlying the ore deposits was formerly continuous with the body to the south and constituted a minor offshoot. Exploration has clearly shown that the lower diabase and the body south of the ore field are one and the same. A magnetic survey of the district conducted by the Bureau of Mines outlined an area of magnetic attraction over the northern edge of the large east-west-trending mass of diabase which borders the Dillsburg district on the south. Subsequent drilling proved the existence of ore-bearing sedimentary rocks beneath the diabase, and diabase was shown to be present also underneath the metamorphosed sedimentary rocks. The sediments do not crop out to the south within the diabase; hence they must wedge out somewhere south of the southernmost drill hole, and the lower diabase must therefore be continuous with that exposed at the surface. Thus there is a plate of sedimentary rocks 200 to 300 feet thick lying between two nearly horizontal diabase sheets and wedging out where the two masses join.

Figure 16. Structure sections of the Dillsburg district, Pennsylvania. For location of sections see Figure 2.



SECTION A-A'





SECTION B-B'

The structural interpretation favored by the writer is that the diabase underlying the Dillsburg area is part of the same mass which surrounds the district. Its general structure would be that of a broadly concave, platter-like sheet which truncates the gently-dipping sedimentary rocks (Fig. 16). The whole body apparently is an offshoot of the Gettysburg sill.

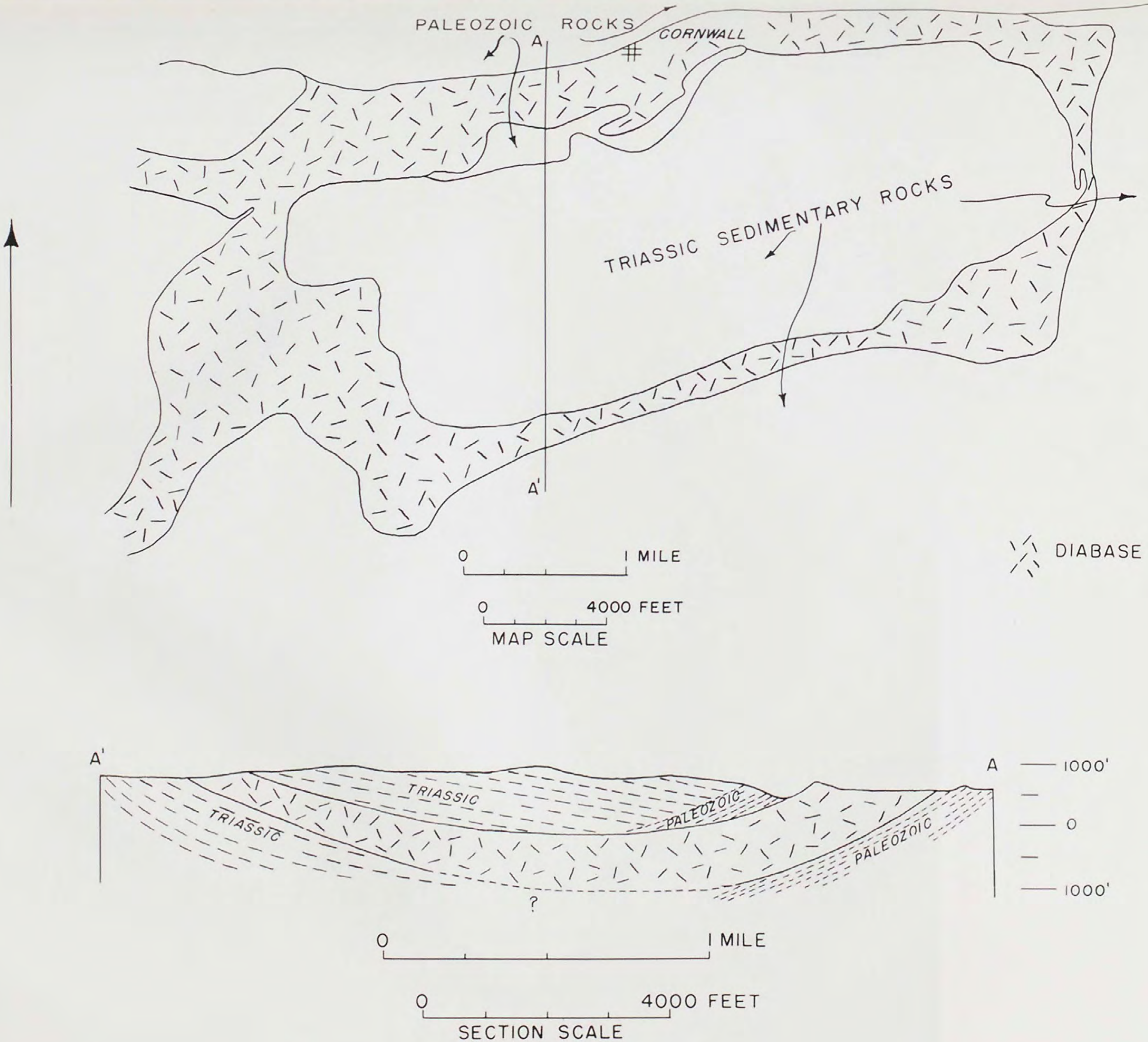
In the Dillsburg area there is evidence of disturbance of the sedimentary rocks by intrusion of the diabase. Uplift of the sediments above the lower diabase sheet has caused an apparent horizontal displacement of the Heidlersburg member of the Gettysburg shale (Fig. 2). A continuous belt of Heidlersburg is interrupted by the large mass of diabase, and a displaced segment occurs in the nearly isolated plate of sedimentary rock east of Dillsburg. The change of strike of the bedding east and southeast of Dillsburg may also be the result of tilting of the rocks above and adjacent to the intrusion.

The Cornwall District

The Cornwall magnetite deposits are situated on the north side of a small diabase ring 7 miles south of Lebanon (Fig. 1). The deposits occur in a wedge of Paleozoic limestone between Triassic sedimentary rocks on the south and diabase on the north (see Fig. 17). The diabase has been interpreted by Spencer (1908, p. 19-20) and others as a more or less vertical dike on the north with a thin sill-like offshoot which comes to the surface at the south.

Diamond drilling by a private company has shown that the diabase on the north side is not a dike but a sheet about 1,000 feet thick dipping gently south (Fig. 17). Drilling to the south toward the center of the ring, which is occupied by Triassic sedimentary rocks, has shown that the diabase extends beneath the area, where it becomes a nearly flat-lying body. The diabase is here interpreted as a continuous shallow basin-like structure only locally concordant with the structure of the sedimentary rocks, which dip gently to the north.

Figure 17. Geologic map and structure sections of the Cornwall district, Pennsylvania.


PALEOZOIC ROCKS
CORNWALL
A
A'
TRIASSIC SEDIMENTARY ROCKS
DIABASE
0
1 MILE
0
4000 FEET
MAP SCALE
A'
A
TRIASSIC
TRIASSIC
PALEOZOIC
PALEOZOIC
?
1000'
0
1000'
0
1 MILE
0
4000 FEET
SECTION SCALE

The Wheatfield District

The Wheatfield group of magnetite deposits is situated about 7 miles southwest of Reading (Fig. 1) in a re-entrant of Triassic rocks at the northwest end of a large ring of diabase whose long axis trends northwest-southeast. The map in figure 18 shows the geology of the Wheatfield district.

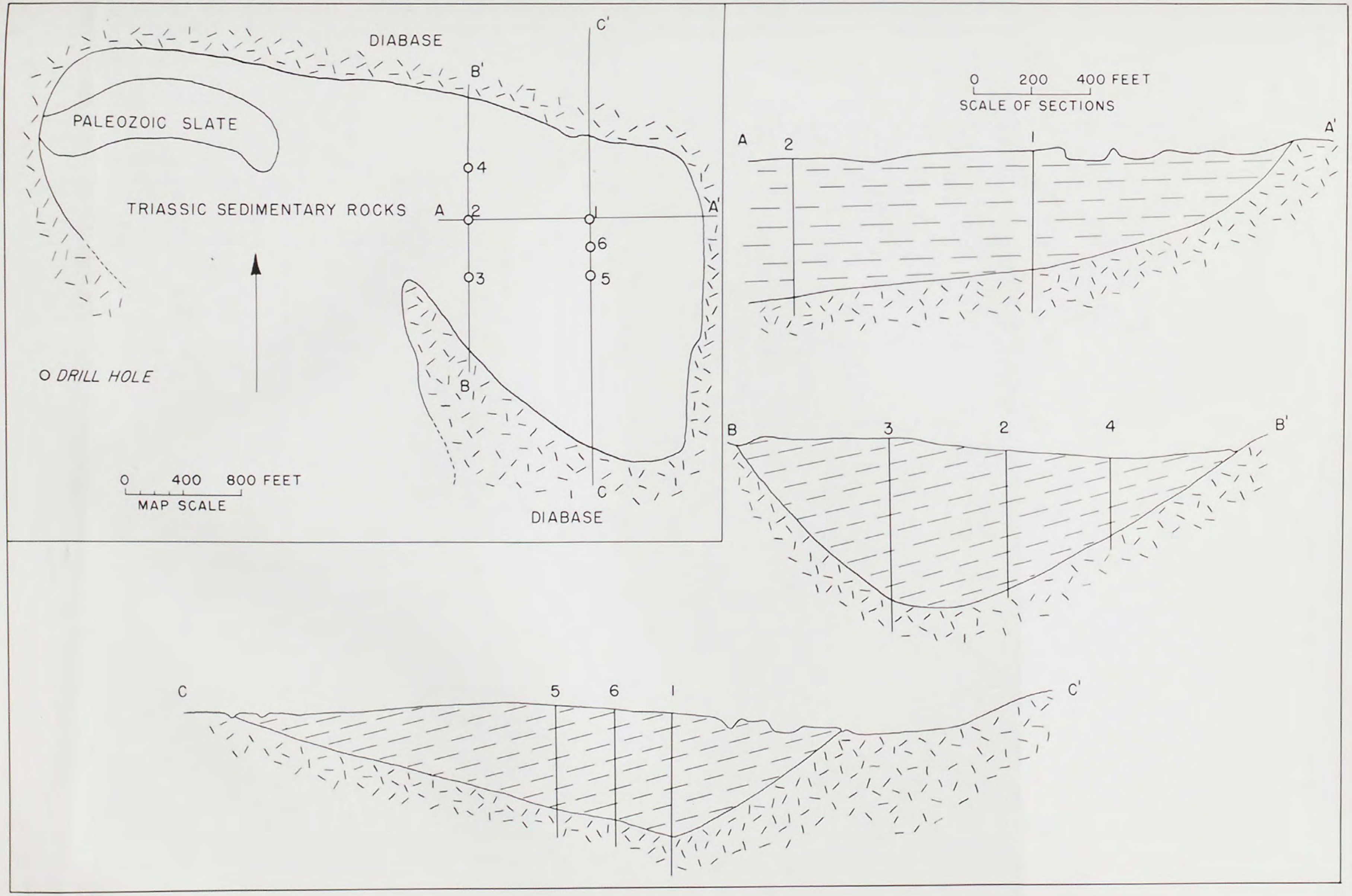
Exploration by diamond drilling has clearly revealed that the diabase forms a basin-like structure which is somewhat more concave than the intrusive sheets at Dillsburg and Cornwall. The Triassic strata dip about 30° south and the upper surface of the diabase, though more or less concordant on the north side of the basin, is markedly discordant on the south. Information is lacking to prove or disprove that the diabase is a sheet, since no drill holes passed through the igneous rock.

The Quakertown District

An elliptical body of diabase whose long axis strikes northeast is present at Quakertown about 12 miles southwest of the Delaware River (Fig. 1). This area was recently the subject of a gravity survey by J.B. Hersey (1944).

Although the Triassic sedimentary rocks occupy the center of the ellipse at the surface, a gravitational "high" over the area (Fig. 19), indicates the presence of diabase beneath a thin plate of sedimentary rocks. The gravitational pattern is symmetrical and conforms to the shape of the diabase outcrop pattern. The anomaly, according to Hershey, suggests a thickening of the diabase toward the central axis of the structure. If one flank was the feeder (dike or sill) and the underlying sheet a minor offshoot from the main mass, one would expect to find the "high" over one edge of the structure directly above the dike-like feeder. Hershey states (1944, p. 439) that "the gravity anomaly could be caused

Figure 18. Geologic map and structure sections of the Wheatfield district, Pennsylvania.



DIABASE
PALEOZOIC SLATE
TRIASSIC SEDIMENTARY ROCKS
A
A'
B
B'
C
C'
1
2
3
4
5
6
O DRILL HOLE
0 400 800 FEET
MAP SCALE
DIABASE
0 200 400 FEET
SCALE OF SECTIONS

by an intrusive roughly 100 feet thick near its edges and about 1800 feet thick along its axis. Figure 19 illustrates the possible structure of the diabase body as modified from a diagram by Hershey.

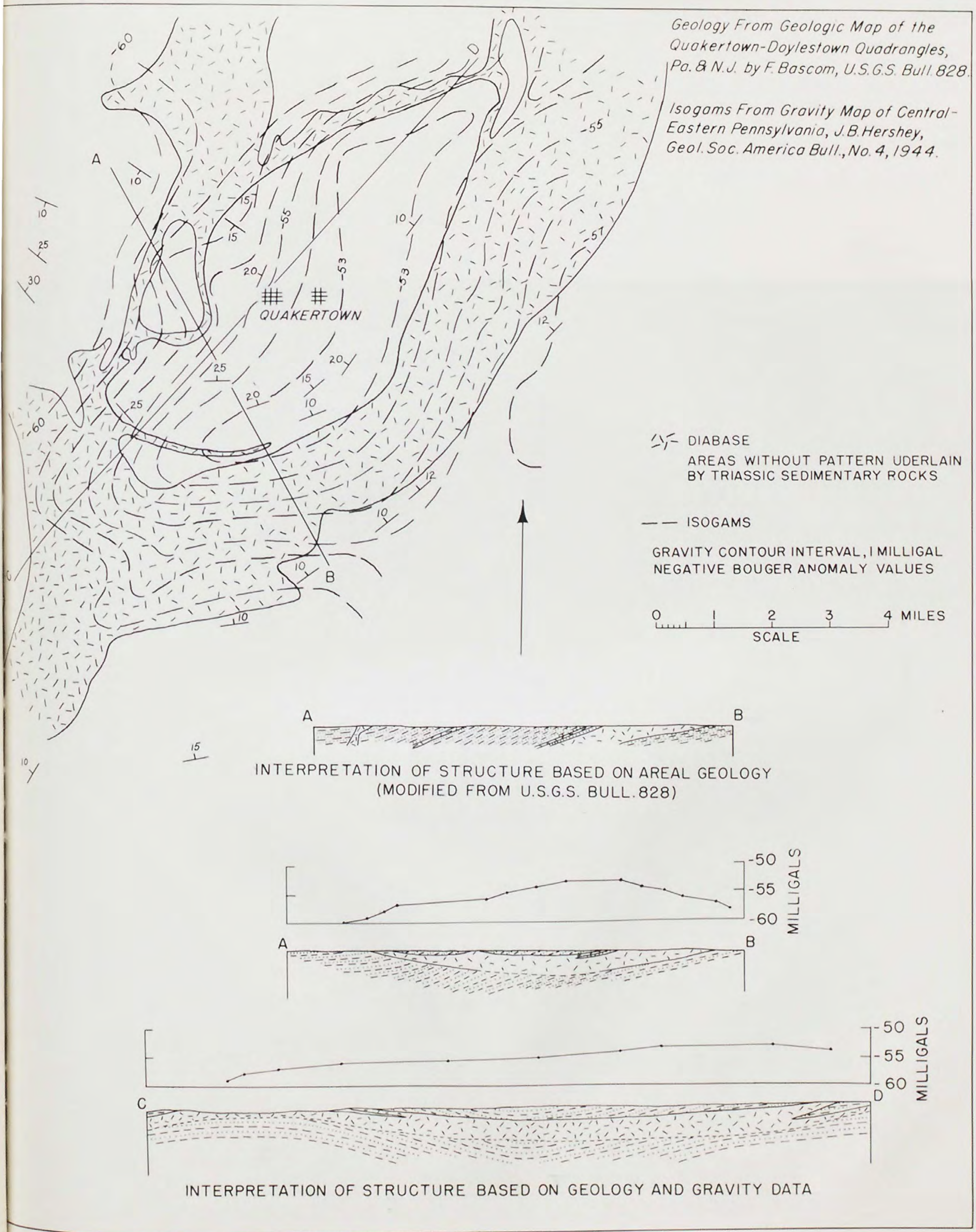
The Boyertown District

The Boyertown magnetite deposits are located at the eastern end of an elliptical mass of diabase, as shown in figure 1. The following discussion is based on a written description by A.F. Buddington and H.E. Hawkes, who studied the deposits and mapped the western part of the elliptical structure.

At least the western end, and possibly all, of the diabase ellipse occupies the flanks of a synclinal structure in the Triassic sedimentary rocks. The syncline in the vicinity of Boyertown is asymmetrical, with dips of 50°S on the north limb and 20°N on the south limb (See figure 20). The western end of the syncline apparently abuts discordantly against the contact between the Triassic sediments and the Paleozoic limestones. This contact, where it has been mapped in the course of mining and exploration of the Boyertown ore bodies, dips 30° to 45° east-southeast. The diabase here apparently occupies fractures in the limestone immediately adjacent to and approximately parallel with the contact. As far as can be inferred from the very meager field exposures, the diabase sheets in the vicinity of the mine sharply transgress the bedding of the Triassic sediments.

The main diabase outcrop is broken in two places, leaving an isolated area of diabase about a mile north of Boyertown. It may be reasonably inferred that this diabase body is connected at depth with the main mass and is an integral part of the major igneous structure. Local exposures of granophyre similar to that described from Dillsburg were found near the southwest edge of the isolated

Figure 19. Geologic map and structure sections of the Quakertown district, Pennsylvania.



INTERPRETATION OF STRUCTURE BASED ON AREAL GEOLOGY
(MODIFIED FROM U.S.G.S. BULL. 828)

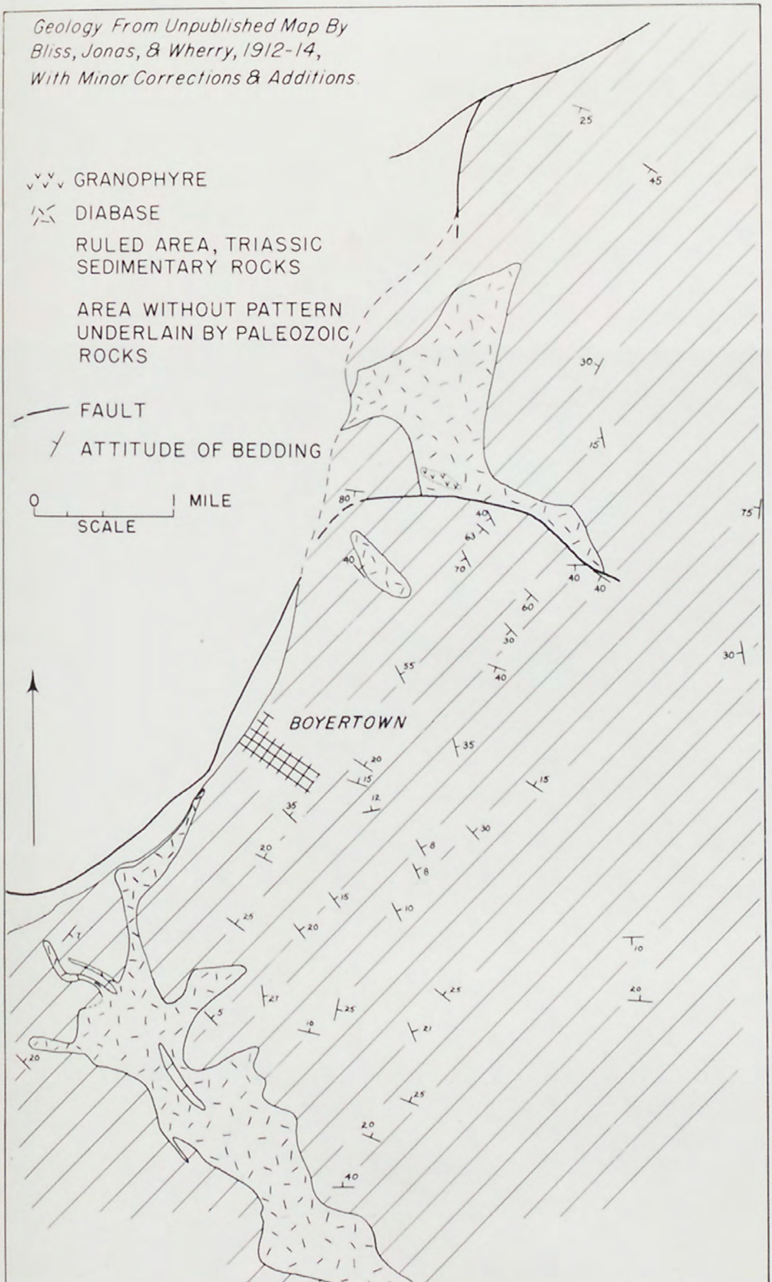
INTERPRETATION OF STRUCTURE BASED ON GEOLOGY AND GRAVITY DATA mass. The position of the granophyre with respect to the contacts and apparent structure of the enclosing diabase suggests that it occurs in the upper part of a thick sheet dipping moderately to the south.

Evidence is not available to indicate whether the diabase forms a sill conformable with the sedimentary structure, as postulated by Spencer, or whether it is a discordant, platter-shaped mass similar to that described from Dillsburg.

Comparison With the Dolerite Sheets of South Africa

A.L. Du Toit (1920) and D.L. Scholtz (1936) have described dolerite intrusions in the Karoo system of South Africa which have forms remarkably similar to the diabase bodies in southeastern Pennsylvania. The bulk of the sill-like intrusions are curved sheets whose "...outcrops...determined chains of hills snaking across the country" (Du Toit, 1920, p. 7). Figure 21 taken from Du Toit's paper shows the irregular ring-like plan of the outcrop of these intrusions, almost the exact counterpart of which is to be found in figure 1 which shows in plan the diabase bodies of southeastern Pennsylvania. The sheets of East Griqualand and Pondoland studied by Scholtz (1936) are well known because of their associated nickeliferous ore deposits. According to Scholtz many of the sheets are rudely circular in ground plan and exhibit a basin-like structure with diameters up to 10 miles and thicknesses ranging from less than 1,000 to more than 3,000 feet. The sheets are characterized by rudely parallel, but markedly undulatory, upper and lower surfaces.

These are discordant intrusions but, unlike the bodies which were intruded into generally westward-dipping, locally gently folded beds, the rocks which they intruded are essentially horizontal.



Geology From Unpublished Map By
Bliss, Jonas, & Wherry, 1912-14,
With Minor Corrections & Additions
GRANOPHYRE
DIABASE
RULED AREA, TRIASSIC SEDIMENTARY ROCKS
AREA WITHOUT PATTERN UNDERLAIN BY PALEOZOIC ROCKS
FAULT
ATTITUDE OF BEDDING
0
1 MILE
SCALE
BOYERTOWN

The similarity between the Pennsylvania and South African intrusions is not only one of structure. The South African sheets exhibit doleritic marginal chill zones, and the crests of the arches of the intrusions are in some places characterized by the presence of rocks of granitic composition similar to the granophyre in the upper parts of the sheets in York County and at Boyertown.

Origin of the Diabase Sheets

In this region of Pennsylvania there are few true sills in the usual meaning of the term. The Gettysburg sill apparently fulfills the requirements of the definition, being in most places a gently inclined concordant body. The many other masses of diabase with their elliptical or circular outcrop pattern are in part conformable to the bedding of the enclosing sediments but in many places are discordant. Although the data are not yet complete the available information presented above indicates that many if not all of these diabase bodies are continuous beneath a cover of Triassic sedimentary rocks and are basin-shaped. The succession of a series of shallow, basin-like bodies suggests that in places, as for example south of Quakertown, the diabase forms an effectively continuous, gently rolling sheet. Erosion has removed some of the cover of sedimentary rocks so that the high parts of the sheet are exposed, giving the effect at the surface of a series of connected links in a chain.

The only form in which the diabase intrusions occur in the older rocks outside the Triassic basin is as dikes. It would seem as if the older rocks with their complex structures were more resistant to the intrusion of the diabase magma, and restricted its course to a few well-defined, predetermined vertical fractures. In the Triassic sedimentary rocks the invading magma, finding easy access along bedding planes and relatively flat-lying potential open spaces or

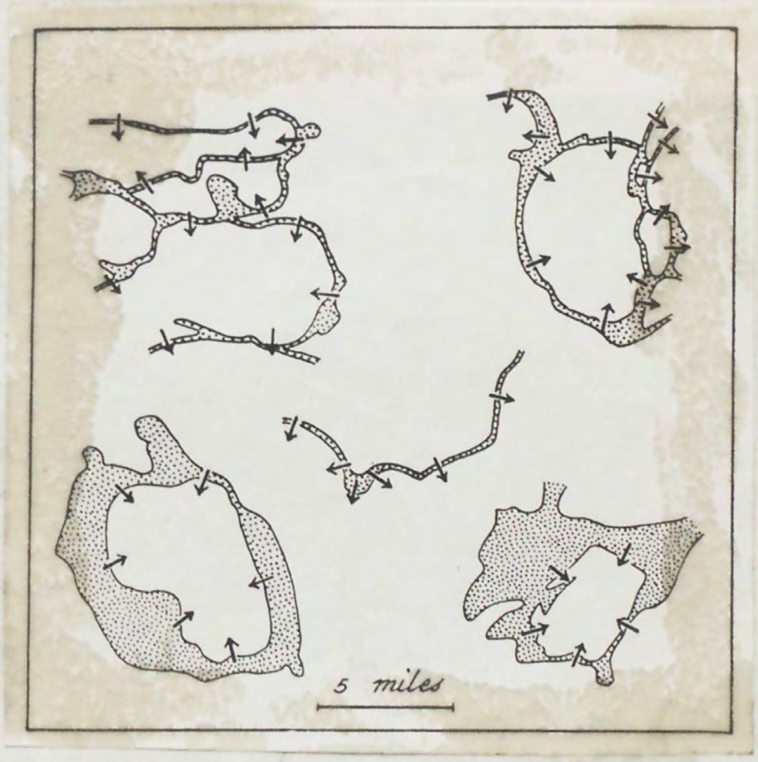


Figure 21. Types of curved intrusive sheets of Karoo dolerite, (stippled) in plan. Du Toit (1920, fig. 2, p. 7).

actual fractures, was able to raise its roof and spread laterally.

Diabase dikes are known to occur throughout the Triassic belt as well as in the adjoining areas of older rocks. Some of these may have been the avenues through which the diabase magma was fed to the sheets. Some of the sheets may be in part offshoots from larger intrusions. For example, the large mass of diabase east of Dillsburg and the flat sheet beneath the ore deposits appear to be offshoots from the Gettysburg sill. Some of the diabase may have risen along fault zones at the northwest border of the Triassic basin.

The mechanism which controlled the basin-like form assumed by these intrusions is not clearly understood. The curved form of the diabase sheets might be interpreted as being due in part to the development of nearly flat to gently undulating fractures in the Triassic sediments. These were subsequently filled by magma which consolidated as diabase. Where these fractures were joined, the filling of diabase was continuous. Some of the sheets may be controlled by original gentle synclinal structures in the sediments. Du Toit (1920, p. 29) suggested that the curving form in the Karoo dolerites "...may have been partly or wholly determined under the stresses set up through thermal expansion." Fractures developed during the tilting of the Pennsylvania Triassic basin probably served as conduits through which the diabase magma rose into the accumulated sediments. Perhaps relatively flat fractures were also produced at this period.

It is possible, however, that no actual fractures were necessary in order for the magma to seek a sheet-like form. Some physical conditions may have existed such that the magma found it easier to spread laterally than to rise to higher levels. Under these circumstances the magma could probably make its own way by starting with initial irregularities in the conduit wall or by following potential planes of weakness brought about possibly by tension in the subsiding sediments.

According to E.M. Anderson (1942, p. 23, 142) the thin edge of an advancing magma sheet has a powerful wedging effect by means of which it is able to advance itself.

Scholtz (1937, p. 202), discussing the mechanism of intrusion of the Karoo dolerites, postulates that the initial stages of magmatic activity resulted in "...the extrusion of great quantities of lava at the surface, which eventually consolidated and acted as an effective barrier to the escape of the rising magma, which now penetrated potential lines of weakness developed in the still subsiding sediments." So far as is known there was no thick overburden of lava in the Pennsylvania Triassic basin. The amount of sedimentary material above the present level at the time of diabase intrusion is also unknown. It must have been considerably in excess of 10,000 feet, because the difference in elevation between the pre-Cretaceous Schooley surface on South Mountain west of Dillsburg and the present Triassic surface is about 800 to 1,000 feet. However, under proper circumstances a considerable thickness of sediments might constitute a barrier to the vertical rise of the magma, which then found its easiest relief by spreading laterally.

Scholtz pictures "...the injection (of magma as sheets)...as being of the nature of a mutual exchange of place between the settling sedimentary formations and a concomitant hydrostatically elevated quantum of magma..." without producing any arching of the roof. Du Toit (1920, p. 28) on the other hand considers that introduction of the Karoo sills must have "...produced vertical uplift of the overlying strata amounting to the thickness of the intrusion at that point measured vertically." As we have seen in the case of the Dillsburg intrusion there is evidence of uplift and disturbance of the overlying sedimentary formations.

GENERAL SUMMARY

Small local masses of granophyre occur in the upper part of diabase bodies in the Triassic (Newark-Gettysburg) basins of southeastern Pennsylvania, particularly in the Dillsburg district in northern York County. Although it has generally been assumed that the granophyre bodies were derived from the diabase by differentiation, no detailed study of their petrologic relationships has heretofore been undertaken. The core from a diamond-drill hole which penetrated the upper part of a large diabase mass underlying the Dillsburg magnetite deposits revealed a complete section of diabase passing into granophyre. Thus an excellent opportunity was afforded to make a detailed petrographic and chemical study of the diabase-granophyre relationships and, in doing so, to contribute to a better understanding of the genesis of granophyre from diabase in this area and its possible relation to the origin of the magnetite deposits. In addition, general field and laboratory studies were made of the other granophyre bodies occurring at the surface in this and adjoining areas.

In the drill-hole section five main rock types were recognized: diabase chill facies, diabase, diabase pegmatite, granophyric diabase intermediate between diabase and granophyre and granophyre. These occur in the section from top to bottom in the order named. Granophyric diabase also underlies the granophyre and is presumably succeeded in depth by an unknown thickness of diabase not penetrated by the drill. The units pass gradationally one into the other, and there are no sharp boundaries or other features indicative of intrusive relationships.

The small lenticular masses of granophyre in diabase exposed at the surface elsewhere in southeastern Pennsylvania occur in the upper part of the diabase bodies beneath a roof of diabase. Unlike that encountered in the drill hole at Dillsburg, most of these granophyres are coarse-grained and may have miarolitic cavities. Hornblende rather than pyroxene is the usual mafic mineral. A fine-grained miarolitic granophyre has an intrusive relationship into a diabase dike at Safe Harbor.

Following detailed description of the petrography and mineralogy, the possible origins of granophyre are considered. It is concluded that crystal differentiation in large intrusions of diabase after emplacement most satisfactorily explains the genesis of granophyre in this region. The course of differentiation can be traced from chemical analyses and petrographic evidence.

Analyses of the chilled facies of the diabase show that the original magma was of the saturated, tholeiitic type which shows free quartz in the norm. Due to differentiation the magma was progressively enriched in iron, alkalies and silica. Correspondingly, the pyroxenes became richer in iron, the feldspar more sodic, and the amount of quartz increased. Iron increases in the residual magma up to a late stage but declines in the final fraction product. Pyroxene follows the expectable trend from a magnesian variety in the early stages toward iron-rich members in the late periods of crystallization. However, optical data indicate that the composition lies on the diopside join in the rocks of later crystallization and hence is rich in lime and divergent from the augite curve indicated by Hess as the expectable course to be followed in rocks of this composition.

The mechanism of differentiation at Dillsburg is visualized by the writer as follows. Subsequent to intrusion the magma body began losing heat from the top and bottom. By the time crystallization had progressed to the "intermediate" stage there remained in the upper part of the nearly solid mass of diabase a residual liquid rich in iron and titania, alkalies, and volatile constituents.

Before this residual magma completely solidified, fractures in the roof permitted the escape under pressure of volatile-rich, iron-bearing solutions which passed into the overlying sedimentary rocks, altering them and replacing layers of limestone conglomerate with magnetite. The residual liquid, now much depleted in volatiles and most of the mafic constituents, crystallized to relatively fine-grained granophyre. Where it retained its volatile constituents, large crystals developed, with hornblende predominant over pyroxene. When internal pressures reached values high enough to overcome the superincumbent load, the magma began to vesiculate; but the loss of the volatiles resulted in increased viscosity, and the magma froze, trapping some of the bubbles and developing miarolitic structure. Diabase pegmatite commenced crystallization in the intermediate stage from local concentrations of volatile-rich magma. Because of low viscosity of the liquid, crystal growth continued over a longer period, and the minerals attained large dimensions. With continued crystallization the remaining solution changed in composition, altering and replacing the earlier phases.

Ring-like outcrop patterns are characteristic of the diabase intrusions in southeastern Pennsylvania. Drill-hole exploration and geophysical data indicate that the diabase in these rings has the form of generally <u>discordant</u> curved sheets or basins. Comparisons are made with the Karoo dolerite intrusions which have a similar surface expression. No definite conclusions are reached as to the origin of the sheet-like form, but alternative suggestions of the controlling factors are discussed. These are that the magma followed pre-existing curved fractures or potential lines of weakness developed under stresses due to thermal expansion or tension brought about by sinking of the Triassic basin. Or, because of pressure conditions in the rock, the invading magma reached a position where it could spread laterally rather than continue in a vertical direction.

ACKNOWLEDGEMENTS

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BIBLIOGRAPHY

Anderson, E.M. (1942) The dynamics of faulting and dyke formation, Edinburgh.

Bailey, E.B., et al (1924) Tertiary and post-Tertiary geology of Mull, Loch Aline, and Oban, Geol. Survey Scotland, Memoir.

Barth, T.F.W. (1936) The crystallization process of basalt, Am. Jour. Sci., 5th ser., vol. 31, p. 321-351.

Bowen, N.L. (1928) The evolution of the igneous rocks, Princeton.

Bowen, N.L., Schairer, J.F., and Posnjak, E. (1933) The system $CaO-FeO-SiO_2$, Am. Jour. Sci., vol. 26, p. 193-284.

Collins, W.H., (1934) Life history of the Sudbury nickel irruptive, Trans. Roy. Soc. Canada, sec. 4, 3rd ser., vol. 28, p. 123-177.

Cornwall, H.C. (1947) Differentiation in doleritic lavas of the Michigan Keweenawan and the origin of the copper deposits, Thesis for the doctorate, Princeton University Library.

Daly, R.A. (1905) Secondary origin of certain granites, Am. Jour. Sci., 4th ser., vol. 20, p. 185-216.

____________(1917) The geology of Pigeon Point, Minnesota, Am. Jour. Sci., 4th ser., vol. 43, p. 423-448.

____________(1933) Igneous rocks and the depths of the earth, New York.

____________, and Barth, T.F.W. (1930) Dolerites associated with the Karoo system, South Africa, Geol. Mag., vol. 67, p. 97-110.

Dana, E.S. (1920) Descriptive mineralogy, 6th edition, New York.

Du Toit, A.L. (1920), The Karoo dolerites of South Africa: A study in hypabyssal injection, Geol. Soc. South Africa, Trans., vol. 23, p. 1-42.

Edwards, A.B. (1942) Differentiation of the dolerites of Tasmania, Jour. Geol. vol. 50, p. 451-480, 579-610.

Emmons, R.C., (1940) The contribution of differential pressures to magmatic differentiation, Amer. Jour. Sci., vol. 238, p. 1-21.

Fenner, C.N. (1926) The Katmai magmatic province, Jour. Geol., vol. 34, p. 746-775.

Fenner, C.N. (1948) Immiscibility of igneous magmas, Am. Jour. Sci., vol. 246, no. 8, p. 465-502.

Frazer, P. (1877) Pennsylvania 2d. Geol. Survey, Rept. CC on York, Adams, Cumberland and Franklin Counties.

Grout, F.F. (1918) A type of igneous differentiation, Jour. Geol. vol. 26, p. 626-658.

Hall, A.L. (1932) The Bushveld igneous complex of the central Transvaal, South Africa, Geol. Survey South Africa, Mem. 28.

Harder, E.C. (1910), Structure and origin of the magnetite deposits near Dillsburg, York Co., Pa., Econ. Geol., vol. 5, no. 7, p. 602-612.

Hershey, J.B. (1944) Gravity investigation of central-eastern Pennsylvania, Geol. Soc. Am., Bull., vol. 55, p. 417-444.

Hess, H.H. (1941) Pyroxenes of common mafic magmas, Am. Mineral, vol. 26, p. 515-535, 573-594.

Holmes, A. and Harwood, H.F. (1928) The age and composition of the Whin sill and related dikes of the north of England, Mineral Mag., vol. 21, p. 493-542.

Holmes, A. (1932) The origin of igneous rocks, Geol. Mag., vol. 69, p. 543-558

Hutton, C.O. (1938) The stilpnomelane group of minerals, Mineral Mag., vol. 25 p. 172-206.

__________ (1945) Additional optical and chemical data on the stilpnomelane group of minerals, Am. Mineral, vol. 30, p. 714-718.

Hutton, C.O. (1947) The nuclei of pleochroic haloes, Am. Jour. Sci., vol. 245, p. 154-157.

Johannsen, A. (1939) A descriptive petrography of the igneous rocks, vol. 1, Univ. Chicago Press.

Kennedy, W.Q. (1933) Trends of differentiation in basaltic magmas, Am. Jour. Sci., 5th ser., vol. 25, p. 239-256.

Koomans, Cath., and Kuenen, P.H. (1938) On the differentiation of the Glen More ring dike, Mull, Geol. Mag. vol. 75, p. 145-160.

Krikström, T. (1933) On the ophitic texture and order of crystallization in basaltic magmas, Geol. Inst. Upsala, Bull. vol. 24, p. 197-216.

__________ (1937) The Hällefors dolerite dike and some problems of basaltic rocks, Bull. Geol. Instit. Upsala, vol. 26, p. 113-263.

Lewis, J.V. (1908a) Petrography of the Newark igneous rocks of New Jersey, N.J. Geol. Survey, Ann. Rept. 1907, p. 97-167.

__________ (1908b) The Palisade diabase of New Jersey, Am. Jour. Sci., 4th ser., vol. 26, p. 155-162.

Lewis, J.V. and Stose, G.W. (1916) Triassic igneous rocks in the vicinity of Gettysburg, Pennsylvania, Geol. Soc. Am., Bull., vol. 27, p. 623-644.

Larsen, Esper S. Et. al. (1938) Petrologic results of a study of the minerals from the Tertiary volcanic rocks of the San Juan region, Colorado, Am. Mineral. vol. 23, no. 4, p. 227-257.

Morey, G.W. (1922) The development of pressure in magmas as a result of crystallization, Jour. Wash. Acad. Sci., vol. 12, p. 219-230.

Neumann, G.L. (1947) Investigation of the Dillsburg magnetite deposits, York County, Pennsylvania, U.S. Bur. Mines, Rept. of Investigations 4145.

Phillips, A.H. (1899) The mineralogical structure and chemical composition of the trap of Rocky Hill, New Jersey, Am. Jour. Sci., 4th ser., vol. 8, p. 267-285.

Prescott, Basil (1908) Ilvaite from Shasta County, California, Am. Jour. Sci., 4th series, vol. 26, p. 14-16.

Richey, J.E. and Thomas, H.H. (1930) The geology of Ardnamurchan, Northwest Mull and Coll, Geol. Survey Scotland, Memoir.

Schlotz, D.L. (1936) The magmatic nickeliferous ore deposits of East Griqualand and Pondoland, Geol. Soc. South Africa, Tr., vol. 39, p. 81-209.

Schwartz, G.M. and Sandberg, A.E. (1940), Rock series in diabase sills at Duluth, Minnesota, Geol. Soc. Am., Bull., vol. 51, no. 8, p. 1135-1172.

Shannon, E.V. (1918) On the occurrence of ilvaite in the South Mountain mining district, Owyhee County, Idaho, Am. Jour. Sci., 4th ser., vol. 45, p. 118-125.

__________ (1920) Notes on anglesite, anthophyllite, calcite, datolite, sillimanite, stilpnomelane, tetrahedrite, and triplite, U.S. Nat. Museum, Pr., vol. 58, p. 437-453.

__________ (1924) The mineralogy and petrology of intrusive diabase at Goose Creek, Loudoun County, Virginia. U.S. Nat. Museum, Pr., vol. 66, art. 2.

Sorenson, R.E. (1927) The geology and ore deposits of the South Mountain mining district, Owyhee County, Idaho, Idaho Bur. Mines and Geol., Pamphlet 22.

Sosman, R.B. and Merwin, H.E. (1913) Data on the intrusive temperature of the Palisade diabase, Wash. Acad. Sci., Jour. vol. 3, p. 389-395.

Spencer, A.C. (1908) Magnetite deposits of the Cornwall type in Pennsylvania, U.S. Geol. Survey, Bull. 359.

Spencer, A.C. and Paige, Sidney (1935) Geology of the Santa Rita mining area, New Mexico, U.S. Geol. Survey, Bull. 859.

Stose, G.W. and Lewis, J.V. (1916) Triassic igneous rocks in the vicinity of Gettysburg, Pennsylvania, Geol. Soc. Am., Bull., vol. 27, p. 623-644.

__________ and Bascom, F. (1929) Description of the Fairfield and Gettysburg quadrangles, U.S. Geol. Survey, Atlas 225, Fairfield-Gettysburg folio, Pa.

Stose, G.W. and Ljungstedt, O.E. (1931) Geologic map of Pennsylvania, Scale 6 miles to 1 inch, Pennsylvania Geol. Survey.

Stose, G.W. and Jonas, A.I. (1933) Geology and mineral resources of the Middletown quadrangle, Pennsylvania, U.S. Geol. Survey, Bull. 840.

____________________ (1939) Geology and mineral resources of York County, Pennsylvania, Penna. Geol. Survey, 4th ser., Bull. C-67.

Thomas, H.H. and Richey, J.E. (1930) The geology of Ardnamurchan, northwest Mull and Coll, Geol. Survey Scotland, Memoir.

Tomkeieff, S.I. (1929) A contribution to the petrology of the Whin sill, Mineral Mag., vol. 22, p. 100-120.

Tomlinson, W.H. (1945) Notes on the derivatives of the Triassic diabases of Pennsylvania, Econ. Geol., vol. 40, no. 8, p. 526-536.

Wager, L.R. and Deer, W.A. (1939a) Petrology of the Skaergaard intrusion, Medd om. Gronland, Bd. 105, no. 4.

____________________ (1939b) Olivines from the Skaergaard intrusion, Kangerdlugssuak, East Greenland, Am. Mineral., vol. 24, p. 18-25.

Walker, F. (1940) Differentiation of the Palisades diabase, New Jersey, Geol. Soc. Am. Bull. vol. 51, p. 1059-1106.

Walker, F. and Poldervaart, A. (1940) Petrology of the dolerite sill of Downes Mountain, Calvinia, Trans. Geol. Soc. So. Africa, vol. 43, p. 159-173.

________________ (1941) The Hangnest dolerite sill, S.A., Geol. Mag., vol. 78, no. 6, p. 429-450.

Winchell, A.N. (1927) Elements of optical mineralogy, Pt. 2, Descriptions of minerals, 2d. edition, Wiley, New York.