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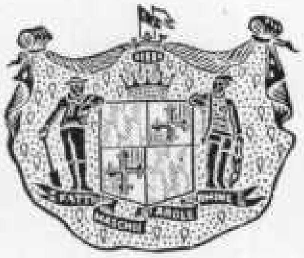

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LETTER OF TRANSMITTAL

H. C. BYRD,
President of the University of Maryland.

Sir: I have the honor of presenting herewith the thirteenth of the general reports of the Maryland Geological Survey containing a series of papers embodying the results of investigations carried out by the Survey.

The reports of this volume deal chiefly with the application of new methods in geological research which are proving of great value in solving problems presented by the oldest highly metamorphosed rocks of the State and which have been of help in solving difficulties of the quarrymen and in the elucidation of conditions of the flow of underground waters.

Yours respectfully,
EDWARD B. MATHEWS,
State Geologist.

Johns Hopkins University,
Baltimore, *July 6, 1937.*

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ILLUSTRATIONS

PREFACE

The present volume is the thirteenth in the series of general reports issued by the Survey. It consists of six parts showing the methods and application of structural studies to highly metamorphosed members of a complex series of crystalline rocks like those of the Piedmont portion of Maryland. At first sight these papers seem to have little economic value but experience has shown that they are very helpful in the development of quarries, location of underground waters and other economic attempts to develop the mineral resources of the most intricate and least understood rocks of the state.

Part I. *The Application of recent Structural Methods in the Interpretation of the Crystalline Rocks of Maryland*, by Ernst Cloos, is a statement of the new methods adopted by students of the highly metamorphosed regions in which the older relatively simpler geological features have been destroyed by recrystallization and deformation or obscured by the development of new structures.

The description and use of the phenomena and methods require a high degree of geological knowledge and experience but in skilled hands they give an insight into the history of the rocks which has not been attained by the older methods.

Under the personal supervision of Dr. Cloos the authors of the succeeding reports have been trained to use these newer methods in a restudy of four well defined units of the geological structures of the state.

Part II. *The Structure and Age of the Port Deposit Granodiorite Complex*, by H. Garland Hershey, is a summary of the results of several years study of the mass of granitic rocks which has been the foundation of one of our best known quarrying centers. The study of fragments caught up during the intrusion of this mass of igneous material into the older including country rock has shown that the intrusion of the granite occurred at a much later date than had previously been assumed.

Part III. *The Structure of the Gneiss Domes near Baltimore, Maryland*, by Carl H. Broedel, gives the results of a long continued study of the ovoidal domes into which the rocks have been folded to form the well known hills and valleys between Towson and Woodstock. He shows that they are a product of a series of earth movements beginning early in the pre-Cambrian time when the Baltimore Gneiss received the general form which is still maintained and that during subsequent periods of deformation the upper members of the Glenarm series received various new structures due to their greater pliability. This explains the discordance between the structures of the Baltimore and Glenarm series and the remarkable variations in thickness of the Cockeysville marble.

Part IV. *The Structure and Age Relations of the Volcanic Complex of Cecil County, Maryland,* by John Marshall, is a summary of the results of a field and microscopic study of the rocks of an old volcano in Cecil County. The volcanics are a folded mass of the country rock which was enveloped by the granitic magma of the Port Deposit Granodiorite. The volcanic activity is the oldest geological incident in the history of this region since the lavas include fragments of all subsequent rocks formed prior to the close of igneous activity after the invasion of the gabbros and granites which now form the rocks of the Susquehanna gorge.

Part V. *Structure of the Metamorphosed Gabbro Complex at Baltimore, Maryland,* by Charles J. Cohen, is a restudy with new methods of an area made classic by the work of the late George H. Williams fifty years ago. The earlier work was a geological study in which the microscope was first used to perfect the petrographic details. The present paper is a summary of the results of a study of the structures rather than the minerals of the well known "nigger head" rocks. The author has distinguished the primary flow lines formed when the molten mass was intruded, from the secondary structures which have been superposed during subsequent deformations. These later structures are due to intense shearing between different portions of the rock masses, which consolidated as a saucer like body between adjoining domes of Baltimore Gneiss.

Part VI. *The Upper Cretaceous Deposits of the Chesapeake and Delaware Canal of Maryland and Delaware,* by Charles William Carter, represents the results of a restudy of the stratigraphy of a portion of the Coastal Plain deposits in Cecil County under particularly favorable conditions afforded by the fresh cuttings incident to the widening of the Canal. The author has been able to subdivide the Matawan into a series of carefully measured sections and profiles and an ample discussion of the fossils contained in the various formations.

PART I

THE APPLICATION OF RECENT STRUCTURAL METHODS IN THE INTERPRETATION OF THE CRYSTALLINE ROCKS OF MARYLAND

BY

ERNST CLOOS

THE APPLICATION OF RECENT STRUCTURAL METHODS IN THE INTERPRETATION OF THE CRYSTALLINE ROCKS OF MARYLAND

INTRODUCTION

Accurate topographic maps are the basis for all geologic work. Approximately 40 per cent of the area of the United States is adequately covered by maps into which geological data may be platted. Maryland is one of the most fortunate States because good topographic maps cover the whole area. If an accurate base is available all geologic data gathered in the field may be made readily available for general use. Geologic mapping is a slow work because the geologist in the field must find all rock exposures in order to ascertain accuracy. Most of the area of the eastern United States is covered by soil, vegetation, glacial debris etc., and the rock floor is rarely exposed. Rivers, valleys, road and railroad cuts, water tunnels, steep slopes, etc., offer an opportunity for the study of the rocks. If a geologic map is wanted, theoretically every square foot of territory should be examined. Fortunately rocks occur in certain formations which can be recognized, grouped together conveniently, and then be inserted on topographic maps. Such geologic maps, usually in several colors indicating the formations encountered, are the basis for all other geologic work. They are indispensable for the engineer in road building, water supply problems, construction of dam sites and power plants, flood control, soil erosion, and in the finding of commercially valuable deposits of all kinds.

Such geologic maps are available for a large portion of the State of Maryland and other states. They have been prepared for many years with great care. Besides rock mapping it is essential to map the distribution of rock structures, such as the position of the different beds in sedimentary rocks or the bands of lighter or darker color in gneisses, cleavages in metamorphic rocks, joints, fractures and faults, thrusts, and a large number of other structural elements. These have to be measured in the field and then also platted on maps.

Microscopic investigations have to be made of the composition of the rocks, their mineral content, and also of the orientation of these minerals within the rocks. An investigation of the "rock fabrics" is not only valuable scientifically but also important economically because certain physical properties of rocks vary in different directions with their fabric.

The observation and collection of such data on the rock structures and the structures of regions require a great deal of time and care. As a rule only few geologists can afford the necessary time. The results, however, indicate that detailed structural data are essential everywhere and that in many regions a general geologic map may be insufficient. This is particularly true in regions like central Maryland underlain by metamorphic rocks which have undergone profound changes and probably suffered metamorphism and folding not only once but several times during their geologic history.

Since nobody has ever witnessed the events that led to the present distribution of rocks and formed the rocks which we observe today, and since we know that the original rocks have undergone changes and have been subjected to intense heat and pressure through millions of years during the earth's history, it becomes necessary to reconstruct these former conditions from all data available. Even seemingly insignificant data become important where facts are scarce. The work of a geologist resembles that of the archaeologist where small fragments of antique vases permit conclusions concerning the general culture, language, habits, and maybe conflicts of peoples which now have vanished.

A large portion of the original evidence for deciphering the geological history is now lost forever. It is therefore the more necessary to recover all the evidence available in order to piece those fragments together into a picture of former conditions and from this to deduct the history of the region and its component rocks.

In the following pages an attempt will be made to present some of the methods used in the investigation of the crystalline rocks, the results of which are presented in this volume. Much highly valuable and necessary work has already been done. The present structural investigation is only the beginning. Because little can be said about the evolution of a region from a study of only some parts, much more detailed work is necessary before comprehensive and far reaching conclusions can be drawn.

The Piedmont Province of Maryland includes igneous rocks which were intruded as molten masses into already metamorphic rocks. Both were then again subjected to forces which changed them. Igneous and sedimentary rocks behave differently under stress, and structural criteria vary widely according to the rock types. In the present discussion igneous rocks will be taken up first and then the metamorphic and sedimentary rocks. The four special studies (pts. II–V) illustrate the application of these methods in Maryland. Part VI of this volume represents the results of a special investigation of the Chesapeake and Delaware Canal. Recent dredging operations have exposed a section which offered a splendid and probably singular opportunity for a revision of the section of the Coastal Plain sediments.

ECONOMIC SIGNIFICANCE OF DETAILED STRUCTURAL INVESTIGATIONS

Applications of detailed structural methods to economic problems are very abundant but can not be treated here in full. Only a few examples are presented for a better understanding of their application and value.

Many granites have a very fine structure, often called grain or rift by the quarrymen. It is the direction in which blocks of stone can be split most easily. This direction should be known to everybody who wishes to open a stone quarry on a profitable basis. Granite blocks can often be taken out in one way only and any other approach may prove costly and in combination with topographic difficulties render such operations unsuccessful.

Fracture systems in rock bodies must be studied by those who undertake dam building or tunneling. The spacing of fractures can be studied and localities with great fracture density avoided wherever a strong foundation is wanted. Groundwater circulation is aided by fractures and weathering may destroy the original strength of a rock. Tunneling for aqueducts may find difficulties because of leakage of water through fractures in the rock penetrated by the tunnel.

The recovery of building and ornamental stone in larger pieces is greatly disturbed by fracture in the rock. A property underlain, for instance, by an otherwise very desirable type of marble may be worthless if fracturing has cut the stone into units too small for profitable recovery. This, however, may greatly facilitate the recovery of crushed stone for other purposes and reduce the cost of crushing and blasting greatly.

Even the study of orientation of calcite grains in a marble ("rock fabric") with the help of a microscope may be helpful and prove of immense value for the recovery of transparent marble for illumination purposes. Marble is a metamorphic limestone in which all particles are recrystallized. Under the condition of stress during the process of deformation, the calcite grains have been oriented in such a way that certain physical properties like the optical axes are now more or less subparallel. The direction in which light will penetrate the calcite crystal more easily than in others can be determined under the microscope and it is then only necessary to cut the stone plates in such a way that the calcite crystals are cut perpendicular to this direction. The difference is so striking that a one-inch plate of such marble is very translucent if cut in the right way and absolutely opaque if cut in any other direction. The orientation of the rock fabric can easily be studied with the help of a "universal stage" under the microscope.

Ground water circulation in solid rock masses depends entirely on rock fractures. Wherever fractures are abundant water circulation is facilitated. The detection of ground water for all kinds of purposes depends therefore largely on a study of fractures and their distribution.

The extent of valuable stone deposits like pure limestones is largely determined by fractures and faults. Contamination along fractures is frequently observed; staining is well known, and even the introduction of magnesium may follow fractures thus rendering much valuable stone useless. Faults may likewise bound such stone deposits and a knowledge of their presence and orientation is most important in the acquisition of property and the planning of future development. The distribution of silica in limestones can be studied under the microscope and since silica is highly undesirable in pure limestones it is often possible to outline highly silicious limestone regions as to avoid them. The quality of a limestone deposit may depend on different beds of limestone, some being of higher quality than others. A study of bedding in limestone can therefore be most helpful.

Cleavage in sediments, especially in slates, is an important factor in the recovery of good slate. Cleavages which transect each other may not permit the recovery of good thin slabs, while one cleavage intersecting with bedding or another cleavage at approximately right angles may be very favorable.

The distribution of ore bodies of all kinds is closely linked with fracturing and faulting of the country rock. Intersecting fractures may facilitate ore shoots. In general, the fractures observed in rocks open the way for ground water circulation and also for the emanation of ore-bearing magmas or solutions from below. They are the only connection downward and thus may form important channels and connections with lower levels of the earth's crust. These levels have furnished many of our present ore bodies and almost all the metals on which our present civilization is based.

GEOLOGIC UNITS OF THE REGION

The following reports (pts. I–V) deal with different geological units in the complex body of crystalline rocks comprising the Maryland Piedmont and emphasis is laid on the structural characteristics of each rock body rather than the detailed petrographic descriptions and general geological relations which have been more fully treated in other reports of the Survey, especially that on the crystalline rocks of Baltimore County (64).

The following table comprises those rock formations and their constituent rocks which are mentioned in subsequent reports and an attempt has been made to show the age relations by relative positions in the geologic column. The column varies somewhat from that given in 1929 in order to incorporate new data that have been gathered and are presented in the following papers of this volume.

TABLE I

LIST OF FORMATIONS AND CONSTITUENT ROCKS MENTIONED IN PTS. I–V OF THIS VOLUME

Age	Formation or rock type	
Triassic	Diabase dikes and sills	
Epi-Paleozoic?	Woodstock Granite Ellicott City Granite	with Pegmatite and Aplite dikes
Post Lower Ordovician	Hornblende Lamprophyre dikes Granite Porphyry Pegmatite and Aplite dikes Port Deposit Granodiorite Hornblende Granodiorite with quartzdiorite Hornblende Granodiorite	Port Deposit complex
	Relay Quartz Diorite Gabbro within the Port Deposit complex and Baltimore Gabbro	
?	Gunpowder Granite	
?	Pyroxenite Peridotite	
Ordovician	Conestoga Limestone of Lancaster County, Pa.	
Ordovician?	Peach Bottom Slate Cardiff Conglomerate	
Lower Cambrian	Antietam Quartzite of Lancaster County, Pa.	
?	Metadacite of Cecil County	
Pre-Cambrian?	Peters Creek Formation Wissahickon Schist Cockeysville Marble Setters Quartzite	Glenarm Series
Pre-Cambrian	Hartley Augen Gneiss Baltimore Gneiss with included Amphibolite	

The most conspicuous change is the reference of the whole Port Deposit complex, including the Baltimore gabbro, to post-Ordovician times.

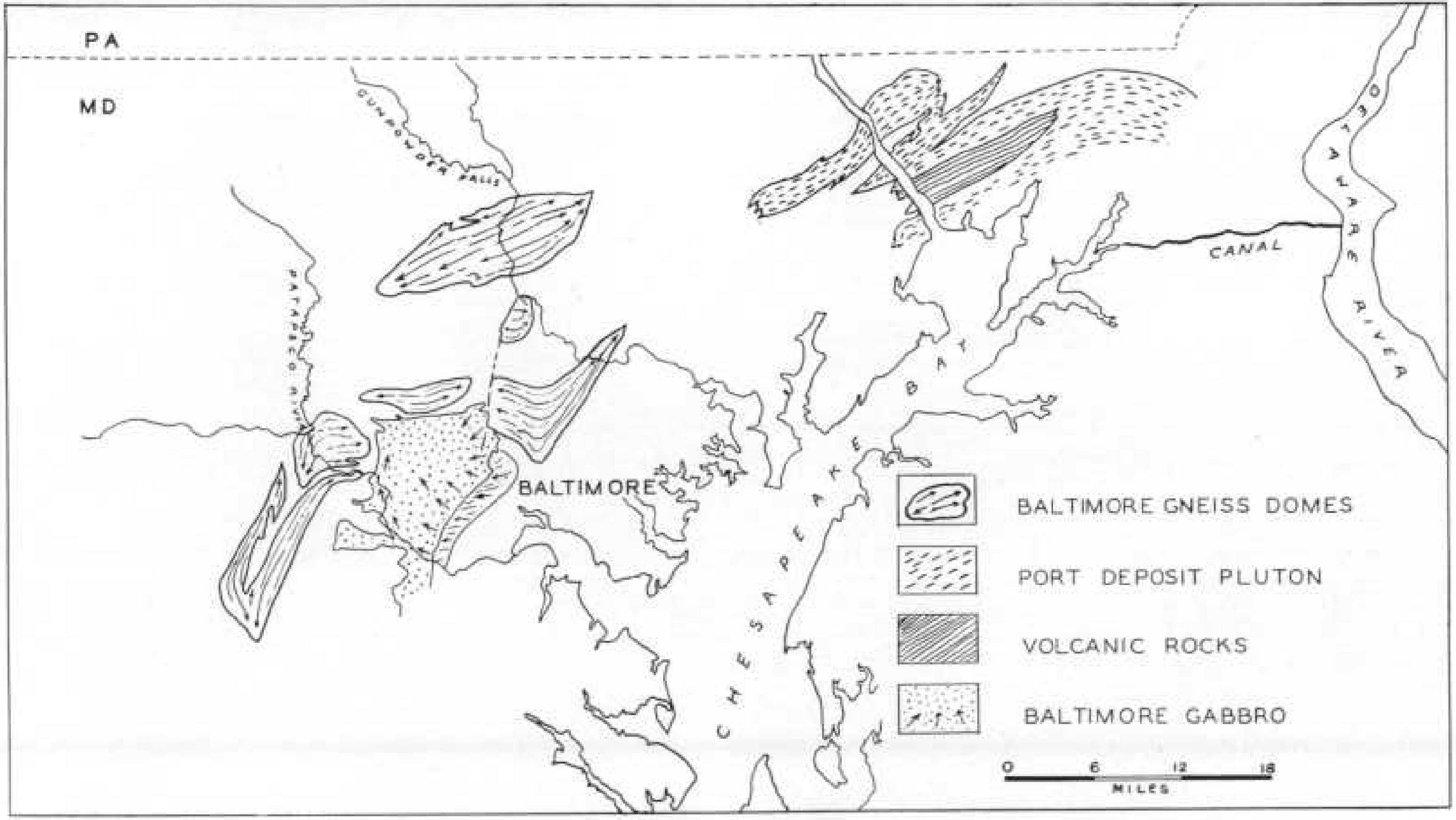
This was done on structural evidence collected by the writer and Hershey (26) and the evidence is presented in detail in Part II. Since this affects the interpretation of most of the igneous members of the complex and makes uncertain their geologic age, this fact is indicated by a question mark.

The age of the Glenarm Series which has been assumed to be pre-Cambrian (64) has been questioned recently by several workers in the field (72, 78). Since no definite proof has been presented as yet as to whether the Glenarm Series is pre-Cambrian or paleozoic it should be indicated as uncertain.

The Piedmont complex of Maryland consists of a number of distinctly different geologic units. The oldest group of highly metamorphosed rocks is the Baltimore gneiss, so-called because of its typical appearance in the vicinity of Baltimore. It contains basic rocks like amphibolites and granitic intrusions like the Hartley augen gneiss. The gneiss series is a very heterogeneous group of metamorphosed sediments and granitic intrusions, strongly foliated and of varying composition. It is the basement complex of the entire region and appears in the well known "domes" which are described by Broedel in part III of this volume.

The gneiss complex was highly folded, metamorphosed, and to a large extent beveled by an erosion surface when the Glenarm Series was deposited. An unconformity between the gneiss series and the lowest member of the Glenarm Series, the Setters quartzite, is evident and may represent a long period of erosion followed by deposition.

The Glenarm Series comprises a group of metamorphosed sandstones, limestones, dolomites, and shales which occur now as quartzites, marbles, and schists and may also include some evidence of volcanic activity in the metadacites of Cecil County and maybe in Frederick County. This series is of great extent and forms a belt of thoroughly recrystallized rock in which fossils have not been found so far. Several facies of schist have been distinguished and zones of metamorphism have been described. The Setters formation rests on the Baltimore gneiss. Above it occurs the Cockeysville marble, so called because of its great extent near Cockeysville, Maryland. The marble is extensively quarried north of Baltimore and forms the valleys between the gneiss domes. Above the marble occurs the Wissahickon schist, which is a vast group of schists of varying metamorphism. This group extends from Philadelphia into Virginia and its equivalent most likely occurs along the entire Appalachian mountain system from New York to Alabama. No fossils have been found and the age of the series has been subject of controversy for many years. The belt of Wissahickon schist reaches to the northwest into the area of known



General map showing the areas described in this volume: Port Deposit Pluton (pt. II), Baltimore Gneiss Domes (pt. III), Volcanic Rocks of Cecil County (pt. IV), Baltimore Gabbro (pt. V), and Chesapeake-Delaware Canal (pt. VI).

Paleozoic rocks in Pennsylvania and Maryland. The contact is believed by some workers to be an overthrust of large extent and the schist series has been held to have come from the southeast, being thrust over Paleozoic rocks for many miles. Up to the present there is not sufficient evidence to either prove or disprove this theory, but the geological map of southern Lancaster County, Pa. (65) suggests an overthrust.

Above the Wissahickon schist a series of quartzites and conglomerates, interbedded with shaly members, has been observed and called the Peters Creek formation. It occurs in a syncline between a highly metamorphosed facies of Wissahickon schist in the southeast and a less metamorphosed facies to the northwest. The Peters Creek series is also of low metamorphism and extends through the State of Maryland from the Pennsylvania boundary to the Potomac River.

In the lowest portions of the Peters Creek syncline are slates and a basal conglomerate near Peach Bottom and Cardiff. They are folded into the synclines and may have been unconformable above the Glenarm Series. Because of the intense folding this unconformity is obliterated and the age of this slate group is also undetermined. It seems very probable, however, that they are of Ordovician age since they resemble Ordovician slates farther north in Pennsylvania.

This entire group of metamorphosed sediments is invaded by a large series of igneous rocks. They occur everywhere in the crystalline rocks and are part of a larger belt which accompanies the Appalachian Mountains along their entire length. The composition of the intrusives varies greatly and the different types have been described in former reports of the Maryland Geological Survey and in parts of the following reports by Hershey and Cohen (pts. II and V).

Since rocks of known age are not invaded by this group of intrusives, their age determination is difficult and indirect evidence had to be used. The method applied and the results are outlined by Hershey in Part II of this volume.

In the above table reference is made to a few rocks of known age like the Antietam quartzite and the Conestoga limestone which are mentioned in the following reports. These strata are of great significance if they can be used to correlate the unknown series either in respect to their position, as above or below, or in respect to their metamorphism and structures, as older or younger. Table I on page (33) has been inserted merely to guide the reader in the use of formation names which are mentioned. Further and more detailed information on the general geology and petrology of the area can be found in the reports and maps of the Maryland Geological Survey.

STRUCTURES IN IGNEOUS ROCKS

GENERAL STATEMENT

Igneous rocks have once been hot and molten and have been intruded into higher portions of the earth's crust or poured out over its surface. They have been uncovered by erosion in many areas and they are the largest and most important group of rocks. Their chemical composition varies greatly. Black, very basic rocks are connected with the most acid ones through a long range of intermediate gradational types. Whatever their composition may be, they are all more massive than the sediments or metamorphic rocks and their origin can be ascertained from their mineral composition, texture, structure, and their relations with the surrounding country rocks. Many types of igneous rocks have invaded the Piedmont Province of Maryland.

Since igneous rocks were once soft, molten, and able to flow into their present position most of them show traces of flowage or flow structure. Any materials that flow, especially the highly viscous ones, will show an orientation of small particles, minerals, inclusions, or other impurities, in the direction of flowage. Gas bubbles in glass melts are oriented mutually parallel either in the direction of flow or in some direction related to the internal friction of the flow and to the position of the surrounding confining walls. If the medium freezes—consolidating to glass or crystallizing to igneous rocks—the particles and their orientations become fixed. It is then possible to study the orientations within the consolidated flow and deduce the direction of flowage with a fair degree of accuracy. If the movements continue after consolidation fractures appear and these fractures become oriented in a very definite relation to the direction of flow and the forces prevailing at that time. If the consolidation of a flowing mass progresses slowly from the marginal portions toward the center, these marginal regions begin to fracture while the central portions still flow. A stage is then reached in which flowing and fracturing will occur side by side. After complete consolidation of the rock body it will be fractured in its entirety.

During the last 20 years flow structures and related fractures have been studied in many igneous masses in Europe and America (3, 31). The method has become known as "Granittectonics" because granites were the first igneous rocks examined. Robert Balk has recently published a comprehensive treatise on this method in the memoir series of the Geological Society of America (3). It will therefore be treated only briefly here and only as far as the igneous rocks of Maryland are involved.

The method consists in measuring as many of the primary "elements" as possible in a given igneous mass. The directions are read with a compass and then platted in maps and sections or evaluated in statistical diagrams. From these maps it is then possible to obtain information as to the direction of flow during the emplacement and consolidation of an igneous mass. This generally gives information as to the direction from which the mass came and as to its shape, its relations to the country rock, and frequently as to its downward continuation. The reconstruction of the history of such regions is also possible if later deformations have left their traces superimposed as long as some of the primary elements have been preserved. Superposition of later structures occasionally follows older directions. In such cases the separation of the two is difficult. Larger early elements, like inclusions of wall rock fragments in the melt, will be preserved most readily. It is hardly conceivable that such fragments, embedded in a consolidated rock, will ever change their directions by any process except by a complete remelting of the entire complex. In that case the inclusion would probably be obliterated also and an entirely different rock would result. Wall rock inclusions will, as long as they are recognizable, always be reliable primary elements in igneous rocks, even if these have suffered deformation after consolidation.

The igneous rocks of the Piedmont of Maryland have probably suffered some deformation after consolidation. Primary elements, however, are still preserved to a large extent. An investigation of an igneous complex should go back to the earliest traces of movement because the entrance of a magma into its chamber is the most important phase of its history and may throw much light on its later development.

In table II a list of those elements is given which were used as criteria in the work of recent years. (See also pts. II and IV of this volume.) The page references following localities are in reference to the following pages in this volume.

PRIMARY ELEMENTS IN IGNEOUS ROCKS OF THE PIEDMONT OF MARYLAND

TABLE II

I. Elements of the flowage phase.
  A. Linear Flow structures, flow lines.
      Subparallel arrangement of minerals or groups of minerals, inclusions or groups of inclusions with one axis distinctly longer than the two shorter axes (Pencil or spindle-shaped bodies of all kinds).
    1. Single minerals:
        Hornblende, tourmaline (in pegmatite), Port Deposit granodiorite complex (p. 135); Baltimore gabbro (p. 232); Ellicott City granite (28); many porphyry dikes and lamprophyres (p. 136); hornblende granites in Cecil County (p. 135).

TABLE II—*Continued*

2. Mineral groups:
   - Accumulation of mica flakes in patches and streaks, clusters of hornblende and micas, etc.
   - Port Deposit granite (pl. XVI, fig. 1); Ellicott City granite; Baltimore gabbro; Sykesville granite.
3. Oriented inclusions:
   - a. Magmatic segregations (autoliths):
     - Ellicott City granite; Port Deposit granodiorite complex.
   - b. Wall rock fragments (xenoliths):
     - Port Deposit granodiorite complex; Baltimore gabbro; Ellicott City granite (28, p. 136); Woodstock granite.
   - c. Amygdaloidal inclusions in volcanics:
     - Meta dacite of Cecil County (p. 194).
4. Groups of inclusions:
   - Frequent in all igneous rocks of the Piedmont Province.

B. Planar flow structures, flow planes:

Subparallel arrangement of minerals or groups of minerals, inclusions or groups of inclusions. Disc or leaf-shaped with one very distinctly short and two longer diameters.

1. Minerals:
   - Biotite or muscovite flakes, feldspar phenocrysts.
   - Port Deposit granodiorite complex (pl. XV, fig. 2); Gunpowder granite; Ellicott City granite; Woodstock granite (very weak); many of the porphyry and lamprophyre dike.
2. Mineral groups:
   - a. Patches and clusters of mica, hornblende, etc.
     - Port Deposit granodiorite complex (pl. XV, fig. 2); Baltimore gabbro; Ellicott City granite.
   - b. Segregation of minerals in layers:
     - Baltimore gabbro (very strongly banded (pl. XXXVIII, fig. 1).
3. Inclusions:
   - a. Magmatic segregations (autoliths):
     - Clusters, layers of different composition.
     - Port Deposit granodiorite; Baltimore gabbro; Ellicott City granite.
   - b. Wall rock fragments (schist, gneiss, most frequent near contacts).
     - Port Deposit granite (pl. XIV, fig. 2); Baltimore gabbro, Ellicott City granite (28 fig.); Woodstock granite; otherwise very abundant in almost all intrusives of the province.
   - c. Groups of inclusions:
     - Port Deposit granodiorite; Baltimore gabbro; Ellicott City granite; Relay quartz diorite.

C. Linear and planar flow structures:

The two types of flow structures may be combined, either in one rock type or in one intrusive mass. They may also occur together at one locality, in one inclusion, flow layer, etc.

Port Deposit granodiorite; Baltimore gabbro (p. 225); Ellicott City granite (28, fig. 4).

TABLE II—*Continued*

- II. Elements of the transition phase.
  - A. Flexures.
    - Flow structures are bent, inclusions are folded but not fractured.
      - Port Deposit granodiorite, particularly in the earlier phases; Baltimore gabbro (p. 227).
  - B. Fractures restricted to contact zones.
    - 1. Marginal thrusts:
      - Small thrusts toward the contact.
      - Port Deposit granodiorite at Canal (p. 138).
    - 2. Planes of stretching.
      - Port Deposit granodiorite (rare).
    - 3. Fractures along contacts without displacements.
      - Port Deposit granodiorite; Baltimore gabbro; many fractures in dikes.
- III. Contacts.
  - A. Petrographic boundaries of igneous masses.
    - 1. Internal contacts between parts of one igneous complex. These boundaries may be sharp or gradational.
      - Port Deposit granodiorite complex between granodiorite and quartz-diorite (p. 142); Baltimore gabbro complex (p. 227).
    - 2. External contacts between igneous complex and country rocks.
      - All igneous masses. Contacts are always sharp.
  - B. Attitude of contacts.
    - 1. Concordant contacts, following the wall rock structures.
      - a. Internal contacts between parts of an igneous complex:
        - Port Deposit granodiorite complex, between granodiorite and quartz-diorite (p. 142); Baltimore gabbro complex between the different varieties of basic igneous rocks.
      - b. External concordant contacts.
        - All igneous contacts are predominantly concordant (p. 46); Port Deposit granite complex; Baltimore gabbro; Ellicott City granite; *not* Woodstock granite.
    - 2. Discordant contacts, igneous rock boundaries transect the wall rock structures.
      - All igneous contacts occasionally transect wall rock structures. The Woodstock granite is predominantly discordant (pl. XXV, fig. 2). All dike-like bodies are discordant and only few concordant (for instance pegmatites in schist (p. 158).
    - 3. Conformable contacts, internal structure of intrusive parallels wall rock structure.
      - Very frequent in all igneous masses of the region. Port Deposit granodiorite complex; Baltimore gabbro; Ellicott City granite. *Not* Woodstock granite.
- IV. Elements of the rigid phase—fractures.
  - A. Joints.
    - 1. Joints in local zones, along contacts or shear planes.
      - Port Deposit granodiorite complex (p. 138); Baltimore gabbro; Ellicott City granite.

TABLE II—*Concluded*

2. Joints restricted to *parts* of an igneous complex. "Feather joints," shear zones, etc.
   Port Deposit complex, particularly in quartz diorite (p. 142).
3. Fan joints (very abundant in many of the larger dome-shaped igneous masses).
   Entirely absent in this region.
4. Cross joints forming an angle of approximately 90 degrees with the flow lines under IA.
   In all igneous bodies with distinct flow lines (p. 47); Port Deposit granite complex, very distinct (p. 139; pl. XVIII, fig. 1); Baltimore gabbro, locally (pl. XL, fig. 2); Ellicott City granite, locally; hornblende granite in Cecil County.
5. Strike joints, parallel planar flow structures.
   In all igneous masses with distinct flow planes; Port Deposit granodiorite complex, Ellicott City granite a. o.

B. Dikes.
   Dikes are intrusive material filling fractures. Granite, aplite, pegmatite, porphyries, lamprophyres.
      Very abundant in the entire region, occurring in many directions. On cross joints, local joints, or at random.

DESCRIPTION OF ELEMENTS LISTED IN TABLE II

In the above table the primary elements have been listed with the rock types in which they were observed in Maryland. In other regions other elements occur, other combinations of elements prevail and have been described in the literature (pts. II–V of this volume and 4, 25, 31). In the following descriptions of individual areas the elements are taken up in detail, localities where they can be seen are given, and illustrations of individual occurrences cited. It becomes evident that each rock type and each area shows different structures in accordance with the mineral combination, the viscosity of the melt, the amount of flowage that has taken place during emplacement of the rocks, and the degree of deformation that has changed the rock since its intrusion. The last factor is clearly related to the age of the rock; that is, the oldest rocks in a region are usually more metamorphosed than the later ones.

THE FLOWAGE PHASE

Linear flow structures, flow lines

Any minerals, clusters of minerals, or inclusions within the melt may make "linear flow structures" visible as long as they are available during a stage in which the magma is still flowing and relative movements are able to orient these included particles into subparallel directions. Minerals of prismatic, elongated shape, like hornblende or tourmaline crystals, may be oriented into subparallel positions like logs drifting on a stream. Mica crystals frequently form clusters from one-half to two inches long, stretched out on both ends like willow leaves. Linear structures in the Port Deposit granodiorite are predominantly of this type (pl. XVI, fig. 1). Fragments of schist may be spalled off the walls and drawn into long sharp pieces and also oriented into the magma stream.

All these possibilities may be combined or may occur alone. The combination of all oriented elements produces a fibre, comparable to the fibre of a tree and has frequently been called "rock fabric" in metamorphic rocks (62).

The orientation of linear flow structures with respect to the shape of the intrusive varies with each mass. It depends entirely on the local conditions and the physical properties of the original magma. The rock fibre may indicate the direction of flow of the magma and all its portions and then represent lines of flowage; or, the flow lines may only indirectly indicate the direction of the advance of the magma. In the latter case they may form arches which bend on to the contacts and flatten out toward the center, indicating a direction of tension between the contacts (34).

The Baltimore gabbro shows flow lines (arrows on pl. XLI) converging downward and inward from the contacts on all but the west side. These lines, combined with planar foliation point toward a central focus of intrusion, a possible opening which was easiest accessible between a basement of Baltimore gneiss which surrounds the gabbro mass on three sides (p. 235).*

The granite at Ellicott City (28) is a steep walled mass which has entered its present chamber from below, probably at a steep angle. Its flow lines point straight upward and obviously indicate the direction of flow directly. The gap through which this magma entered is an opening between the adjacent Baltimore gabbro (pl. XLI) and the Wissahickon schist. Long spindle-shaped inclusions and clusters of biotite point the way.

In the Port Deposit granodiorite complex several directions are indicated (pl. XXI). The earlier intrusions of the complex seem to have come from straight below; other portions seem to have moved at a gentle angle for part of the way. It is highly probable that the granodiorite has in part taken advantage of pre-existing structures in the metamorphic wall rocks.

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* It is not certain that these flow lines are primary. Cohen (p. 217) believes that they are secondary metamorphic structures and uses the term linear schistosity (p. 234).

Planar flow structures, flow planes

Flake-like leaf or sheet-like minerals, clusters of minerals or inclusions of all kinds may be oriented by the flow of the magma. Mica flakes, feldspar tabloids, sheet-like magmatic segregations, or fragments of schist may thus produce planar flow structures. Linear orientations of elements indicate *one* direction. Planar elements, however, only show a plane in which movements leading to such orientation have taken place. Within such planes there are no preferred directions, unless they are combined with a linear direction within that plane.

Flow planes are most abundant in igneous rocks. They may parallel the confining walls of the mass, or they may form dome-shaped structures arching toward the center (25). In each case only the direction of motion at the point of observation is ascertained by one measurement, but not of the entire mass. A large number of observations in the whole area is necessary to obtain a picture of the movements of the intrusive body.

The orientation of flow planes in relation to the shape of an igneous intrusion varies as much as that of the flow lines. Some of the larger masses clearly show dome-like arrangements; as for instance, the granites of the Sierra Nevada of California (25). Here the movement is comparable to that in a glacier with ice bands parallel with the confining walls, near the walls, and trending across the stream towards the center. This structure is caused by intense friction along the sides of the glacier and a tensional stress and relative movement between parts in the center (34, p. 106, fig. 54). Here the relative movements between small units of the glacier are at right angles to the movement of the whole glacier.

The Piedmont intrusives show simple planar arrangements, probably in the direction of the general flow. Dome-shaped structures have not been observed.

The Baltimore gabbro shows very distinct banding; that is, layers of lighter and darker minerals (pl. XXXVIII, fig. 1), almost everywhere outside of its massive portions. Cohen has measured these structures systematically and platted them on a map (pl. XLI). Towards the center of the mass they seem to converge in conformity with the flow lines mentioned above, confirming the contention that the feeding channel for the intrusion of the gabbro was centrally located.

Flow planes in the Port Deposit granodiorite complex are very distinct. Some of its rocks are gneissic. The structures have been measured by Hershey (pl. XX). Sheet-like fragments of schist reach proportions of many square feet; the smallest measuring square inches. Mica clusters parallel this orientation rigidly and deviations from the general orientation are extremely rare. Since the Port Deposit granodiorite shows cataclastic deformation of its constituents under the microscope and formation of new minerals (pl. X, fig. 2) it was believed that its structure is largely due to metamorphism which affected the granodiorite and the adjacent schist after intrusion. In that case the regular and widespread orientation of schist fragments would remain wholly unexplained. It seems much more likely that the orientations occurred during the intrusion of the granodiorite complex and its phases and that later deformations have only intensified preexisting structures.

The Ellicott City granite shows flow planes as distinct as the Port Deposit granodiorite complex. Mica crystals and clusters, inclusions of Wissahickon schist and magmatic segregations (schlieren) are oriented without exception. Feldspar phenocrysts, wherever present, join the general orientation. This granite is supposedly much later than the Port Deposit complex but its orientations are nevertheless just as distinct. Flow lines, combined with the flow planes leave little doubt as to the shape of this intrusion and its direction of ascent into the earth's crust.

Almost all the other intrusive rocks of the Piedmont region show flow planes in varying orientation and intensity.

Linear and planar flow structures

Linear and planar flow structures may occur combined. The planes will then eliminate all other planar directions and the linear orientations within the plane will confine all the directions within the planes to two. This combination is thus of great value wherever the relation can be ascertained. Deviations of linear structure from the direction of the planar ones are rare and do not occur in the Piedmont intrusives (25).

In the Port Deposit complex the planar arrangement is very regular throughout the region, with slight regional bends and without abrupt changes of direction between the different intrusive phases. The linear arrangement is less consistent. While the planar direction remains the same in all intrusives of this complex, the linear directions differ as much as 90 degrees between the individual phases.

THE TRANSITION PHASE

After the magma masses have been emplaced in the spaces which they now occupy consolidation or freezing progresses slowly. The country rock has probably been heated considerably, but not above the melting point of rocks, because sharp fragments which have been broken loose from it prove that fusion and melting have not been very extensive. Very great mineral changes also have not taken place which is shown in the very small extent of contact metamorphism. Typical contact minerals are confined to the immediate neighborhood of the intrusive contact, indicating that the invaded rock has been relatively cooler than the invading magma. Consolidation began near or at the contacts and progressed inward. As the magma became stiffer and more viscous, movements which otherwise only produce an orientation of minerals or inclusions have caused fracturing or banding of structures just formed. Such structures are typical for many igneous masses but rather rare in the Piedmont. The larger intrusives, particularly those which are composed of several successive intrusions which followed each other at close intervals, show such structures near their contacts (25).

In the Port Deposit granodiorite complex occur flexures along which the original flow structures are bent or inclusions folded (p. 137). Fractures are not evident, however. These readjustments must have taken place within a pliable magma.

Further consolidation of the magma near its walls leads to fracturing within these areas. Such fractures are rare but of theoretical and general interest. In the Port Deposit granodiorite complex fractures occur which dip gently toward the center of the intrusives and small displacements can be seen always with a tendency of relative motion towards the walls; that is, away from the intrusive. It seems that the magma has pressed against its walls and pushed some of the already consolidated portions outward. In other regions (29, p. 392) such fractures have been called marginal thrusts. Aplite dikes may follow such joints locally (25, fig. 25A). Since fractures do not continue into the intrusive farther than about 30 to 50 feet and seem always oriented at similar angles to the contact planes, they were probably formed in close relation to the igneous intrusion. Some of the occurrences are described below in detail (p. 138).

CONTACTS

The structural elements in igneous masses can be understood fully only if they are considered in their relation to the contacts of these masses. The shape of an intrusive is determined by its boundaries or its contacts. Any flowing matter will fill its container and if frozen assume its shape. But contacts are not mere boundaries where two types of rock touch each other for they also influence the direction of flowage in the magma chamber and the arrangement of internal structures within the molten mass intruded into the chamber. The space which is available is also largely determined by the contacts and if the space is made by the magma by breaking the country rocks this is also indicated in the form of the contacts.

Several types of contacts can be distinguished. Within larger igneous masses, which are composed of several intrusions which have followed each other at short time intervals, there are contacts between the individual phases. These are termed internal contacts because they occur within a larger composite igneous complex (Port Deposit granodiorite complex). Such boundaries may be sharp and fragments may be torn loose to float in the later intruding rock. This indicates that the earlier phase had been consolidated and that fracturing has been possible.

If the contact is gradational and one rock type seems mixed with the earlier in fairly wide zones, this may indicate a shorter time interval between intrusions or fusion of the earlier phase by the later. Such gradations have been observed and can be from one inch to 1000 feet wide. They do not, however, occur very frequently in Maryland intrusives. Contacts between individual layers of gabbro (pl. XXXVIII, fig. 1) are always gradational but these zones are very narrow and at best only about one to two inches thick.

The majority of the internal contacts are sharp and indicate breakage. Angular fragments are torn loose and their boundaries are sharp enough to be traced with a pencil point.

Boundaries between larger igneous complexes and the country rock have been called external contacts; that is, they are the boundaries between any intrusive body or group of bodies with the country rocks which may be schist, gneiss, limestone, or any type of igneous, metamorphic, or sedimentary rock.

External contacts as a rule are sharp and gradations are rare. Contact metamorphism is not pronounced in the Piedmont intrusives because the schists were metamorphosed before the arrival of most of the intrusives under discussion. Since highly foliated schists are the country rock for the intrusions, the contacts have as far as possible followed their pre-existing schistosity. The intrusives are largely intertongued with the wall rocks. This is very clearly shown in the boundaries of the Baltimore gabbro, the Port Deposit granodiorite complex, or the Ellicott City intrusive where thin sheets of igneous material penetrate into narrow openings parallel with the schistosity (28). Occasionally this process resembles "lit-par-lit" injections, as they are known and described in many regions like the old gneissic terraines of Canada or Scandinavia (94).

Such contacts will naturally determine the direction of flowage and the orientation of internal structures. Narrow spaces probably permit only flowage into the space in one direction. Complicated arc or dome-like relative movements between parts rarely occur and consequently the structures are parallel to the nearby walls because friction between these and the parts of the magma is at a maximum. In this way the majority of structures are parallel to the walls of the intrusives and also parallel with the wall rock structures since they served as guiding planes during the intrusion.

Attitude of contacts

For better understanding the attitude of contacts has been classified under different terms, such as concordant, discordant, conformable, and disconformable.

Concordant contacts are parallel with the wall rock structure as described above. They are almost the rule in the Maryland intrusives. The contacts between two intrusive phases within one larger complex are concordant if the internal contact follows the structures of the earlier phase.

Discordant contacts transgress the wall rock structures. Many of the dikes in the region are transgressive and cut sharply across any other structures. The larger intrusives show discordant contacts also but to a lesser degree. They are, however, present and *must* be present. Long sheet-like inclusions show concordance most of the way around and only at the ends does the magma transgress the structure of the inclusion. The quartz diorite within the Port Deposit granodiorite complex shows millions of small inclusions of many types of sedimentary rocks. Schist fragments, quartzite, and well-bedded sediments of all kinds, even conglomerates, occur (pl. XIII, fig. 2). Many of these inclusions are folded and the bedding planes are bent and cut off sharply at the ends of the inclusions.

Conformable contacts are those in which the internal structures of the intrusives parallel those of the wall rocks. Most of the contacts of the Piedmont intrusives are conformable. Since many of the spaces filled with igneous rocks are narrow and long, and parallel to the wall rock structures, the internal structures follow the longest extension of these spaces. Conformable contacts render the recognition of primary structures in igneous rocks difficult. It is very difficult to ascertain whether the wall rock structures are later than the intrusive with both rock types having a later superimposed structure; or whether the structure in the wall rocks is older and that of the intrusive later. Detailed observations generally decide the question because even in regions with completely conformable contacts discordant contacts occur, showing the age of the structures. If in addition to conformable contacts, the whole complex has undergone intense deformation after intrusion, the distinction between early and later structures becomes a very intricate problem. Inclusions and their structures often remain the best help because early structures are fixed within an intrusion and very rarely become obliterated, even under strong deformation.

In part II of this volume Hershey has shown in detail how the history of a region may in part be reconstructed with the help of inclusions and their detailed structures (p. 126).

Fig. 1.—Flowage folds in Baltimore gneiss, one-half mile east of Alberton.

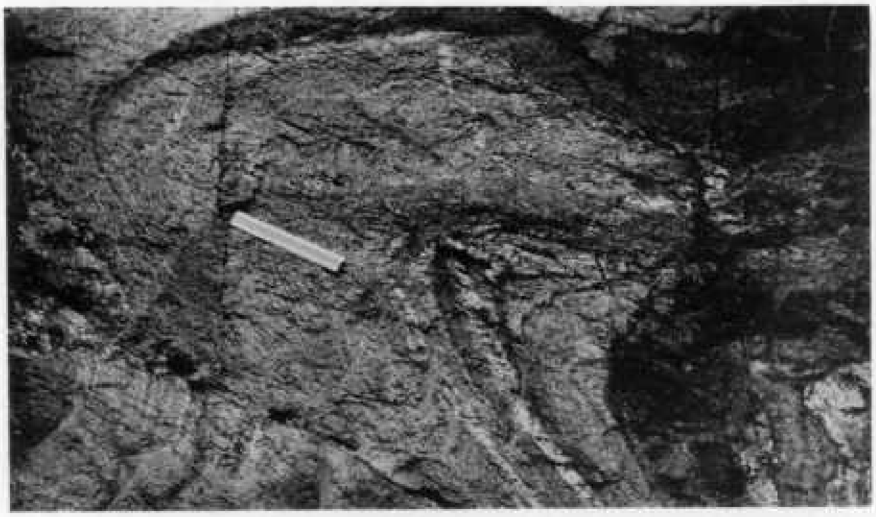

Fig. 2.—Shear fold in isoclinally-folded ribbon gneiss. A strong cleavage parallels the axial plane and dips gently north. Southeast bay of Lake Roland.

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Contacts are of utmost importance as long as the magma moves within its boundaries and as long as magma and country rock are not cemented together by consolidation. After complete freezing the intrusive becomes a part of the region and any movements which may take place or any stresses which may act on the region will affect both the intrusive and its walls.

If the impulse which pushed the magma into its chamber continues into later phases and survives the consolidated phase, structures like fractures may result which overlap the contacts and affect a larger region.

ELEMENTS OF THE RIGID PHASE

Joints

Every portion of the Piedmont rocks shows innumerable fractures of many kinds due to repeated and intense metamorphism and the intrusion of igneous masses during the millions of years since their formation. These fractures may be described in many ways or loosely grouped together under the term joints and jointing. They occur in both igneous and metamorphic rocks but for ease of treatment they will be discussed separately.

Jointing or fracturing of rocks in a more or less regular arrangement without serious movement of the sides may occur singly or in related groups over small or large areas, in zones, or restricted to certain rock types. Their character is always closely related to the material and its properties. In smooth or fine-grained homogeneous rocks the joints may be clean-cut, straight and even-surfaced while those in foliated rocks may be uneven, wavy, or irregular. Their character depends largely on the physical homogeneity. In foliated rocks the joints may open easily parallel to a strong wavy foliation, but only with difficulty across it.

The most conspicuous fractures in igneous bodies are "cross joints" and "strike joints." The former occur in all intrusives at an angle of approximately 90 degrees with the flow lines. They seem to form after tension in the direction of the flow lines could not be relieved by magmatic flow and fracture became the only answer to its relief. Such tension seems to vary and in areas where it has been greatest flow lines are most pronounced. Here cross joints are also most distinct. In larger intrusives flow lines may form arcs and span the entire mass from contact to contact. Here cross joints remain perpendicular to the flow lines and form a fan with the joints converging downward (25, pl. XVIII).

In the Maryland Piedmont such structures do not occur. Small bends in the course of flow lines, however, are accompanied by a change of strike and dip of cross joints. It is evident that flow lines and cross joints are interdependent. (Compare also cross joints in metamorphic rocks p. 74, pl. VIII, fig. 1 and pl. XXXI.)

The granodiorite complex at Port Deposit shows very large and regular cross joints. They transect the entire intrusive complex and overlap far into the country rock. The granite quarry at Port Deposit shows such joints in large walls (pl. XVIII, fig. 1) many feet high and bounding the quarry at its east side for hundreds of feet. A map by Hershey (pl. XVII) shows the direction and frequency of these fractures statistically. They are the most numerous joints in the region.

At Ellicott City, where flow lines are steep, cross joints are smaller and dip gently or lie flat. They never reach large dimensions. In the adjacent portions of the Baltimore gabbro flow lines are very distinct, particularly at Illchester where cross joints are flat or dip gently north and thick pegmatite dikes have followed these fractures.

Second to the cross joints are strike joints. They follow the planar structures and are numerous in the Port Deposit region, in the Ellicott City granite, and all other intrusives. They seem also closely related to the igneous intrusions and always maintain a constant direction in respect to the foliation.

A third set of joints is frequent. If cross and strike joints are approximately at an angle of 90 degrees, this set is at almost 90 degrees to both. It may be a primary direction closely related to the intrusive phase (34) or may be secondary and parallel to the present surface. In regions where dikes have filled these fractures they must have been available as loci for their intrusion at an early period.

In the Piedmont of Maryland flat dikes are rare and the flat joints are probably secondary exfoliation joints and parallel to the present surface. They are of little value in a structural analysis since their character can be ascertained only rarely.

Dikes

The weak planes of jointing with their regularity and parallelism offer a particularly favorable course for the apophysis of an invading magma which on cooling can produce rocks easily distinguished from the invaded country rock. Such dikes indicate the direction of fracturing and furnish clues as to the manner of formation and the character of these parent magmas when they are frozen. Obviously magmas still liquid were nearby, and the dike material was in connection with a source of liquid magma.

The composition of dike material filling the joints gives some indication as to the lapse of time between invasion of the main mass and that of the satellite dikes.

Cross joints, strike joints, and flat joints can be filled with pegmatite, granite, aplite dikes, or lamprophyres. Later dikes; as for instance, the diabases of the Triassic, cut across the regional structures at an angle that seems without relation to the early structures described above. They represent a much later phase in the history of the region.

STRUCTURES IN SEDIMENTARY AND METAMORPHIC SEDIMENTARY ROCKS

GENERAL STATEMENT

The following chapter is an outline of structure elements and methods used in the investigations of the metamorphic rocks of the Piedmont of Maryland and other regions. Structures which were observed in the field and laboratory are listed, described, and analysed. A large number of elements are found and the diversity of the phenomena is at first bewildering. One soon finds, however, that the repetition of such elements shows regularities, systems of elements, mutual relations of certain groups of structures, and the number of tectonic directions becomes rather small. A structure map shows major and minor directions at first sight and it is thus possible to bring order out of the chaos of detailed and seemingly incoherent data (pl. XXVII–XXXII).

Every structure in a rock is significant, none is unimportant, even if at first it may seem irrelevant. No fracture will occur, no fold will appear, no new mineral be formed without good reason. Only in a few cases and only under fortunate circumstances is it possible to determine the cause of deformation. Special problems may be solved if sufficient evidence is available but the major reasons for the deformations of the earth's crust and the rocks in it are unknown. Many hypotheses have been offered and explanations have been tried but one should not forget that hypotheses are not facts but should be conclusions from facts. Only a very small portion of the earth's surface is geologically known and very little of this known territory is now known in detail. Only a small portion of the United States is geologically mapped and many of these maps are more than 30 years old. Since then much has been learned and new methods have been introduced so that some of these maps are today inadequate. It is necessary to collect new and unbiased data. No detail is irrelevant and the details have to be presented in orderly fashion—in maps, charts, tables, and diagrams—for the use of those who are in need of information. The presentation of large masses of data is often difficult. Maps are essential but mostly difficult to publish on a scale which is large enough to permit the presentation of the necessary data without too much generalization. The selection of data to be included in maps is a subjective work and care should be taken that *all* pertinent data are presented without suppression of the irregular. Statistical diagrams are, therefore, important because all data are presented and regularities or "laws" will emerge without prejudice (p. 90).

The following chapter and parts II to V are largely based on detailed field work and an attempt has been made to present without prejudice some of the more important structures for further use by others. All the material has been gathered in great quantities—thousands of compass readings of directions were taken in the different areas and platted on large scale maps and sections. Some of the detail was then eliminated as far as possible to avoid unnecessary repetition. For instance, one arrow indicating a certain linear element was kept instead of four or five parallel ones in one small region. This presents the facts adequately and correctly.

The regions were mapped geologically as far as necessary and structural mapping was done throughout. In the laboratory thin sections of rock specimens were examined under the microscope. Statistical rock fabric diagrams were made for several regions (p. 90).

To many it may seem a waste of time to investigate structures in such detail. That this is not the case follows from the many detailed geologic maps that have been prepared for commercial enterprises. All practical problems require very careful and detailed geologic preparations and the finding of natural resources is one of the most important geologic tasks. Much can be learned, however, from regions without immediate practical value and many of the experiences in these regions have helped to solve economic problems.

The following chapter can not pretend to be a comprehensive treatment of metamorphic rocks. The literature on this subject is very extensive and it is here only possible to deal with the structures as they can be observed in the field and to a certain extent in the laboratory.

METAMORPHIC ROCKS

Metamorphic rocks are those of igneous or sedimentary origin which have been recrystallized after their formation. Recrystallization can be caused by intense heat, pressure, movements within the crust, by penetration of solutions from below, or by any combination of these factors. Granites can be deformed into gneisses, sandstones into quartzites, shales into schists, or limestones into marbles. Many other rock types are the results of metamorphism of a larger or a lesser degree. They all were completely changed; their structure, chemical composition, and their mineral content were reorganized. Many of the metamorphic rocks are so much recrystallized that the original rocks can only be surmised. A large number, however, still show traces of original structures which are

Fig. 1.—Combination flow and shear folds in Baltimore gneiss. Amphibolite layers are sheared and folded. Gwynns Falls Parkway, south of Edmondson Avenue bridge.

Fig. 2.—Fracture cleavage in Wissahickon schist, seven miles north of Conowingo Dam, east side of Susquehanna River. Bedding dips gently, cleavage steeply to the left.

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important in any attempt to reconstruct the history of the rock and to analyse the causes of its metamorphism.

In the following, structures of metamorphosed sedimentary rocks are taken up first; metamorphosed igneous rocks follow below.

BEDDING

Bedding, or stratification, is the most important structure of sedimentary rocks. It occurs in all sediments but is not always easily recognized. Bedding is a planar structure which becomes visible through differences of material within a rock complex; for instance, successive layers of different colors, grain size, composition, or thickness. Shaly partings only fractions of an inch thick may divide a massive limestone into layers or strata. Shale and limestone, sandstone and shales, conglomerates and shales, and different sandstones may be interbedded and make bedding or stratification a very distinct structure.

The individual strata may be very thin or thick but their lateral extent is always many times their thickness. Every bed reflects a certain condition of sedimentation. The sum of all the influencing factors, like climatic conditions, the agencies of transport of the materials, and the area of deposition will be preserved in the resulting stratum.

Primarily bedding is horizontal; that is, parallel to the surface of a body of water at the particular locality where a sediment is deposited. There are exceptions like cross bedding, irregularities in a sedimentary basin, river channels or deltas; or deposits like dunes, fans of debris, mud flows, and others. All beds are also lenses. They grade into other beds laterally or may even overlap other rocks.

If bedding is assumed to have been horizontal the mistake is usually very small. The few exceptions that occur can easily be recognized in the character of the sediment and be disregarded. This renders bedding the most important planar element since it is the only formerly level or horizontal direction preserved in metamorphic rocks. Unfortunately this is not a level like the present sea level, which serves as reference plane for the determination of altitudes, but only a direction parallel to it. Since in mapping geologic structures the position of bedding is measured and referred to a horizontal projection plane, this ancient horizontal plane becomes the level of reference. In any strata deformed by folding, faulting, or other dislocations, the total deformation or the sum of all the deformations can be referred to the original horizontal plane, and the deformation can be analysed.

All metamorphic terraines are folded, most of them very intensely. The first step in the investigation of such an area is a thorough search for bedding on a large scale which will permit the distinction between formations or groups of formations; as for instance, the Cockeysville marble and the Setters formation in Maryland. From this the formational boundaries can be drawn on topographic maps, thus providing the basic data for all further investigations.

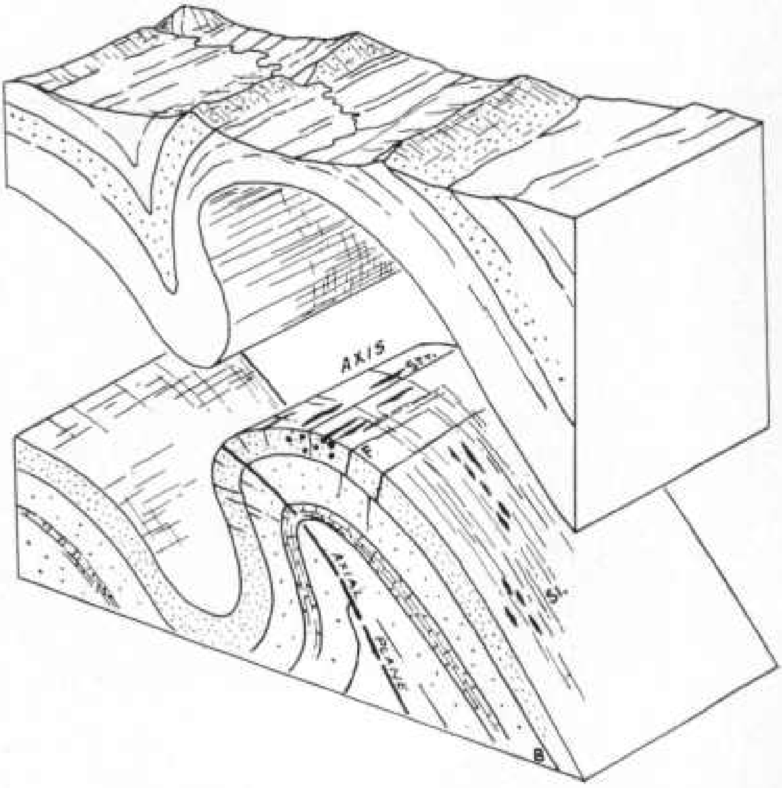

FIG. 1.—Schematic block diagram showing the elements of a fold. Str: stretched particles parallel to the axis of the fold; sl: striation and grooving on bedding planes perpendicular to the axis; B: bedding (after H. Cloos, 1936).

The next step is the study of bedding within a formation. Smaller beds a few feet or only inches thick may be identified. Their attitudes must be carefully recorded because they mostly reflect on a smaller scale the attitude of the larger units.

FOLDS

When the original sediments are metamorphosed the horizontality of the beds becomes deformed by folding or displacement and may be nearly obliterated by recrystallization of the material. The first step in this deformation is the bending of the bedding into folds. Many types of folds have been distinguished and their types and their description can be found discussed widely in the literature (68, 111).

Although a classification of the forms of folds may have its advantages for certain purposes, most folds are incompletely preserved in metamorphic terraines and such classifications are rarely applicable in the field. A classification of forms is usually too schematic to be valuable in regions where no two phenomena are alike and all investigations consist in assembling fragmentary evidence.

The elements of an ideal simple fold are shown in fig. 1. Here the different beds are folded into large waves and slightly overturned to the left. The upper portion of the fold has been drawn as being lifted off in order to show the anatomy of the fold. The highest portion is called the crest of the fold. Here thick small lenses can be seen, indicating the stretching parallel to the fold axis (pl. VII, fig. 2). Fractures occur as tension fractures due to the bending of the thick strata. The axial plane comprises all the axes in the different strata. On the surface of the limbs of the fold streaks and grooves are indicated and marked "SL". They are due to slippage of bedding planes during folding and are further elaborated below. The surface topography shows the influence of folding in that more resistant beds form ridges between valleys underlain by softer rocks.

AXES OF FOLDING

The most important element is the axis of a fold. Its position is measured in the field with compass and clinometer and then its horizontal projection platted on maps. The horizontal projection is the intersection between the vertical plane which contains the axis and the horizontal plane. The strike of the axis is thus the direction of that intersection. In the field a notebook may serve to indicate this vertical plane if necessary. The plunge of an axis is its deviation from the horizontal and can be read directly with a clinometer. Both measurements are essential for a definite determination of the position of an axis or any other linear element.

In Figure 1 the axis of the fold is horizontal. The two ridges at the surface are parallel, indicating that the strike of the limbs of the fold is parallel to the strike of the axis or to the axis itself. If the axis plunges the strikes of the two limbs converge and finally intersect with the strike of the axis. Since most axes of folding plunge, a pattern results on maps in which the beds may show a very irregular trend. The variation in strike may be 180 degrees and the results seem rather confusing. The determination of the axes of folds is therefore essential for the determination of the trend of a region because the axial trend will be much more consistant over larger distances. For instance, the trend of the Appalachian Mountains can be seen on any geologic map of the region (115, 116), in spite of the fact that the individual beds of formations may curve like contour lines in many places.

In recent years it has been found convenient to locate a fold with reference to a coordinate system to which other elements can also be referred. The general practice which has been widely adopted is to place

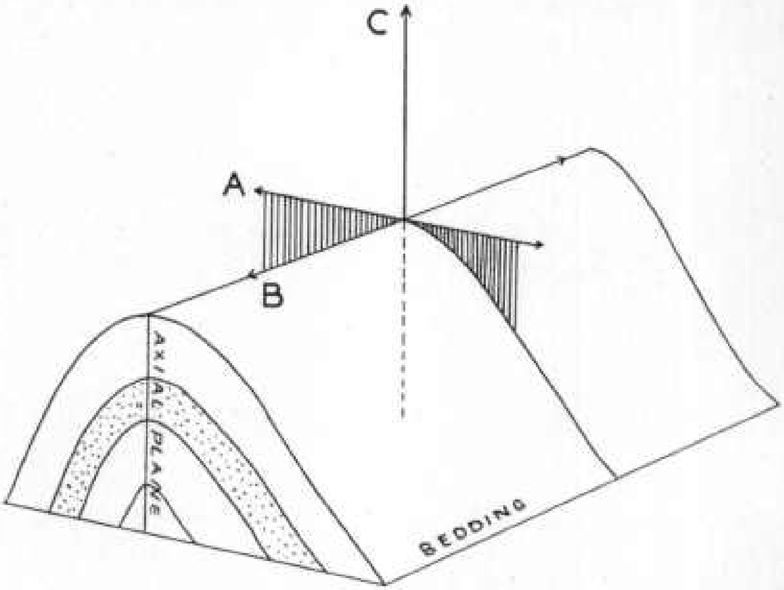

FIG. 2.—Diagram of a fold which is located in a coordinate system of three axes: A. B. and C.; shaded plane = A C plane perpendicular to axis of folding B. Axial plane = B C plane.

the axis parallel to the coordinate *b*, perpendicular herewith are *a* (horizontal) and *c* (vertical). The *ac* plane is then perpendicular to the axis *b* and can be used in all references to the deformation (fig. 2).

Not only bedding planes may be folded but also any other planar element like unconformities, banding in igneous rocks, foliation planes in metamorphic rocks, faults, or thrust planes. Folded thrust planes are frequently mentioned in the literature (51).

SLIPPAGE ON BEDDING PLANES

If folding takes place the individual beds will slip over each other. This slippage is unavoidable, as can easily be seen in the bending of a stack of paper sheets. Such slippage frequently causes markings on the bedding planes like grooves, slickensides, or even stretching of minerals. These lineations are then oriented in a plane (*ac*) approximately perpendicular to the axis of the fold and have the position of the intersection of the *ac* plane with the bedding plane (fig. 2). In regions where only fragments of folds can be observed such lineations have often been mistaken for axes of folding or for structures like stretching (p. 52), or they have been interpreted to be the intersections between cleavage and bedding. Great care is necessary because measurements of such slippage traces may mean a mistake of 90 degrees and a map on which such directions are platted along with real folding axis may suggest chaos where regularities would otherwise be evident.

TYPES AND MANNER OF PRODUCING FOLDS

A pre-existing planar structure (bedding, foliation, unconformity, etc.) can be folded by bending, shearing, or flowage. Combinations of these types of deformation are very abundant and almost the rule in metamorphic terraines.

FOLDING BY BENDING

If a stratum is bent, either by lateral compression in the direction of the bedding plane or by forces perpendicular to it or a combination of the two, true folding will result. The thickness of the individual bed as measured vertical to the bedding plane remains constant. Slippage will occur in the bedding planes as one bed slides over the other. The curves thus produced are concentric.

During this deformation compression occurs on the inside and tension on the outside of such a bed as indicated by small arrows in fig. 3. This may lead to crinkling or fracturing in the respective regions. If a complex of strata consists of more resistant layers interbedded with weaker ones, the weaker may be wrinkled into small folds between the uncrinkled massive beds. Under continued application of forces, the softer material may even migrate or be squeezed into the anticlinal or synclinal areas between the massive beds. The resistance of beds against folding varies with their physical properties and their thickness. Thus stronger beds are competent, the weaker incompetent in respect to their ability to resist folding.

Pure folding occurs in many folded terraines; for instance, the Appalachian Mountains where it has been studied since 1850 in great detail (111).

In metamorphic terraines, however, this type of folding is not as frequent as its combination with shear folding.

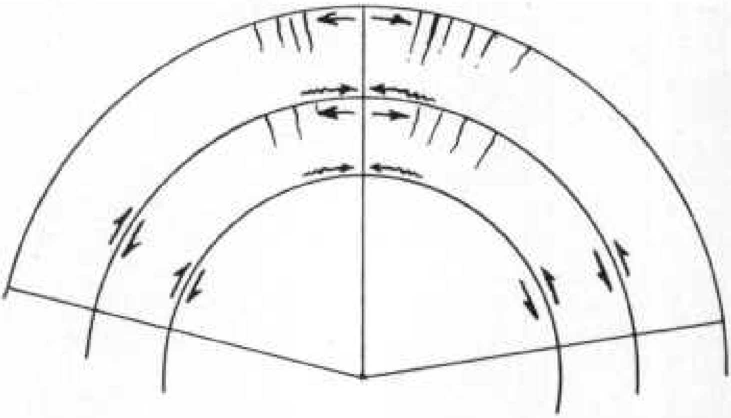

FIG. 3.—Diagram showing a bent fold. Note consistent thickness of bedding with reference to a center of curvature. Half arrows indicate relative direction of slippage. Full arrows indicate areas of tension and compression within the crest of the fold.

SHEAR FOLDS

If a stratum is transected by a cleavage (pl. II, fig. 2) or a cleavage is being formed during the folding process, another planar structure in addition to the bedding plane is mechanically effective. Slippage on bedding planes is one way of readjustment of the bending strata to new conditions. Slippage along transecting cleavage planes is another possibility of readjustment. Provided this slippage is the only adjustment—pure shear-folding will occur.

In this case movements take place on the shear (cleavage) planes *without lateral shortening* and a fold will result. The thickness of the beds, however, remains constant parallel to the shear plane and may be parallel to the axial plane of the fold and not in reference to a center of curvature. The fold is therefore not concentric and the thickness varies greatly along the radii of the fold. This process can be demonstrated with a stack of cards. If a line is marked on the side of the cards and they are then pushed over parallel to the table on which they rest, the line will be deformed into a fold if the center cards are pushed farther than the upper and lower layers. The motion is then a gliding along shear planes (fig. 4).

If the same stack of cards is bent, however, over the edge of the table true folding can be visualized, with slippage between the cards perpendicular to the edge of the table. The table edge would then parallel the axis of the fold and slippage lines between the individual cards would be vertical to it.

FIG. 1.—Flow cleavage transecting bedding in Vintage Dolomite. Burnt Mills, Pennsylvania.

FIG. 2.—Flow cleavage in fan-like arrangement. Quartz veins emphasize bedding. Height of exposure 6 feet.

P. 56 B

Shear folds are most abundant in all metamorphic rocks with cleavage. Since cleavage planes are more closely spaced than most bedding planes they facilitate deformation, particularly if they are older than the act of deformation under consideration and planar minerals, like the micas, have arranged themselves in such cleavage planes.

It can easily be seen that the two types of folding are different in principle (compare figs. 3 and 4) and that they can not result from the same setup of stresses during deformation. If bent folds are smoothed out theoretically they will show the actual size of the bent bed and show the amount of lateral shortening and transport. The shear fold can never be straightened out because it is formed *without lateral shortening*. This is of utmost importance in attempting a reconstruction of the conditions prior to folding.

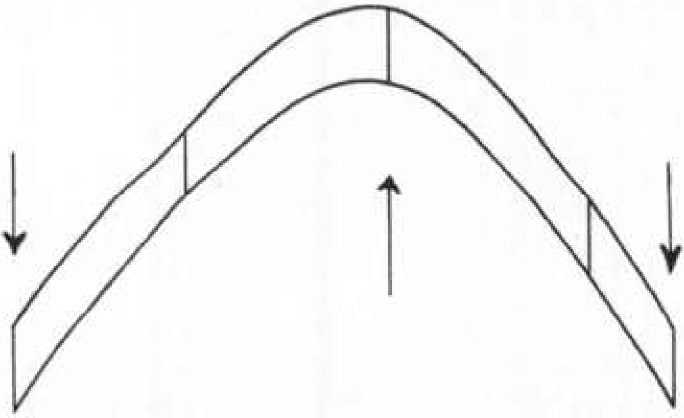

FIG. 4.—Diagram of a shear fold which is the result of slippage on subparallel planes in the direction of the arrows. The thickness of the beds is not constant in reference to a center of curvature and there is no lateral shortening.

FLOW FOLDS

Rocks which are subjected to sufficient heat and pressure begin to flow in accord with their physical properties. They then resemble igneous rocks which intrude into higher portions of the earth's crust. One has spoken of "salt intrusions" or "sandstone dikes" and the process is comparable to true igneous intrusion.

Folds which form under such circumstances are forms which conform to hydrostatic pressure and not to directed stresses. Flowage of this type produces highly irregular folds seemingly without definite directions. In gneissic terrains they have been called ptygmatic folds and examples are numerous in the literature (96).

Figure 1, plate II shows such folds which occur abundantly in metamorphic regions. Irregularity of thicknesses and axes in these folds are typical. They are neither concentric in any direction nor symmetrical with reference to a coordinate system, an axial plane, or any existing cleavage. The original planar structure—bedding or cleavage planes—have no mechanical significance; they are passively deformed and represent only a design which renders the deformation visible. Competence or incompetence of beds is also extinguished—all the designs flow like foam on water or flow bands in igneous rocks.

The classic areas for flow folds are deep-seated metamorphic regions like Canada and Scandinavia, or regions underlain by easily flowing salt deposits.

COMBINATION OF TYPES OF FOLDS

Physical conditions within the earth's crust vary greatly with depth and with the materials present. There are no sharp boundaries between temperature or pressure zones but they all grade into each other. Since the types of folds are in part related to the amount of deformation that has taken place and since this deformation is closely related to the temperature and pressure governing the deformation, the folds which result grade as much into each other as the conditions. A strict and schematical classification of types means therefore forcing nature into conditions that do not exist.

Bent folds and shear folds may be superimposed and shear folds and flow folds grade into each other. Clean-cut types are very rare and a consideration of structures must deal necessarily with gradations. This renders the task much more difficult because the plan of deformation loses simplicity and the combinations possible and the directions which result become very numerous. In metamorphic terrains with a multitude of local conditions it is then difficult to analyse the deformation of the region and no simple schematic conclusion will ever satisfy the facts.

In regions where limestones are interbedded with shales or sandstones, the limestone may begin to flow during a phase in which the sandstone is still being fractured or sheared into shear folds, or even bent into larger concentric anticlines and synclines. It is therefore necessary to investigate the details and to analyse the general plan of deformation of the region.

Such analyses have recently been attempted with the help of microscopic studies of rock fabrics and reference of all structures to a coordinate system as mentioned above. If the total deformation observed results from one act of deformation, it may be possible to find in each of the different types of folds those structures which they have in common, like an axes or a plane or any other linear or planar elements or their combination. Details of this type of investigation are discussed on pages 82–93.

SYSTEMS OF FOLDS

Single folds are rare and occur only in non-metamorphic regions; as for instance, in the major anticlines and synclines in the western and southern United States where they are of economic significance as oil-bearing or mountain-forming structures. Systems of folds are the rule where many small folds with parallel trending axes occur together within one formation or larger folds, each one comprising one formation, may have parallel trends and form a mountain system. No portion of a metamorphic region is unfolded therefore horizontal bedding occurs only in the crest of anticlines or synclines. If folding is intense the limbs of the folds close tightly and may become parallel, isoclinal, or nearly so. If the axes are horizontal or nearly horizontal the strike of the bedding will parallel the axes and be rather consistent over distances of many square miles. The dip of the bedding, however, may vary considerably or be overturned.

Constant parallel strike of stratification is always an indication of horizontal axes of folding and horizontal axes also mean parallel strike of the beds. The first can be observed and the other safely assumed because the two elements are then mutually interchangeable.

If, however, the strike of the bedding varies greatly within short distances the axes plunge and mutual substitution is impossible. The determination of the axes is then important because only the axes will show the regional trend of the fold system.

In the regions with many folds of different order of magnitude the axes of the smaller frequently parallel those of the major folds. It is then possible to measure the general trend by determining a large number of minor axes. This is much easier than to measure larger folds, because the chances of finding exposures of small folds are infinitely greater than for larger ones.

As a rule, the axis of a fold will not remain horizontal for a long distance. At the plunging ends other folds parallel to the first will appear thus creating a dense interwoven string of folds, which seem spliced together like the individual strings of a cable.

Such systems of folds can continue for thousands of miles with more or less constant trend; or more frequently, the system is bent whereby the axes of all the smaller folds participate in this change of direction. The Appalachian Mountain system trends northeast-southwest as a whole, but several bends are obvious particularly in Pennsylvania and Maryland (73, 115, 116). One bend seems to have Baltimore as the approximate center of curvature where the strike changes from northeast-southwest to east-west, and towards the south to north-south and back to northeast-southwest. Mathews (73) has called attention to this change in trends and pointed out that as the bend occurs the belt of Baltimore gneiss (p. 153) becomes wide and dome-shaped uplifts appear. Other more striking examples of such bends are well known in the Western Alps or the Carpathian Mountain system.

In systems of folds it is often possible to show that not all folds have been formed at one time. The first folding occurred where the folds are now most intense. From here as the intensity declines, the folds become more open, lower, and smaller. Finally at the outer margin of the folded system folding dies out and the same beds may be unfolded and flat. The Appalachian Mountain system is probably the clearest example. At its southeast side all folding is very intense, isoclinal folds are numerous, overturning towards the northwest is the rule. Along the northwest side the folds die out entirely and only a scarcely noticeable waving is visible.

CLEAVAGE

Rock cleavage is the property of a rock by virtue of which it will part along smooth surfaces. Cleavage planes are planes of parting and may be closely spaced as in slate, or farther apart as in gneiss, or schist. They may be due to rock texture; that is, mineral arrangement, or caused by closely spaced fractures and they can occur in almost any rock at any time under suitable conditions. The physical properties of a rock, its grain size, brittleness, elastic limit, and its position with reference to other geologic units may cause or prevent it from attaining a cleavage. Many rocks are primarily cleavable parallel with their bedding or flow structure. One may thus speak of primary cleavages inherent in the rock, and secondary cleavages which are superimposed in later stages, particularly in consequence of metamorphism.

Cleavage is one of the most common structures in metamorphic rocks and very important in the study of their history. The appearance of cleavage may vary greatly between certain regions and also between rock types in one region. Rarely is cleavage the same over larger areas because its directions and relation to other structures, like bedding, varies.

Because of the many possible age relations and orientations and the varying appearance of cleavages a great confusion of terms has arisen in the literature. It is at present almost impossible to use any of the many terms for principally the same phenomenon without a definition of the meaning of the term which is used. The following table shows the terms for cleavage according to Van Hise and Leith and modified after Willis.

Fig. 1.—Cleavage transecting bedding in Setters Formation, one-half mile northeast of Notch Cliff.

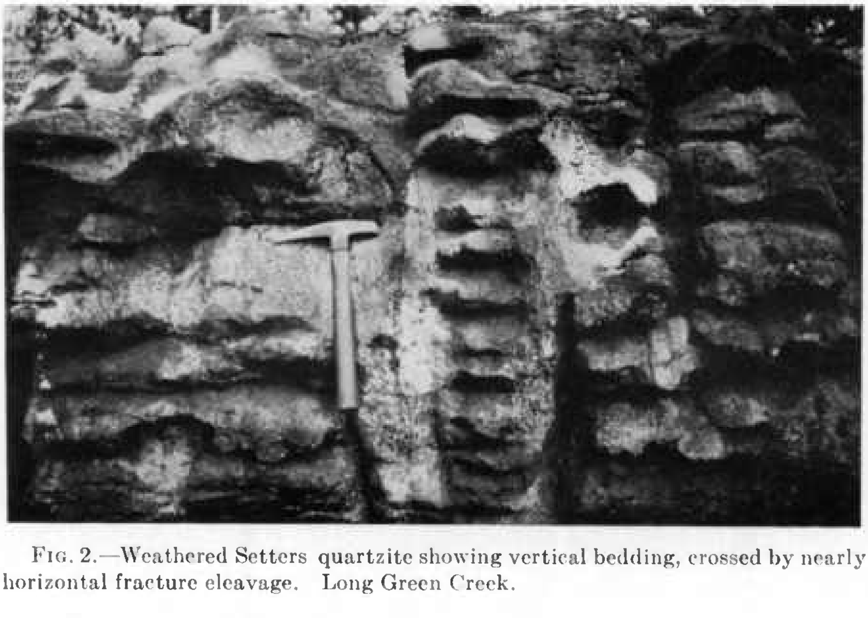

Fig. 2.—Weathered Setters quartzite showing vertical bedding, crossed by nearly horizontal fracture cleavage. Long Green Creek.

ROCK CLEAVAGE

- I. Primary cleavage (inherent in the rock and dating back to its formation).
  - A. Bedding or stratification in sediments, partings, etc.
  - B. Flow planes and layers in igneous rocks, "foliation," "rift" in granites, foliation in gneissic granites (and orthogneisses?)
- II. Secondary cleavage.
  - A. "Flow cleavage," due to arrangement in subparallel planes of planar minerals like mica and chlorite due to recrystallization in planes.
    - Schistosity (in schists)
    - Slatiness (in slates)
    - Foliation in paragneisses (and orthogneisses)
    - Ultimate cleavage, cleavage, cleavage proper.
  - B. "Fracture cleavage," due to fracturing either without or with subordinate, largely mechanical, rearrangement of minerals.
    - False cleavage
    - Close joint cleavage
    - Strain slip cleavage
    - Fissility
    - "Ausweichungscleavage"
    - "Schubklüftung"

The above classification is far from perfect and can never be entirely satisfactory because natural phenomena grade into each other. Flow and fracture cleavage can not always be clearly distinguished. There is fracture cleavage with rearrangement of minerals into these cleavage planes, but also with fracturing. Flow cleavage can originate from complete recrystallization without fracturing; fracture cleavage, by definition can not.

Furthermore, there are slight differences between the terms schistosity and foliation. Every recrystallized metamorphic rock may be called a crystalline schist, but not every schist in this definition is schistose or shows schistosity. Mica schists may possess a very distinct slaty cleavage, thus resembling a slate but without being slates only because of this similarity. The term false cleavage implies that there is also a "correct" cleavage without stating what "correct" would mean. Close jointing cleavage implies a mechanical cleavage by jointing, but many of these cleavages are accompanied by rearrangement of minerals and, on the other hand, different rocks do not joint in the same way. Joints may be closely spaced in one rock and they may be farther apart in another, or their orientation may change with a change of the physical properties (pl. XXXVIII, fig. 2).

Further analysis of the terms listed above would only tend to throw more light on the difficulty of describing with adequate distinctions phenomena which are almost but not quite alike.

As a whole, the terms flow and fracture cleavage are very serviceable and if outlined at the outset fulfill the requirement of a clear description. In the Piedmont of Maryland most rocks clearly show these two cleavages and quite often also bedding to which they can be referred as reference plane. In certain localities, however, a third cleavage appears and under the microscope a fourth. It then becomes rather cumbersome to speak of flow cleavage 1 and 2 and of fracture cleavage 1 and 2. In addition some of these cleavages are microscopic and impossible to correlate from one location to another.

It seems, therefore, that a general purely descriptive terminology would be of advantage. Such a system has been introduced recently by Schmidt and Sander (88, 89) in Europe and has been widely used. There is no genetic implication connected with these terms and the different planes are merely called S_1, S_2, S_3, S_4, etc. S_1 would be the first one formed; for instance, bedding which may still be visible in a certain metamorphic rock. A cleavage (schistosity) that cuts across bedding or may parallel it would then be S_2; a fracture cleavage which crosses, and maybe along slips, offsets both previous ones is S_3, etc. Joints could also be included into this system and easily be determined.

If this system is referred to a coordinate system with three mutually perpendicular axes (p. 54) the relation of planes to each other, to mineral orientations, axes of folding, stretching, and any other structural element would be fixed and the complicated data could at once be grasped. For the actual presentation of such a system it would be necessary to project all data into a net and show the data diagrammatically. This method of presentation is described briefly on page 85.

There is no doubt that such a strictly logical-mathematical treatment of cleavages would be highly desirable. Since not everybody would want to give up terms he has used for many years and since such terms as fracture cleavage convey an idea along with a description, it may be best to add in a discussion of cleavages the correct "S" to help others in the understanding of the phenomena; for instance, fracture cleavage (S_3). In this way misunderstanding could be reduced to a minimum. Reference to a coordinate system shows immediately all the planar and linear structures which belong to one act of deformation. Others which may have formed later and have been superimposed on older ones will show because of the difference in symmetry.

ORIGIN OF CLEAVAGE

The origin of cleavage is not known with certainty. Several theories have been proposed but none completely explains the formation of a series of subparallel planes and their direction in relation to forces which have produced the deformation. Several relations enter the explanations of cleavage: the relation between cleavage and crystallization, between cleavage and pressure and its direction, between cleavage and movements; and between crystallization, pressure and movement.

Static recrystallization

If a complex of rocks is submerged under a large quantity of rocks and thus brought into areas of higher pressure and temperature, certain metamorphic changes will take place. Certain minerals will be dissolved, others crushed. If this load metamorphism is without movements, a static recrystallization may be the result. It is conceivable that crystals under pressure will dissolve where pressure is greatest and that the dissolved substance will migrate to points where pressure is less (Becke). This would lead to a recrystallization perpendicular to the direction of pressure in that the crystals would grow where pressure is least, perpendicular to it. In such a way a cleavage would be formed most likely perpendicular to the load from above, or more or less horizontally.

Theoretical considerations and field observations, however, hardly favor this explanation. Most cleavages have been formed in combination with motion, as indicated by small slips and the orientation of cleavage in relation to the direction of folding.

"Abbildungscrystallization"

If a planar structure like cleavage is present before recrystallization it may favor the growth of tabular minerals like mica in these planes. In this way the mineral orientation and its combination with cleavage planes could be explained. It would mean, however, that the growth of minerals and the formation of the planes would be two independent processes. The cleavage could then be a primary cleavage; for instance, bedding or foliation, or any secondary one which favored the recrystallization process. Such processes seem to be highly probable and in regions where a secondary cleavage parallels bedding mineral orientations have obviously been facilitated by pre-existing structures.

Cleavage by crystallization with movement

A combination of the two principles outlined above seems the most likely explanation of cleavage. Mineral growth in the direction of the least stress and deformation in shear planes represents the most complete accommodation to stress conditions.

DESCRIPTION OF CLEAVAGES

Primary cleavage (bedding in sediments, foliation in igneous rocks) has been mentioned on pp. 51, 61 and needs no further description.

Flow cleavage is accompanied by a parallelism of planar minerals which have oriented themselves in the new direction of the cleavage. In a rock which is completely recrystallized all minerals will have adapted themselves to the new conditions. Stratification under the influence of gravity or the flow layers in an igneous mass are past history and the cleavage may cut across all previous structures, indicating that adaptation has been complete. Such cleavages have been called schistosity, true cleavage, etc., because the character of the rock is dominated entirely by its cleavage. This new rock does not always show traces of older structures and if they are present they may be difficult to find. Simultaneously the rock fabric and probably its composition have changed, either by recrystallization alone or in combination with the introduction of new materials.

The appearance of flow cleavage differs with the rock type in which it is found. Many fine-grained rocks show thin foliae; coarser rocks have a slabby appearance and the flow cleavage planes are wavy. New minerals, like garnets, mica, albite, staurolite, tourmaline, and many others may have grown in these cleavage planes, emphasizing the direction and rendering it more visible (5, pl. 5) Hardly two schistose rocks look alike. The cleavage, however, is due to parallel arrangement of minerals and one speaks of mica schist, chlorite schist, if garnet is present of garnetiferous mica schist, etc.

The Piedmont of Maryland includes vast areas of schist in which a flow cleavage is the dominant structure. The Wissahickon formation is the largest but there are others, like the Peters Creek formation, Peach Bottom slate, and the gneiss areas (116).

Fracture cleavage is predominantly the result of fracturing along subparallel planes. These may be spaced closely or farther apart. In slates large smooth fracture surfaces produce thin sheets of rock which may be only fractions of an inch thick and thus be suitable for roofing. In mica schists the fractures may transect the flow cleavage at any angle, frequently forming thin slabs. Usually fracture cleavage planes are smoother than flow cleavage planes. Since fracture cleavage transects and mostly displaces flow cleavage planes, it has been formed later than the latter. Fracture cleavage planes may show a silky lustre which results from a coating of micaceous minerals which are either bent into the new plane mechanically or have grown there during a period of partial or beginning recrystallization.

Relation of cleavage to bedding

Bedding can be deformed by folding as described above (p. 56). If this deformation continues, particularly after folding has become nearly isoclinial so that the limbs of the folds approach almost parallelism, cleavage appears. Recrystallization may accompany the deformation and the cleavage planes serve as loci for new or newly oriented minerals. In the case of complete recrystallization bedding planes may locally be paralleled by cleavage planes in the limbs and dissected by cleavage planes in the crest of the fold (68, 69).

The intensity of a cleavage depends on the degree of deformation and on the material which is deformed. Large thicknesses of shale, for instance, will be readily cleaved and bedding which may consist of thin layers of different colors or only slightly differing materials will be entirely obscured and obliterated. Thick beds of quartzite or conglomerate may be preserved. Bands of limestone frequently are sheared along the cleavage planes but may still be visible because of changes in chemical composition between individual beds.

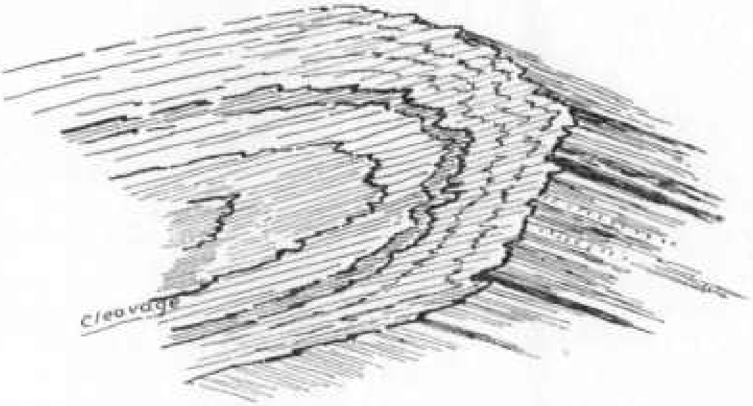

FIG. 5.—Diagram showing the relation between cleavage and bedding in a fold. The cleavage parallels bedding only in the limbs of the fold and transects it within the crest. Intersection between cleavage and bedding appears in lines on the bedding planes which can easily be mistaken for stretching parallel to the axis.

In many regions a cleavage is formed before the folds are isoclinal and close enough to parallel the cleavage. Here it transects bedding and may even participate in further tightening of the folds. As a result the cleavage is slightly tilted and arranged in a fan which spreads toward the crests of folds. In such cases it becomes possible to analyse the amount of folding which has taken place after the cleavage was formed (32).

In the metamorphic rocks of the Piedmont Province of Maryland bedding is rarely observed with certainty. Certain areas show bedding clearly but as a rule recrystallization has been very effective and complete. Wherever quartzite or limestone layers appear stratification becomes visible. It is, however, never possible to trace bedding planes or individual strata over larger distances. In larger groups like the Setters formation the formation as a whole is traceable, as shown in the maps by Broedel (pl. XXVII) or the geological maps of Maryland. This formation is composed of a series of resistant beds of thick quartzite which form marginal rims around the anticlines of Baltimore gneiss. Within the formation bedding is observable and cleavage can be seen crossing the beds.

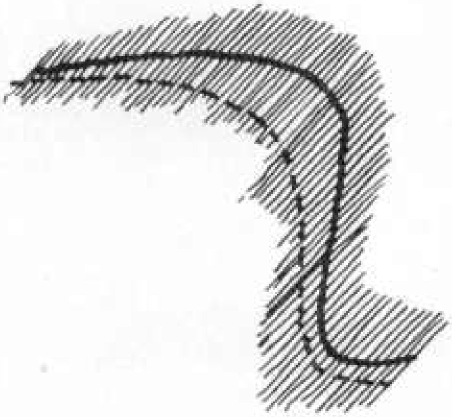

FIG. 6.—Diagram showing axial plane cleavage in a shear fold. The original bedding (dashes) has been bent further by displacements along very many closely spaced subparallel shear planes.

The orientation of flow cleavage planes in relation to the axial plane of a fold has been described by Leith (69) and is usually symmetrical to the fold and parallel or nearly parallel to the axial plane. It has been called axial plane cleavage. Later folding may change this parallelism but the trace of a flow cleavage plane on a folded bedding plane remains parallel to the axis of folding.

In bent folds the position of the flow cleavage is not always that of an axial plane cleavage, depending on the stage of deformation during which the cleavage appeared. In shear folds the cleavage plane is the plane along which the gliding took place, comparable to the individual cards in a stack of cards sliding over each other (p. 56). In these folds the flow cleavage is always an axial plane cleavage.

If the fold and its cleavage is referred to a coordinate system (fig. 2)

FIG. 1

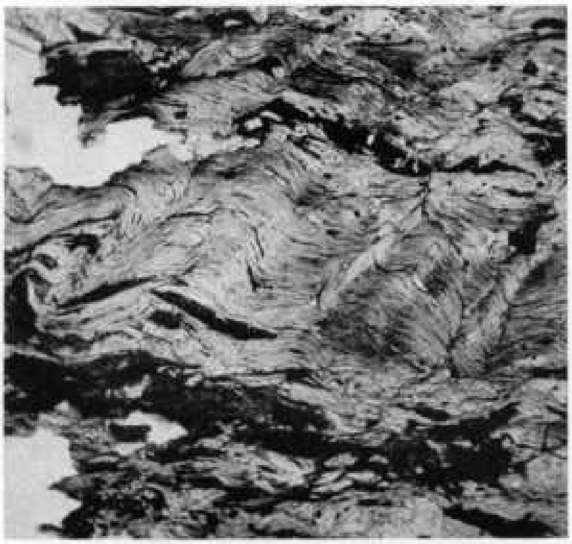

FIG. 2

FIGS. 1, 2.—Photomicrographs of fracture cleavage in Wissahickon schist, Prettyboy Dam. The mica folia bent sharply into a new planar direction. Parallel Nicols. Approx. × 15.

and the axis of the fold is parallel to the intersection of bedding and cleavage is also parallel to *b*, the plane itself contains the direction *b* and will be perpendicular to the *ac* plane.

In regions like the Piedmont of Maryland or Pennsylvania this direction is remarkably constant and it becomes possible to determine the direction of folding axes by measuring the trace of the cleavage on bedding planes wherever they can be ascertained. In any highly folded and intensely recrystallized region it is much more likely that such bedding plane fragments are found than the whole fold and its axis. It is therefore very serviceable to ascertain this relation and then substitute the cleavage trace for the axes. This of course is only possible when one deals with a well established cleavage trace.

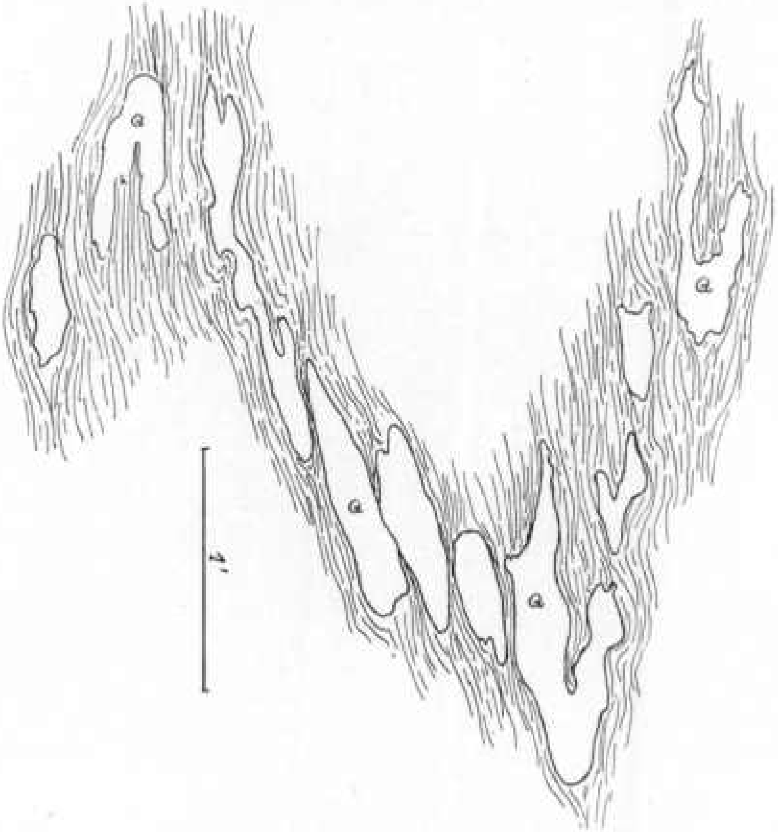

FIG. 7.—Folded quartz veins in Wissahickon schist. Susquehanna River section.

As a rule it has been observed that wherever cleavage and bedding planes are parallel the bedding planes are smooth; in the case of intersections they are very rough and uneven and both directions can then be observed. In limestone regions newly formed calcite or small quartz veinlets may mark the one plane and slaty partings the other.

Other elements parallel to the axes of folding are lineations or stretching; for instance, in conglomerates which will be described on page 70.

If the formation of a cleavage is followed or accompanied by introduction or intrusion of magmatic juices and deposition of materials like quartz or pegmatites on cleavage planes, the recognition of bedding planes becomes mostly a difficult task. In the Wissahickon formation stratification is occasionally found but rarely with certainty. Innumerable quartz veinlets and lenses follow the cleavage and probably not the original bedding.

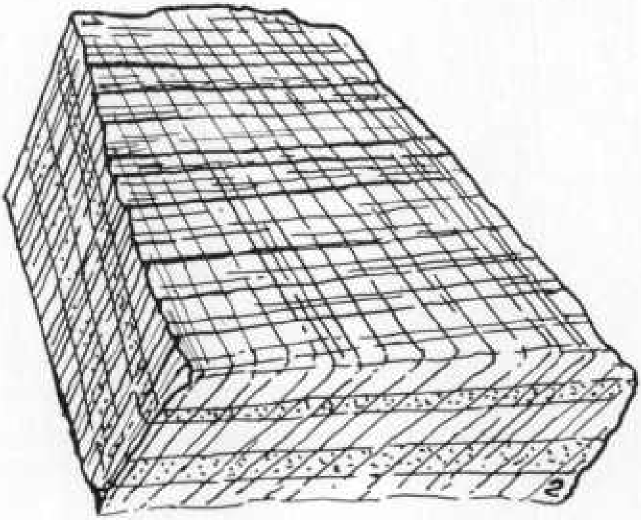

FIG. 8.—Combination of bedding, flow cleavage, and fracture cleavage (Diagram). Specimen of Vintage dolomite (shaly member), Lancaster County, Pennsylvania. Bedding top surface, flow cleavage right front side, and fracture cleavage left front side.

Folded cleavage

Cleavages can be folded as well as any other design in a rock. Many cleavages are strongly deformed. The above-mentioned quartz veins in the Wissahickon formation are mostly folded and crinkled into very irregular small folds (fig. 7). They thus indicate a continuation of the deformation beyond cleavage and recrystallization and it is not certain whether these folds still belong to the same phase of deformation or to a later one. As a rule these small axes parallel the larger and older ones, thus representing folds like drag folds as described in the literature (68). They do not, however, show any relation to the limbs of the master fold.

Aside from folding the cleavage planes can suffer from a deformation by another cleavage. They can be transected by later cleavage planes at any angle and their intersection can be parallel to the axes of the fold or can deviate from it considerably. Usually this later cleavage is not accompanied by as extensive a recrystallization as the earlier cleavage and it is frequently a fracture cleavage. These planes have mostly served as planes along which small displacements have taken place, thus wrinkling the flow cleavage planes into millions of small folds.

In the Piedmont of Maryland and in the highly metamorphosed Paleozoic area of the adjacent territory to the northwest, this fracture cleavage is very distinct and never fails. Almost every rock outcrop shows the very typical wrinkles on the flow cleavage planes and displacements vary from microscopic size to a half inch.

Figures 1 and 2 on Plate VI show such fracture cleavage under the microscope in Wissahickon schist from Prettyboy Dam, Baltimore County. It can also be observed in the Peach Bottom slate near Delta and Peach Bottom, or anywhere along the east side of the Susquehanna River south of Lancaster, Pa. It is clearly evident as a mechanical deformation of the flow cleavage planes and is widespread in Paleozoic and pre-Cambrian rocks in Maryland and Pennsylvania.

In certain portions of the Piedmont region the fracture cleavage cuts across the axes of the folds at an oblique angle. It can therefore not readily be referred to the coordinate system because it cuts all three axes at an angle. This may indicate a later phase of deformation during which this fracture cleavage has been superposed over all previous structures.

Cleavage and older structures

Any planar structures can be deformed by cleavage transecting them. Flow layers in gneisses or igneous rocks are frequently folded and then cleavages, parallel to the axial plane, transect them in the crest of folds. In the Baltimore gneiss, which contains many amphibolite bands and micaceous layers, folds and cleavages are visible (pl. II, fig. 2). Here shear folds are combined with bent folds and axial plane cleavage becomes very distinct. The Baltimore gabbro is also folded and cleaved. In all these cases the pre-cleavage structures act only as a planar design which is deformed. Mechanically they are hardly different from bedding in sedimentary rocks.

LINEAR ORIENTATIONS IN METAMORPHIC ROCKS

Cleavage is a planar structure and indicates deformation and recrystallization in planes of certain orientations with respect to deforming stresses. In the coordinate system the cleavage planes are definitely oriented with respect to the folding axes and the axial plane of the folds. Within these directions linear arrangements are possible theoretically in all directions within that plane. Such linear orientations are frequent and also are rigidly oriented in the coordinate system. The most frequent orientation is parallel to the axes of the folds and therefore also parallel to the *b* axis of the system.

Such orientations are visible as streakings, mineral patches (blebs), grooving, or stretching of particles which were originally spherical. The most obvious of such an arrangement is the alignment of lengthened pebbles in conglomerates. Such pebbles are well known from other regions and occur wherever conglomerates are stretched. The individual pebbles may attain a length of 20 times their diameter and resemble cigars or torpedos (30, fig. 266).

Fragments of folded bedding in intensely folded marbles may also be stretched into long fragments and "rolled around" until they are hardly distinguishable from such pebbles. They were observed by the author in the Conestoga limestone in Lancaster County, Pennsylvania, and all gradations between a coarser limestone bed and such lengthened fragments have been traced. The direction of elongation is parallel to the folding axes and parallels the *b* axis. This is the same direction which results from the intersection between bedding planes and flow cleavage. The latter probably dislocated bedding to such an extent that only disconnected fragments remained and these were then elongated (fig. 9).

These observations are particularly easy in limestones which suffered considerable deformation because limestones will readily yield to any type of deformation. Newly-formed, larger, usually black calcite crystals are abundant in these localities, indicating a thorough recrystallization. The cleavage planes, however, are mostly obscured and uneven because of their formation during the "flow" of the limestone. Slaty and graphitic partings are abundant. It is obvious that in such rocks the bedding has been completely destroyed.

If new minerals are formed during the deformation; for instance tourmaline, or hornblende, or any others which show an elongated crystal shape, they are also included in the orientation process during the deformation. Tourmaline in the Setters formation is frequently aligned very rigidly and then the individual crystals are broken and the fragments pulled apart up to one-tenth of an inch. A locality where such tourmalines can be

Fig. 1.—Aligned blebs in volcanic rocks of Frederick County, Maryland. Approx. ¾ nat. size.

Fig. 2.—Elongated components in conglomerate of Conestoga Limestone, transsected by cross fracture, Burnt Mills, Pennsylvania. Height of exposure 6 feet.

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observed particularly well is at Martic Forge, Lancaster County, Pennsylvania, in the Wissahickon formation. Here thousands of tourmaline crystals are parallel like needles and then pulled apart and lengthened up to twice their original length.

The orientation of hornblende crystals in the Baltimore gabbro in its amphibolite phase is ascribed also to deformation and stretching by Cohen (p. 235). Here the hornblende may have grown in the direction which corresponds to the flow lines of granites and other primary intrusive rocks, or may have been rotated and stretched into a direction corresponding to the *b* axis in the coordinate system.

FIG. 9.—Bedding in Conestoga limestone almost obliterated by slippage along cleavage planes. Burnt Mills, Pennsylvania. Height of the exposure 10 feet.

Any other particles in sedimentary or igneous rocks may also be elongated by the deformation. Amygdules or vesicules in volcanic rocks often are beautifully aligned. In Frederick County, Maryland, large masses of volcanic rocks are exposed and occur as slaty, purple or green schists with a very distinct narrowly-spaced cleavage. Stratification can be observed in many localities and is due to almost laminar interbedding of volcanic material with sandy layers or conglomerates with small components. The cleavage is mostly parallel with the bedding planes, perhaps due to isoclinal folding. In the volcanics are innumerable small blebs up to one inch long and shaped like willow leaves. Their longest dimension is about 2 to 3 centimeters. They are approximately one-half centimeter wide and very thin within the cleavage plane. On the surface of these planes the orientation is obvious and can hardly ever be overlooked. This orientation of blebs is striking and parallels the axes of folding (fig. 1, pl. VII).

If axes of folding can not be observed these lineations are most valuable in ascertaining their direction. It is, however, essential to determine first the relation between axes of folding, lineations and cleavage planes. In other words, between all these structural elements in reference to the coordinate system in a sufficient number of cases (at least one hundred). Without this preliminary investigation no substitution should be undertaken because it is quite possible that the lineation is an orientation vertical to the axes of folding within the *ac* plane and due to slippage on bedding planes during folding by bending; or also due to slippage on cleavage planes during shear folding. Both types of lineation have been frequently observed and great confusion would arise in case of a mistaken correlation. It is possible that lineations in both directions occur in the same locality and they can be found only if a very careful search of the exposure is made.

The quarry at Cromwell Bridge northeast of Baltimore, exposes the Setters formation which consists of thick quartzite layers with shaly or schistose partings. Within the quartzite beds tourmaline crystals are aligned and stretching is distinct parallel to the axis of the fold and in the schistose layers a distinct lineation trends down the dip of the beds almost at right angles to the former orientation.

The contemporaneous occurrence of two lineations is particularly frequent in slaty or shaly rocks. Here any type of deformation leaves its traces much more marked than in more resistant sediments.

If fracture cleavage is present; as for instance in the mica schists (Antietam quartzite) of Lancaster County, Pennsylvania, or in the volcanic rocks of Frederick County, Maryland, the intersection between it and the flow cleavage mostly shows in small wrinkles which very frequently can be seen as slight grooves on the cleavage planes. This grooving resembles striation and lineation but has no direct relation with the coordinate system referred to above. Since this cleavage intersects all three axes and also the axes of folding at an oblique angle the striation is no indication of folding axes or slippage on bedding and cleavage planes.

After some knowledge of a region is accumulated these elements can be kept apart without any difficulty, particularly if compass readings are recorded in sufficient number and platted on maps. Any measurements which are entirely apart in an otherwise regular direction have to be checked and can then be corrected. Insofar platting of measurements gives assurance that the elements observed are the correct ones. Very abrupt changes in axial pitch or the projection of lineation is rare in any area except if faults or fault zones are approached. In this case many measurements in a zone should show the same deviation, which also gives assurance of correct observation.

It is very obvious that a large number of measurements will eliminate mistakes automatically and that the presentation on maps will show any irregularities at once—either to be rechecked or confirmed.

FRACTURING

Fracture cleavage consists of an accumulation of fracture planes at very close intervals. Frequently a new mineral arrangement is found on these cleavage planes but no complete recrystallization of the rock has taken place. Micaceous minerals have been bent into the new direction (pl. VI, fig. 2) mechanically or, if new minerals were formed, they are restricted to the new planes. Fracture cleavage may be comparable to the intermediate stages between jointing and flowage in igneous rocks (p. 43). Flexures are common. They indicate a condition which lies between flowage and fracturing; that is, between plastic flow and breakage.

The terms fracture cleavage, close-spaced jointing, false cleavage, Schubklüftung, and others indicate the difficulties which arise in recognizing the character of these structure planes. Some observer feels that jointing is the major process while another gains the impression of a genuine cleavage.

Fracturing is a complete separation of portions of a rock by joints. New mineralization may take place along such fractures, dikes may intrude the fractures, or new minerals may be deposited on the joint surfaces. Flexures rarely occur and the structures on either side of the joint planes are completely separated.

Single joints rarely occur but large numbers follow one, two, or more directions. They always occur in large numbers in each direction as subparallel planes.

If one direction of joints is prominent this direction may be the direction of a *set* of fractures. If two conjugate fracture directions are present they form a *system* (conjugate system).

Most of the distinct joint sets or systems can be referred to the coordinate axes *a*, *b*, and *c* mentioned above and are closely related to the elements of folding and cleavages. One may consider folding as comparable to flowage with molecular flowage-recrystallization-rearrangement of all minerals into new directions. Flow cleavage is the latest element of this phase. Fracture cleavage indicates the beginning of a new phase between flowage structures and leads up to the fracturing of a consolidated rock without mineral rearrangement grain by grain. A fractured rock resembles a set of dominoes or cubes which are set up on a table. They can be taken away from each other or they can be moved along their parting planes without any internal effects.

Fractures may be classified according to their relation to the older structural elements. They can also be referred to a compass direction which is less useful because they are of interest mainly as representatives of the direction of the last phase of deformation, during which flowage or recrystallization has become impossible but the forces have not ceased to function.

CROSS JOINTS (JOINTS IN THE *AC* PLANE)

The term cross joints has been applied for fractures which transect the axes of folding and lineations which are parallel to the *b* axis of the coordinate system at an agle of approximately 90 degrees. In igneous rocks the same term has been applied to those joints which are perpendicular to flow lines. Axes of folding, linear stretching, and flow lines are closely related structures and indicate a direction of flowage but in different rocks. With reference to the coordinate system cross joints may conveniently be called *ac* joints because they are parallel to that direction.

As a rule these joints are smooth surfaces and very plane. Pebbles in conglomerates are cut as with a knife and all structures are transected without deviation. Their relation to the linear elements is the same as in igneous rocks with respect to flow lines. If the axes of the folds pitch the dip of cross joints become gentler; with horizontal axes the cross joints are vertical. Steep axes necessitate very gently dipping joints and vertical axes, which are rare, are accompanied by flat cross joints (pl. XXIII, fig. 1, and pl. XVIII, fig. 2).

If the lineation and stretching parallel to the axes of folding are due to flowage movements of particles parallel to these axes, as indicated by the elongation of pebbles, cross joints are tension joints and are closely related to the deformation preceding their formation. They are the most abundant joints but have never been quite satisfactorily explained.

As structural elements these joints are most useful since they frequently permit the detection of hidden axes which otherwise can not be determined.

In the Piedmont of Maryland and Pennsylvania cross joints are most abundant. They have been most carefully measured by Broedel (pt. III, of this volume) in the area underlain by the Baltimore gneiss and the Setters formation. Cohen has observed them in the Baltimore gabbro (p. 226), and Hershey in the Port Deposit area (p. 139).

Since the strike of all the geologic units along the Susquehanna River is northeast and consistently parallel from Port Deposit to Safe Harbor and Turkey Hill in Pennsylvania, the cross joints in this region strike northwest and the river parallels this direction in its general course.

FIG. 1.—Linear stretching in Setters quartzite, transected by cross fractures. Quarry on east side of Brice Run, north limb of Jew Bottom Anticline.

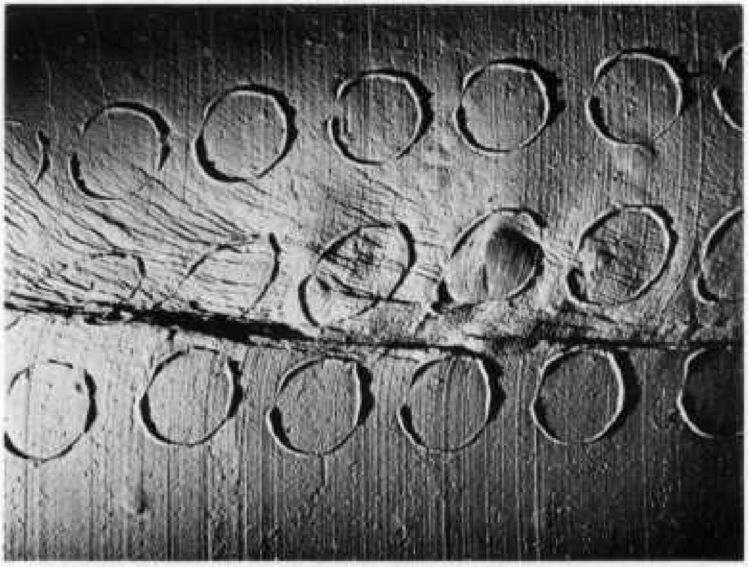

FIG. 2.—Shear fractures produced artificially in clay. Diameter of circles 1 cm.

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Everywhere these joints can be observed in this section forming large and very dominant rock walls on both sides of the river.

Their close angular relation to the strike of axes of folding can be seen in plate XXX and XXI by Broedel. Here the cross joints participate in the bends of the strike and remain perpendicular to the axes, forming an open fan to the northwest.

LONGITUDINAL JOINTS (STRIKE JOINTS)

Perpendicular to the cross joints another set of fractures frequently occurs. They include the *b-axis* = the axis of folding and may be parallel to the axial plane, the cleavage, or any other plane. They are very abundant and frequently facilitate the splitting of rocks in this direction.

Strike joints parallel to the flow cleavage are determined by mineral orientation and represent the mechanical expression of easiest separation of rock masses. Flow cleavage alone does not produce joints since the unweathered schistose rocks are mostly very coherent in spite of a distinct cleavage. The process of recrystallization, if complete, does not destroy the strength of a rock; it only rearranges its mineral constituents and the result is a rock which is frequently found to be much stronger than the original sediment.

OBLIQUE JOINTS

Aside from the above mentioned fractures which can be referred to the coordinate system by simple angular relations, there are many others which do not seem definitely oriented with reference to other older elements.

The only set, frequently accompanied by a complementary one and almost vertical to the first, thus forming a system which is of some regularity, is composed of diagonal joints in the orientation of shear joints. They form an angle of approximately 45 degrees with the *b* axis but this angle is not constant. It very clearly depends on the material which is jointed (pl. VIII, fig. 2).

Other joints which are irregular and seem to have any direction that one may conceive are most abundant. It is mostly difficult to find regularities in these fracture directions and they are not fully understood. There is no doubt that they all fulfill a purpose and have been formed in an answer to some stress relation, but they have rarely been investigated and without definite results.

Certain directed fractures which have simple and direct angular relations to the coordinate systems, or in other words, to the act of deformation under investigation, are most valuable and furnish data which are useful. It is possible by elimination, either statistically or in the field, to choose the ones of value and to disregard the many others. Statistical treatment frequently furnishes reliable results. If all the joints present are measured in selected areas and all the measurements entered into a diagram certain maxima may emerge. The maxima may then be platted in relation to other structures and thus cross joints, longitudinal joints, and maybe diagonal ones will at once show very clearly (figs. 19–26). It may also become evident that the scattered irregular fractures are in the minority.

Aside from the directions the shape and size of fractures should be compared; regular systems mostly furnish larger joint planes. Their age is important especially in metamorphic terranes where several formations may have been superposed on each other. Here joints will intersect, small offsets may occur, dikes follow the one set and not the other, or the joint planes may be coated with minerals like calcite, quartz, garnet, albite, magnetite, pyrite, and others. In this case some joints may show mineral coating; others may not and if they intersect their age may be ascertained in relation to each other and possibly to former structures.

As a rule joint systems are more prominent if the other structural elements are very distinct. A strong lineation parallel to the *b* axis is generally accompanied by very regular and sharp cross joints. This also shows a close relation between these two structures. For instance, cross jointing is well developed only where the Baltimore gabbro is strongly stretched (pl. XL, fig. 2). Here the joints are smooth and plane and can at once be recognized.

Under any circumstance it is necessary to ascertain as much of the relation in the field as possible and to assure the proper genetic sequence without prejudice.

The distribution of joints is a helpful criterion in any structural analysis and frequently helps to distinguish the more important from the unimportant fractures. In the Piedmont of Maryland and Pennsylvania a rather constant general strike has been observed. Certain exceptions were noted by Broedel (p. 169) and others. The strike, however, does not vary abruptly. One set of fractures seems closely related to a tectonic direction and can always be recognized. Throughout the entire region cross joints can be measured without difficulty. They may be called regional joints, since they can be observed over a large region. If they are the tectonic expression of deformations that have taken place, they indicate a widespread uniform application of forces during that phase. It seems as if the entire region has consolidated sufficiently to permit such uniformity and disregard of petrographic boundaries.

Local joints are those which are restricted to smaller units; for instance fault zones or individual rock formations, as a dike, a bed between others, or a small intrusive mass. They may show direct relations to the older structures of that particular rock mass but no general structural relation.

One of the most useful types of such local fractures has been called "feather joints" because of their relation to a master fracture like the barbs of a feather (29). They have been discussed in the literature and serve in the determination of movements along faults or fault zones, or any small displacement along separating planes. These small joints form an acute angle with the master fault which opens against the direction of displacement. Such determinations of displacement of rock masses may gain economic importance in many ways. Ore bodies and veins may be displaced and their continuation may be sought; bodies of rock are offset and the existence of an industrial plant may depend on the determination of this offset. Many other possibilities could be cited.

TABLE III

STRUCTURAL ELEMENTS IN METAMORPHIC SEDIMENTARY ROCKS

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1. Planar structures.
    - a. Bedding, stratification.
    - b. Axial planes of folds.
    - c. Cleavage.
        - Flow cleavages.
        - Fracture cleavages.
    - d. Fractures and joints.
        - Cross joints.
        - Longitudinal joints.
        - Oblique joints.
2. Linear structures.
    - a. Axes of folding.
    - b. Intersection of bedding and flow cleavage.
    - c. Intersection of bedding, flow cleavage, and fracture cleavage.
    - d. Stretching parallel to the axis of folding (*b*).
        - Stretched conglomerate, tourmaline, hornblende, volcanic blebs.
    - e. Slippage on bedding planes normal to the axis (*b*).
        - Striation on bedding plane, volcanic blebs.
    - f. Slippage on cleavage planes.

Internal structural arrangements or rock fabrics will be dealt with below.

In general, a close inspection of jointing is valuable because no stone quarry could exist without joints. They facilitate road building, mining, the formation of ore deposits, and the weathering of the rocks to soil, thus preparing the ground for agriculture. Joints influence topography, river channels follow them, creeks are guided by them. They dissect the earth's surface everywhere and transform the solid crust into millions of small fragments, thus facilitating the ascent of valuable solutions from below and water circulation and weathering from above. They are always present even if not always conspicuous and without them man would be prevented from penetrating the rocks or to live on them.

One of man's most important commodities is water. In regions underlain by crystalline rocks water circulation in pore spaces is very small and millions of fractures serve as circulation channels as well as storage spaces. A knowledge of the distribution and orientation of joints is therefore most helpful in predicting well locations for any purpose. It is one of the most responsible and difficult tasks to give advice on water problems in the Piedmont region.

STRUCTURES OF METAMORPHIC IGNEOUS ROCKS

GENERAL STATEMENT

A sedimentary rock may be metamorphosed to such an extent that no primary structures are preserved to distinguish it from an igneous rock. Chemical composition may furnish the necessary information as to the origin unless the introduction of igneous materials, for instance granite magma, causes a complete assimilation of the original rock, overwhelming all primary characteristics. Migmatites, gneisses, and rocks, that are thoroughly recrystallized and remolded are frequently found in which occasional structures, like conglomerate fragments, banding, and layers of different composition, have been preserved. In such cases primary structures can not be expected frequently and only the new ones may serve in the study of the rock history.

Igneous rocks may suffer similar metamorphism and they may also show reformed structures and chemical composition. When primary structures have been preserved they may serve as lines or planes along which solutions enter or movements take place.

Para- and orthogneisses thus originate from a complete metamorphism of sediments and igneous rocks, respectively. The chemical composition may have to be determined by analyses to ascertain their original state. As a rule, much igneous intrusion accompanies the formation of gneisses of either kind. Therefore banding is an outstanding prevalent structure in both types. In igneous or other gneisses such bands may be produced by movements, intrusion of later phases into an earlier one, or by the assimilation of fragments which have participated in the metamorphic process.

Wherever banding or layering occurs it becomes an important design in later deformations. Bands can be folded or transected by cleavages or fractures. Linear stretching is frequent and long drawn out patches of minerals may follow definite directions (pl. XXVI, fig. 2). Flow folding or shear folding is much more frequent than bending. Wavy cleavages are abundant and fracture cleavage is rare. Primary structures of the igneous rock are unreliable features, because it is rarely possible to recognize them as such and they may easily be confused with later structures.

A metamorphic igneous rock may show, either in the field or under the microscope, many indications of deformation and reconstruction. Recrystallization, replacement of older by newly grown minerals, breakage of crystals into small fragments (mortar structure) are frequently observed. A newly formed igneous rock, on the other hand, will show a sequence of crystallization, little or no breakage, no displacement, and very rarely the gneissic banding. Schlieren and flow structures should not be confused with gneissic banding. They can be distinguished by their distribution, their relation to the contacts, to inclusions of wall rocks, and their orientation within the rock mass.

Between unmetamorphosed and metamorphosed igneous rocks are many gradational stages. Granites, for instance, may be primarily gneissic because movements of the magna were intense during intrusion; as for instance, in the Ellicott City granite or many of the gneissic granites of the Variscian system in Europe (23). The Baltimore gabbro may have been metamorphosed shortly after its intrusion or even during its intrusion into the present chamber. Here an intense linear schistosity conforms with the shape of the gabbro mass and with its contacts. Cohen ascribes this structure entirely to later metamorphism because of the mineral composition and the process of uralitization (p. 234). It is strange, however, that all these later structures follow the direction which primary structures should show if they could be ascertained. This type of metamorphism is localized within the gabbro and does not overlap its boundaries. It is not quite clear why there should be no overlap into the adjacent territories of the Wissahickon schist and the Baltimore gneiss if metamorphism had taken place after the consolidation of the entire region. It is most likely that a gradation between primary and secondary conditions exists here and that the two phases cannot be separated because they follow at close intervals and are parallel with each other.

STRUCTURAL ELEMENTS

The elements observed in metamorphic igneous rocks are a combination of those in igneous and sedimentary rocks. Primary elements of the igneous rocks may be preserved and then folded. These folds may resemble an ordinary fold with the only difference that it is not the bedding but some other design which is folded. Linear elements can occur resembling flow lines but actually consisting of stretched minerals or mineral clusters. In this way "Augen"-texture can be produced, which is comparable to the stretched-out pebbles of a conglomerate.

In spite of the difference of the materials which are metamorphosed the end products may have similar structures or the equivalent of the structures as they are typical for the individual rock type.

In this way planar structures may be distinguished from linear ones. Their mutual relation can be referred to a coordinate system as described on pages 54 and 90. Axes of folding and linear stretching follow the *b* axis while foliation or schistosity intersect banding in the same axis. Flow cleavage occurs frequently and transects bands of different composition in lines which parallel the direction of stretching.

Since primary elements can hardly be expected and are rarely preserved it becomes increasingly necessary to investigate such rocks in detail and particularly with the finest microscopic methods available. Such methods are outlined briefly on page 82.

Metamorphosed igneous rocks are reactivated consolidated masses. Large quantities of heat and probably solutions are necessary and it is generally believed that these rocks have been formed in the lowest portions of the earth's crust. Their study will always be difficult because of the lack of the original (primary) elements. Their history can hardly be traced back as far as their origin. Indirect evidence, however, may supply data as to their age and limit the period of their deformation. Here the environment has to be taken into consideration; adjacent rocks overlying them must be dated and their contacts must be studied in detail. Later igneous rocks may intrude the earlier ones and their contact relations may show the minimum age for their origin; unconformably overlying sediments may determine the maximum age. It is thus possible to limit their history indirectly and with a study of their deformation to piece together a part of the history of the rock masses.

In the Piedmont of Maryland metamorphic igneous rocks occur sparingly. The Hartley augen gneiss is probably a strongly deformed granite. It is overlain by the Setters formation and never transgresses it and must, therefore, be older. This granite, however, intrudes the Baltimore gneiss and its origin must therefore be placed between the formation of the latter and before the deposition of the Setters formation. The deformation to a gneiss is also probably closely connected with the deformation of those rocks which now represent the Baltimore gneiss. In this way an investigation of this augen gneiss might furnish pertinent information on the metamorphism of the Baltimore gneiss.

The Port Deposit granite shows a strong foliation but also primary elements—inclusions, foliation, linear elements (flow lines) etc. (p. 131). It transgresses also the formations of the Glenarm series and carries inclusions with structures of post-Ordovician age. This granite must therefore be younger than rocks and structures which it included (for further details see page 129). It thus becomes evident that the metamorphism in the Port Deposit granite is not a complete but only a comparatively slight recrystallization. The primary elements have not been obliterated.

In general, metamorphic igneous rocks are treated similarly to the sedimentary and igneous rocks. The structural elements are similar, with the exception of those, like bedding, which are only typical for sediments. The elements can be platted on maps, or referred to an axial system of coordinates, or studied statistically. Because of the frequent lack of clear primary elements, however, a microscopic treatment is particularly recommended (p. 82).

FAULTS

Faults are fractures along which slippage has occurred. They are defined as fractures with "appreciable displacement," or even with microscopic displacement. In common usage microscopic faults have seldom been termed faults. Joints, fracture cleavages, and bedding planes show slipping but they are also rarely called faults. Therefore a strict definition cannot be given and a subjective one is substituted. For this reason the vague term "appreciable displacement" has been used. A displacement of other structures, as for instance beds of one foot, two feet, ten, one hundred, or thousands of feet, are called faults.

Faults may be classified in several ways, according to the amount of displacement, as being of first, second, or third order of magnitude. If their altitudes are taken into consideration they may be termed low-angle or steep faults. In respect to the structures displaced they may be called normal or reverse faults; or overthrusts if they are flat movements of one portion of the crust over the other.

In the Piedmont of Maryland faults are abundant but exposures are too widely scattered and the formations which can be distinguished do not differ sufficiently from each other for their recognition on a small scale. The larger ones can be ascertained by mapping the distribution of formations and their possible offsets.

Several faults were recognized; as for instance, the Ruxton fault and others by many workers (73-76, and pl. XXIX of Part III). Larger faults are occasionally accompanied by a breccia along the fault zone, that is, a body of rock that shows intense breakage, fracturing, and mylonitization. Such breccias are described by Broedel in Part III, p. 160.

Overthrusts have been assumed by Jonas and Knopf (65) as bounding part of the region in the northwest against the Paleozoic sediments.

These thrusts are supposedly of a large order of magnitude with a horizontal displacement of many miles. It should be borne in mind, however, that no proof has been presented and that the overthrust explanation is a theory. Many of the facts seem to favor such an explanation.

Lateral almost horizontal, movements along fault planes must have occurred between several of the formations. The very rigid and resistant foundation of Baltimore gneiss has only in part participated in the general deformation of the region, as is shown in the wide open anticlinal structures (domes), as compared with the very close folding of the overlying marble and schist formations. A separation of these formations from the basement seems inevitable.

Smaller faults have been observed in many localities but they never have been traced farther than through one exposure. They can be seen in many of the quarries and are only of local significance. Usually they are in the direction parallel to the cross joints and perpendicular to the axes of folding.

MICROSCOPIC INVESTIGATIONS

(*PETROFABRIC ANALYSIS*)

GENERAL STATEMENT

In many highly metamorphosed regions like the Piedmont of Maryland, a megascopic, geological, and structural investigation may not be sufficient, particularly if the conditions are complicated by repeated metamorphism. Microscopic examinations of rocks and structures should therefore support field observations.

Such microscopic investigations should be undertaken in two steps: first, the rocks of the region should be examined as to types, mineral composition, textures, metamorphism, and general petrographic characteristics; second, the rock fabrics should be studied by means of a special method which is able to support the megascopic structural analysis. Rocks with little or no visible structures may yield much pertinent information if studied under the microscope with the help of a universal stage and statistical methods. Highly crystalline polymetamorphic schists are the ideal object for such work.

A study of rock fabrics, however, is almost useless if entirely separated from a regional investigation. A few specimens, collected in a number of scattered localities without a study of mutual field relations, contacts, and general geological and structural conditions, are almost useless. A structural analysis cannot be built up on a pile of loose rocks. It is therefore essential that all possible information be gathered in the field before petrofabric analyses are attempted. The region has to be mapped geologically, structurally, petrographically, and every other detail which can be gathered should be available as a basis for detailed petrofabric studies.

A complete geological investigation should begin in the field and cannot be begun in a laboratory. A microscopic rock slide is a small area and it is impossible to generalize the knowledge gained in such a small area for many square miles of territory without carefully analyzing the links between the small and the large area (103). As a tool in carrying the investigation into the finest detail and into the structural arrangements of minerals and rocks, the petrofabric analysis is of great value. It cannot, however, be an end in itself to investigate rocks under a microscope without geologic implications if the investigation is supposed to be geological (103).

Since the investigations are time consuming and have to be done with great care, some investigators have missed the geologic connections and stagnate in a mere analysis of one or several disconnected specimens. This may be valuable if a commercial question in a small region is examined or if the method of petrofabric analysis is to be illustrated, but not if geologic problems are attacked. In connection with geologic investigations petrofabric studies may yield much pertinent information and will at least show whether the structural data gathered are correctly interpreted in their mutual relation and whether there may be others which have been overlooked.

To give a clearer understanding of the value of the detailed studies recently made in the Piedmont complex of Maryland the following pages are devoted to a brief summary of the method and application of these recently developed petrographic techniques.

METHOD OF PETROFABRIC INVESTIGATION

A complete presentation of the method of petrofabric investigation is far beyond the scope of this paper. Such presentations can be found in the literature in English (40, 53, 62) and in German by Sander and Schmidt who are the originators of this method (86–88, 89).

The method consists in determining the orientation of the rock-forming minerals with the aid of a universal stage under the microscope. Many measurements are essential in each rock slide and the resulting orientations are platted in an equal area net and afterwards treated statistically. Diagrams thus result which show maxima and minima of mineral arrangements within the rock. From these diagrams it is possible to refer the orientations to the same coordinate system mentioned above in which field measurement have been platted. A complete diagram into which all structures have been inserted will then show the plan of the deformation and its symmetry.

Since metamorphism is a mineral rearrangement of the most intricate kind and with different proportions of newly created and older remaining structures, it is possible to detect many hidden relations which are still preserved in a thoroughly recrystallized rock and to find the mutual relationship of a group of structures and to determine which ones belong to one act of deformation and which are later or earlier.

The statistical treatment is of great advantage because subjective conclusions are almost eliminated. Accidental orientations will disappear and the maximum distribution of structures and their orientations will appear without prejudice.

During recent years the literature on the method and its application has grown rapidly. Rocks from all parts of the world have been analyzed successfully. Commercial applications have shown the value of these investigations, particularly in rocks without any visible structures like marble.

Since rock deformations associated with recrystallization affect the entire rock including every mineral, it is evident that much of this deformation can be detected in the orientation of the finest particles of the rocks; that is, its mineral constituents. Certain ones are easily deformed, others are more resistant. New arrangements occur next to old ones and all of them have to be investigated in order to gain a complete picture of what has happened during the process of deformation. Minerals that lend themselves to such investigations are particularly the micas, calcite, quartz, feldspars, tourmaline, hornblende, and others. Minerals can be oriented according to their shape (see also flow structures in igneous rocks, page 40), to their cleavage (mica), or to other physical properties. In each case, however, the mineral will show physical and optical properties bound together as they are known from crystallographic investigations. Under the microscope optical properties are investigated since crystallographic outlines are rarely preserved. The optical properties are therefore studied and if possible predominant cleavages, as they occur in mica or calcite, are recorded. From these it is then possible to determine the orientation of other physical mineral properties indirectly since they are well known and definite with respect to the optical orientation.

THE UNIVERSAL STAGE

The universal stage consists of a number of circles each of which is moveable around an axis and thus permits the measurement of a mineral orientation in any position that may occur. Usually five axes can be used in a modern stage and any position of any of the circles or axes can be read on scales and graduations. It is thus possible to measure any plane or line in a mineral that has been placed upon the stage directly and accurately. An optic axis in quartz, for instance, can be observed and measured and then platted into a suitable projection.

A detailed description of the technique of measurements can be found in Fairbairn (40), Sander (87), Ingerson (53), or Knopf (62).

THE PROJECTION

The projection method is the same as that used in crystallographic projections with the only difference that an equal area net is used and that the lower half, instead of the upper half, of a sphere is projected on to a plane. Lines are platted as through the center of the sphere and perforating its surface at one point. This point is projected into the net and thus locating the line definitely. Planes are shown with their poles; that is, with a line perpendicular to the plane, from the center of the sphere to its surface. This pole is then the presentation of only one definite plane through the center of a sphere.

In this way it is convenient to show points, lines, and planes within a mineral in a diagram. Each position is definitely fixed and can easily be reconstructed. If many such data are measured their projections will gather in certain parts of the net and maxima and minima will become visible. If, for instance, many optic axes of quartz crystals are parallel within one slide, the projection points of these axes will accumulate in a certain very restricted portion of the projection net. If the cleavage planes of biotite, on the other hand, are subparallel, as is frequently observed in highly schistose rocks, their poles will also concentrate in a well defined area of the net.

STATISTICAL EVALUATION

After at least one hundred or more minerals have been identified and their properties measured and platted into the projection net, the points will appear in the diagram in different groupings. In order to evaluate these measurements statistically the projection net is covered with a sheet of transparent coordinate paper (square centimeters). Then a piece of paper or celluloid into which a circular hole of one square centimeter area has been cut is placed over the projection and the number of points showing through the hole are marked at each intersection of the centimeter lines of the coordinate paper. Special attention must be paid to the marginal areas where the unit area will overlap the projection net. Here the points on the opposite sides of the circumference of the projection net have to be added together and marked. If one hundred measurements have been made before, the figures represent the percentage of points in respect to the whole area directly. If more points were determined the values have to be referred to the total number of points measured in terms of per cent of the total area of 100 square centimeters which had been used in the projection net. If for instance, 7 points out of 100 fall within a unit area the density is 7 per cent of the total area. If the total number of points is 200 the percentage is only 3.5%. In this manner areas with an accumulation of points can be expressed in terms of density or frequency and maxima and minima will appear as they occur in the rock slide investigated.

The different densities which appear on such a diagram can then be contoured in such a way that lines are drawn which separate areas of different percentages. The contour lines in fig. 12, for instance, are drawn for 2-4-6-8-10-12-14-16 and 18 per cent. The black area in the diagram represents a region in which the density of points is over 18 per cent. The blank area outside the 2 per cent line does not contain any points.

The number of points, however, should not be too small. If orientations are very conspicuous a lower number will suffice; as for instance, in many schistose rocks if the cleavages of mica flakes are used. Quartz axes are, as a rule, rarely so well aligned and if possible between 200 and 300 axes should be measured.

This projection of mineral properties can also be applied to the presentation of any other structural data. Its advantages are discussed on page 95.

ORIENTATION OF ROCK SAMPLES

If a petrofabric analysis of a rock specimen is made its value depends entirely on its bearing on the geologic history of the region. It is therefore absolutely necessary to know what orientations the measured values possess in the outcrop, just as much as the orientation of a joint plane, a cleavage plane, or the axes of folding is ascertained with reference to north and south. The compass is used in measuring such directions and in the same way it should be used in orienting the properties of a petrofabric diagram. Any specimens taken for this purpose have to be oriented with respect to north and south in the field.

Consequently specimens for petrofabric analysis can only be taken from rocks which are known to be in place; that is, from good fresh exposures such as cliffs, quarries, road cuts, etc. If a sample is being removed its directions have to be marked on its surface before removal; this can easily be done with adhesive tape on which the strike and dip (or plunge) of a surface plane (or axis) are marked. If this first orientation is improper the whole analysis is worthless.

After removal of the specimen the thin sections have to be cut in relation to a visible structure, like cleavage, linear stretching, or any other according to the purpose of the investigation. Here greatest care is necessary because if the orientation is lost at this stage the analysis is also worthless. It is, however, easy to obtain commercially oriented thin sections when the specimens are marked properly. No specimen can be too well marked. If a section is sawed off an arrow can be marked on the cut plane as well as on the slide. This arrow is then transposed on to the glass surface and with it the thin section can be placed back on the original surface and be reoriented in space. Diagrams from such sections can then easily be reoriented and the data thus collected can be used together with structures measured in the field. It then becomes possible to relate a direction of cleavage which is obvious in the field to a mineral orientation which is only visible under a microscope or an axis of a fold can be related to cleavage in mica or to the orientation of optical axes observed in quartz.

The accuracy of orientation during any of these stages of investigation determines the value of all later work and one mistake may render the final results worthless.

EXAMPLE OF ROCK FABRIC INVESTIGATION

During recent years the writer has carried out a detailed investigation of an area in the southern part of Lancaster County, Pennsylvania, selected because of its favorable situation, its exposures, and its bearing on the problem of the "Martic overthrust" and the age of the Glenarm Series in Pennsylvania and Maryland. This problem has been discussed by many workers during the last thirty years and any data which can be obtained on this subject may be valuable because the interpretation of the Piedmont province as a whole depends entirely on the validity of the assumed presence of this large-scale overthrust and the consequent correlation of the large masses of metamorphic rocks composing the Glenarm Series.

In this investigation a small area has been selected and thoroughly examined. Structures have been measured and maps have been constructed. The geology of the region is also being remapped and the stratigraphic relations are being checked. As this geologic work proceeds petrofabric analyses are made of carefully oriented specimens of the rocks of the region and it is hoped that the results can be published in the near future. Supplementary work has been carried out in Maryland since the problem affects not only Pennsylvania but a much larger region of which Maryland is a part.

From the series of rocks of the Paleozoic group one sample is presented in the subsequent pages as an illustration of a petrofabric investigation. The sample was taken from the Lower Cambrian Antietam quartzite in a small quarry on the east side of the road from Marticville to Lancaster, about 2.3 miles north of the former.

MEGASCOPIC PREINVESTIGATION

The Antietam quartzite formation shows very plainly bedding (S_1), flow cleavage (S_2), and fracture cleavage (S_3). Calcareous or quartzitic beds occur between shaly beds, now transformed into a very homogeneous mica schist. The minerals in the specimen investigated are: quartz, biotite, muscovite, albite, garnet, tourmaline, and occasionally chlorite. The flow cleavage (S_2) is parallel to the axial plane of a fold which is overturned approximately 60 degrees southward, thus dipping 60 degrees north with a strike east-west. The axis of the fold and the intersection between flow cleavage and bedding are almost horizontal. The distinct fracture cleavage (S_3) transects the axis at an angle of approximately 20 degrees and dips 85 degrees southeast.

MICROSCOPIC INVESTIGATION

Under the microscope the same minerals as mentioned above can be seen. A small amount of zircon is evident in the centers of radioactive haloes within the biotite crystals. Muscovite occurs in different sizes; in large much-deformed and bent laths, in smaller slightly-deformed flakes, and in very fresh and cross-growing small needles. A foliation is very obvious but the orientation of the mica flakes is so confusing that under the microscope the foliation is not clearly measurable. Large albite porphyroblasts are abundant and contain innumerable small inclusions. Magnetite and some pyrite are accessories.

PETROFABRIC INVESTIGATION

The sample which served for examination has been oriented in the field with adhesive tape on which the direction of strike and dip of the flow cleavage were marked and noted. Three mutually perpendicular sections were sawed off; one parallel to the flow cleavage, and two at right angles to it and to each other (pl. IX, fig. 2). The specimen is No. 39 and the three sections have been called 39a, b, and c. All examinations described below were made in section 39c which is perpendicular to the flow cleavage and almost at a right angle to the axis of the fold. 39a and b were also measured as a control for section 39c and the maxima obtained can easily be rotated into the position of 39c, thus confirming the measurements.

Orientations of mica flakes

The micas were the first minerals examined and their cleavages were measured under the universal stage. In this examination four different diagrams were constructed, according to observations on four types of micas: 1. biotite, 2. muscovite of the larger type with deformation, 3. muscovite of the intermediate sizes, and 4. muscovite of the small needle-like type. As a control another diagram was constructed for all mica cleavages regardless of size or type. The position of the cleavage in 500 mica grains have been measured. In the total diagram all the maxima which can be seen in the individual diagrams are also recognized. The poles of the mica cleavages furnish very distinct maxima as can be seen in figs. 10 and 11.

Mica diagrams

Since mica flakes are usually parallel to the flow cleavage (S_2) it was expected that a distinct flow cleavage would furnish one strong maximum for all mica cleavages. This is not the case. Three distinct areas are visible: the main maximum including the biotite and the large deformed muscovite, a second maximum including the intermediate size muscovite, and another very distinct maximum for the cleavage of small needle-like muscovite crystals. These two submaxima are very significant (p. 91).

The trace of the flow cleavage plane is indicated in figs. 10–13 as S_2 and the main maximum coincides with its pole. If the section cut had been exactly perpendicular to this cleavage the poles should be on the periphery of the diagram and the axis of the fold (F) and the intersection of S_1 and S_2 in the center. Its slightly inward position shows that the cut was not entirely accurate. It also shows how the section was cut exactly and the slight inaccuracy in the cutting of the section can be corrected.

The two submaxima indicate the poles of two more planes in which muscovite cleavages are oriented. The axis of the fold coincides with the intersection of these planes and also indicates that the section has not been cut perpendicular to it. Further discussion of the significance of these diagrams will follow on p. 91.

Inclusions in albite porphyroblasts

The Antietam schist is a highly albitized rock. Albite porphyroblasts, which are prominent crystals formed during metamorphism, are numerous and contain many small inclusions of quartz, calcite, muscovite, and biotite. The orientation of these inclusions which are very definitely

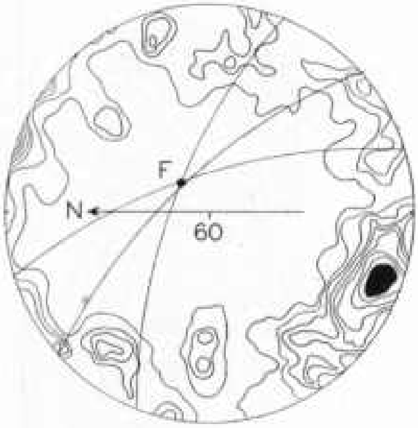

FIG. 10

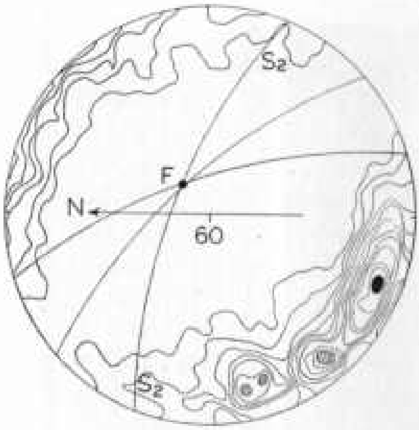

FIG. 11

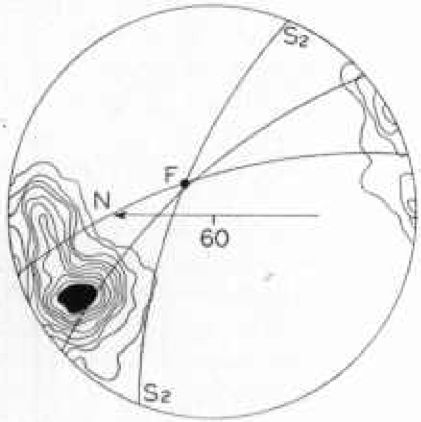

FIG. 12

FIG. 13

FIG. 10-13.—Statistical diagrams of mineral orientations in Antietam schist. The arrow points to the north (N), the dip figure (60) indicates the dip of the slide in the exposure. F is the projection of the axis of the fold. S_2 = (flow cleavage plane (trace)).

FIG. 10.—Orientation of biotite cleavage, 200 grains. Contours: 1-2-3-4-5-6-8-10 per cent. Solid black area from 12-17 per cent.

FIG. 11.—Orientation of muscovite cleavage, 300 grains. Contours: 1-2-3-4-5-6-7-8-9-10 per cent.

FIG. 12.—Orientation of inclusions in albite crystals, 160 inclusions. Contours: 2-4-6-8-10-12-14-16-18 per cent and over. Solid black over 18 per cent.

FIG. 13.—Orientation of quartz axes (c) 200 grains. Contours: 1-1½-2-3-3½ per cent. Black area over 3½ per cent.

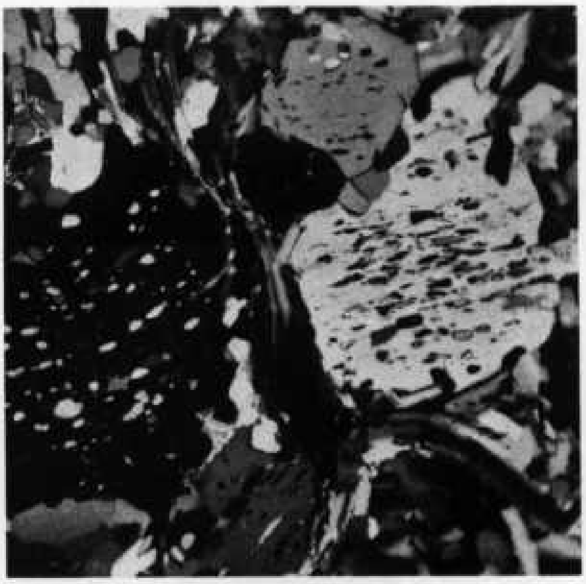

FIG. 1.—Photomicrograph of Antietam mica schist. Same section as Figs. 10-13 (Statistical diagrams). Note curves in Albite trends indicating rotation. Road three miles north from Marticville, Pennsylvania. Approx. 20 ×. Crossed nicols.

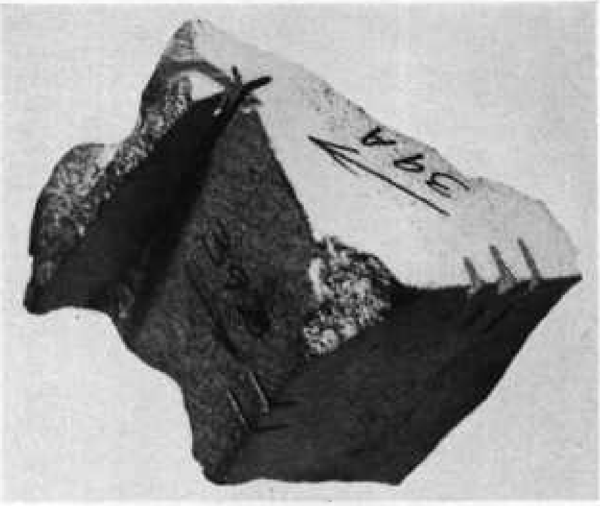

FIG. 2.—Oriented specimen used for statistical diagram in Figs. 10-13; 39c, plane of which thin sections have been prepared = top plane; 39a and 39b perpendicular to 39c serve for control measurements (Cut by H. Bird, New York.).

aligned have also been subjected to measurements under a universal stage in specimen 39 and in section c as described above.

The inclusions are planar elements within the albite and their orientations were measured along their contacts and their dimensions (not optical axes) were determined. In plotting the poles of these planar elements a very distinct maximum was found (fig. 12). No points are scattered outside of the maximal area and all of the 160 measurements gather in one area of accumulation. It is very obvious that the orientation of these inclusions is in no way related to the cleavage shown in figs. 10 and 11 by the mica flakes. This orientation seems almost entirely independent of all other alignments.

Quartz orientations

The same rock slide (39c) has also been investigated in regard to the orientation of quartz. The optical axes of 200 quartz grains were measured and platted in the diagram, fig. 13. The quartz arrangement is not as clear as those of the micas and albites. It can be seen, however, that the three planes which are indicated in the mica poles of fig. 11 intersect almost in one quartz maximum (near F). The maximum in the right lower quadrant, which is the most distinct, is also the pole of the plane in which the majority of small muscovite crystals is oriented. A third maximum coincides with the pole of the albite inclusions. It becomes evident that the quartz orientations are related to the other orientations and their interpretation seems to be furnished through the relation with older mineral orientations.

DISCUSSION OF THE ORIENTATIONS AND RESULTS

A comparison of the diagrams figs. 10–13 shows clearly that all the orientations are related to a rather complicated plan of deformation.

The orientation of micas indicates a rotation of cleavage planes or a successive formation of cleavages. The first and main cleavage is S_2 which corresponds with the flow cleavage plane, indicated by the main maxima for the orientation of muscovite and biotite. Aside from this, however, occur two maxima, each successively rotated and tilted *southward* through an angle of 27 and 22 degrees against the former. The flow cleavage dips approximately 70 degrees north. The next maxima for muscovite cleavages is rotated 27 degrees, corresponding with a plane which dips only 43 degrees north; the last maximum for the smallest muscovite is rotated 22 degrees and is the pole of a plane which dips only 21 degrees north. There is little doubt that these successively rotated planes are cleavage planes which cannot be observed megascopically.

Since the biotites and the largest muscovites are broken, folded, and generally much deformed it seems clear that the deformation, which produced folds and flow cleavage continued further until it died out during the last cleavage stage; however, without obliterating earlier structures and without complete recrystallization. It is striking that all these cleavage planes intersect in the direction of the axis of the fold (F). All these structures seem to pertain to one continuous act of deformation with successive stages, *but are transected by an independent later fracture cleavage.*

The albite inclusions furthermore indicate still more rotation and no relation to the cleavage planes. It may be that albitization has fixed a former structure and preserved it, or that the albite grains have been rotated farther than the new cleavage planes. Signs of rotation are obvious since the borders of the albite porphyroblasts show drag in contact with the other minerals. In some instances S-shaped lines are produced and a clockwise rotation seems obvious (pl. IX, fig. 1).

The quartz diagram finally shows a close relation to the mica and albite maxima. The strong maximum 1 almost represents the pole of the flow cleavage plane as in Fig. 11; maximum 2 coincides exactly with the latest muscovite maximum; maximum 3 is the same as the pole of the albite inclusion, and maximum 4 is near the axis of the fold F. The orientation of the optical axis of quartz is thus related to all stages of the deformation as shown by the orientation of the minerals investigated.

It is very striking that the later fracture cleavage, which is very plain megascopically, does not at all show in the mineral orientation of the rocks. This latest cleavage is a true fracture cleavage, that is, fracturing but not recrystallization.

If these results are compared with the relation in the field a close coincidence between megascopic and microscopic conditions becomes evident. In the area under investigation all folds whether small or large are *overturned to the south.* In the diagrams the overturning can be traced beyond the stage of folding and into the last phase of dying recrystallization. Two more cleavages are indicated beyond the formation of flow cleavage; that is, two stages between flow and fracture cleavage.

These results are highly significant in relation to the problem of the region.

The Martic overthrust is supposed to have moved pre-Cambrian rocks over Paleozoic rocks by a *northward* movement. The above results point *southward* beyond doubt and throughout the entire traceable phase of recrystallization. Another point in the controversy is the number of phases of deformation which the pre-Cambrian or Paleozoic rocks have undergone. Albite "trends" in the pre-Cambrian supposedly show traces of older structures. Albite, however, shows trends in the Paleozoic

Antietam schist also and indicates nothing of older structures at all. The number of cleavages has been used in relating the amount of deformation in one rock to the deformation in the older rock. The investigation shows very plainly that the Paleozoic schist has 1, an albite stage; 2, three flow cleavages; 3, a fracture cleavage that transgresses all other structures.

The investigation furthermore shows clearly that nothing can be said about two rock masses and their relative deformations or their age before a thorough and detailed structural examination has been made for both types of rocks under consideration. In the present case the microscopic-statistical investigations provide a great deal of additional evidence which cannot be furnished by a structural examination alone, particularly not by a reconnaissance study. Much more data has to be accumulated before sufficient evidence can be presented.

The writer did not intend to discuss the controversial question of the Martic overthrust here but only wished to show how such detailed methods can be applied and to indicate that they are able to provide a great deal of otherwise hidden information which is, however, essential before a problem of this order of magnitude is to be solved or discussed.

PRESENTATION OF STRUCTURAL DATA

GENERAL REMARKS

Large numbers of measurements are best presented statistically. This has the advantage that no choice has to be taken and no subjectivity enters the presentation. The data are ready for anybody to use and they are complete. The disadvantage of this method is the lack of accessibility to the reader and the lack of a direct connection with the field orientation. Any map will convey a picture at once and permit a quick comprehension of the situation as seen in nature. It is much more impressive, just as a line drawing or diagram is easier to read than a long description of geologic detail. Maps are therefore essential and in many ways much more valuable. They carry with them the disadvantage that only a limited amount of data can be presented on a small scale and that publication of maps meets with difficulties. They are costly and frequently reduced to mere diagrams without any visible detail preserved. Large-scale maps and the details, however, are desirable and should under no circumstances be treated as a necessary evil and be reduced below a minimum which is different with each map and with the features that are to be shown on it.

Attempts have been made to combine statistical diagrams with maps. A situation has been outlined, some topography is shown, and on to this base map large numbers of diagrams have been inserted. This combination, however, is neither a map conveying a picture, nor a diagram because the original diagrams have been reduced too much to be used as diagrams for the sake of the introduction into a map.

The only way seems to be a presentation of selected pertinent information on a map *and* the presentation of details in diagrams or tables for the use of other workers in a region.

MAPS

Geologic maps are well known and abundant in the literature. They show the distribution of formations and rock types—frequently in colors—and occasionally some structure symbols, indicating strike and dip of selected structural elements. One of the most complete geologic-structural maps has recently been published by Robert Balk (5). The amount of data here presented is astonishing and the combination of areal geology and structure is very valuable, in addition is a structure map of the region showing its pertinent features. The danger of this map lies in its fullness and the possibility of overlooking important details.

Structure maps as line drawings which are comparatively cheap to publish, without colors may serve the purpose best. In these presentations the individual exposures are represented and the measurements platted on an exaggerated scale. The locality is thus overemphasized. This is necessary because any symbol for strike and dip will be, according to the scale of the map, a quarter to a half mile long but measurements will comprise only ten or twenty feet of rock exposure. Thus certain exposures are vastly overstated and the danger exists that the fitting measurements may be inserted; the abnormal ones omitted.

In regions where axes of folding are rather regular and their strike does not deviate considerably over miles, this overemphasis of one exposure is permissible, since 100 measurements between two overstated exposures would not change the average direction. Attitudes of bedding may vary much more and usually do so, and in this case cannot be inserted in a map; the axes of folding will give the necessary information.

If a set of joints is observed; for instance, as north-south throughout a region of several square miles, it is entirely sufficient to show one or two such directions for the region, representing the average. Any other structural element can be treated the same way without danger. If, however, a restricted area shows great irregularities a detailed figure on an enlarged scale becomes inevitable. The map should then contain an average for the region and the detailed map or sketch may support the evidence.

If, for instance, axes of folding and cross joints which are interdependent are platted together into a structure map, their relation will be readily seen and the presentation will be accurate (pl. XXX). In this way it is possible to show certain relations of structures on maps. It is often advisable to group structures together and produce several maps showing groups of elements and not all elements. In maps which are too full and thus too complicated, the author defeats his own purpose because the complicated pattern may make a map entirely unreadable.

In igneous rocks it has been advisable to connect isolated data with lines indicating directions between the individual exposures. These lines are form lines only and serve to help the reader's eye.

Attention may be called to structure maps as presented by F. F. Grout in which he shows the average direction, for instance of linear elements, in thick arrows and the details in smaller ones (45). In this way the reader can at once overlook the details and gain a picture of the general situation. The data, however, are not omitted but also present for the more interested reader.

Maps should, as much as possible, show facts as well as present a picture of the general situation which is easily comprehended. It is evident that large numbers of measurements provide a better basis for such presentations than a few scattered ones which are almost useless. A map, based on sufficient detail, is also accurate if the material presented is not modified by the author's intention to present his conception of the geological history of the region. It easily happens that when an idea is incorporated into the map of a region the map becomes misleading to the reader.

STATISTICAL DIAGRAMS

Diagrams vary with the purpose for which they are constructed. If just one direction is to be shown a maximum may be drawn in a curve on which the directions have been platted. Since directions can vary 360 degrees around the compass it seems more adequate to draw a curve around a center in such a way that north is on the top of the page; east-west runs from right to left; and south is at the bottom. The frequences to be platted may then be shown by differences in length of lines in different directions. The resulting figure indicates at once the directions in which the most frequent observations can be found. A scale will then indicate clearly how many measurements have been found in a certain direction and where the maxima are located. The diagrams on page 177 of this volume were drawn in this manner.

If only one dimension, like the strike of joint planes, is to be shown this method may be sufficient and it has been widely used in the literature. If a second direction has to be presented simultaneously the diagram is insufficient, for instance if strike and dip of a joint plane is presented. On page 96 an additional diagram has been given. The lower half of the circle has been used for the dip; the upper half for the strike of joint planes. This method makes reading somewhat difficult but presents the data correctly.

Another method uses the projection onto an equal area net of the pole of a plane or the intersection of a line with a sphere. Here the lower half of the sphere with its points is thought projected onto the drawing plane. In this way points and lines as well as planes can be recorded. The points in the net are then evaluated statistically and counted by percentage in a unit of area, referring either to 100 units or other quantities. In this way the areas with equal numbers of points are contoured similar to contour lines on a topographic map. Shading or ruling will at once bring out areas with more or less than normal density of points (figs. 14 and 15).

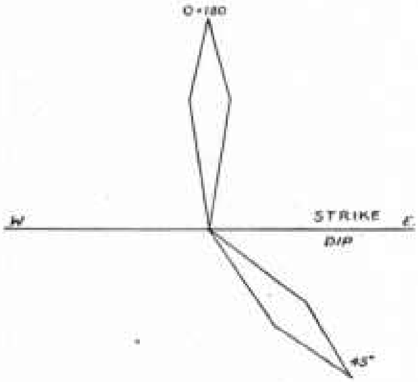

FIG . 14

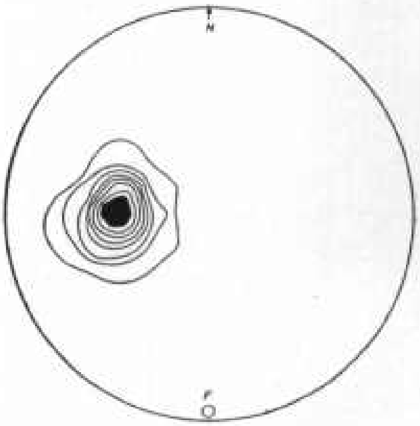

FIG. 15

FIG. 14.—Diagram showing directions of joints in Setters quartzite. Strike above, dip below E-W line. The maximum shows that the joints strike north-south and dip 45° to the east.

FIG. 15.—The same joints shown in a projection of their poles in a spherical equal area net.

In this presentation all data are used regardless of direction, quality, number, or any other factor. The diagram shows simply the orientation of certain elements and the maximum orientation as well as the minimum. Strike and dip are shown simultaneously and any reader who is accustomed to use such presentation will at once realize the important features of a particular locality. Several elements, as for instance axes of folding and cross joints, can be shown together and their mutual relation emphasized. Many readings on directions are, however, essential as a basis for this treatment. A few measurements cannot be treated in this manner, or in any other statistical way.

If these projections are inserted into maps they usually lose in value.

It is then necessary to limit the directions which are to be inserted into a map to the maxima and to a symbol for a direction rather than a spherical projection. The ideal accuracy may be obtained if a statistical diagram is made for each locality and the values then used in the map presentation. This is not always possible because of the lack of data in one locality and the large amount of work involved in the drawing of many hundreds of diagrams. They are, on the other hand, not always necessary because a regular distribution of structures and their directions render such detail unnecessary. It is perfectly sufficient if the major lines of structures are shown in the maps and the general data thus presented are supported by a number of detailed diagrams for type localities.

SECTIONS

Structure sections should be drawn with every map. They should, however, not only include and present the author's views but actual facts. Dips of strata or fractures, folds, cleavages can very well be shown in sections but are rarely found. Series of many parallel sections are very useful and will convey a good picture of the structure of a region (pl. XXXII). All the details which can be presented in maps can also be shown in sections and should be shown. This will give the same data which are presented in the map in another view and many details are easier to comprehend in sections than in maps

Sections should not be exaggerated in height, but horizontal and vertical scale should be the same. In exaggeration the dip of elements is changed, the whole mutual relation is destroyed and no picture is conveyed to the reader. If rock thicknesses have to be shown, scaler presentation in sections with measured thicknesses are best.

DETAILED MAPS AND SECTIONS

If mutual relations of structural or other geologic information is to be presented it frequently shows best in a large-scale map or section, amply supported by photographs or drawings. A map of one location may show the entire principal situation—an unconformity, overlap, fold, fault, or any other group of elements. Such maps or sections may furnish the clue to an important geologic problem better and much more accurately than any generalized section through a quadrangle which can only be drawn with a great deal of interpretation and in which the reader sees only the author's views and not the facts. Such quarry maps can be found in the literature in great number and in each case they show more than the map and section of a larger region. H. Cloos has analyzed the anatomy of a fold in great detail and described the history of that structure, which at the same time is the history of the region and of the structures found in it. In this volume Hershey has mapped the region south of Conowingo dam (pl. XI) on a large scale and shows the sequence of intrusions and their structures which are the key to the relationships of the entire region.

ILLUSTRATIONS

The best illustrations are hand sketches and line drawings in combination with photographs. They should accompany any geologic presentation in sufficient number and with an accurate indication of the locations. A general statement "2 miles west of X" may prove insufficient. Road intersections, railroad crossings, villages, etc., should be mentioned because it is impossible to find locations after a number of years if they are overgrown with bushes or weeds. From reports the finding of type localities is often rather difficult. Even type sections have been lost because of the lack of a sufficiently accurate location on maps. It may be best to indicate type localities on maps with symbols—letters or numbers—if they are mentioned in the text.

A simple line drawing will always tell more than a long explanation in words and at the same time the author has occasion to check on himself and his conceptions.

STRUCTURAL ANALYSIS AND SYNTHESIS

Any geological investigation of a region, a geologic unit, formation, rock type, or of a problem of any kind begins with a determination of *conditions* as they are at present. The data which can be observed have to be gathered and assorted, age relations have to be ascertained and the sequence of events must be determined as far as possible.

After all this preliminary work is done a systematic analysis of earth *movements* which have led to the present conditions should follow. In this analysis of regions or problems field and laboratory observations will still predominate because all structures are traces of movements and the actual movements can frequently be ascertained. Theoretical considerations will necessarily enter at this point and the proportion between fact and theory varies with the region and its exposures, with the problems attacked, and with the worker in the field and laboratory.

After the field work is done and the structures are carefully studied the data will be assembled and evaluated and an attempt will be made to analyze the *forces* that produced the structures and the *dynamic conditions* which persisted.

From here the last step leads to a synthesis of the *history and evolution* of a region. These last steps are theoretical and by far the hardest. They demand a large amount of ingenuity as well as knowledge and experience in the field of geology. Many workers may be excellent observers in the field and laboratory but few only will reach the farsightedness of a prophet.

Geological synthesis is most essential if the immense amount of data gathered shall be of any value. A large number of bricks without the guiding hand of the architect will never resemble a house. On the other hand a house cannot be built from the second floor on up and also not without bricks. The collection and assemblage of facts in itself is useless unless it is the first step and the data are adequate and correct and can be used as a basis for a later synthesis. The value of a geological theory depends entirely on the soundness of the data on which it is based.

Our geological knowledge of the earth has grown rapidly during the last century and continues to grow steadily. In spite of this our knowledge is meager for the largest portion of the earth's surface. A synthesis of earth deformation is therefore handicapped by lack of knowledge everywhere. Many gaps have to be filled and also many regions have to be restudied more intensely and with new methods.

In the present paper the writer has made an attempt to call attention to some of the structural features which should be carefully observed before a structural synthesis is attempted, thus preparing the tools for later work which has to follow necessarily. Theoretical discussions have been *avoided intentionally* because they are found in the literature in abundance. The structural elements and relations have been listed and described systematically. They can be observed by anybody in the field and assembled in the laboratory.

Parts II–V of this volume are the presentation of the elements discussed as they were found in different geological units in the Piedmont of Maryland. The facts presented in maps and illustrations represent the results of many years of field work. In the reports stress is laid on the material gathered in order to supply information which is needed for many purposes. Conclusions are at the end of each paper—presenting the authors synthesis.

Many examples of excellent structural synthesis could be cited from the literature. Systematic structural investigations of igneous rocks have been carried out for about 20 years. The minute structures of many igneous masses have been investigated with great care and in each case have the results been new and have filled gaps—partly in geologically well known territory. In many localities has it been possible to furnish data on the movements of the magmas, on their history during consolidation, and on the shape of the pluton. One of the larger European batholiths has been found to rest on a floor of wall rock. Graphite mines penetrate the granite and the valuable mineral is found below the surface of the "batholith." Innumerable measurements have been taken in igneous masses and they all led to a new and much more accurate conception of igneous intrusions.

The structural investigation of metamorphic terraines has also progressed rapidly. New methods have been applied and as a result it is now possible to gain a much more accurate insight into metamorphic-dynamic deformation. New results are forthcoming steadily and this is reflected in the increasing number of maps, charts, diagrams and discussions which are published.

Whether the investigation is a megascopic one in the field or a microscopical-statistical one in the laboratory, the time spent is always worth the effort because of the rich returns in pertinent information and the security which is offered as a basis for all further considerations. It may be time-consuming to make thousands of measurements in an area, but after the work is completed the area and its structures are known and any questions—whether economical or theoretical—can be answered on the basis of facts which are readily available at any time.

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Maps

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(118) MARYLAND GEOLOGICAL SURVEY. Map of Cecil County showing the Geological Formations. 1902. 1: 62, 500.

(119) MARYLAND GEOLOGICAL SURVEY. Map of Harford County showing the Geological Formations. 1904. 1: 62, 500.

(120) VIRGINIA GEOLOGICAL SURVEY. Map of Virginia showing the Geological Formations. 1928.

PART II

STRUCTURE AND AGE OF THE PORT DEPOSIT GRANODIORITE COMPLEX

BY

H. GARLAND HERSHEY

STRUCTURE AND AGE OF THE PORT DEPOSIT GRANODIORITE COMPLEX

INTRODUCTION

Location and Geologic Setting

The Port Deposit granodiorite is a part of the Appalachian Piedmont complex in northeastern Maryland and northwestern Delaware. The Piedmont in these states, as elsewhere, is composed of metamorphosed sedimentary formations and intrusive igneous materials. In Maryland and Pennsylvania metamorphism in this belt increases from NW to SE (65). Most of the igneous rocks are found in the southeastern portion and of these the Port Deposit granodiorite complex is the largest. It is composed of three large and several small rock bodies, separated by schists, and extends over an area approximately thirty miles long and nine miles wide (Plates XX and XXI).

The main masses lie chiefly in Cecil County east of the Susquehanna River, but extend westward into Harford County. Here they split into numerous tongues, the largest of which continues southwest from the river for a distance of nine miles. The easternmost mass ends in the town of Newark, Delaware, two miles east of the Maryland-Delaware boundary line. Smaller bodies are found in Harford and Baltimore Counties and as far southwest as Baltimore City.

Gabbro makes up parts of the north, west, and south boundaries of the granodiorite complex. The remainder of the north boundary is composed of schists, probably of the Glenarm Series, and serpentine. A belt of metamorphic sedimentary rocks occurs north of the gabbro and south of the Paleozoic rocks. It is interrupted by a narrow, northeast striking syncline of slate and conglomerates just north of Peach Bottom. The remainder of the south boundary is marked by the overlap of unconsolidated Coastal Plain sediments and "Baltimore gneiss."

Included within the granodiorite are several large bodies of foreign material. A mass of metadacite occupies an area of about thirty square miles beginning at the Susquehanna River two miles north of Havre de Grace and continuing in a northeast direction for a distance of fifteen miles (pt. IV of this vol.). A belt of schistose and gneissic material splits the granodiorite complex. From Rising Sun and Calvert it extends southwest across the Susquehanna River, where it is a mile wide, and continues across Harford County with an increasing width. Gabbro occurs between Zion and Providence, near West Nottingham, and south of Principio.

Five types of dikes are intrusive into the granodiorite.

The most striking general feature of the area is the persistent NE-SW to E-W trend. The outlines of all formations are conformable to this trend.

EXPOSURES, DRAINAGE AND TOPOGRAPHY

The best exposures of the area are along the Susquehanna River which has cut a steep-walled gorge, two hundred feet deep, across the regional strike and empties into the Chesapeake Bay. Its major tributaries—Octoraro Creek, Rock Run, and Happy Valley Branch from the east and Deer Creek, Rock Run and Velvet Rock Branch from the west—show good exposures in their lower courses. With the exception of the valleys of Octoraro and Deer Creeks, the exposures are scarcely a mile from the river. Since the building of Conowingo Dam in 1926 one can walk over much of the river bed between the dam and Port Deposit during periods of low water. This area, four miles long and a mile wide, shows almost continuous exposure. Previously it was explorable only by boat.

Good exposures are found on Big Elk Creek between Appleton and one mile south of Elk Mills, on Little Elk Creek between Providence and just south of Childs and locally on Northeast, Little Northeast, Principio, Mill and Christiana Creeks. All of these streams flow south at right angles to the regional trend, and all but Christiana Creek empty into estuaries of the Chesapeake Bay.

Exposures are widely separated and often poor between the streams of the plateau which averages four hundred feet in elevation. Approximately two hundred test holes from one to two feet deep were dug and it was possible in most cases to reach the underlying rocks and obtain reliable data on the strike and dip of the formations (pl. XX). The excellent mutual confirmation of these data proved that the rock surface was reached and that it had not been displaced. Deeply weathered artificial outcrops thus obtained were well supported by data from fresh outcrops in streams, ditches and road cuts.

PREVIOUS WORK

Much has been published concerning the granodiorite or granite as it was called originally. The most detailed and comprehensive of the earlier works are by Grimsley (44), Leonard (70), Bascom (11–15), Mathews (77), Insley (54), and Knopf and Jonas (64). Most of these investigators dealt primarily with petrographic features. Recently a preliminary paper to this report was published by Ernst Cloos and Hershey (26) in which the age of the intrusives was discussed from a structural viewpoint. A paper on the structure of the metadacite by Marshall is part IV of this volume.

The region was mapped topographically and geologically by the United States and Maryland Geological Surveys, on a cooperative basis, before this work was begun (118, 119).

PRESENT INVESTIGATION

Approximately eight months were spent in the field and more than ten thousand compass readings were recorded. The field work consisted of measuring flow structures and associated phenomena, in studying contact relationships, and in investigating features relative to the age determination of the granodiorite and the rocks associated with it. Approximately twelve months were spent in the office and laboratory compiling the results of field work.

ROCKS OF THE REGION AND THEIR RELATIVE AGE RELATIONSHIPS

WALL ROCKS OF THE PLUTON

The rocks of the region have been studied and described by many previous workers (11–15, 20, 24, 44, 50, 54, 55, 60, 64–66, 70, 77, 102, 104–111, 118, 119). The present investigation is based upon previous ones and the results of former workers will not be repeated. The rocks and formations are listed for the sake of completeness and only new results or differences of opinion between the writer and previous workers will be outlined.

The wall rocks of the Port Deposit granodiorite pluton are composed of: "Baltimore gneiss", metadacite, Glenarm schists, Cardiff conglomerate, Peach Bottom slate and gabbro.

Detailed descriptions of these rocks are abundant in the literature. The metadacite has recently been investigated by John Marshall (pt. IV of this vol.). The gabbro has been investigated near Baltimore by Charles J. Cohen (pt. V of this vol.).

All of the above mentioned sediments and the gabbro occur in contact with the pluton or in its inclusions. A discussion is, therefore, limited to the wall rock structure and the reaction of the plutonic rocks on the wall rocks.

SEQUENCE OF INTRUSION

The sequence of intrusion has been observed by previous workers and their results are tabulated in Table IV (A-C). The writer's views deviate considerably from those previously expressed and are added in the last column of the table (D).

TABLE IV

SEQUENCE OF INTRUSIONS IN THE PORT DEPOSIT COMPLEX

A	B	C	D
GRIMSLEY 1894	BASCOM 1902, 1920, 1935	INSLEY 1919, 1928	HERSHEY 1936
	Port-*Triassic* Diabase dikes	Post-*Triassic* Diabase dikes	Post-*Triassic?* Diabase dikes
	Pre-*Triassic* Diabase dikes	Pre-*Triassic* Diabase dikes	
Post-*Glenarm* Diorite and Metadacite in part Gabbro? Rowlandsville granite Gabbro? Port Deposit granite Gabbro?	Post-*Glenarm* Pegmatite dikes Serpentine Peridotite Pyroxenite Norite and hypersthene gabbro Hornblende norite and quartz norite Quartz-hornblende gabbro Quartz-biotite-hornblende gabbro Metadacite Hornblende-quartz monzonite Biotite-quartz monzonite	Post-*Glenarm* Rowlandsville granite Pyroxenite Peridotite Epi-diorite Gabbro	Post-*Conestoga* Hornblende lamprophyre dikes Granite porphyry dikes Pegmatite and aplite dikes Massive granodiorite Biotite granodiorite Hornblende-biotite granodiorite with quartz diorite Hornblende granodiorite Gabbro Pyroxenite? Peridotite? Metadacite
		Pre-*Glenarm* Port Deposit granite included in Baltimore gneiss	

In order to ascertain the true relationship between the successive intrusions of the area a large number of inclusions were investigated in the Susquehanna River section. The relationship between gabbro and the Port Deposit granodiorite complex is clearly shown by contacts, inclusions of gabbro within granodiorite and apophyses of granodiorite in gabbro.

This can be very well observed below Conowingo Dam (pl. XI), and one half mile south of Lapidum.

All of the dikes mentioned in Table IV are intrusive into the granodiorite complex and are therefore also younger than the gabbro.

Age relationships within the complex are somewhat uncertain. The hornblende-biotite granodiorite is penetrated by the biotite granodiorite (Port Deposit type) which is, therefore, younger. Innumerable examples of this can be examined immediately below Conowingo Dam (pl. XI). The relation of these two types and the hornblende and massive granodiorites has not been definitely established because of the lack of contact exposures and inclusions. The writer, believes, however, that the earliest intrusion of the complex is the hornblende granodiorite because of its intense linear flow structure and the amount of metamorphism it has undergone. It has been much more deformed and recrystallized than any of the other types. The massive type appears to be younger than the hornblende granodiorite because it is almost devoid of flow structures. It has frequently been observed that the structureless components of a composite mass are the youngest. The inclusions within the different types of granodiorite are described below.

INTRUSIVE ROCKS OF THE REGION

GABBRO

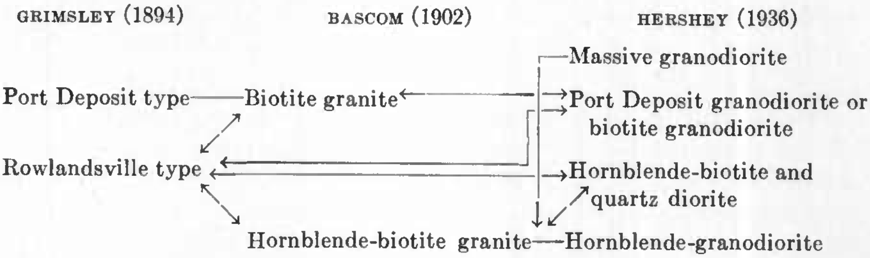
Numerous types of gabbro have been described from the region. Earlier workers consider them to be differentiates of the same magma. The gabbro is usually found to be hornblende-bearing when the granodiorite contact is approached and as the hornblende is secondary the gabbroic rocks containing it have been called metagabbro.

The metagabbro is medium grained, dark green and holocrystalline. The feldspar is labradorite or bytownite replaced in part by hornblende and epidote. Albitization has taken place to varying degrees. In the southern portion of the region the feldspars are almost completely albitized and specific determinations are impossible. Green hornblende is the chief mafic constituent. It may be either fibrous or occur as compact blades and composes about 50 per cent of the rock. Magnetite, biotite and apatite are accessories. Quartz is usually present in varying amounts.

Two types of metagabbro are easily recognizable in the field—massive and foliated. Inasmuch as slightly foliated massive material was observed, it is apparent that they grade into each other. Parallel arrangement of the hornblende causes foliation. The foliated type is finer grained than the massive type. It is more widespread and can be seen at most localities. The massive type is well exposed on the north tip of Garrett Island and in the vicinity of Mountain Hill.

PORT DEPOSIT GRANODIORITE COMPLEX

Rocks of the pluton consist roughly of four types:



The Port Deposit or biotite-granodiorite occupies the central part of the pluton. The hornblende-biotite type occurs as a belt of varying width along part of the northern margin. The massive and hornblende types occur along part of the southern border. The contacts of the various types of granodiorite were not well enough exposed to allow accurate mapping.

Certain characteristics are common to all types. All have the composition of granodiorite although there are local variations. The peripheral types, according to chemical analyses, are somewhat less silicic. They are holocrystalline, medium grained hypidiomorphic rocks with a somewhat porphyritic texture. The color varies from a light to medium gray usually with a bluish tone. All show variable foliation due to parallelism of ferromagnesian minerals, which has caused them to be called gneisses. Under the microscope they show a certain amount of cataclastic structure but neither recrystallization nor rotation have played an important rôle.

It was felt that an exhaustive petrographic study of the granodiorite was beyond the scope of this work, since it would have demanded the examination of several hundred thin sections. The general descriptions of the various types are included chiefly for the sake of completeness and are, therefore, brief. Details will be furnished in the body of the report. Some data are repeated from earlier reports. They have been checked where possible and are included with additions from this investigation.

BIOTITE GRANODIORITE

The biotite granodiorite (Port Deposit granodiorite) is medium gray and mostly very strongly foliated. The essential constituents are quartz

40%, feldspar 30% and biotite. The accessories are apatite, allanite, hornblende, titanite, tourmaline, zircon, and probably magnetite and garnet. The last two may be secondary. Epidote, muscovite, chlorite and calcite are secondary. Apparently a very small amount of the muscovite is primary.

The quartz in certain localities shows undulatory extinction in euhedral crystals. In other places it is granulated and exhibits sharper extinction which shows that although crushing has taken place locally it has not affected the whole mass.

The feldspars have altered in part to muscovite (pl. X, fig. 1) and epidote. Where elongated, these secondary minerals often parallel the twinning planes of the plagioclases or arrange themselves at 45° to that plane. The feldspars like the quartz locally show pressure effects in peripheral granulation and a minor amount of undulatory extinction. They are often zoned.

Biotite is of the dark brown pleochroic variety. No evidence of recrystallization on a large scale has been found.

HORNBLENDE-BIOTITE GRANODIORITE

The fact that hornblende becomes an essential constituent in part of the hornblende-biotite granodiorite is the criterion for separating it from the biotite facies. Because of the increase in hornblende and magnetite this type is darker in color and more basic. These two minerals increase in amount as the gabbro contact is approached.

The essential constituents are hornblende, quartz, feldspar and biotite, while the accessories are allanite, apatite, titanite, tourmaline, zircon and probably magnetite and garnet. The chief secondary minerals are muscovite, epidote and calcite.

The hornblende is green, strongly pleochroic and contains inclusions of magnetite, epidote and zircon. It varies greatly in amount but seldom exceeds the biotite.

One of the outstanding characteristics of the hornblende-biotite type is the great abundance of inclusions that are contained in it (pl. XIV, figs. 1 and 2). There is some crushing but this type appears on the whole to be less crushed than the Port Deposit granodiorite. Locally it grades into a quartz diorite in which hornblende is usually lacking. This occurs just below Conowingo Dam, and at several localities along Deer Creek.

QUARTZ DIORITE

Megascopically the quartz diorite is holocrystalline, medium grained and darker than the granodiorites. Sometimes it has a greenish tinge, due to abundant green biotite. In the hand specimen quartz, feldspar, and biotite, can be easily recognized. The quartz is often smoky blue.

Under the microscope the rock is found to be composed chiefly of feldspar, quartz and biotite. The quartz almost always shows strain shadows and mosaic patterns. Exactly as in the granodiorites, the feldspars contain a great number of inclusions of muscovite and epidote. The plagioclase is andesine or calcic oligoclase with many of the crystals zoned. Orthoclase is present in very small amounts. Biotite, the chief ferromagnesian mineral, is approximately twice as abundant as it is in the granodiorite. It is greenish brown or olive green and mostly considerably altered. The first step in alteration is a bleaching to light green biotite then to green chlorite and finally to a colorless chlorite. All of the stages of this transition can be seen under the microscope and are accompanied by a decrease in the indices, pleochroism and double refraction. Pleochroic halos surrounding small zircon crystals are noticeable in much of the biotite. A small amount of muscovite appears to be primary but most of it is secondary after feldspar. Magnetite, always closely associated with biotite or its alteration products, is always present in varying amounts. The appears to be less crushing in the quartz diorite than in most of the granodiorites.

HORNBLENDE AND MASSIVE TYPES

The hornblende and massive granodiorites were previously considered as equivalent to the hornblende-biotite type, chiefly because of their hornblende content. A closer study shows that they differ from the hornblende-biotite granodiorite in that biotite is not present over wide areas and never equals the amount of hornblende. Generally they are finer grained and lighter than the northern type. They contain fewer inclusions than the hornblende-biotite facies. The silica content seems to be about the same in the three types.

Under the microscope the hornblende and massive granodiorites appear to be slightly different from the hornblende-biotite type: there is evidence of somewhat more crushing; mortar structure is locally developed; and feldspar locally shows bent and cross twinning ascribed by Grout (46) to deformation. There is, however, no evidence of large scale recrystallization. The quartz is in mosaic patterns and exhibits both undulatory and sharp extinction. In other respects the southern types are the same as the northern hornblende-bearing variety.

The massive granodiorite is separated from the hornblende type chiefly because the former possesses a very weak foliation or none at all, while the latter is strongly foliated. Both are hornblende granodiorites. The

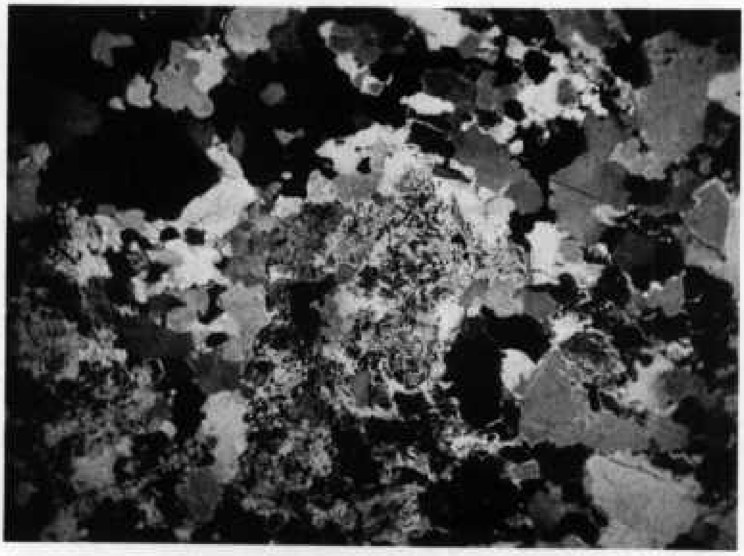


Fig. 1.—Altered feldspar (center) in Port Deposit granodiorite. Photomicrograph × 13.

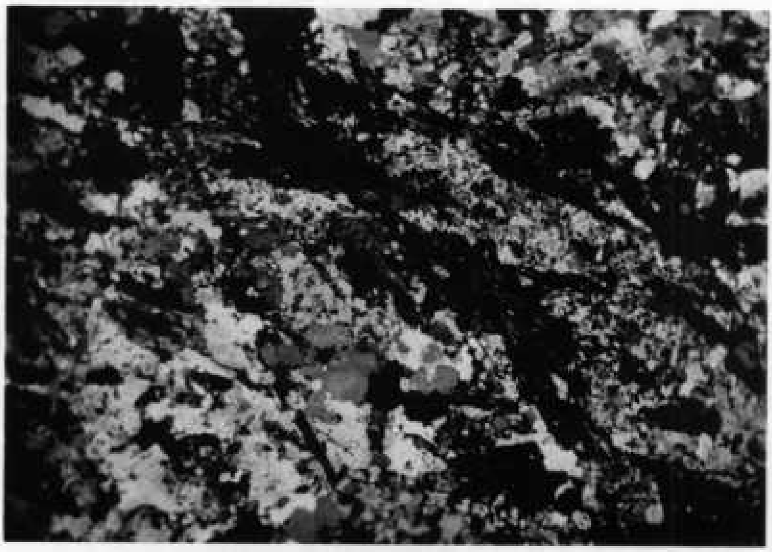


Fig. 2.—Cataclastic structure in hornblende granodiorite. Photomicrograph × 10.

hornblende crystals seem smaller and less abundant in the massive type and it is usually coarser grained.

Two types of hornblende granodiorite are found at Principio Furnace on Principio Creek. Megascopically they appear to be two entirely different rocks. One is dark colored but the other is light and contains many inclusions of green schistose material. Their appearance, however, is similar in thin sections.

DIKES

The most widespread and important dike rocks of the area are aplite, pegmatite, granite porphyry, hornblende lamprophyre and diabase.

Aplites

Aplite dikes are found in all types of the granodiorite and in all of the earlier rocks in contact with it. No aplite was observed in the granite porphyry, lamprophyres or diabase. Their thickness varies from a fraction of an inch to twenty feet. The thicker dikes appear to be slightly more coarse grained.

Megascopically they are light colored, fine grained and have sugary texture characteristic of aplites elsewhere. Usually they show a faint parallel mineral arrangement, which is concordant with the walls.

Microscopically they are holocrystalline, allotriomorphic and have a fairly even fine grain. Their composition depends directly on that of the granodiorite. Those associated with biotite granodiorite contain biotite while those in or near the hornblende granodiorites carry hornblende as their chief ferromagnesian product. Quartz and feldspar, usually partially altered to muscovite, are the essential constituents. Perhaps microgranite would be a more fitting term for these dikes since they carry the same mineral assemblage as the granodiorites.

Biotite aplites are well exposed in the Port Deposit quarry. Hornblende-bearing aplites occur along Principio Creek near Principio Furnace.

Pegmatites

Pegmatite dikes are not numerous in the granodiorite, gabbro or metadacite. However, they are abundant in the Glenarm Series and in the Baltimore gneiss.

Soda feldspar predominates although the potash variety has been reported. Tourmaline is a common accessory. Large quartz boulders containing masses of tourmaline crystals are found in several localities. The masses are as large as five inches in diameter, but the boulders containing them are not in place. One such locality may be found one-half mile northeast of Principio, well within the granodiorite. There the material is located on top of a hill, consequently it could not have been moved far.

The pegmatites are believed to have followed soon after the intrusion of granodiorite, because the feldspars show a close affinity in both rocks. This feature will be more fully discussed in the chapter on relative age relations.

Granite Porphyry

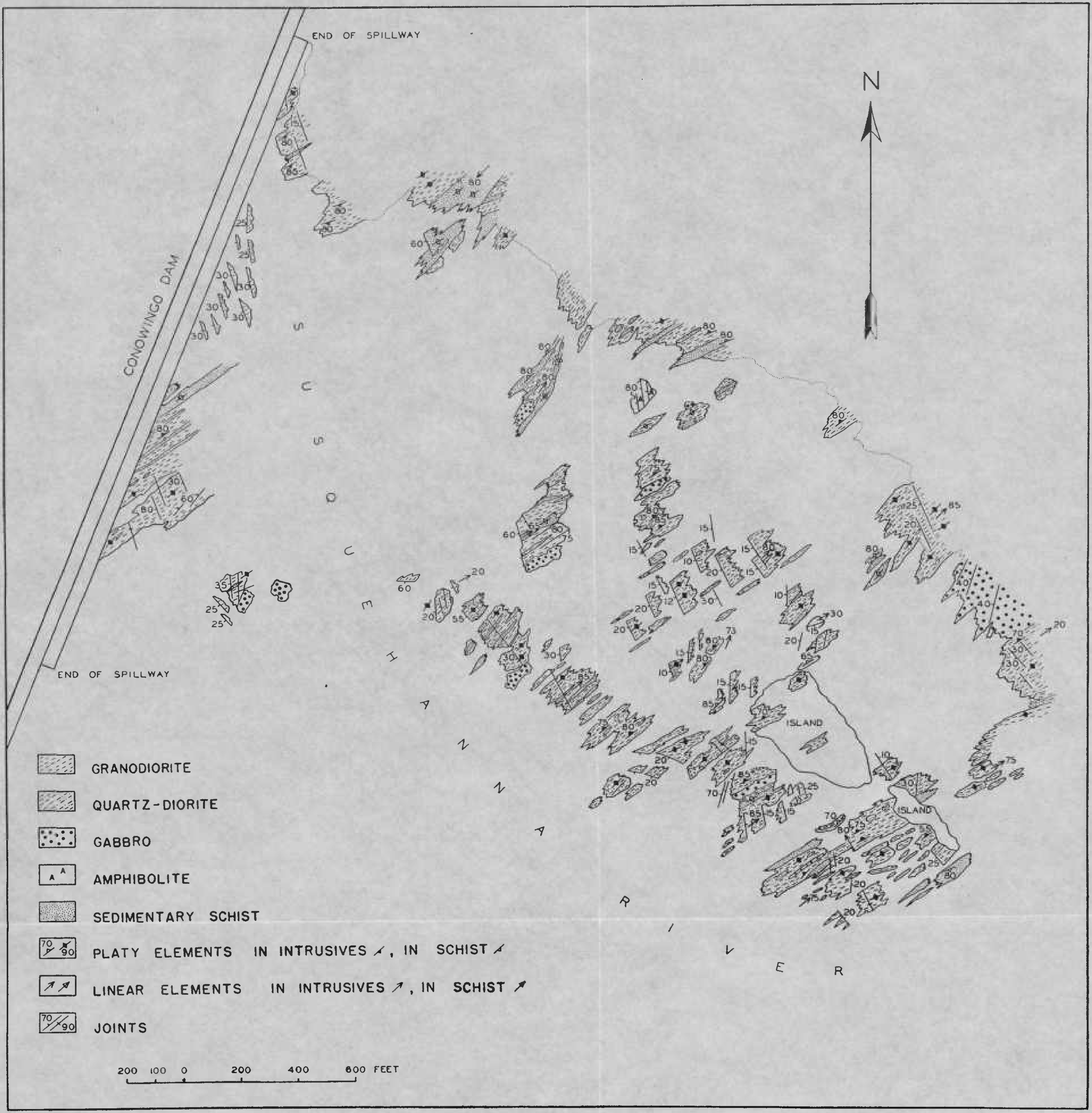
Dikes of granite porphyry are well exposed within the granodiorite only in the Bridge quarry where four of them were observed. All are highly sheared and the shearing is most intense along the contacts where mylonites were produced. Marshall (pt. IV) reports that numerous dikes of this type occur within the metadacite and cut the gabbro dikes. At several localities granite porphyry masks the contact between the granodiorite and volcanic rocks; for example, about half a mile north of Frenchtown along the Susquehanna River and at the south contact on Stoney Run.

Megascopically the rock is dark colored and fine grained. Foliation may or may not be pronounced. Under the microscope the structure is porphyritic. The rock is holocrystalline, the groundmass consists of feldspar and quartz averaging 0.05 mm. in which are held phenocrysts of the same materials as large as 2.0 mm. The feldspar is orthoclase and zoned plagioclase showing myrmekitic intergrowths. Foliation is caused by biotite, muscovite and some poikilablastic hornblende. The amount of hornblende is highly variable and the biotite shows alteration to chlorite. Other secondary minerals present are garnet, magnetite and zoisite.

Micro-granite was the name originally applied to this rock. Micro-granite, however, implies a more or less uniform grain size, whereas, in this material, phenocrysts occur in an aphanitic groundmass. Granite porphyry is considered a more fitting term.

Hornblende Lamprophyre

Hundreds of dark dikes are found in the granodiorite and older rocks associated with it. They are best seen along the east side of the Susquehanna River. Between Rock Run (east side) and the northern contact of the metadacite over one hundred and fifty dikes of this type may be observed. They strike approximately NE-SW and can be found on the west side of the river at Lapidum. In and near the Bridge quarry north of Havre de Grace twenty of them occur. North of Rock Run they are



Inclusions and intrusive relationships on islands south-east of Conowingo Dam on the east side of the Susquehanna River.

extremely scarce; only four were observed between that point and Conowingo Dam, a distance of three miles.

These dikes vary in width from less than one foot to fifteen feet. Variation in color and appearance are also characteristic, due in part to the variable amount of shearing that they have undergone. In many cases they greatly resemble diabase, but under the microscope they lack the characteristic ophitic texture. Other types include black, fine-grained, massive material and variously green colored, coarser grained rocks which are often difficult to distinguish from gabbro with the naked eye. Chilled, fine-grained borders are common in these dikes and their centers are often quite coarse grained.

Since hornblende is always present in large amounts, usually over 60%, these dark dikes are called hornblende lamprophyres. Quartz, orthoclase and plagioclase make up the remainder of the major constituents. The hornblende is of the green variety and occurs as well aligned needles and more stubby unoriented aggregates. Epidote, chlorite and magnetite are usually present.

A late period of intrusion can be established for these dikes. They cut the foliation of the granodiorite, transgress aplite and pegmatite dikes. Marshall reports that they cut the foliation of the granite porphyry. They are also later than the longitudinal joints. In the south end of Port Deposit a hornblende lamprophyre dike is found which follows preexisting longitudinal joints.

WALL ROCK INCLUSIONS AND THEIR STRUCTURES IN THE PLUTON

Structural Rôle of Inclusions

Inclusions within the intrusives are important structural elements in this region. Not only are they a vital factor in establishing the relative age of the granodiorite to all other rocks except the dikes, but they also aid in determining what structures were present before the emplacement of the intrusives, in establishing the geologic age of the intrusives, and in demonstrating the primary nature of the flow structures.

Thousands of inclusions occur immediately south of Conowingo Dam on the east side of the Susquehanna River. The largest of these are represented in Plate XI which also shows the intrusive relationship of the igneous rocks. The sedimentary schists are believed to be representatives of the Glenarm series and possibly the Peach Bottom slate. Many of them have been highly metamorphosed by the intrusives while some have suffered little alteration, and there is every gradation between the two.

ROCK TYPES OCCURRING IN INCLUSIONS

Inclusions within the granodiorite may be classed roughly as metadacite, metamorphosed sediments, ultrabasics, gabbro and quartz diorite.

METADACITE

Material which can be proven to be metadacite occurs within the granodiorite only in large masses. These are best seen on Plate XX (in pocket). Small inclusions are found in the granodiorite near the northern and southern contact on Principio Creek and at Mechanics Valley. In thin sections the relationship of these inclusions to the volcanics cannot be established, but since they increase in number toward the contact they are considered to be inclusions of that material.

Granodiorite and gabbro dikes within metadacite confirm the belief that the metadacite is the older rock.

METAMORPHOSED SEDIMENTS

Sedimentary materials metamorphosed to schists, phyllites, quartzites and "conglomerates" occur in abundance along the northern periphery of the granodiorite mass. They are best exposed in the bed of the Susquehanna River, south of Conowingo Dam where thousands of them occur. They can be seen also along Deer Creek, south of Darlington; in the river bed in the vicinity of Canal, and the mouth of Deer Creek; and in a small exposure on Northeast Creek just south of the Baltimore and Ohio Railroad.

Much of the metamorphism in these rocks was imposed before inclusion, but contact metamorphism has also been effective. The original rocks were apparently quite variable. The subsequent metamorphism was not uniform. The end products, represented by the inclusions, are much too heterogeneous to allow a complete discussion, but some of the main types will be described.

Quartz phyllite

Megascopically the quartz phyllite is a light bluish to greenish gray, fine, even grained, schistose material with a silvery luster. Flow cleavage and fracture cleavage are strongly developed.

Microscopically muscovite, green chlorite and quartz, in about equal amounts, are found to be the major constituents. The quartz occurs as small grains or aggregates around which are wrapped the foliae of muscovite. There are few tabular crystals of muscovite or chlorite. The quartz appears to obliterate fracture cleavage or prevent its formation.

FIG. 1.—Amphibole from an inclusion south of Conowingo Dam. Large central crystal with three stages of alteration from pyroxene to amphibole. Photomicrograph × 50.

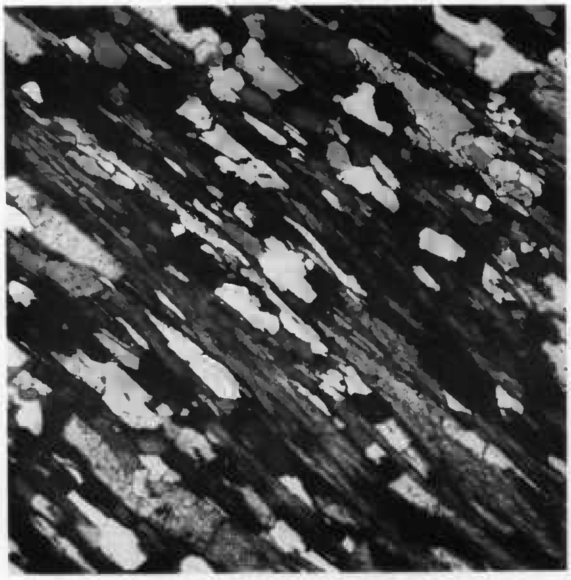


FIG. 2.—Calcite-chlorite-quartz schist from an inclusion south of Conowingo Dam. Photomicrograph × 31.

Magnetite, with a grain size up to 0.3 mm. is present. It is closely associated with the micas. Apatite and epidote are present in small amounts.

Chlorite schist

Megascopically the rock is grayish green, fine grained, schistose, but with weak flow cleavage.

Microscopically it is composed almost entirely of bluish green massive chlorite. Some quartz is present but it is less than 10% in amount. No feldspar or ore minerals were seen. Secondary epidote is abundant.

Quartz-muscovite schist

Megascopically the rock is bluish gray, fine grained, schistose and has a silvery luster. The flow cleavage is strong and fracture cleavage weak.

Under the microscope muscovite proves to be the most abundant constituent. Green pleochroic chlorite almost equals muscovite in amount, the two constitute about 80% of the slide. Quartz is the other major constituent. Magnetite is more abundant than usual, and there is a very small amount of altered feldspar present.

Quartz-calcite-chlorite schist

In hand specimen, the material is dark green, fine grained and schistose. Flow cleavage is well developed, fracture cleavage is not so apparent.

Microscopically it is composed of pale green slightly pleochroic chlorite in long crystals. This mineral makes up 50% of the slide. The remainder consists of equal amounts of quartz and calcite (pl. XII, fig. 2). The quartz is arranged in long lath-like aggregates, the calcite, also in laths, is usually about four times as long as it is wide. This would indicate that the rock must have been very highly stretched. Pyrite grains are scattered through the slide and a few fragments of biotite were observed.

The calcite gives every appearance of having been one of the original constituents of the rock.

Quartzite

Megascopically the rock is light gray, vitreous, quartzitic in appearance and contains a few visible grains of pyrite

In thin section it is found to be composed almost entirely of quartz (pl. XIII, fig. 1), most of which shows sharp extinction and no apparent arrangement. Biotite, chlorite, a little muscovite and albite-oligoclase plagioclase make up most of the remainder of the slide. Pyrite is abundant but zircon and apatite are present in only small amounts.

Conglomerate

A few inclusions of conglomerate were observed. They are usually less than six inches in length, and megascopically appear to consist of small rounded quartz grains. In thin section much of the quartz is found to be angular. The thin section resembles almost identically a photomicrograph of quartzite from Frederick County, Maryland. The interstices between the grains have been invaded by feldspar, (chiefly plagioclase now partly altered) chlorite and quartz (pl. XIII, fig. 2). The crystallization of these minerals was governed by the boundaries of the original quartz grains.

The origin of the conglomerate may have been either from the Glenarm series, which contains many conglomerate beds, or from the Cardiff conglomerate. Conglomeratic layers in schist may be seen in Figure 2, XIX. Pebbles clearly indicate bedding now obliterated by schistosity which is followed by granitic intrusion.

ULTRABASIC ROCKS

Inclusions of ultrabasic rocks occur sparingly within the granodiorite. Several may be seen at the locality below Conowingo Dam and a number were found at Principio Furnace. Here the rock occurs in hornblende granodiorite and appears to be an amphibolite, the borders of which have been metamorphosed by contact metamorphism. The contact rims reach a thickness of one inch, and in this zone large crystals of hornblende predominate. Numerous crystals of garnet occur in these inclusions.

Peridotite altered to amphibolite was found below Conowingo Dam in a large inclusion. Megascopically the rock is holocrystalline, rather fine grained and very dark. In thin sections it shows a cataclastic texture. Hornblende is by far the most prominent mineral and is essentially of the green variety, its bluish pleochroism suggesting glaucophane. Some of it is poikiloblastic and suggests strong recrystallization while other crystals are free of inclusions and clear. It is quite apparent that the hornblende is derived from a pyroxene. Often remnants of the original material, having a high double refraction, can be seen grading over into hornblende with a much lower birefringence in the same crystal. Several distinct stages of alteration are often apparent within one crystal (pl. XII, fig. 1). Alteration usually proceeds from the rim to the center.

Feldspar, andesine or labradorite, is much altered. It shows strain shadows and contains so many small inclusions that accurate determination is impossible.

Quartz is crushed to a fine mosaic and shows undulatory extinction. Very little of it, however, is present in the slide.

Magnetite is highly developed and is apparently a secondary product. Crystals averaging 0.5 mm. often contain hornblende inclusions. A small amount of biotite is present.

GABBRO

Both massive and foliated gabbro are found included within the granodiorite. Their relationships can be seen best immediately below Conowingo Dam, where both types are also engulfed by quartz diorite (pl. XIV, fig. 1).

Foliated gabbro inclusions occur also in the biotite granodiorite along Deer Creek south of Darlington; in the bed of the Susquehanna River in the vicinity of Canal and the mouth of Deer Creek; one half mile south of Lapidum; and in the railroad cut immediately west of the Baltimore and Ohio Railroad bridge over the Susquehanna River. Inclusions of the same type can be seen in the massive granodiorite on Stony Run just south of the Baltimore and Ohio Railroad. It is thus apparent that the gabbro consolidated before the quartz diorite, biotite and massive granodiorite were intruded.

QUARTZ DIORITE

The quartz diorite is older than the granodiorite. This is shown by many inclusions south of Conowingo Dam and along the north side of Octoraro Creek between Rowlandsville and Porters Bridge.

STRUCTURES OF INCLUSIONS

Structures which existed before the intrusion of the granodiorite may be reconstructed, in part, from a study of the inclusions. Among the thousands of inclusions which occur south of Conowingo Dam, bedded and folded metamorphic sediments with flow and fracture cleavages are held in a matrix of gabbro, quartz diorite and granodiorite (pl. XV, fig. 1). Exact replicas of these structures can be seen farther north where the metamorphosed sediments are exposed outside of the intrusives. Inclusions of gabbro and quartz diorite are found in the granodiorite.

Bedding, folding, flow cleavage and fracture cleavage are cut off at all angles and in some cases destroyed by the intrusives. Although the inclusions are arranged parallel to the flow structures of the intrusives with respect to their external forms, their internal structures show neither parallelism with respect to their host nor conformity with one another.

BEDDING

Bedding in the Glenarm series consists chiefly in alternating schistose and quartzitic bands (pl. XV, fig. 1) and less often in quartzitic bands of variable grain-size. Both types were found included in the intrusives.

Numerous inclusions contain a fine grained light core-like band often with very fine streaks of darker material through it. These bands run the length of the inclusion and may occur anywhere within it. They are, therefore, distinct from contact metamorphism. The contact with other layers is usually not sharp.

In thin sections quartz, averaging 0.01 mm., was found to constitute over 50% of the rock. The other constituents are zoisite and clinozoisite, apparently alteration products of tremolite which has now disappeared almost entirely. A small amount of later epidote is present. These bands are considered to be beds of fine grained quartzite.

FOLDING

The folding, prevalent throughout the Wissahickon and Peters Creek formations, can be observed in the inclusions within the intrusives. It is most impressive where schistose and quartzitic bands occur together (pl. XV, fig. 1), although it may also be expressed by fine- and coarse-grained quartzitic layers or by schistose material alone.

FLOW CLEAVAGE

In this paper flow cleavage is used synonymously with schistosity, slaty cleavage and Schieferung (69, 92). It is the dominant structure of the metamorphosed sediments of the area and, therefore, of their inclusions within the intrusives. It is one of the chief criteria by which the nature of the inclusions can be recognized and it often governs their orientation parallel to the foliation of the intrusives.

The direction of easiest splitting of the invaded sediments is parallel to their flow cleavage. An inclusion torn from the wall rock will usually have two long directions coinciding with the flow cleavage plane and the short direction across it. In the flowing mass of the intrusive an inclusion of this shape will tend to be parallel to planar elements of the host. For this reason many inclusions, especially the larger ones, have their flow cleavage parallel to the foliation of the intrusive.

Parallelism of flow cleavage in the sediments and foliation in the intrusives is not necessarily an indication that the sediments are inclusions. However, where fracture cleavage varies widely in its direction of strike or in its amount of dip in two closely associated bodies of sedimentary material surrounded by intrusives, one can be sure that the sediments are inclusions, because outside of the intrusives fracture cleavage exhibits little or no variation in strike or dip over wide areas.

Thin sections show that granitic juices enter most readily along the flow cleavage plane, and the phenomenon can also be observed megascopically (pl. XVI, fig. 2).

FRACTURE CLEAVAGE

Fracture cleavage is used here instead of false cleavage, slip cleavage or Schubklüftung (92). It was observed megascopically and in thin sections in numerous large inclusions. The uniformity in strike and dip which is so prominent outside of the granodiorite contacts is lost in the intrusives. Inclusions with fracture cleavage were turned into odd positions by the intruding magma, were carried by it, and participated passively in its movements.

That fracture cleavage is the most delicate structure of the sediments is shown by the fact that it is the first to be destroyed by contact metamorphism.

FOLIATION OF INCLUDED INTRUSIVES

The secondary foliation of the gabbro and metadacite and the primary flow structures of the quartz diorite are cut off by the granodiorite. In these rocks mineral parallelism is not nearly as intense as it is in the schists. Inclusions of them, therefore, have a more equant form than do the tabular schist inclusions.

In the small inclusions believed to be metadacite the structures are so altered that little accurate information concerning them could be obtained. In the larger ones, however, regional mapping shows that their flow structures are often cut off at a slight angle by the granodiorite (Plate XX). Usually, of course, the structures in the two rocks are nearly parallel.

The foliation of the gabbro when in place does not vary greatly over wide areas. When included in the granodiorite and quartz diorite, however, two inclusions several feet apart may show a variation of 90 degrees in the strike of their mineral alignment.

CONTACT METAMORPHISM OF INCLUSIONS

Contact metamorphism can destroy all structures of inclusions. Four thin sections from one large inclusion south of Conowingo show the progressive changes from the center of a large schist fragment toward a quartz diorite contact of that inclusion. Flow and fracture cleavage are strong at the center, but as the contact is approached they become gradually weaker and finally disappear. Parallel with this transition is an increase in newly formed minerals. Plagioclase, entirely absent in the central portion of the inclusion makes its appearance several inches from the contact and increases greatly as the contact is approached. The center of the inclusion is a quartz phyllite composed of chlorite muscovite and quartz in nearly equal proportions.

The contact metamorphic rim around inclusions is highly variable. It may be either an inch or less, or over a foot thick. Many small inclusions have been entirely altered. Thus folding and bedding can be destroyed by contact metamorphism.

Metamorphism is also effected in some of the inclusions by what appears to be a "soaking in" of granitic juices. The schists are most vulnerable. Juices enter most readily along the flow cleavage planes and form long narrow wedges or bands chiefly composed of fine grained quartz, a little feldspar and some ferromagnesian mineral. The quartzitic beds, described earlier, have a much smaller amount of magmatic material present which is more evenly disseminated than in the schistose varieties.

Gabbro and quartz diorite have been only slightly affected by contact metamorphism.

AGE OF THE PORT DEPOSIT GRANODIORITE AND ASSOCIATED GABBRO*

GENERAL STATEMENT

The writer is convinced that the Port Deposit granodiorite and the gabbro associated with it are paleozoic (post-Conestoga limestone) and not pre-Cambrian, as previous workers believed (Table V). New evidence shows that post-Conestoga structures, recognized in inclusions and in wall rock, are transgressed and engulfed by granodiorite and gabbro.

PROBLEMS AND METHODS

Port Deposit granodiorite and the gabbro associated with it, including the Baltimore gabbro (105, 108), are intrusive into the Glenarm series

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* The assumption of the Paleozoic age of the intrusives, discussed in this chapter, was arrived at through cooperative work with Ernst Cloos who studied fracture and flow cleavage in the sediments north of the intrusives and elsewhere in Maryland and Pennsylvania. He measured a section along the Susquehanna River from Safe Harbor to Conowingo. On this and many other of his field excursions he was accompanied by the writer. Port Deposit granodiorite structures and the internal structure of inclusions in it were studied by the writer. A joint preliminary paper on this phase of the study has been published (26).

TABLE V

AGE RELATIONSHIPS

	KNOPF AND JONAS 1928		BASCOM 1902–1920–1935		HERSHEY 1936	
Mesozoic	Cretaceous	Unconformity		Cretaceous		Cretaceous
	Triassic	Diabase Unconformity		Diabase		Diabase
	Epi-Paleozoic?	Woodstock allanite granite and associated pegmatites	Meso-zoic		Meso-zoic	
Pre-Cambrian		Aplite Port Deposit granite (granodiorite) Relay quartz diorite Gunpowder granite Serpentine, peridotite and pyroxenite Hypersthene gabbro Quartz-hornblende gneiss	Pre-Cambrian	Pegmatite dikes Serpentine Gabbro Metadacite Granodiorite	Paleozoic	Hornblende lamprophyre Granite porphyry Pegmatites, Aplites Port Deposit granodiorite complex Gabbro Pyroxenite? Peridotite? Conestoga limestone
	Glenarm-Series	Peters Creek formation Wissahickon formation Cockeysville marble		Wissahickon mica-gneiss	?	Peach Bottom slate Cardiff conglomerates Peters Creek schist Wissahickon schist Metadacite
		Setters formation Unconformity Hornblende gneiss Hartley augen gneiss Baltimore gneiss		Baltimore gneiss	Pre-Cambrian	Baltimore gneiss

which is considered pre-Cambrian (64). A pre-Cambrian age has also been assigned to most of the intrusives in the Piedmont region of Maryland and Pennsylvania by many workers.

The age determination outlined below is based on the correlation of structures in the Paleozoics outcropping in the northwestern portion of the region with structures of the Glenarm series and those shown in inclusions within the intrusives in the southwestern portion of the region; and on the intrusive relationship between the igneous complex and the schist structures.

The intrusives are separated from known Paleozoic sediments by a belt of rocks of the Glenarm series which is approximately 20–30 miles wide. Therefore, intrusive relationships between the plutonics and the unmetamorphosed Paleozoics cannot be observed directly and the 20–30 mile gap must be bridged by other means. Persistent structures which can be recognized over a large territory and which transgress formational boundaries regardless of their trend serve the purpose. Two such structures were utilized in this work: flow cleavage and fracture cleavage. The study of inclusions and thin sections discussed in the preceding chapter was made primarily for comparison of these structures. The orientations of cleavage planes were measured and their directions platted on maps.

BEDDING, FLOW CLEAVAGE AND FRACTURE CLEAVAGE

In the Glenarm series bedding (original stratification) is observed with difficulty in many localities because of its intense and probably repeated deformation. The lately renewed controversy regarding the age of the series depends to a large extent on the recognition of bedding and on the question of whether or not Paleozoic and Glenarm beds are conformable (78). The relation of bedding and schistosity is not involved in this paper. Although bedding can be seen in many localities it cannot always be proven. Schistosity or flow cleavage is always recognizable.

Flow cleavage and fracture cleavage (false cleavage) are used in this study because they are widely distributed and well known. Both have been observed by all workers in a belt which parallels the Appalachians from Maine to Alabama (5, 18, 19, 37, 65, 76, 111).

Flow cleavage in the region studied is the one cleavage that is accompanied by thorough recrystallization and that is regionally dominant. It can follow bedding or can transect it. Quartz veinlets and granite dikes follow it. Numerous granite dikes were found in the section along the Susquehanna River. One such dike occurs six miles northwest of the Port Deposit pluton. Flow cleavage is present in Paleozoic and Glenarm sediments of the area studied and is conformable across their boundaries.

Its direction is persistent over large territories. Knopf and Jonas ascribe it to a late period of deformation and suggest that it is late Paleozoic.

Albitization and replacement of older structures can be seen in the Wissahickon schist clearly following flow cleavage planes (98). A similar phenomenon was observed in the Conestoga limestone at Safe Harbor (26, fig. 3). Oligoclase is very abundant here and follows certain layers parallel to bedding and flow cleavage planes.

Fracture cleavage transects flow cleavage (p. 68). The writer prefers the term fracture cleavage because these planes are not accompanied by recrystallization. The deformation is largely mechanical. It displaces bedding and flow cleavage planes which, in extreme cases, are highly crinkled. Older structures may be entirely obliterated.

Small quartz veins which carry a minor amount of feldspar follow fracture cleavage planes. A thin section of such a vein one-quarter inch thick found at Fishing Creek Station shows quartz and feldspar in the center, and green chlorite unevenly distributed along the contact. The host material is chlorite-sericite Peters Creek schist.

The direction of fracture cleavage is remarkably persistent over large regions. Its distribution can be studied in the literature and its constant direction can be seen from the map (26 fig. 5).

The "Martic overthrust" produces no noticeable changes in directions of the cleavage planes. Knopf and Jonas imply that the age of this overthrust is post-Carboniferous (65 p. 79). The Peach Bottom syncline which contains presumably Paleozoic slate is transgressed by fracture cleavage planes without regard for any boundaries. The only change in strike and dip occurs between the Wissahickon and Peters Creek schist belts. Here the strike changes from NE-SW to E-W and the dip from vertical to gently north.

Since both cleavages are found in the Paleozoic Conestoga limestone as well as the Glenarm series, and since their direction is not influenced by the contact between the two formations, and since albitization was found in both the Wissahickon schist and Conestoga limestone, the writer agrees with Knopf and Jonas that the two cleavages were formed in post-Conestoga times and possibly during late Paleozoic periods of deformation.

AGE OF THE INTRUSIVES

Flow cleavage in the Glenarm series is followed, transgressed and engulfed by the granodiorite and gabbro of the Port Deposit complex. Furthermore, it is contact metamorphosed and recrystallized by these intrusives (p. 125). The primary gneissic foliation of the granodiorite (p. 133) is neither governed by nor is it strictly parallel to the flow cleavage.

The writer believes, therefore, that this foliation was formed during intrusion and consolidation of the magma and after flow cleavage was imposed on the sediments.

Fracture cleavage, strikingly uniform in strike and dip outside of the granodiorite, is turned into odd positions in the inclusions which were carried by the intrusive and participated passively in its movements.

Contact metamorphism has destroyed flow and fracture cleavage within inclusions. If both flow structures in the granodiorite and cleavage in the schists were due to the same causes, the cleavages would not have been destroyed. Reactions of the intruding magma on the structures of inclusions would not be possible. A condition which forms a structure cannot simultaneously destroy it.

Flow cleavage and fracture cleavage were formed after the deposition of Conestoga limestone. The Port Deposit granodiorite and the gabbro associated with it which have cut and engulfed these structures must also be post-Conestoga and, therefore, not pre-Cambrian but Paleozoic.

The correlation of structures and age determination may be listed as follows:

1. NW region. Safe Harbor, Schenks Ferry.
   a. Flow cleavage and fracture cleavage is conformable in Glenarm and Paleozoic sediments.
   b. Fracture cleavage transgresses all boundaries with no measurable change in direction.
   c. Albitization follows flow cleavage in Glenarm series and Conestoga limestone.
2. Central region. Peach Bottom, Peters Creek, etc.
   a. Granite dikes follow flow cleavage planes.
   b. Quartz veins follow flow and fracture cleavage planes.
   c. Fracture cleavage transects the contact between Paleozoic Peach Bottom slate (78, p. 70, footnote 65) and Glenarm series without deviation in strike and dip.
3. SE region. Conowingo, Baltimore.
   a. Inclusions engulfed by granodiorite, quartz diorite and gabbro, show their flow cleavage cut by those rocks.
   b. Inclusions within granodiorite, quartz diorite and gabbro show fracture cleavage and flow cleavage with random orientation.
   c. Flow and fracture cleavage within inclusions are destroyed by contact metamorphism.
   d. Fracture cleavage is not present in any of the intrusives.
   e. Flow and fracture cleavage in schist wall rock are followed and transgressed by granodiorite, quartz diorite and gabbro.

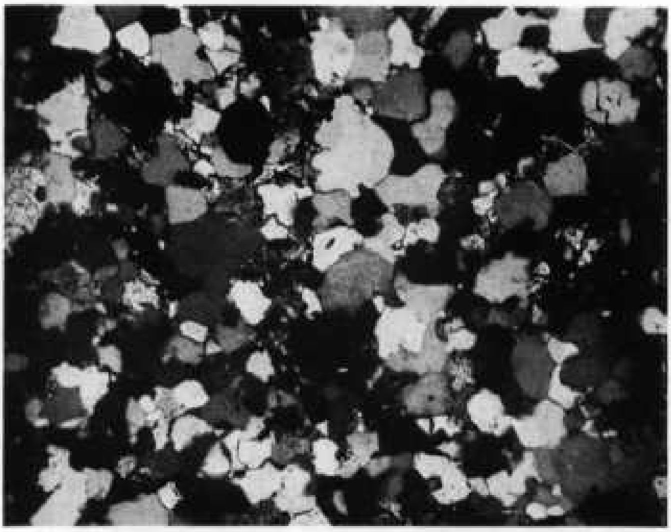


Fig. 1.—Quartzite from an inclusion south of Conowingo Dam. Photomicrograph × 30.

Fig. 2.—Conglomerate from an inclusion south of Conowingo Dam. Photomicrograph × 12.

STRUCTURES OF THE PORT DEPOSIT GRANODIORITE COMPLEX

In the following chapter the internal structures of the pluton are discussed systematically. First, reasons for the primary nature of flow structures are given; second, the structures themselves are taken up and illustrated by examples; third, the elements of the transition phase are outlined; and fourth, the primary and secondary elements of the breaking phase are considered. The systematic discussion of the elements is followed by a chapter in which the writer attempts to summarize the regional distribution of all structures and to show their mutual relations. The regional foliation and joint maps (plates XX and XXI in pocket) are essential for the understanding of the following chapters.

PRIMARY NATURE OF FLOW STRUCTURE

All rocks of the region exhibit flow structures. In the Glenarm series the flow phenomenon is a secondary flow cleavage. Foliation in the intrusives roughly parallels the general regional strike and the flow cleavage in the Glenarm series. This was recognized by the earlier workers and was generally assumed to be due to a post-intrusive period of deformation. There is strong evidence, however, to support the conclusion that the flow structures in the Port Deposit granodiorite were formed before complete consolidation. They are, therefore, thought to be largely primary.

The primary nature of the flow structures in the Port Deposit granodiorite is attested by its internal arrangement, by the discordance of the internal structures of engulfed xenoliths and by contact relationships. The internal arrangement of the granodiorite is characterized by the mutual parallelism of minerals, mineral groups, inclusions, groups of inclusions, and schlieren. This parallelism must have been imposed while the granodiorite was still mobile.

Most geologists would agree that it is impossible to turn inclusions in a consolidated rock without changing its internal structure and without deforming the associated minerals of the host. The most delicate pre-intrusive structures and mineralogical characteristics in many xenoliths are preserved in this area. Associated minerals within the granodiorite do not show the effect of large scale recrystallization or deformation. There can be little doubt that the present parallel arrangement of xenoliths was effected before consolidation. Since the other structures within the granodiorite maintain such a strict parallelism to the inclusions they too are considered to have been aligned before complete consolidation.

If it is argued that a post-consolidation deformation could have aligned the minerals in the granodiorite parallel to the pre-existing, parallel included elements minerals within xenoliths should show some effect of such a deformation. None were found, however. Contact metamorphism has affected some of the inclusions but no effect of regional dynamic metamorphism was recognized.

Flow structures in the granodiorite are always conformable with their contacts. Similar structures in schist, gabbro, and metadacite are often cut at various angles by the contact. It is not believed that dynamic forces are capable of such selective deformation.

Foliation in the granodiorite often increases in strength as its contacts are approached. Sometimes gneissic borders are formed, but in other cases, in the immediate vicinity of the contact, the granodiorite is porphyritic. Like phenomena are lacking in the materials in contact with the granodiorite. Explanation of these facts as due to metamorphism again demands a selective and extremely local deformation. It seems much more plausible to follow Balk (3) in believing that frictional forces along the contact are responsible for increased strength of foliation and border gneissosity, neither of which show counterparts in the country rock.

Recrystallization in the Glenarm series is cut by fracture cleavage which is, therefore, a post-recrystallization structure. No recrystallization has been effected in the Glenarm since the fracture cleavage was formed. The granodiorite intrudes Glenarm rocks, and cuts and engulfs fracture cleavage. Intrusion, thus, took place after the formation of fracture cleavage and, consequently, after the latest recrystallization within the Glenarm series.

A deformation which would have developed the strong foliation in the granodiorite would also have effected recrystallization in the wall rock. Since there is no post-granitic recrystallization or deformation in the wall rock the granodiorite foliation must be primary and is probably due to "autometamorphism" during or at the end of the intrusive phase of the granodiorite.

The Port Deposit granodiorite pluton consists of several separated bodies of intrusive rocks. The arrangement of their structures differs widely. Flow lines in the northern intrusive at Conowingo Dam are always steep, in the Port Deposit body they are flat. The angle between the two is never less but is usually more than 45 degrees (the average is approximately 70–80 degrees). The schist between the two bodies shows linear stretching which is also flat. On the other hand, structures in the Conowingo body and the schists along its southern contact deviate, up to 90 degrees. They are, therefore, not parallel as frequently assumed. If all the structures within the entire complex were caused by secondary metamorphism they should be more or less parallel. The massive granodiorite shows almost no foliation or flow lines.

The writer believes that all of the igneous structures are primary because they are not mutually parallel in the different bodies. They vary in intensity and are almost invisible in one intrusion, while in others they are extremely strong. They are not parallel with wall rock structures. All eventual alterations which are evident in the different intrusions must have followed primary structure lines, which they have not been able to obliterate.

ELEMENTS OF THE FLOWING PHASE

PLANAR FLOW STRUCTURES

Planar flow structure is present in all types of granodiorite in the area. It is characterized by the mutual parallel planar arrangements of minerals, mineral groups, inclusions, groups of inclusions and schlieren. The essential characteristic of these elements is that they possess one short dimensional direction. The shapes may vary from thin and leaf-like plates, represented by the micas, to oblate spheroids, represented by some of the inclusions.

Minerals and Mineral Groups

Biotite is the most pronounced and abundant mineral exhibiting planar flow phenomena in the Port Deposit granodiorite. Along with quartz and feldspar it is one of the essential constituents of the most extensive type of granodiorite constituting the pluton.

Biotite may express planar flow in single crystals or in aggregates of overlapping individuals. The latter are by far the most common. These groups are lense-shaped and usually wavy. They are mutually parallel and the individual crystals constituting them are parallel to their form boundaries.

The biotite is the brown pleochroic variety and there is no evidence of recrystallization or rotation after its original crystallization. It has been considered primary by all earlier workers. The Port Deposit granodiorite shows the best planar structure in the area because of its high biotite content. The best examples are found in the quarries at Port Deposit.

The hornblende types, in which biotite is subordinate or lacking, do not have well developed planar structure except locally. Hornblende, usually considered a linear mineral, can also produce a true planar structure. This is well developed in the hornblende granodiorite at many localities. An especially good example occurs on Principio Creek at Principio Furnace. In the massive granodiorite it is elusive, but is well developed just north of the north metadacite contact on Principio Creek.

Hornblende arranged so as to exhibit platy flow planes may be explained if we assume a flowing mass. Hornblende crystals will then tend to be aligned with their long direction parallel to the line of flow—planar minerals are arranged parallel to the plane of flow. Both take the position of least resistance. The linear elements consequently are elongated in the plane of foliation. This is true throughout the area under discussion, although an exception has been noted in another place (45, p. 881).

Deviations from the true line of flow occur within the plane of least resistance, i.e. the foliation plane. When hornblende is found to have a dominant orientation in the horizontal plane it may be measured as a planar element, provided, of course, that linear elements are not horizontal. In this case the linear is stronger than the planar arrangement. Where the dip of the linear elements is nearly horizontal, care must be taken that their trace on the horizontal plane is not confused with planar structures.

Feldspar and quartz do not as a rule show planar orientation because they are equidimensional. Along contacts, however, they become planar elements which are worthy of note.

Inclusions and Groups of Inclusions

Inclusions represent planar flow structure both as autoliths and xenoliths. They are mutually parallel and this parallelism coincides with that of the minerals (pl. XIV, fig. 2). Autoliths seem more widespread and more abundant than xenoliths. They are found everywhere in all types of the granodiorite. Their size is variable. In the biotite type they are small, usually measuring less than a foot in their longest direction. In the massive and hornblende types they are somewhat larger. They are largest and most abundant in the hornblende-biotite type where the longest measured was seven feet. The xenoliths are less widespread, but were found in all types. They are usually localized near contacts.

In shape the inclusions vary from almost spherical to platelike. Orientation depends on the shape of the included body. Flat bodies are nearly parallel, while spherical bodies show a random orientation. This is well demonstrated by schist fragments, which are quite flat and exhibit good orientation, and gabbro inclusions which are more equidimensional and are poorly oriented. Because of their variability, the inclusions have a more devious alignment than the minerals which are usually flat and more constant in size and shape.

Inclusions may represent planar flow singly or in groups. Single inclusions can be seen everywhere in the region. The best exposures of groups are found in the bed of the Susquehanna River south of Conowingo Dam, along Octoraro Creek between Rowlandsville and Porters Bridge, and on Principio Creek at Principio Furnace.

FIG. 1.—Gabbro inclusions in granodiorite one and a half miles south of Darlington on Deer Creek.

FIG. 2.—Schist inclusions in quartz diorite below Conowingo Dam. Note fold in upper left. Scale—white object 2¾ inches.

Schlieren

Schlieren representing planar flow structure are found in all types of the granodiorite, but are best developed in the hornblende type. Here they consist of streaks and layers relatively rich in hornblende associated with streaks poor in hornblende. The latter are lighter since the essential constituents in addition to hornblende are quartz and feldspar. In the Port Deposit granodiorite the same phenomenon occurs, where biotite takes the place of hornblende.

The schlieren are parallel to the inclusions and planar minerals. Biotite schlieren are found in the Port Deposit quarry. Hornblende schlieren occur in many places, and are well exposed on Principio Creek near Principio Furnace.

LINEAR FLOW STRUCTURES

Linear flow structures occur in all parts of the pluton. They result from the mutual parallel arrangement of minerals, mineral groups, inclusions, groups of inclusions and schlieren. The essential characteristic of these elements is one long form axis. Linear flow structures or flow lines develop if one direction of flow dominates the others.

Minerals and Mineral Groups

Hornblende is the most conspicuous linear mineral in the area and is highly developed in the hornblende granodiorite. Here the linear parallelism is the outstanding megascopic feature wherever that rock is exposed.

Flow lines occur also in the massive granodiorite in which they are usually due to the orientation of hornblende crystals. They can be seen on Principio Creek north of the metadacite contact, on Northeast Creek at the Pennsylvania Railroad and on the same Creek between Leslie and Bayview. Hornblende is less important as a linear element in the hornblende-biotite type because it is masked to a large extent by biotite inclusions. In the biotite granodiorite the hornblende is not an important linear element.

Quartz and feldspar crystals show a linear parallelism along contacts, but they are rarely elongated in the central part of the pluton.

The biotite aggregates of the Port Deposit pluton have the shape of willow leaves, i.e. they are thin flakes which are somewhat drawn out in one preferred direction. Since all these patches are strictly sub-parallel a very distinct planar and a faint linear structure results (pl. XVI, fig. 1). The flow lines can be ascertained only if a large number of such aggregates are measured in three dimensions.

Inclusions

Measurements on inclusions show that their longest dimensions are mutually parallel and are also parallel to the longest dimensions of the mineral aggregates. The indistinct linear element is thus well supported.

Schlieren

Schlieren may locally show linear arrangements. A good example occurs in the hornblende granodiorite on Principio Creek in the vicinity of Principio Furnace.

COMBINATION OF PLANAR AND LINEAR FLOW STRUCTURES

Both platy and linear parallelism may occur together. This is to be expected because the same elements constitute both structures. The two, however, are independent of each other, i.e. one may be absent where the other is strongly developed. As a general rule the platy arrangement is stronger in granodiorite with abundant biotite. The linear parallelism is more pronounced in hornblende-rich rocks. Autoliths show platy and linear parallelism which is equally well developed. Xenoliths are governed by previous structures. Schist and metadacite inclusions usually have a strong planar and a weak linear structure. Gabbro may exhibit the two structures equally well. Schlieren are almost exclusively a planar element.

FLOW STRUCTURES IN DIKES

Most of the dikes of the area exhibit flow structures which originate exclusively in mineral arrangement. Linear orientation is dominant because hornblende is abundant in almost all dikes. Flow structures in dikes usually parallel their walls whether or not they are concordant or discordant to the flow structures of the granodiorite.

ELEMENTS OF THE TRANSITION PHASE

The Port Deposit granodiorite passed through a transition period between the flowing and the rigid phases, and it shows some characteristics of both. The period was one of decreasing temperature with beginning of consolidation. Since the marginal portions of a pluton tend to consolidate first it is in them that transition phenomena chiefly occur. Typical elements are flexures, border gneisses and ruptures restricted to the contact zones.

FIG. 1.—Bedding, folding, flow cleavage, and fracture cleavage in the Glenarm Series north of Conowingo Dam on the east side of the Susquehanna River.

FIG. 2.—Foliation in Port Deposit granodiorite and displacement of an inclusion by movement along a cross joint. Port Deposit quarry.

FLEXURES

In the central part of the pluton the mica clusters are bent but not broken. They are all bent at the same angle and give the appearance of a superimposed structure. In the Port Deposit quarry their strike is 20 degrees east of the general strike. Locally this direction and the flexures appear to be constant. Inclusions are not flexed, nor do hornblende crystals show evidence of flexing. The deformation seems restricted entirely to the biotite clusters.

The flexures may be interpreted as due to movements after the crystallization and aggregation of the biotite crystals, but before complete consolidation of the mass.

BORDER GNEISS

Toward the contacts the intensity of foliation in the granodiorite often increases and the rock becomes highly schistose or gneissic, often with a vitreous appearance. Feldspar and quartz, equidimensional away from the contacts, may be stretched and become planar or linear elements. The process has gone so far locally that quartz and feldspar have been drawn out into "augen." This occurs at the south metadacite-granodiorite contact on Principio Creek.

Thin sections show that the hornblende crystals which are wrapped around these "augen" are conformable to the other minerals. They must have been present at the time that the border gneiss was formed and are, therefore, primary constituents.

The wall rocks, gabbro, schist and volcanics do not show gneissic borders. They are transgressed and engulfed by the granodiorite and are, therefore, older. The only new structure produced by the intrusion of the granodiorite is contact metamorphism, which varies from place to place and is easily distinguished from the gneissic borders of the granodiorite.

Border gneisses are thought to be a result of increasing viscosity and consolidation of a pluton along its margins with continued movements in the center of the mass. These marginal portions may have consolidated but were repeatedly crushed and infiltrated by the plutonic mass (3, 9, 25).

ELEMENTS OF THE RIGID PHASE

The most outstanding elements of the rigid phase are joints. Closely associated with them are faults and dikes, and slickensided surfaces of various kinds. Joints in the Port Deposit granodiorite are both primary and secondary.

Primary joints, as used in this paper, are directly related to the flow structures of the pluton. Cross joints are perpendicular to flow lines (p. 47); "longitudinal joints" parallel flow planes or flow lines; marginal thrusts are local tension fractures restricted to the marginal zones of the pluton; marginal joints are local fractures restricted to contact zones and closely related to the emplacement of the mass. Certain flat joints which are independent of surface topography are also primary.

Secondary joints were formed after consolidation of the pluton. They are widely distributed, very regular and continue from the pluton into the wall rock. They are, in the present case, called regional tension joints because they seem distinctly related to the shape of the intrusive, i.e. they are always perpendicular to the longest axis of the mass. A number of other joints occur locally, but they are not persistent throughout the region.

The entire region is transgressed by a large number of shear zones which are accompanied by mylonitization, slickensiding and recementation by quartz. They are very persistent in strike and dip and approximately parallel the long axis of the pluton.

Grimsley (44), Bascom, and Mathews (77), recognized the major joint systems and those locally developed along the Susquehanna River.

The joint map of the Port Deposit quarry (pl. XVII) and the accompanying strike diagram show the relationship of joints to each other and to the flow structures in this locality. All measurable joints in the quarry are not represented, but their relative distribution has been maintained.

Two major directions are outstanding. One striking roughly N-45°E is parallel to the foliation and is paralleled by shear zones and dikes. These are the longitudinal joints. A second direction is developed at right angles to the first and at this locality represents the strike of two sets of joints: regional tension joints, and cross joints.

Control for this map was established by a stadia survey. The shot points are represented by small circles.

PRIMARY JOINTS

Longitudinal Joints

Longitudinal joints are the most widespread and consistent joints of the area. All types of granodiorite are traversed by them and they are rarely absent in even the smallest outcrops in which flow structures can be measured. A bend in the direction of the foliation is paralleled by a corresponding bend in the direction of the longitudinal joints. In localities where the foliation is intense, these joints are more closely spaced and more numerous. This is well demonstrated in the fact that the number of

Fig. 1.—Flow lines in Port Deposit granodiorite. Dark patches are aggregates of biotite. Port Deposit quarry.

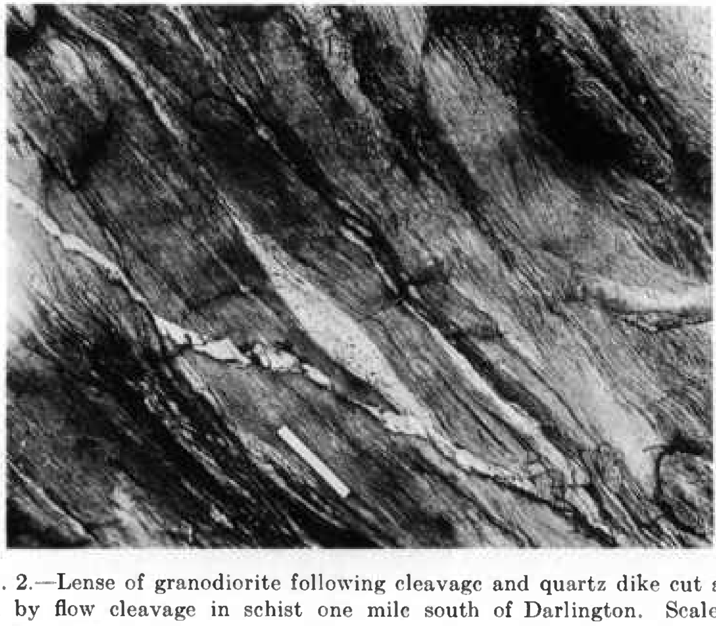


Fig. 2.—Lense of granodiorite following cleavage and quartz dike cut and displaced by flow cleavage in schist one mile south of Darlington. Scale—white object $2\frac{3}{4}$ inches.

longitudinal joints is much larger in the strongly foliated biotite granodiorite than in the weakly foliated massive type. The other granodiorite types exhibit a similar relationship.

Longitudinal joints are usually large, rough and highly variable in strike and dip (pl. XVIII, fig. 1). They displace the foliation and are, therefore, later. It is believed that they formed after consolidation but before dike intrusions because many dikes follow them. Joints of this type are called compression joints by some authors. Their origin is not fully understood.

Shear zones which follow the same direction as longitudinal joints are found everywhere in the region. They vary from a fraction of an inch to fifty feet in width and in several cases the deformation is accompanied by mylonitization. Shear zones are also the locus of later dike intrusion and are probably of early formation.

The direction of movement on longitudinal joints is difficult to reconstruct owing to its intensity. Few structures cross them and slickensiding has been almost entirely destroyed by later movement. In the Port Deposit quarry a cross cutting flat joint has been displaced four feet in the attitude of reverse faulting. In the Bridge quarry normal faulting has taken place along these joints probably after the shear zones were formed. The direction of movement can be determined from feather joints (29).

The longitudinal joints have been filled by calcite, quartz, clay minerals and zeolites probably of hydrothermal origin.

Cross Joints

Cross joints are less consistent and less widespread than the longitudinal ones. They are found in all of the granodiorite types although they are much more pronounced in the eastern part of the region than elsewhere.

Flow lines are transected approximately at right angles and any change in their orientation is accompanied by a change in direction of the cross joints. The normal (90°) relationship is thus maintained and because of it cross joints are believed to be primary joints. Local deviations from this rule are thought to be due to the adherence of the cross joints to an average direction of flow. Since joints represent the breaking phase, their reaction to movements is not as sensitive as that of flow lines. The latter may form narrow arches but joints will respond to similar stresses in larger fans, because the units involved are larger, bulkier and less mobile.

The relation between flow lines and cross joints is particularly consistent in the eastern portion of the area where they are well exposed along the east bank of Big Elk Creek south of the Conowingo-Newark Road, and immediately north of Elk Mills. Farther west, where the granodiorite is very much intertongued with wall rock and flow lines are thus locally deviated, the mutual relation is less regular. This is believed to be due to the many irregularities in the outlines of the pluton. Cross joints are poorly developed in the biotite granodiorite although they occur in the Port Deposit quarry and below Conowingo Dam.

Dikes follow the direction of cross joints, for example, in the river bed one and one-quarter miles south of the mouth of Octoraro Creek, along Principio Creek near Principio Furnace and at Rising Sun (Plate in pocket).

Flat Joints

Flat and gently dipping joints are found in all parts of the area. Most of them are considered exfoliation joints, but locally they appear to be primary. In the Port Deposit quarry several such joints dip gently east. They have been displaced by shear zones. One quarter mile north, movements on a similar flat joint are indicated by feather joints which have been filled with secondary minerals.

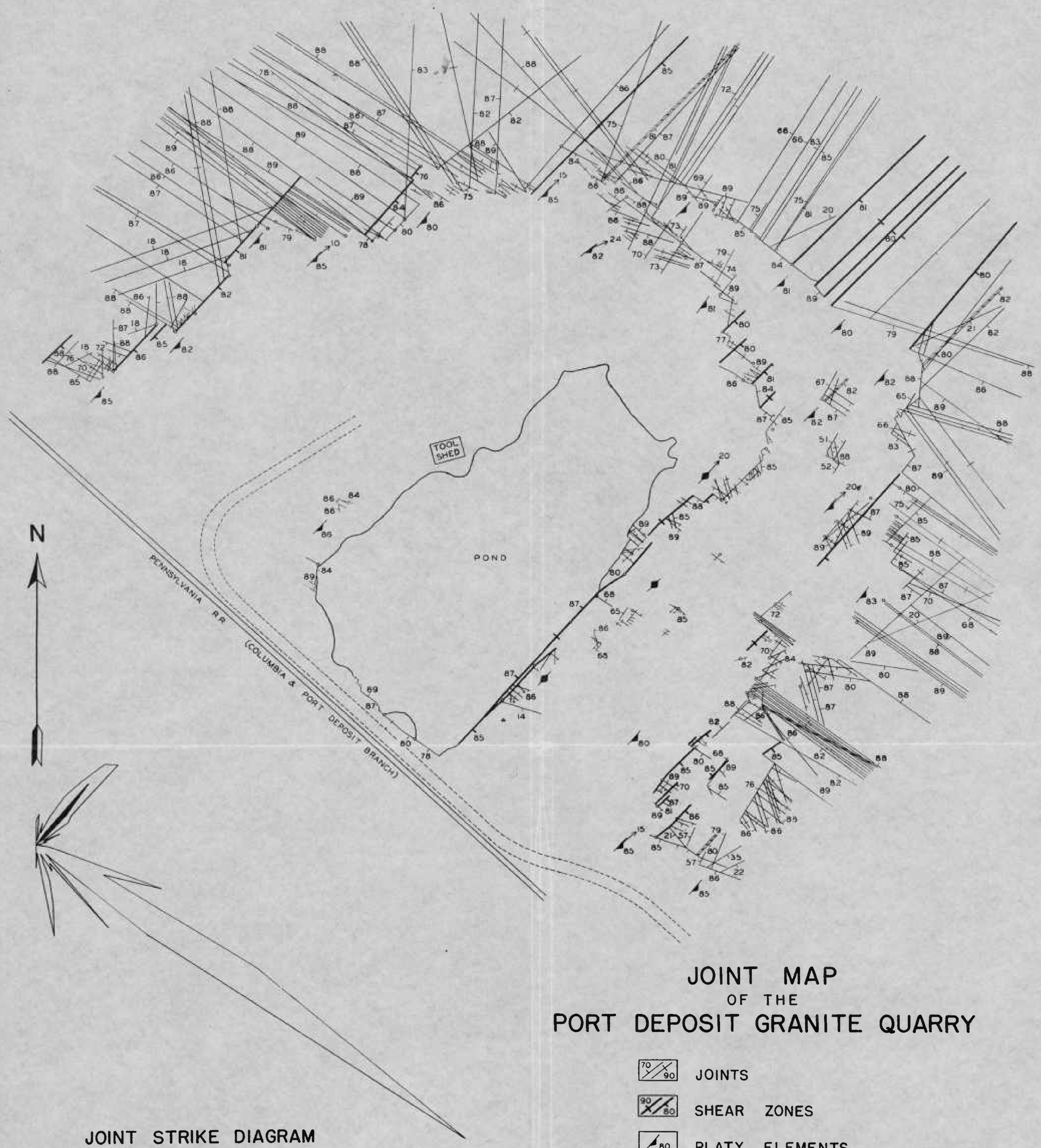
SECONDARY JOINTS

Regional Tension Joints

One system of joints is found in all rocks of the region: granodiorite, gabbro, volcanics, gneiss and schists. Their surfaces are large and smooth (XVIII, fig. 1). They are usually at right angles to the flow planes in granodiorite (but not to flow lines), the flow cleavage in the wall rock, and the longest axis of the pluton. They are nearly vertical. Wherever they are normal to the flow lines they coincide with cross joints and then it is difficult to distinguish the two. Unlike the cross joints, however, the regional tension joints do not deviate from their nearly vertical position when the flow lines change their attitude.

The joints form a large regional fan which is evident from the map on which they are plotted (Plate XXI). Joints corresponding to these have been discussed by many authors who called them regional tension joints.

Regional tension joints are slickensided everywhere. The best exposures are in the Port Deposit and Bridge quarries. In Rock Run on the east side of the river small quartz veins, showing displacement, cross these joints. Figure 16 shows this feature and gives a generalized view of the amount and direction of displacement. The east block has been moved north with respect to the west side. Although only a very slight amount of movement has taken place on each joint plane, the total displacement must have been considerable. Hornblende lamprophyre dikes were dis-



JOINT MAP
OF THE
PORT DEPOSIT GRANITE QUARRY

- 70/90 JOINTS
- 90/80 SHEAR ZONES
- 80 PLATY ELEMENTS
- 20 LINEAR ELEMENTS
- 80 APLITE DIKES

0 50 100 150 200

SCALE OF MAP IN FEET

JOINT STRIKE DIAGRAM
REPRESENTING
850 JOINTS

SOLID AREA = STRIKE OF PLATY ELEMENTS

0 20 40 60 JOINTS

SCALE OF DIAGRAM

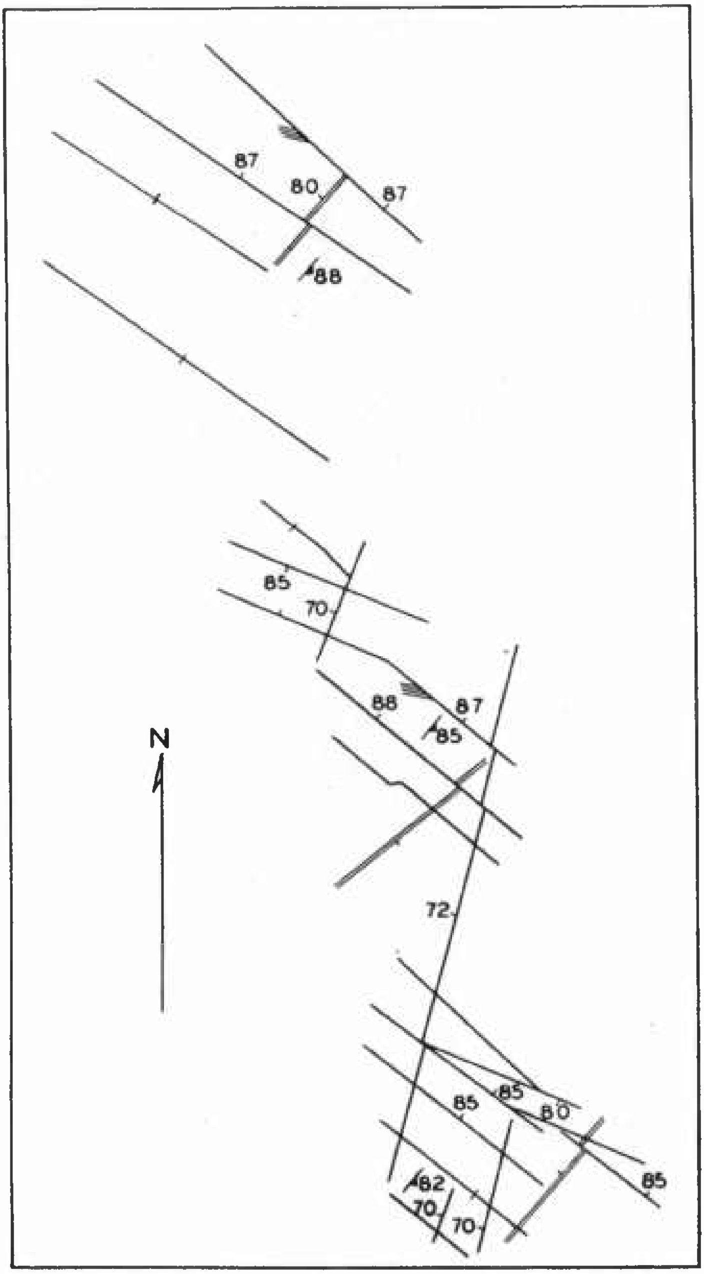


FIG. 16.—Sketch showing displacement of quartz dikes and joint along regional tension joints. Displacements average two inches. Small closely spaced joints. Length of N-line equals 2 feet.

placed by this movement. A good example is in the quarry one thousand feet south of the mouth of Rock Run on the east side of the Susquehanna River.

Another set of regional joints occurs locally. It usually strikes just east of north and since these joints are displaced by the movement along the regional tension joints they must have been formed before that movement took place. One such joint is shown in Figure 16 with its displacement. Faults of this type are common along the river and appear in both the Port Deposit and Bridge quarries, but they are always subordinate to the longitudinal and regional tension joints.

Feather Joints

Feather joints occur in many localities in the area. Usually they are only a few inches long and originate at joints along which movement, evidenced by slickensides, has taken place. In the Bridge quarry, however, they are especially well developed in association with normal faults. They reach a length of thirty feet and a maximum width, at the fault, of six inches. Often they show the effect of drag, which suggests relatively large movements. They are usually filled with quartz and calcite. They are always widest at the fault, grow narrower away from it and finally pinch out entirely. These joints have been interpreted as caused by tension and were dragged open by movement along the fault.

CONTACTS

Contacts and contact phenomena are important in determining the age relationships of the granodiorite to its wall rocks and in demonstrating the primary nature of the flow structures.

Flow structures in the granodiorite are always parallel to the contacts without regard to the character of the wall rock. As the boundary is approached foliation in the granodiorite usually becomes more intense and often gneissose although fine grained porphyritic borders are observable. Flow structures in the wall rock, on the other hand, are often transected by the contact and granodiorite structures.

INTERNAL CONTACTS BETWEEN ROCKS OF THE PLUTON

Contact exposures between the various types of granodiorite are few. Examples of the biotite granodiorite cutting the quartz diorite occur south of Conowingo Dam (pl. XI). These contacts are usually quite sharp and there appears to have been little or no interchange of material or contact metamorphism. In numerous cases the two types were found

FIG. 1.—Longitudinal joints facing reader, regional tension joints and cross joints normal to them in the Port Deposit quarry.

FIG. 2.—Gently dipping cross joints in the Susquehanna River bed south of Conowingo Dam.

to be concordant and conformable (33). In others, however, the contact and the granodiorite structures parallel to it transect the quartz diorite structures. The quartz diorite and its structures are, therefore, older than the Port Deposit granodiorite.

In the Bridge quarry two types of granodiorite are fully exposed but their contacts are complicated by dikes and shear zones which make an accurate interpretation impossible. Other contacts were not observed. Most of the earlier workers considered the contact between gabbro and granodiorite gradational, although Grimsley (44) has described an eruptive contact in the vicinity of Porters Bridge which has been questioned by Bascom. Apparently the latter investigations were confined to the northern contact where the relationships were not clear at the time. As a result the relative age of the two rocks was uncertain. Observations in new exposures in this locality provide a basis for an accurate interpretation. In other localities in the area the gabbro is the older rock. Inclusions of gabbro within the granodiorite show that the latter was intruded after at last part of the gabbro was consolidated (pl. XIX, fig. 1).

Gradational Contacts

The northern contact between gabbro and granodiorite is gradational in the western and central portion of the area. Its structures have been well described in the vicinity of Porters Bridge (44, 70), except for a new exposure on U. S. Highway #1 on the hill immediately north of Porters Bridge. Here a contact breccia may be seen in which closely spaced blocks of dark material, which are believed to be gabbro, are held in a matrix of a lighter intrusive granitic rock, probably highly contaminated granodiorite. The blocks show evidence of assimilation and it is difficult to determine the types of rock present. Flow structures found in the interstitial material, although very weak, add credence to the belief that the granodiorite intruded later. The width of this brecciated zone cannot be accurately determined because numerous inclusions of unknown origin occur in the granodiorite mass to the south. The hornblende content of the granodiorite, which in this locality appears to increase toward the contact, suggests a mixing of the two rock types. Fresh gabbro xenoliths in the granodiorite and quartz diorite are numerous three miles west at Conowingo Dam.

Sharp Contacts

The majority of the contacts within the pluton are sharp. Gabbro and Port Deposit granodiorite contacts are exposed three-eights of a mile north of Frenchtown on the east bank of the Susquehanna River, in the

Baltimore and Ohio Railroad cut just west of its Susquehanna bridge, and on the north tip of Garrett Island. In the first two localities mentioned the gabbro is foliated, but on Garrett Island it is massive.

Often the granodiorite has intruded the gabbro very intimately in small stringers. This is best exposed in two localities near Lapidum (one mile west, one-half mile south), and along Big Elk Creek one and one-quarter miles northwest of Appleton. In all cases the contacts are sharp and the rocks preserve their identity with no apparent exchange of material.

OUTSIDE CONTACTS BETWEEN PLUTON AND WALL ROCK

Sharp contacts prevail also between the plutonics and their wall rocks. These boundaries, however, are too poorly exposed to provide data for an adequate discussion.

At the schist-biotite granodiorite contacts north and south of Canal, the boundaries are sharp, in spite of finely laminated intertonguing. Lit-par-lit injection of gabbro and granodiorite into schist on Big Elk Creek one and one-quarter miles northwest of Appleton also shows sharp contacts. Metadacite-granodiorite contacts are also sharp.

All of the dike rocks show sharp boundaries although shearing has often taken place along the contact. Chilled borders are common.

ATTITUDE OF CONTACTS

Concordant contacts

As a whole the Port Deposit granodiorite complex consists of a number of concordant bodies and, as would be expected, most of their contacts are concordant (pl. XX in pocket). Such contacts are exposed west of Lapidum, along Big Elk Creek northwest of Appleton (gabbro-granodiorite); and south of Canal (schist and granodiorite); one mile south of Port Deposit, and one mile north of the Bridge quarry (metadacite-granodiorite). Most of the dikes within or outside of the pluton are also concordant and can be observed especially well on both sides of the Susquehanna River.

Where the contacts are concordant they are also conformable except in a few aplite dikes in the vicinity of Principio Furnace. Age relations, therefore, are difficult to determine from contacts of this type.

Discordant contacts

Discordant contacts are numerous in the area although the angle of discordance is usually small. They are always disconformable since the structures in the granodiorite invariably parallel the contact (33)

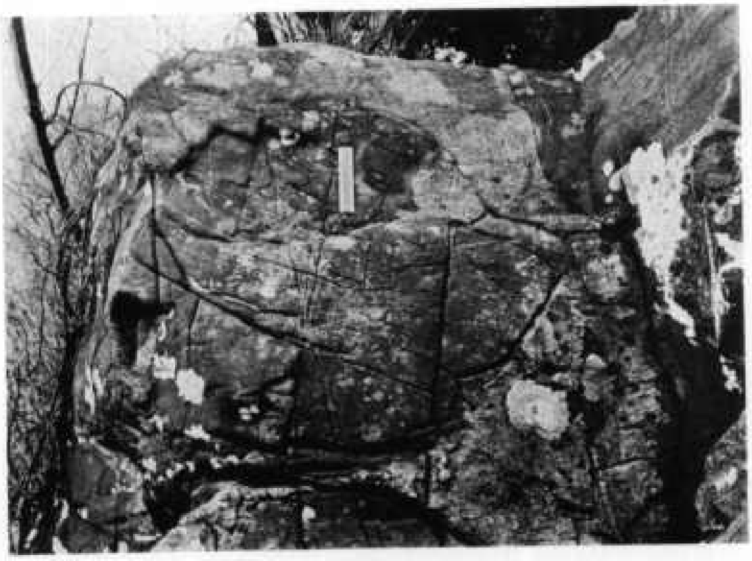


FIG. 1.—Contact between gabbro and granodiorite one-half mile south of Lapidum, looking down on cross joints. White scale equals 6 inches.

FIG. 2.—Quartz dike parallel to bedding, both at an angle to foliation and displaced along foliation plane in schist one mile south of Darlington. Bedding exhibited by quartz pebbles seen just below white object. White object $2\frac{3}{4}$ inches.

P, 144 B

Good examples of discordant contacts occur three-eighths of a mile north of Frenchtown on the east bank of the Susquehanna River (gabbro-granodiorite). Here the granodiorite structures cut off those of the gabbro at an angle of about twenty degrees. Discordant contacts also occur in the Baltimore and Ohio Railroad cut just west of the Susquehanna River, and one-half mile south of Lapidum. Here the granodiorite apparently flowed into place in the direction of the flow lines of the gabbro. The granodiorite cuts both the linear and platy structures of the gabbro and in both of these localities gabbro inclusions are present in the granodiorite.

The metadacite and granodiorite are discordant in many instances. Often the platy structures are parallel in strike but the granodiorite cuts the metadacite in dip. This can be observed at the north contact on Northeast Creek and at the eastern extremity of the metadacite body, two miles north of Mechanics Valley. Other discordant contacts of these two rocks occur on Northeast Creek one and one-half miles north of Leslie, one half mile north of Jackson and immediately north of Cokesbury.

REGIONAL DISTRIBUTION OF STRUCTURES

The Port Deposit granodiorite complex consists of a number of petrographically different and structurally independent units (See Foliation Map, Plate XX in pocket). Planar structures in all of them conform roughly to the general trend of the region. The Conowingo intrusive contains innumerable inclusions of older rocks which are all aligned within the foliation plane. The Port Deposit unit is strongly foliated and almost devoid of inclusions. The massive granodiorite to the southeast shows a very feeble foliation and also very few inclusions.

Strong flow lines were observed in the Conowingo intrusion. They are feeble in the Port Deposit unit and almost entirely absent in the massive granodiorite. The orientation and intensity of the linear elements is so typical for the different units that it is possible to map them according to their structures. Flow lines in the Conowingo intrusive are always steep. In numerous localities they are vertical. In all the exposures of typical Port Deposit granodiorite they dip gently. Along the Susquehanna River they dip east up to 60 degrees, four miles northeast from Port Deposit they dip 20 degrees east, and north of Elkton they dip gently east and west.

Cross joints in all the intrusives maintain an angle of approximately 90 degrees to flow lines. They dip, therefore, gently west near Conowingo where they are very conspicuous (pl. XVIII, fig. 2). They are steep and perpendicular north of Elkton and near Port Deposit. At Port Deposit they coincide in places with regional tension joints (pl. XXI; XVIII, 1).

Wall rock schistosity frequently parallels the foliation of the intrusives. Linear stretching, however, deviates up to 90 degrees. The intrusives obviously follow foliation planes of the wall rocks. Thus innumerable wall rock inclusions are torn loose and oriented. Dikelets of granodiorite follow this foliation and cut across bedding (pl. XIX, fig. 2). Because of this relationship and the pre-granitic structures of the wall rock the contacts usually appear concordant. Instead of a clear transgression much intertonguing is observed.

The relationship between contacts and flow structures is so dependable a criterion that contact trends can often be mapped by following granitic flow structures.

Structures in inclusions and occasional discordant contacts clearly prove the age relationships. Regional tension joints are perpendicular to the longest axis of the intrusive bodies and, therefore, are perpendicular to the regional wall rock trend. These joints, however, are steep and independent of local linear orientations. Wherever they coincide with cross joints they are particularly well developed and conspicuous. Since the regional trend varies between NE-SW and E-W these tension joints form a fan which opens towards the northwest and converges towards the southeast.

Structures such as border gneisses, marginal thrusts, feather joints, and others which depend upon local conditions along contacts or faults cannot be traced over a larger area. They may occur everywhere if conditions permit. Marginal gneisses and joints occur, for example, near Lapidum; intrusive breccias, along the northern contact; and feather joints, in many localities particularly at the Bridge quarry where displacements along joint planes have taken place.

SUMMARY AND CONCLUSIONS

In the present paper the author has attempted to contribute new facts and conclusions towards the solution of some of the many intricate problems of the Piedmont region. The area investigated is highly complicated and while it has not been possible to solve the problems completely, it is hoped that the data presented will be serviceable to other workers. This investigation was built up on the results of other workers without which it would not have been possible.

The new geological map which deviates considerably from the older ones is based upon new exposures, as for example, an abundance of new road cuts, test holes, and structural data. Conowingo Dam has been constructed since previous workers have examined the region and the author was thus able, during the summer months, to study the excellent exposures in the river bed below the dam.

The new map shows a number of smaller independent granodiorite bodies instead of a large continuous pluton. The amount of granodiorite present is thus reduced considerably and it is believed that it underlies a still smaller area than is shown on the map. It seems necessary to assume many small concordant granodiorite injections.

Since the granodiorite intrusives are structurally independent, and their structures differ from each other and the wall rock structures, they must be primary. A regional deformation produces regional structures.

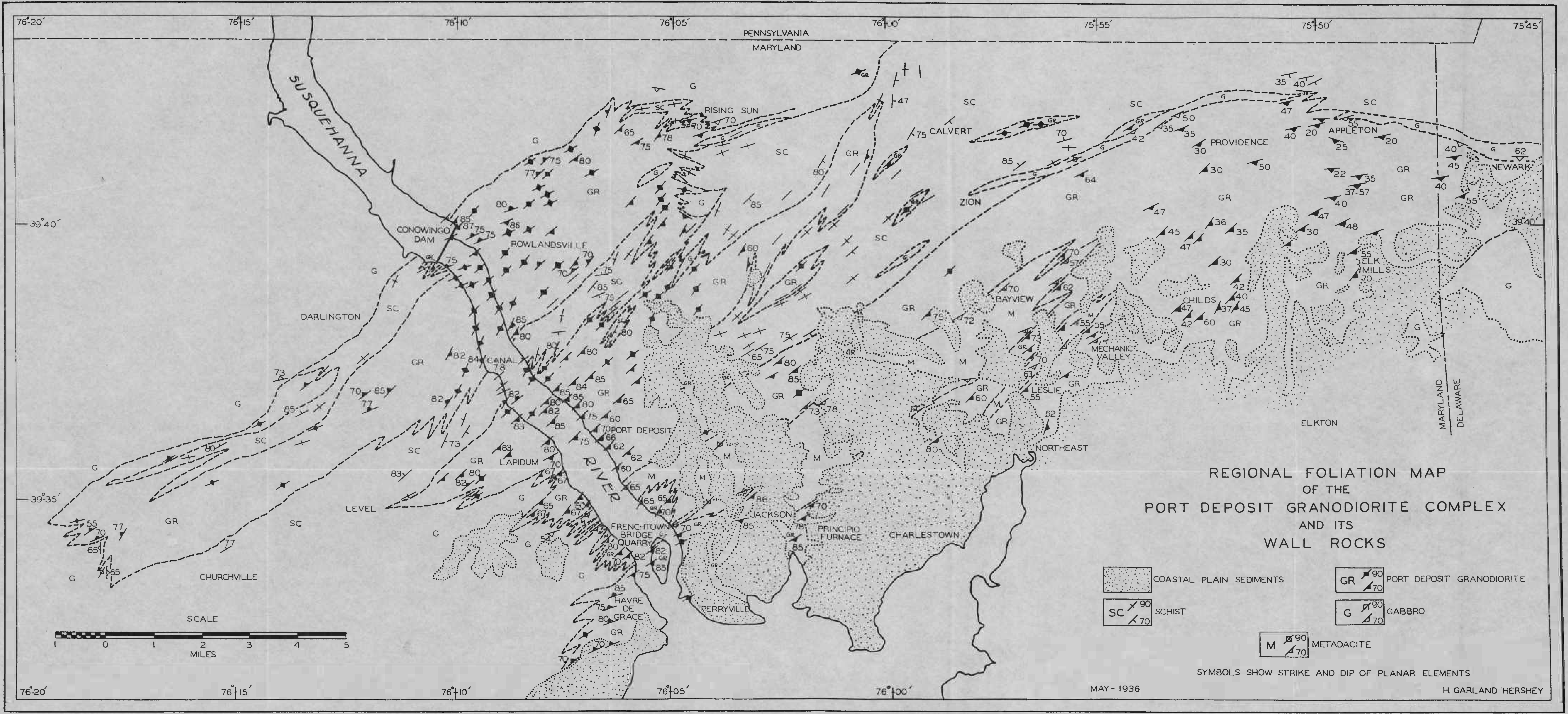
The area shown as Baltimore gneiss or gneiss in Bascom's maps (12, 118) extends toward the northwest through the entire region and underlies most of the territory south of Rising Sun and Calvert. The material is composed of phyllites, quartzites, and conglomerates which were found south of Darlington and within the inclusions in the granodiorite. These materials resemble somewhat the Peters Creek formation further north but an exact correlation is difficult because of weathering and alteration.

The age relationship within the pluton and with respect to the Paleozoic rocks near Lancaster was established on structural evidence. The oldest rocks of the pluton seem to be pyroxenites and peridotites, followed by gabbro, which is intruded by a series of granodiorites. The sequence is clearly from ultrabasic to the most acid intrusive. This sequence is paralleled by a structural sequence. The earliest intrusives are the most altered ones, and have the most intense foliation and stretching. Their structures are transgressed and engulfed by younger intrusives. The decreasing basicity or increasing acidity is paralleled by decrease of intensity of foliation and stretching as well as alteration. The youngest intrusives (massive granodiorite) followed by aplites and diabase dikes etc. are almost structureless. This development is exactly the same as has been found by Cloos, Balk, Scholtz, and Stenzel in the Bavarian Forest by Ernst Cloos in the Sierra Nevada pluton (25) and by others in many localities.

An attempt has been made to establish the age of the entire pluton by structural methods. The evidence was presented in a preliminary paper by Cloos and Hershey (26). Structures such as fracture cleavage and flow cleavage which cut across the boundary between the known Paleozoics near Safe Harbor and the schists of presumably pre-Cambrian age were found to be transgressed, engulfed and followed by rocks of the Port Deposit pluton (granodiorite and gabbro). The pluton itself, therefore, must be younger than these structures. Since these structures transgress Conestoga limestone, the pluton must be post-Conestoga or at least late Cambrian. A more accurate determination has not yet been possible, but it is conceivable that the plutonic rocks are comparable to European syntectonic intrusions. They may thus be even as late as epi-Carboniferous. The age of the Woodstock and Ellicott City granites, the latter of which is strongly foliated, has been assumed to be epi-Carboniferous. The fact that the massive granodiorite is less foliated and fractured than the Ellicott City granite supports this view.

Should the large complex of schist which the writer has mapped be correlated with the Peters Creek formation, because of the conglomerates, quartzites, and quartz phyllites, the schist would be in a synclinal position. A schematic section along the Susquehanna River from NW to SE and from Peach Bottom to Havre de Grace would then be as follows: Peach Bottom slate—Cardiff conglomerate—Peters Creek quartzite and quartz phyllites—Wissahickon schist—serpentine and gabbro—granodiorite—conglomerate, quarzite, phyllite (Peters Creek?)—granodiorite—and altered volcanics. The Port Deposit pluton would in this case occupy a synclinal position. An examination of the contacts between Port Deposit granodiorite and gabbro west of the Susquehanna River and a comparison of this contact with the flow lines within the granodiorite may support this view. If the granodiorite entered its chamber in the direction of these flow lines it must have moved upwards over the gabbro from SE to NW. Detailed observations near Lapidum show that the granodiorite has broken off large spindle shaped fragments of gabbro in the direction of its flow lines.

The writer realizes that conclusions as to the synclinal character of the Port Deposit granodiorite pluton and the assumption of a phacolith is somewhat premature. It is perfectly evident, however, that the Port Deposit pluton is not a batholith but consists of a large number of small concordant intrusions. These are structurally and petrographically independent of each other and represent a sequence of intrusions which followed each other at close intervals and during one major period of deformation.



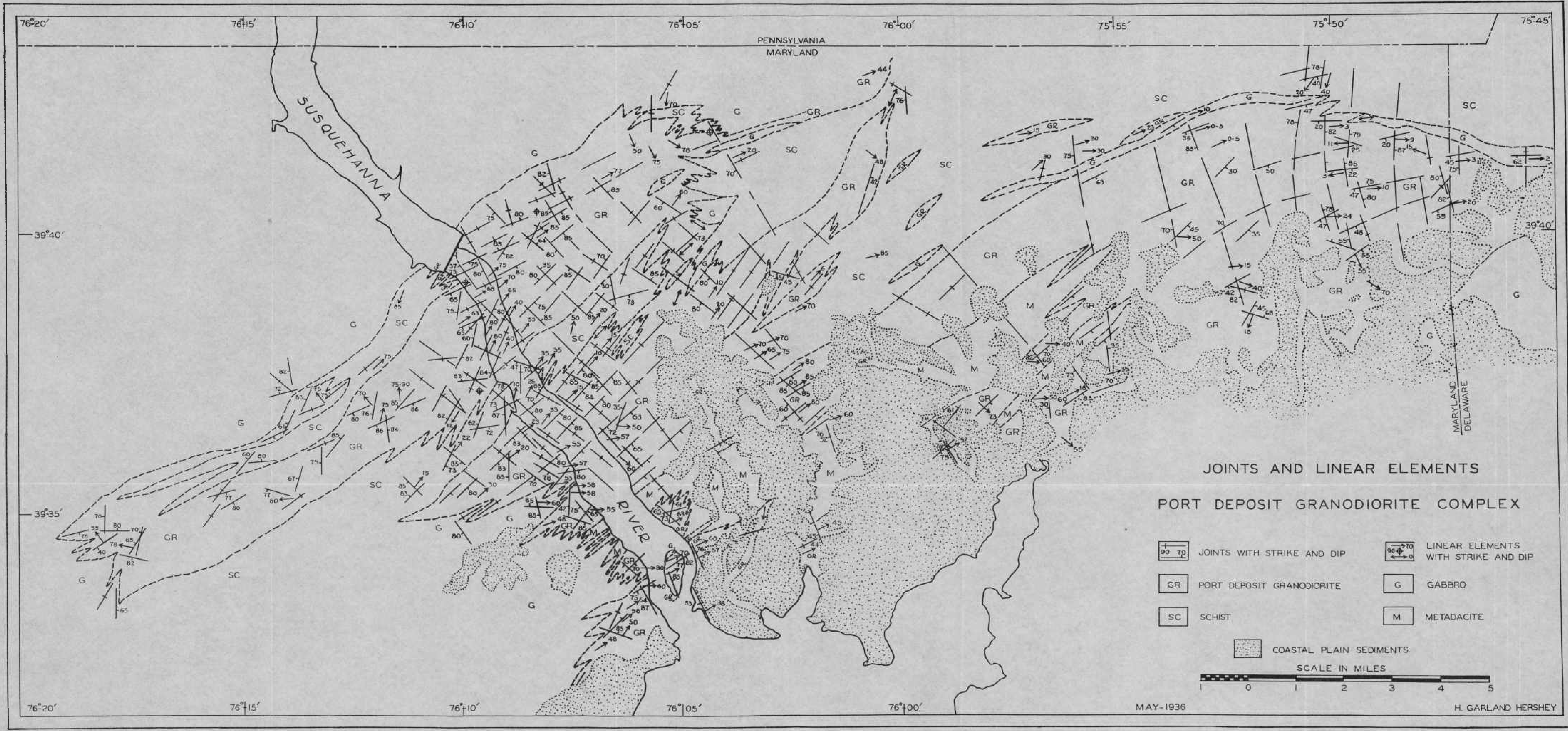
REGIONAL FOLIATION MAP
OF THE
PORT DEPOSIT GRANODIORITE COMPLEX
AND ITS
WALL ROCKS

SYMBOLS SHOW STRIKE AND DIP OF PLANAR ELEMENTS

MAY - 1936

H. GARLAND HERSHEY

Vol XIII 1937



JOINTS AND LINEAR ELEMENTS

PORT DEPOSIT GRANODIORITE COMPLEX

MAY-1936

H. GARLAND HERSHEY

PART III

THE STRUCTURE OF THE GNEISS DOMES NEAR BALTIMORE, MARYLAND

BY

CARL H. BROEDEL

THE STRUCTURE OF THE GNEISS DOMES NEAR BALTIMORE, MARYLAND

INTRODUCTION

Location and Size of the Area

The area under investigation is situated within the eastern portion of the Piedmont Province of Maryland. In a lenticular shaped area of schist extending from Washington northeastward to the Pennsylvania line occur six dome-like areas of Baltimore gneiss to which the writer will refer as the Phoenix, Texas, Towson, Baltimore, Chattolanee, and Woodstock domes. The schist area is about 18 miles wide in its central portion and narrows to the southwest and northeast. It is the eastern, more highly metamorphosed facies of a large major syncline, the axis of which is occupied by a younger, less metamorphosed series. To the west of this synclinal axis is the western less metamorphosed facies of schist. The gneiss domes are normally surrounded by a thin rim of Setters quartzite (pl. XXVII, in pocket). The writer has examined the domes proper, the intervening synclines of marble and schist were not investigated. The domes and the adjacent synclines and anticlines cover an area of approximately 130 square miles.

The axes of the domes trend northeast-southwest, extending from the easternmost portion of Harford County through Baltimore County, where they are largest, and thence across Howard County almost to the Montgomery County line. Eighteen miles northeast of Baltimore are four lenticular areas of gneiss which are correlated with the gneiss of the domes. These differ from the domes both in shape and the lack of bordering crystalline sediments and hence were considered outside the scope of this investigation.

Relief and Exposures

The Piedmont gradually rises from the fall line to the west and northwest and the main drainage is southeastward into the Chesapeake Bay. The difference in elevation is from 100 feet in the southeastern portion of the area to 600 feet in the northwest. The highest portion of the area is an old peneplain (Schooley peneplain) which rises westward. The Patapsco River, Gwynns Falls, Jones Falls, and Gunpowder Falls transect the domes and have entrenched themselves in the crystalline rocks of the Piedmont, forming deep valleys which provide good exposures. Tributary streams which have considerable gradients for a short distance from the main rivers have cut through the residual soil into the crystallines. Farther from the main rivers and towards the central portion of the domes the gradient becomes slight and the streams smaller, yielding only poor exposures and slight relief. The greater part of the area is gently rolling farm country with a relatively thin cover of residual soil and only occasional weathered outcrops. The Little and Middle Patuxent rivers in Howard County have entrenched themselves in the southeastern portion of the Woodstock uplift, providing locally fair exposures, while the same rivers in the central and western portions of the uplift form shallow valleys. The domes stand out relatively high with respect to the synclinal areas underlain by marble which normally surrounds and overlies both the gneiss and quartzite around the borders of the domes. This is due to the fact that the domes, which consist of a core of pre-Cambrian gneiss are normally surrounded by a resistant quartzite. It often forms wooded ridges or slopes around the periphery of the domes protecting the gneiss cores from denudation.

The best exposures in the area are afforded by numerous quarries and railroad cuts. Other exposures were confined to the larger entrenched river valleys, smaller stream beds with sufficient gradient, and road cuts.

PREVIOUS WORK IN THE REGION

The region about Baltimore was first studied by G. H. Williams (104–110). He divided the Piedmont of Maryland into two areas: an older eastern holocrystalline and a younger western semicrystalline area. This division was based on the greater degree of metamorphism and restriction of intrusives to the eastern area. A stratigraphic sequence had not yet been worked out.

In 1893–94 a detailed report on the granites of Maryland was made by Charles R. Keyes (60) accompanied by a summary of the relations of the granites by G. H. Williams (104).

Between 1894–1907 Edward B. Mathews, assisted by W. J. Miller, studied the structures of the Piedmont near Baltimore. A stratigraphic sequence was established and the schist was found to be the youngest sedimentary formation. An unconformity was recognized between the basal gneiss and the overlying quartzite, marble, and schist (73, 76). In 1905 he compared the sedimentary formations of the Baltimore region with similar deposits believed to be of lower Paleozoic age in southern Pennsylvania. He considered the basal gneiss (Baltimore gneiss) as pre-Cambrian and the overlying quartzite, marble, and schist as Cambro-

Ordovician. In the same year Mathews and W. J. Miller (75) published a summary of their work on the general structure in the dome area of Baltimore County. Detailed descriptions were given of the structure in the vicinity of a fault which crosses the county in its central portion in a northerly direction. W. J. Miller (80) made a detailed study of the stratigraphy and structure of the marble areas of Baltimore County.

In 1907 Mathews (73) pointed out the marked swing of the domes into an east-west trend near Baltimore occurring at a focal point of the great Appalachian swing farther west.

In 1923 E. B. Knopf and A. I. Jonas (66) described the crystalline schists of Baltimore County. The quartzite, marble, and schist were named the Glenarm Series. They concluded that the Glenarm Series was pre-Cambrian on the basis of structural relations in southern Pennsylvania and on the presence of metamorphosed lava flows interbedded in the schists, which they consider as probably equivalent to the pre-Cambrian Catoctin basal complex.

In 1929 Knopf and Jonas (64) gave an account of the rocks of Baltimore County with age relations and petrographic descriptions accompanied by a map of the areal geology. All the crystalline rocks of the county were considered pre-Cambrian except the younger granites and diabase dikes. The Baltimore gneiss is believed to be Archean and the unconformable Glenarm Series Algonkian. They state that the typical, even-banded Baltimore gneiss is sedimentary.

The pegmatites in the crystallines near Baltimore were described by E. H. Watson 102).

In 1933 E. Cloos (28) investigated the flow structure of the Ellicott City granite. Recently C. J. Cohen examined in detail the structures of the gabbro mass at Baltimore (see Part V of this volume).

GENERAL GEOLOGY AND PETROGRAPHY

STRUCTURAL AXES

The structural axes emphasized by the domes trend northeasterly, parallel to the Piedmont and Appalachian structure. In the vicinity of Baltimore they swing into an east-west direction. Four anticlinal axes are evident. They are, from northeast to southwest: the Phoenix anticline, the Caves-Texas anticline, the Woodstock-Chattolanee-Towson anticline, and the Baltimore anticline (fig. 17). The Caves-Texas anticline is a small dome of marble 2 miles north of Chattolanee. The Baltimore dome lies directly west of Baltimore City. The Phoenix and Caves-Texas anticlinal axes both strike N 65° E. The longest of these axes is the Woodstock-Chattolanee-Towson axis which forms an open double curve. In the Woodstock uplift the general trend is N 25° E; in the Chattolanee and western half of the Towson domes the trend is from E–W to N 70° W, while the eastern half of the Towson dome swings into a northeast trend. The axis of the Baltimore dome also trends N. E. but at its northern end swings into a northwest direction.

Two structures which appear to be cross folds transect the anticlinal axes. They form one saddle between the Woodstock and Chattolanee domes and another one which trends northward from Mount Washington to Cockeysville.

The arrangement of the Woodstock, the Chattolanee, the western half of the Towson and Baltimore domes about the Baltimore gabbro is unusual. The trend of these domes is older than the emplacement of the gabbro. The gabbro seems to have fitted this synclinal depression within the borders of these domes (see Part V of this volume).

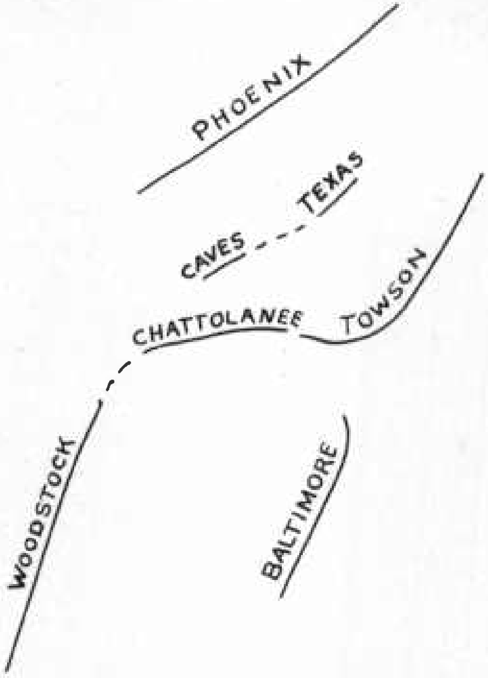


FIG. 17.—Trend of the anticlinical axes of Baltimore gneiss domes in Maryland.

DISTRIBUTION OF THE ROCK TYPES IN RELATION TO THE ANTICLINAL STRUCTURES*

THE BALTIMORE GNEISS COMPLEX

The cores of the domes are composed of an intimately banded gneissic complex principally of four types. The larger portion of the complex

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* For detailed information and localities not shown on plates XXVII–XXXII see geologic map of Baltimore County.

varies from a heavily banded granitoid biotite gneiss to a thinly layered ribbon gneiss (Baltimore gneiss). Interbanded and concordant with the Baltimore gneiss is an augen gneiss (Hartley augen gneiss), which seems to be confined chiefly to the periphery or upper portion of the gneiss cores, although exceptions do occur. The third type is a hornblende gneiss or amphibolite which, like the augen gneiss, is interbanded with the Baltimore gneiss. The bands are from one foot to many feet thick. No regularity in the distribution was observed with respect to the gneiss cores. They are, however, restricted to certain zones. Several zones occur along the Patapsco River for 2 miles in the vicinity of Woodstock. They are common throughout the Baltimore dome and locally in the northwest portion of the Towson dome. The fourth type is a medium grained gneissic granite (Gunpowder granite). It intrudes and injects all of the previous three types as well as the lower Glenarm formations with which it is generally concordant. This granite is difficult to distinguish from the granitoid facies of the Baltimore gneiss, so that only an approximation can be made in regard to its distribution. It is most typically developed in the eastern portion of the Towson dome and occupies a large portion of the Texas dome although here the granite is difficult to distinguish from the Baltimore gneiss. Thin stringers and bands apparently equivalent to this orthogneiss inject the Baltimore gneiss throughout the western portion of the Towson and eastern part of the Chattolanee domes.

Between the Baltimore gneiss complex and the Glenarm Series is a major unconformity. Both stratigraphically and structurally it is an important boundary and will be used in the following text as a datum plane.

THE SETTERS FORMATION

The distribution of the Setters formation is closely related to the shape of the gneiss cores of the domes and associated anticlines normally surrounding them as a narrow rim except locally if it is missing. This formation in its most typical development is composed of three members: a lower mica schist member, a middle quartzite or mica gneiss member, and an upper mica schist member. This threefold division can not always be recognized. Quartzite may dominate the formation in some localities while mica schist may prevail in others. Again, the quartzite member may be replaced by a series of alternating beds of mica schist and quartzite. In general the quartzite is the most characteristic member and forms an excellent guide horizon. Due to its high resistance against weathering as compared with the gneiss and particularly the Cockeysville marble, it frequently forms prominent ridges around the gneiss domes in the more dissected areas.

The Setters formation is exposed as a continuous rim along the northern flank of the *Towson dome* except one-half mile southeast of Oakleigh where it is locally missing or very thin. Along the western end of the dome it is cut out by a prominent fault between Riderwood and Mount Washington (Ruxton fault). Along the southeastern flank of the dome relations are obscured by Coastal Plain sediments. The Setters formation is continuous from the sharply compressed nose near Hartley southwestward to Cub Hill. On the north side of Gunpowder Falls it is intruded by large amounts of Gunpowder granite. Its continuation southwestward to Herring Run where it is again exposed is likely since typical quartzite fragments were found several hundred yards north of Putty Hill Road, 1.4 mile west of the Harford Road. That a closure exists around the southern nose of the dome south of Lake Montebello is indicated by a convergence in strike and new exposures along Lock Raven Boulevard.

The gneiss core of the *Texas dome* is flanked by the Setters formation on its north, east, and southeast sides. Along the southern border of the dome it apparently lenses out at the Pots Spring Road, while along the entire western side it is cut out by a fault. At the south end of the dome it forms a large mass, probably the result of local folding, while along the eastern flank at Pots Spring Road it becomes very thin. The quartzite member is poorly developed except at the north end of the dome. The larger portion of the formation is mica schist with occasional quartzite beds. A highly garnetiferous mica schist forms the upper part of the formation.

The *Chattolanee dome* is surrounded by a continuous rim of the Setters formation except where it is locally cut out by fault breccias along the southern flank. Here two quartzite ridges branch off from the dome and thin rapidly eastward. At Mount Wilson the Setters formation forms two parallel ridges, the limbs of an infolded syncline. The western half of the north limb is largely brecciated while the south limb is locally confused with Wissahickon schist.

The Setters formation is largely missing around the *Baltimore dome*. It occurs only along the northwestern flank of the dome between Gwynns Falls and Hampden where it is largely developed as a mica schist. It is apparently cut out at both ends by an igneous intrusive (Relay quartz diorite).

It forms a continuous rim around the *Woodstock* and associated anticlines (pl. XXVIII, in pocket) with the exception of the southeastern flank of the anticlinorium. Here, due to the lack of exposures and confusion with the Wissahickon schist, its continuity is uncertain. However, along the middle Patuxent River where a typical section is exposed and near Dorseys Run the presence of quartzite was sufficient to establish it at least locally. In the vicinity of Rockland, Howard County, it is very thin and apparently discontinuous.

Around the *Phoenix dome* and associated synclines the distribution of the Setters formation is irregular, frequently thinning or pinching out. It is locally absent near Monkton and Dover and along the southwest flank of the dome. It is also largely missing along the flanks of a large syncline infolded into the northwestern portion of the dome.

THE COCKEYSVILLE MARBLE

The Cockeysville marble is a medium to coarse-grained marble frequently interbedded with dolomitic layers. Locally calcareous mica schist facies are developed. It is the least resistant of the rocks in the region and forms characteristic valleys. The marble has its greatest development in the northern half of the area especially in the broad synclinal area which lies between the Phoenix dome on the north and the Chattolanee and Towson domes on the south. The marble is irregular in distribution throughout this syncline, probably because it lies at a relatively shallow level and where slight uplift has taken place broad valleys have been formed. In the southern half of the area, where structures have been more deeply folded, the marble is restricted areally and frequently lacking. It appears in narrow valleys surrounding the Setters formation.

Marble accompanies the northern border of the Towson dome from Greenwood along the southeastern flank, where it is apparently thrust out, to Hollins Station along the western end where it is cut out by a fault. Along the southwestern flank between Govans and Lake Montebello the presence of marble has been indicated by the character of the water and proven through excavations for the city water tunnel.

It is possible that the marble completely surrounds the Chattolanee dome although its continuation along the southern flank is somewhat uncertain. In the vicinity of Pikesville and south of Horsehead Branch along the western margin of the uplift there is some doubt as to its presence, but locally it is indicated by valleys. It occurs in three narrow valleys which flank the two anticlinal arms or slivers of quartzite along the southeastern border of the dome. Again, at Mount Wilson it occurs in a syncline of the Setters formation about three miles long.

In the Woodstock anticlinorium the marble is irregularly distributed and apparently discontinuous. It normally surrounds the Woodstock dome and associated anticlines, forming narrow valleys around the Setters formation. Marble occurs along the entire northern and western margin of the anticlinorium while it appears to be missing along the entire western margin, except for a narrow strip between Rockland and Alberton. It is most extensively developed in a shallow syncline west of Clarksville, while farther to the north it plunges under a syncline of Wissahickon schist, forming narrow valleys along the limbs of two synclines which lie along the southeast side of the Woodstock dome. It seems to be largely missing along the limbs of the overturned anticlines and synclines lying southeast of the dome. Marble is developed locally in the complicated structures near Alberton, in the syncline near Davis, at Jew Bottom ($\frac{3}{4}$ mile northwest of Alberton) along the south limb of a narrow anticline which may be called the Jew Bottom anticline, and for a short distance along the western flank of the Bens Run anticline.

Marble almost completely surrounds the Texas dome with the exception of the northwest side where it has been cut out by a fault. It surrounds the Phoenix dome except along its northeast and southeast flanks where it is locally missing. It attains its largest development in the broad syncline within the northwestern portion of the dome.

THE WISSAHICKON FORMATION

The Wissahickon formation is the youngest formation of the Glenarm Series encountered in the area occupied by the domes. It has been called the Wissahickon oligoclase mica schist to distinguish it from its western less metamorphosed facies. It is composed largely of mica schist and mica gneiss interbedded with quartzite. This formation has a larger areal extent than any of the preceding formations and occupies the greater part of the synclinal areas between the domes. It is confined chiefly to the northern and western portions of the area, while in the northeastern portion it is either covered or cut out by large igneous intrusions.

The Wissahickon schist completely surrounds the Woodstock anticlinorium as well as the Phoenix and Chattolanee domes, except in the vicinity of Cockeysville and Brooklandville respectively. This appears to be due to slight uplift in those two localities accompanied by removal of the schist. It surrounds the eastern half of the Towson dome from Oakleigh to Lake Montebello, forming a narrow strip along the entire southeastern flank. In the Woodstock anticlinorium the schist is confined to narrow synclines associated with the Woodstock dome.

THE PEGMATITES

Both conformable and cross-cutting pegmatite dikes occur throughout the gneiss complex and overlying crystalline formations although the larger dikes appear to be confined to certain areas. Pegmatites vary in size from small stringers and isolated lenses to large dikes several hundred feet wide and a mile or two long. The larger pegmatite veins generally occur as dike swarms and conform to the local strike of formations. They seem to be most abundant along the flanks of the domes and anticlines as well as within synclines or at contacts. Pegmatite dikes are particularly abundant in the easily permeable mica schist of both the Setters and Wissahickon formations which have lent themselves to pegmatitic solutions. Here the dikes formed are nearly always concordant. They appear to be lenticular bodies having spread apart the schist on both sides.

Pegmatites are most abundant in the Baltimore dome and synclinal structures southeast of the Woodstock dome. In the Baltimore dome a series of large pegmatites occur in the gneiss along Gwynns Falls between its western limb and Claremont. These are largely conformable and in the southern portion are highly schistose. Smaller dikes, stringers, and offshoots from the larger dikes are frequently cross-cutting. Large dikes occur along the contact of the Setters mica schist with both the gneiss and quartz diorite. Swarms of large dikes have injected the mica schist south of Hampden.

Many large and small pegmatites have intruded and injected the synclines and limbs of anticlines between Hollofield and Davis. They are most abundant in the Wissahickon schist and marble and to a less extent in the gneiss and quartzite. A swarm of large dikes follows the eastern flank of the anticlinorium from Rockland northward for three miles. Another swarm occurs in a syncline which swings around the north end of the anticline at Alberton and parallels the north side of the Patapsco River to the vicinity of Davis where it crosses the river in a northwesterly direction (Davis syncline). East of Rockland and Alberton large pegmatite dikes follow the contact between the Baltimore gneiss and Setters formation. A few pegmatite dikes occur within the gneiss core of the Woodstock dome, but these are mostly small. Several large dikes intrude the Wissahickon schist and marble along the northwest border of the dome between the north and south branches of the Patapsco River. In the southern half of the anticlinorium large pegmatites are not common. Several dikes intrude schist and marble in a syncline which extends southward to Clarksville, as well as the gneiss along the western border of the adjacent anticline on the east. Also in the schist along the southeastern flank of the anticlinorium pegmatites are common.

In the Towson dome pegmatites are largely confined to the flanks. A swarm of dikes occurs in the marble and schist along its northwestern limb between Cromwell Bridge and Glenarm. Large pegmatite dikes are not common within the gneiss complex although smaller stringers and lenses are abundant. Two dikes follow the contact between augen gneiss and the Setters formation along the north flank of the dome near Oakleigh and at Gunpowder Falls.

No large pegmatites are associated with the Chattolanee dome, although small stringers and lenses are common. In the Texas dome they are also lacking, although several inject the Setters mica schist along the south side.

THE ALASKITE-PORPHYRY DIKES

A number of alaskite porphyry dikes up to several feet wide cut the marble and schist between Hollofield and Dorseys Run. Locally they conform to the strike of the country rock. The largest dike cuts across the strike of the schist along the northeast limb of the Alberton anticline one-half mile east of Alberton and strikes N 20° E. Along the south side of the Patapsco River one-half mile southwest of Alberton two dikes intrude the marble and contact between marble and Setters formation. They strike northeast and cut across the strike of the country rock. Along the north side of the river, one-half mile northeast of Alberton, 9 large dikes and several smaller ones cut the schist, although several appear to be locally conformable.

THE DIABASE DIKES

A belt of one or more diabase dikes crosses the western part of the area in a north to northeast direction (Plates XXX). It follows the southeastern flank of the Woodstock dome near Dorseys Run, crosses the eastern half of the Woodstock dome and western end of the Chattolanee dome where it appears as two dikes, although these may be connected. Farther north it has been traced as a single dike across the northwestern portion of the Phoenix dome. These dikes have no relation to the domes and clearly cut across all structures. In the vicinity of Dorseys Run evidence of five dikes was found within a distance of one and a half miles and in the northeastern portion of the Woodstock dome there appear to be two dikes. The dikes are rarely exposed, their presence being indicated by scattered boulders which can only be traced for a short distance along the strike. It is possible that some of them may be connected.

FAULT BRECCIA

Breccia occurs at a number of places throughout the area, principally along the periphery of the domes. It is most typically developed along the Ruxton fault between Mount Washington and Warren. It is exposed at the southern end of Lake Roland and occurs along the west side of the Texas dome for two miles. In the Chattolanee dome breccias occur locally along the south side. Along the southeastern flank two breccias occur between the gneiss and quartzite, one of them one and a quarter miles southwest of Rockland and the other a mile and a quarter farther

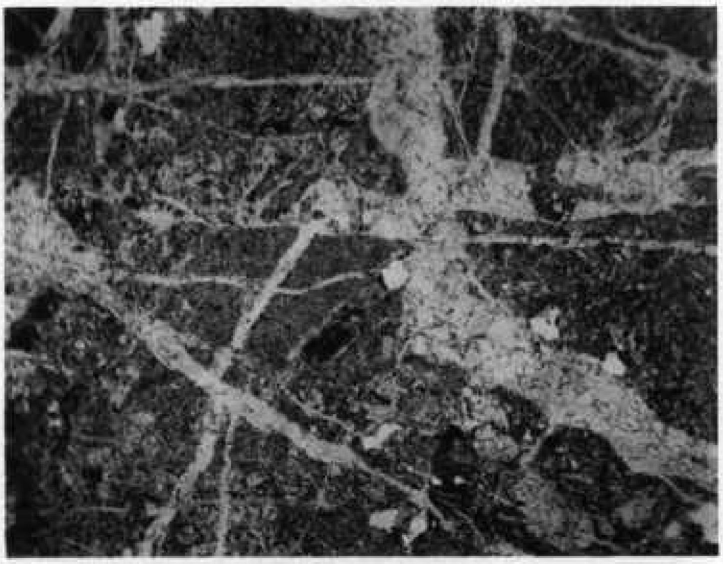

FIG. 1.—Fault Breccia from Lake Roland northwest of Baltimore. Photomicrograph. Approx. × 15.

FIG. 2.—Foliation and gently dipping axes of folding in Baltimore gneiss. North Charles Street, one and a quarter miles southeast of Ruxton.

west. The western portion of the north limb of the syncline at Mount Wilson is largely brecciated. The only definite evidence of brecciation in the Woodstock anticlinorium is a local occurrence on the south limb of the Jew Bottom anticline, $\frac{3}{4}$ mile east of Davis. Breccia also occurs along the limbs of a syncline infolded into the southeastern portion of the Woodstock dome, but those are of a different type and may be brecciated and leached igneous rocks (see Plates XXXI).

RELATION OF GRANITE AND GABBRO INTRUSIONS TO THE DOMES

In general the granites appear to have intruded the domes and associated anticlines while the gabbros and associated basic rocks have sought the synclinal areas, as is shown in many other crystalline terranes. This generalization holds good for the basic intrusives but does not cover all the granitic rocks, large bodies of which have intruded and injected the schist along structural boundaries or as isolated lenticular bodies within the gabbro areas.

The granitic rocks may be divided into older granite gneisses and younger granites. The former are confined to the eastern portion and the latter to the western portion of the area. The granite gneisses have intruded and injected the Baltimore gneiss in the Texas dome and eastern portion of the Towson dome. They occur in the gabbro belt of the Texas dome as well as within the Baltimore gabbro. A gneissic quartz diorite forms a long sill-like body between the Baltimore gabbro and the Baltimore gneiss along the north side of the Baltimore dome. Among the younger granites which have intruded the Baltimore gneiss are the intrusive in the center of the Woodstock dome and smaller bodies in the anticlines to the southeast. Among those in the schist are the octopus-like intrusion at Ellicott City (26) along the southwestern contact of the Baltimore gabbro and a large series of intrusions and injections which follow the entire southeastern border of the Woodstock dome and associated anticlines and synclines (Woodstock anticlinorium).

The basic rocks including gabbro and serpentine are confined to three main zones: an eastern belt which follows the southeastern border of the Towson dome, a large central mass occupied by the Baltimore gabbro (see pt. V), and a western belt which follows the western border of the Woodstock anticlinorium and the northwestern flank of the Phoenix dome. Other small dikes of serpentine occur in minor synclines of schist associated with the domes, as, for example, the dike along the western flank of the Bens Run anticline. The eastern and western belts of basic rocks mark the eastern and western boundaries of the Maryland domes. The former belt of gabbro occupies a synclinal area of the schist into which a series of anticlines or slivers of Baltimore gneiss have been upfolded or upthrust near Belair. The western belt occurs along the western border of the eastern facies of the Wissahickon synclinorium and lies directly east of the Peach Bottom syncline which marks the axis of this synclinorium.

UNCONFORMITY BETWEEN THE BALTIMORE GNEISS AND THE SETTERS FORMATION

An unconformity between the Baltimore gneiss and Setters quartzite, the lowest formation of the Glenarm Series, has been recognized by all who have studied the Piedmont of Maryland. The unconformity in Maryland has been largely obliterated by intense folding during the uplift of the domes. The best evidence for a general unconformity is shown by the much greater deformation and igneous injection in the gneiss as compared with the Glenarm Series. In addition the Hartley augen gneiss and the hornblende gneiss, which occur in the Baltimore gneiss, are absent in the Setters and overlying formations. In contrast to the gneiss with its high degree of minor isoclinal folding and its ptygmatic folds, the quartzite is relatively free from such minor folds except locally. It was protected by and folded along with the old gneiss surface during post-Glenarm deformation.

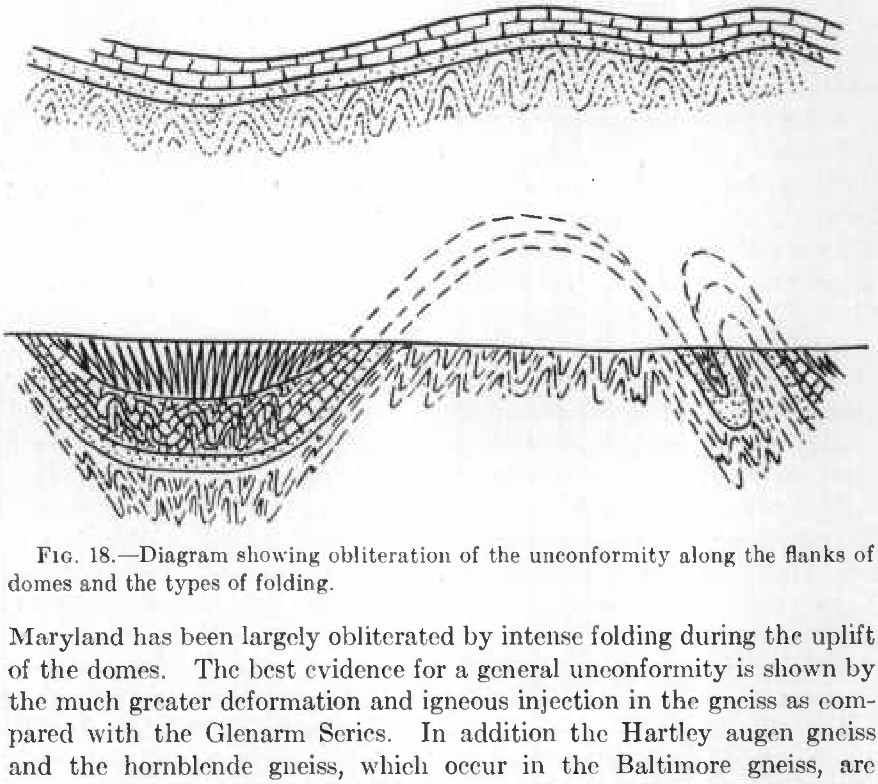

FIG. 18.—Diagram showing obliteration of the unconformity along the flanks of domes and the types of folding.

Knopf and Jonas (64) point out a divergence in strike of 20 degrees between the gneiss and quartzite as evidence for an unconformity. To the writer this appears to be insufficient evidence, since the foliation of the gneiss and the bedding of the quartzite often vary considerably in strike as a result of minor folding even within a short distance of the contact. Where contacts are exposed they are always conformable.

One would expect to find evidence of an unconformity on the crests of domes or anticlines where the quartzite lies flat upon the gneiss but such contacts have either been eroded or are not exposed. The sharp nose of domes and anticlines were also investigated, but exposures at such critical points were either lacking or insufficient to determine an angular unconformity. On the other hand, the general strike and dip of the gneiss foliation, wherever observed along the blunt ends of the domes, was largely conformable to that of the quartzite.

METHOD OF STUDY

The domes near Baltimore are unique elements in the structure of the Piedmont. Their circular-to-oval outline distinguishes them from other similar uplifts to the northeast in Pennsylvania, New Jersey, and southeastern New York, which are anticlinal rather than dome-like. Anticlines and synclines associated with a single dome were found to be overturned in different directions and this leads to a complicated problem as to the type of deformation which produced such structures. The region as a whole is poorly exposed, formations are unfossiliferous and often difficult to distinguish from one another; and sudden thinning or lensing out of formations along the strike occurs in many places. Overlaps, occasional unconformities, igneous intrusion, faults and overthrusts may be responsible for the apparent local absence of formations.

A study of the best exposed profile and most complicated structure in the region was undertaken. The writer spent the summer of 1933 making a detailed map along the Patapsco River from Hollofield to Marriottsville. A section about one mile wide was mapped in detail on a scale of 200 feet to the inch. Later the study was extended to the domes as a whole and the associated anticlines and synclines. The Towson, Baltimore, and Chattolanee domes were surveyed during the fall of 1933 and spring of 1934. The summer of 1934 was spent in the westernmost uplift known as the Woodstock anticlinorium. Two weeks were spent in the granite intrusives in the Woodstock dome. An attempt has been made to determine whether or not structures in the granite conformed to those in the surrounding country rock. Occasional field trips were continued throughout the fall of 1934 in studying the Texas dome. The Phoenix dome was mapped during the summer of 1935.

In such a highly folded region as the Piedmont of Maryland large numbers of measurements must be taken in order to obtain a picture of the structure. All available structural elements were measured in an attempt to ascertain the trend or pattern of these elements with respect to the general outline of the domes. The structures measured were linear elements such as axes of folds and crinkling (see Part I of this volume), parallelism of minerals and grooving on foliation and bedding planes (linear stretching), and slickensides. Platy elements measured include bedding, foliation, joints, cleavage, and axial planes of folds. It was not possible to obtain sufficient readings on slickensides and axial planes to draw any conclusions from them. Particular attention was paid to linear parallelism, axes of folds, and cross joints since these were found to be most useful in interpreting the structures. The strike and dip of foliation and bedding was found to vary considerably within any one locality; this is to be expected in a highly folded region. Therefore large numbers of measurements were taken in order to obtain average values. Likewise, thousands of readings of linear structures and joints were taken because linear structures such as linear parallelism and axes of folding were often exceedingly irregular both in strike and pitch especially in the gneiss.

During the earlier field work joints were measured at random throughout the domes and appeared to be highly irregular, but in the east-west trending structures prominent systems of cross-joints were noted. Large numbers of joints were needed at well exposed points throughout the area for the determination of the major joint systems. A statistical counting of joints in the gneiss, quartzite, and marble was therefore made in 25 quarries and well exposed localities.

Over 3500 measurements were taken of bedding, foliation, joints, linear structures, and other elements. In addition about 3000 joints were read and counted in quarries and plotted on joint diagrams (figs. 19–26).

A Breithaupt compass graduated in 360° was used in the field work. All readings of strike were read in terms of 180°, north being 0 or 180°, northeast 45°, east-west 90°, and northwest 135°. This method of recording was both simple and time saving and found to be very satisfactory when large numbers of measurements are to be made. In the descriptive portion of the text as well as in the joint diagrams the writer will refer to strike directions as 45°, 90°, 135°, and 180° respectively.

The areas overlain by Coastal Plain sediments were omitted from the maps since they would only have confused the outlines and structure of the area.

The following were used as base maps: Baltimore and Ohio Railroad right-of-way maps of the Patapsco River section (1 inch = 200 feet), Maryland State Roads Commission maps of Baltimore and Howard counties (2 inches = 1 mile) and the topographic maps of the State Geological Survey (1 inch = 1 mile).

Plates XXVIII and XXX were platted on a scale 2 inches = 1 mile and reduced to half size. In these maps a large number of readings could not be platted and only averages were used.

Plates XXIX and XXXI were drawn from an enlargement of the topographic maps on a scale of 4 inches = 1 mile, the contour line map (Plate XXVII) being reduced to quarter size and the cross sections (Plate XXXII) to half size.

The contour lines are based on the outcrop of the Setters quartzite and represent its attitude only along the flanks of the uplifts. No attempt was made to reconstruct its entire surface. In plotting the joint diagrams a scale of $\frac{1}{10}$ inch = 1 joint was used. The number of joints at intervals of five degrees were added and plotted between these directions to smooth out irregularities and then reduced to half size.

REGIONAL DISTRIBUTION OF STRUCTURES

GENERAL REMARKS

Soon after the beginning of the investigation it became evident that the unconformity between the gneiss basement and the sedimentary cover (Glenarm Series) was of great importance. The gneiss complex is very closely folded, as shown by frequent reverse dips. Its surface, however, shows a much more open folding and a much less irregular outline. It was recognized that the Setters formation followed this surface closely and is comparatively free from minor folds. On the other hand, the sediments (marble and schist) above the Setters formation are tightly folded and, as a rule, not closely related to the areal distribution of this unconformity. The gneiss surface and the Setters formation seem to represent a twofold unconformity; that is, stratigraphic as well as structural and therefore a plane of great tectonic significance. A contour line map was drawn approximately on the quartzite member of the Setters formation in order to show the shape and configuration of this plane (Plate XXVII).

Because of the significance this plane of unconformity was used as a reference plane in the following and an attempt was made to consider the different structures in relation to it.

STRUCTURES BELOW THE UNCONFORMITY

INTERNAL STRUCTURES OF THE GNEISS DOMES

Arrangement of banding, linear parallelism, and axes of folding

The internal structure of the gneiss domes is dominated by primary elements. The banding, associated with and perhaps in part caused by the intrusion of granitic material into sediments, is undoubtedly older than the unconformity which truncated these structures in a more or less horizontal plane. Later movements and deformations have modified and altered the position of these primary structures. The present arrangement permits a reconstruction of their original attitude. The later and superposed deformation, which also affected the unconformity, can to a certain extent be reconstructed through a consideration of that reference plane.

The question arises: how the presence of these early primary structures affected the formation and shape of the later domes, in other words, the deformation of the unconformity. Did the gneiss possess a structure which facilitated the uplift of the domes and was accentuated by it, or is the structure of the gneiss domes entirely the result of later deformation which took place after the deposition of the Glenarm Series?

The arrangement of primary structures in the gneiss complex can be seen in plates XXVIII–XXXI. Three types of arrangement can be recognized, although combinations do occur: *linear* in which the elements strike parallel to the longest axis of the uplift, *circular* in which the elements parallel the flanks of round domes, and *transgressing*, the strike of the axes of folding and linear parallelism transgresses the axis of uplift and strike of banding.

Linear arrangement.—The strike of banding in the Phoenix, Towson, and Chattolanee domes and the southern half of the Woodstock anticlinorium parallels the axes of uplift, except at the blunter ends where it seems to "run around." At the sharper noses it seems likely that the banding maintains its strike. In general, where the domes are narrow and the gneissic bands dip vertical the strike of banding closely follows the axes; as for instance, in the eastern and western portions of the Towson dome and in the Chattolanee dome (Plate XXIX). Because of the gentle dip of banding in the central portions of these domes the strike is not shown.

Throughout the major portion of the Towson dome, except in its south-central part, banding parallels the axes of uplift. In its southern termination it follows the periphery of the dome. Banding is prevailingly steep to vertical and along the periphery generally dips outward from the center of the dome. There is evidence that banding along the entire southeastern border dips northwest, except in the vicinity of Long Green Creek (Plate XXXII sections 1 and 2). In the western portion of the dome banding maintains its east-west trend up to the Ruxton fault where it is truncated at a high angle (Plate XXIX and Plate XXXII section 3).

Along the north and south sides of the Chattolanee dome banding dips away from the complex or is vertical as along the north side. Along the east end more gentle dips prevail (Plate XXXII sections 4–7). The dome-like representation of banding in sections 4 and 5 is generalized from a number of very gentle dips.

In the southern half of the Woodstock anticlinorium throughout a long V-shaped anticlinal structure, extending from Mayfield southward to Highland and thence southeastward through Dorseys Run to Alberton, banding parallels the axes of uplift except along the periphery of its southern end where it runs around. This anticlinal structure will be referred to as the Mayfield-Highland and Highland-Alberton anticlines (Plate XXVIII). There is a general overturning of the gneiss toward the east from Alpha and Pine Orchard on the north to Highland and Fulton on the south of these anticlines. This overturning is more pronounced in the Mayfield-Highland anticline where very gentle dips are common (Plate XXXII, sections 12–14).

Axes of folding and linear stretching are largely parallel to the long axes of these domes. At the ends of the domes (noses) these linear structures plunge gently but retain their strike. These noses can be rather sharp (east ends of the Towson and Phoenix domes) or comparatively blunt, as the east end of the Chattolanee dome and southern end of the Woodstock anticlinorium.

The northeast end of the Towson dome is the most striking example of a sharply compressed plunging anticline. The Towson dome narrows down from a maximum width of 5 miles in its central portion to one-half mile at Long Green Creek. Three-quarters of a mile to the northeast it is only a few hundred feet wide.

The eastern end of the Phoenix dome resembles somewhat that of the Towson dome and has been likened by some observers to the prow of a boat. Similar sharp noses are seen at the southeastern termination of the Woodstock anticlinorium near Fulton and at the northern end of the Mayfield-Highland anticline.

Linear stretching in the Towson and Chattolanee domes seem directly connected, indicating the close structural relationship between the two. Linear parallelism and axes of folding follow the axes of these domes and plunge gently at their ends. The Chattolanee dome is the simpler of the two. Linear structures throughout the central portion of the dome are approximately horizontal. Along the eastern end they show a marked bend toward the Towson dome and pitch 10 to 30 degrees east (Plate XXXI). The Towson dome, on the other hand, does not show a simple dome-like arrangement of linear structures. Throughout the major portion of the dome from Cromwell Bridge to the Ruxton fault they pitch prevailingly westward 10 to 45 degrees. At Gunpowder Falls they are roughly horizontal and at Long Green the pitch becomes eastward. Where the westward pitch of linear elements becomes marked there is an increase in the width of the dome and the axes spread apart. They closely conform to the axes of the dome, except in its southern termination where they trend across the southwestern flank and pitch 10 to 25 degrees southwest (Plate XXXI).

Throughout the western two-thirds of the Phoenix dome linear structures pitch gently to moderately westward (10 to 40 degrees). Within the eastern one-third of the dome the axes plunge gently eastward. This arrangement is very similar to that in the Towson dome.

In the southern half of the Woodstock anticlinorium linear structures closely parallel the axes of uplift. Gentle to undulating pitches prevail and frequently they are horizontal. In many localities the strike of the axes of folding is rather irregular, pitching gently to moderately both northeastward and southwestward. Linear parallelism at the northern end of the Mayfield-Highland anticline seems to transect the uplift axis, pitching 20 to 25 degrees southwest (Plate XXX). Between Nichols and Fulton linear structures trend across the southwestern flank of the anticlinorium, pitching south 5 to 20 degrees. In the vicinity of Dorseys Run they are roughly horizontal while between Rockland, Howard County, and Alberton they plunge gently to steeply east (Plate XXX).

Circular arrangement.—Structures of this type are principally different from the linear arrangements and include the Texas dome and the eastern half of the Woodstock dome. The western half of the latter dome might be considered under transgressing arrangements below.

The linear as well as platy elements (banding) are bent into a semicircle following the periphery of the domes. The arrangement of structure is broad and more open. The ends of these domes are also broad and a horizontal section through the domes is more or less circular.

Banding in the Woodstock dome (Plate XXVIII) forms a roughly circular trend across the Woodstock granite intrusive. Along the periphery of the dome banding dips moderately to steeply away from the gneiss, except along its southeastern flank where it is overturned to the southeast and south. The banding converges toward the southern end of the dome where it forms a sharp nose. Throughout the southwestern half of the dome banding dips prevailingly westward (25 to 90 degrees) (Plate XXXII, section 11).

The trend of linear structures forms a semicircular arrangement in the eastern half of the dome, while in the western half they diverge slightly toward the west (Plate XXX). The eastern half of the dome is a typical example of circular arrangement of structure. East of Granite they are roughly horizontal. Along the northeastern periphery of the dome they parallel the banding and show a persistent north to northwest pitch (10 to 45 degrees). Throughout the western half of the dome they transect the strike of the banding and maintain a persistent west to southwest plunge (5 to 40 degrees).

Fig. 1.—Cross joints intersecting linear structures at an angle of 90°, Western Maryland Railroad cut at Lyons Mill Road.

Fig. 2.—Crinkled Setters schist showing axes (parallel to hammer handle) pitching gently west. Long Green Creek.

The Texas dome seems to be only a half dome because its western continuation has been faulted out. The eastern preserved portion is very similar to the eastern half of the Woodstock dome. Here the banding as well as linear elements form a semicircle and the shape of this dome is also broad and the eastern termination blunt.

Banding (Plate XXIX) bends around from an east-west trend in the southern portion of the dome to northwest in its northern portion. At the northeastern end the gneiss forms a sharp little nose which plunges gently under the Setters formation. Along the eastern side at Pots Spring Road the gneiss is slightly overturned to the east. The banding is truncated along the west side by the northern continuation of the Ruxton fault.

The trend of linear elements is much more regular (Plate XXXI). From a north-south strike and roughly horizontal position along the eastern side of the dome, they swing into a northwest strike and gentle northwest pitch at the northern end of the dome and into a northeast-southwest to east-west strike and westernly plunge (10 to 45 degrees) in the southern portion. Reverse pitches are found locally.

Transgressing arrangements.—Under this type are included uplifts in which the linear structures plunge down the dip of banding comparable to the arrangement of linear parallelism in the Böllsteiner gneiss described by H. Scholtz. This is, however, not a distinct type but a combination of types of which the Baltimore dome is the most typical. Here the banding trends roughly northeast, except at the northern end of the dome where it swings into a northwest direction along with the axis of uplift (Plate XXIX). Here the gneiss is probably truncated by the Relay quartz diorite. The gneiss dips prevailingly westward (20 to 50 degrees), except at the northern end where it dips steeply westward or vertical.

All linear structures trend west to northwest and plunge in the same direction (Plate XXXI). The dip of banding and linear structures coincide only in the northern end of the dome.

The Bens Run anticline may be included here. In this anticline banding trends north-south and dips steeply east to vertical, indicating a slight overturning towards the west (Plate XXXII, section 10). Linear structures, however, strike east to northeast and plunge moderately to steeply in either direction. This arrangement of linear structures seems to be affected by those in the Woodstock dome.

ARRANGEMENT OF CROSS JOINTS IN RELATION TO AXES OF FOLDING AND LINEAR PARALLELISM

A close relation between linear structures and cross joints becomes evident in Plates XXX and XXXI. Of the many joint systems which are found one direction seems to intersect the linear direction at an angle of approximately 90 degrees. If the linear direction changes in strike the cross joints roughly follow this change. They were, therefore, emphasized by heavy black lines which indicate their average strike. The direction was generalized in many places, because of local irregularities in the strike of linear elements.

The general interdependence can very well be observed in the distinct change in direction of the cross joints within the Towson dome (Plate XXXI). Between its western and northeastern ends they vary from a northeast-southwest to a northwest-southeast trend, or 66 degrees within six miles. The bend of linear structures and corresponding change in strike of cross joints is coincident with a bend of the northern flank of the dome. The anticlinal axis and linear structures are intersected at an angle of approximately 90 degrees by the joints. They are most prominent in the western and north-central portions of the dome where they dip steeply to vertical. In the northwestern portion of the dome cross joints strike 175 to 15 degrees and dip steeply east (Plate XXXI). Slight changes in the strike of linear structures are accompanied by a corresponding change of cross joints, as at Charles Street and Malvern Avenue where they trend northeastward and dip steeply east. Cross joints are not pronounced in the northeastern and southern portions of the dome. At Cromwell Bridge (fig. 20) they strike north-northeast and dip 65 degrees east. At Gunpowder Falls they strike 135 degrees and dip steeply northeast, while at Long Green Creek cross joints seem to strike north-south and dip vertical. In the southern portion of the dome cross joints with a few exceptions are replaced by a very pronounced east-west striking joint system.

The axis of the Chattolanee dome is straight and the internal structure of this dome is comparatively simple. Linear elements are roughly parallel to its axis and cross joints are perpendicular to both. North-south cross joints dominate over all other joints and generally dip steeply to vertical. At the eastern end of the dome they dip steeply west and swing slightly around to the northeast along with a corresponding bend in linear structures. In the western portion of the dome cross joints are abundant and dip steeply east (pl. XXIII, fig. 1).

The same relation is more conspicuous in the Texas and Woodstock domes. The cross joints have a radial arrangement and remain in a perpendicular relation to the linear structure. As in the Towson dome, cross joints parallel the strike of the Ruxton fault along the western portion of the Texas dome. Along its eastern side they strike east-west, while toward the north and south they swing around into a northeast and southeast direction respectively. The attitude of the joints is somewhat irregular but steep dips prevail.

In the Woodstock dome and associated anticlines relations are more complicated. Cross joints form a fan-like arrangement and appear to radiate northward from an area south of Dorseys Run, always remaining perpendicular to the linear structures. Dips are generally steep westerly to vertical in the eastern half of the dome while in its western half, where linear elements plunge gently westward, cross joints dip steeply east (see Plate XXX). Between Davis and Hollofield cross joints are very pronounced and maintain a north to northeast direction. Near Davis they dip steeply east while in the vicinity of Rockland they dip steeply west.

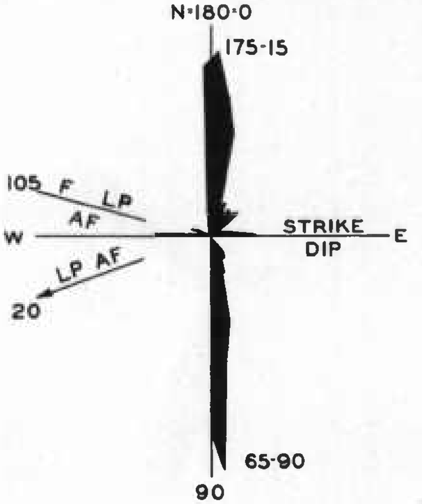

FIG. 19

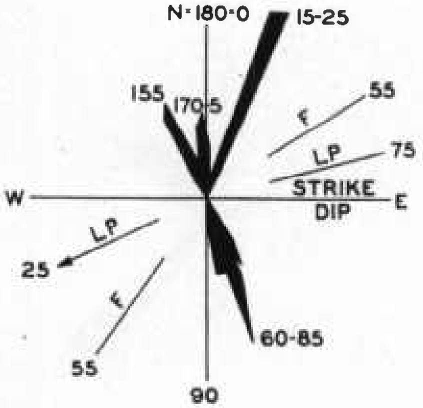

FIG. 20

FIGS. 19-26.—Statistical diagrams of the direction of jointing. B = strike and dip of bedding, LP = strike and pitch of linear structures, AF = strike and pitch of axes of folding, F = foliation.

FIG. 19.—Joints in Baltimore gneiss. Malvern Avenue, near Ruxton.
FIG. 20.—Joints in Baltimore gneiss at Cromwell Bridge.

Relations in the eastern portion of the dome and in the Bens Run anticline are not quite clear.

Throughout the southern half of the anticlinorium cross joints seem to transect the axis of uplift and trend of linear elements. Dips are somewhat irregular but generally steep, varying with the local undulations of the linear structure.

In the Baltimore dome cross joints trend northeastward parallel to the axis of uplift, except at its north end where they transect it. Locally linear structures strike east-west and the cross joints north-south. Throughout the dome they dip moderately to steeply eastward. The relations between linear parallelism and cross joints is shown in the joint diagram of the Falls Road Stone Quarry near Druid Lake and Gwynns Falls and Hilton quarries south of Edmondson Avenue (figs. 21 and 22). In both cases cross joints form the major system and dip moderately to steeply east.

It is very noticeable that cross joints are more conspicuous, numerous, and closely spaced where they occur within long and narrow domes of anticlinal shape as, for instance, the Chattolanee dome or the narrow anticlines along the southeastern side of the Woodstock dome. Cross joints in roughly circular domes are less distinct as may be expected. In the Texas dome they do not form a dominant system, even where locally quite abundant. In these domes all the joints which appeared to be cross joints were measured rather than other joints so that the maps show cross joints as the dominant system, which is actually not the case.

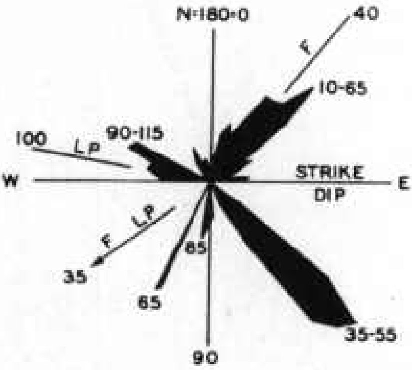

FIG. 21

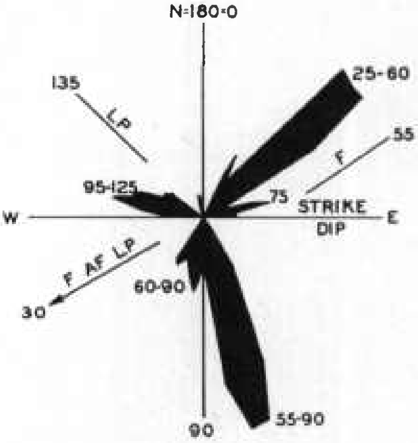

FIG. 22

FIG. 21.—Joints in Baltimore gneiss in the stone quarry at Falls Road.
FIG. 22.—Joints in Baltimore gneiss. Gwynns Falls and Hilton quarries.

Most of the joints measured in the Phoenix dome vary in strike between 145 and 10 degrees. They trend across the strike of linear structures in a north-northwest direction and seem to be largely cross joints. They are abundant along the Falls Road between Shawan and Butler. Dips range from 70 degrees east to vertical.

SECONDARY STRUCTURES

Later deformation, which affected the gneiss complex, left its traces in abundance. The structures which resulted are found both above and below the unconformity. Unfortunately it is rather difficult to detect and correct such elements because the entire complex shows such elements throughout. The elements include flow cleavage parallel to the axial planes of folding (pl. II, fig. 2), slickensides, and joints of irregular arrangement and distribution.

Besides striations down the dip of foliation planes, a number of slickensided joints occur throughout the gneiss complex. The striations are rather irregular in the various domes, but seem to be confined to joints striking northeast and east-west. The horizontal projection of the striations is roughly parallel to these joints and their dips gentle to 25 degrees.

THE UNCONFORMITY BETWEEN THE BALTIMORE GNEISS AND THE SETTERS FORMATION

The unconformity forms the surface of the gneiss complex and the base of the Setters formation. Assuming that this plane was originally horizontal, it now represents in its deformed state a reliable indicator for the degree of minimum deformation, which must also have affected the gneiss complex.

During the post-Glenarm deformation the unconformity has been folded during uplift of the domes and associated anticlines. This folding was on a much larger scale than that in the gneiss complex.

In the circular uplifts with large cores of gneiss the unconformity seems to have been simply domed, while in the more anticlinal structures, as for example, the Phoenix dome and southern half of the Woodstock anticlinorium, considerable folding took place within the uplifts. As a rule, the most intense folding, as well as overturning of the unconformity; has occurred along the southern and southeastern flanks of the domes, as for instance, the Chattolanee, Woodstock, and Towson domes (Plate XXXII).

Southeast of the Woodstock dome the unconformity and Glenarm Series have undergone an intricate folding which has probably obliterated the primary orientation of the dome structure (see Plate XXXII, sections 8 and 9).

Isoclinal folding of the unconformity is confined to the uplift west of the Baltimore, Towson, and Texas domes and eastern half of the Phoenix dome (see geologic map of Baltimore County).

The trend of the unconformity closely follows the outline of the domes and decides their shape. The Setters formation, which parallels the unconformity, shows well its undulations, folding, and overturning.

The trend of primary banding in the gneiss seems to have determined the present trend of the unconformity and all anticlines and synclines and possibly influenced the formation of thrusts (Plate XXXII, sections 4, 5, 9, and 10).

The contour line map (Plate XXVII) shows the normal and overturned attitude of the unconformity. In several cases, where the Setters formation is bounded by gneiss or does not come in contact with it, it was impossible to determine whether it was normal or overturned with respect to the gneiss; as for instance, along the southeastern flank of the Chattolanee dome and west of the Bens Run anticline.

In the Woodstock anticlinorium the overturned isoclinal folding of the unconformity can be seen by the alternating normal and overturned dip of the Setters formation. The eastern flank of the Highland-Alberton anticline is slightly overturned to the east, except in the vicinity of Dorseys Run where it is vertical.

An unusual fold of the unconformity occurs along the periphery of the Woodstock dome one and a half miles northeast of Marriottsville (Plate XXVII). This large fold is clearly shown by the quartzite and its axis seems to strike east-west and plunge gently westward.

STRUCTURES ABOVE THE UNCONFORMITY

GENERAL REMARKS

It is assumed in the foregoing that banding, linear structures, and maybe the cross joints in the gneiss are primary structures. However, the arrangement of linear elements in the anticlinal domes parallel to their major axes could be considered as due to a later and superimposed structure which affected the entire Glenarm Series. This deformation produced subparallel larger and smaller folds, the axes of which have a rather uniform trend and remain more or less constant throughout a large area following the major bend of anticlinal axes. On the other hand, the arrangement of structures in the northeastern portion of the Woodstock and Texas domes with their circular arrangement of elements and their blunt endings can hardly be explained by a later regional deformation.

Since these structures are earlier than the deformation of the unconformity it seems highly probable that their arrangement has profoundly influenced the present shape of the domes. Semicircular arrangements resulted in round domes, while general parallel arrangements with consistent strike and only local plunges resulted in long and anticlinal domes; as for example, the Chattolanee and Towson domes.

Before the deposition of the Setters formation the region may have been one of dome-like anticlinal and synclinal units which have been base-leveled and upon which the Glenarm Series has been deposited. It is also possible that this area has been similar to the structures found in the Canadian shield (see Haliburton and Bancroft sheets 1). Here a larger number

FIG. 1.—Large isoclinal fold of Setters quartzite pitching gently west. Hammer handle parallels the axis of the fold; arrows in chalk indicate linear grooving. One and a quarter mile northeast of Marriottsville, Maryland.

FIG. 2.—South limb of Jew Bottom anticline, looking east near Brice Run. The quartzite dips gently north. Cross joints (in shadow) strike N-S.

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of domes and anticlinal gneiss structures with circular and linear arrangements of banding can be seen and are truncated by the present surface.

SETTERS FORMATION

Bedding, axes of folding, axes of crinkling, and linear parallelism

Bedding parallels the unconformity along the flanks and ends of the domes and anticlines (Plates XXVIII and XXIX).

Linear structures roughly conform to those in the gneiss complex, both in strike and pitch (Plates XXX and XXXI). One exception is striking—along the northern flank of the Towson dome between Cromwell Bridge and Notch Cliff where linear structures strike northwest. At Long Green Creek axes of crinkling in the mica schist pitch west while linear parallelism in the gneiss plunges east.

Linear structures in the Setters formation swing around along the rim of round domes; as for instance, the Texas dome and northeastern half of the Woodstock dome. They parallel the flanks of long and narrow domes and anticlines; as for example, the Chattolanee dome and southern half of the Woodstock anticlinorium.

The circular arrangement of linear elements is well shown in the Texas dome (Plate XXXI). Along the south side of the dome they pitch gently west to southwest. Along the northeastern rim of the dome linear parallelism is horizontal, while throughout the north end it strikes and plunges gently northwest. The wide exposure of quartzite here is probably due to the gentle dip of the formation as well as repetition by minor folding. E. B. Mathews and W. J. Miller (75) consider this as due to a large double fold. The axial planes of folds are steep along the south and east sides of the dome while at the north end they seem to dip gently. The axes strike northwest.

Along the periphery of the eastern portion of the Woodstock dome a circular arrangement seems probable because axes of crinkling parallel the rim one mile southwest of Randallstown. Linear structures also follow the north limb of a syncline infolded into the southeastern portion of the dome one mile and a half north of Dorseys Run which may be called the Brice Run anticline. Along the entire western rim of the dome linear elements plunge westward. Their parallelism with those in the gneiss is striking.

In anticlinal domes and long narrow anticlines linear structures parallel the limbs and at their ends follow the axes of uplift. This can be seen in the Chattolanee dome where they roughly parallel those in the gneiss (Plate XXXI). Similar arrangements are found along the limbs of the anticlines southeast of the Woodstock dome (see Plate XXX). Linear elements parallel the limbs and are either horizontal or pitch gently. At the ends of these anticlines; as for instance between Nicols and Fulton, they maintain their strike and plunge gently down the dip of the Setters formation. In the Bens Run anticline the arrangement of linear parallelism seems to be affected by structures in the Woodstock dome.

Relations in the Towson dome are not as clear but a general parallelism exists with linear structures in the gneiss. The prevailing westward plunge is striking. At the southern end of the dome all linear elements strike and plunge gently southwest.

In the Baltimore dome area axes of crinkling parallel the general strike and plunge of linear elements in the gneiss.

Cross joints

Cross joints in the Setters formation seem to be directly related to and parallel to those in the gneiss. This can be seen in both circular and anticlinal domes (see Plates XXX and XXXI). This relation is best shown in the Texas and Chattolanee domes. In the former cross joints form a radial pattern around the eastern rim of the dome and dip steeply to vertical. They are also abundant at the north end of the dome. In the Chattolanee dome they are vertical and form the major joint system as in the gneiss. Cross joints strike slightly east of north and are vertical near Brooklandville. In the Stone Ridge quarries $\frac{3}{8}$ mile west of Lystra vertical cross joints strike slightly west of north while in Shoemaker quarry $\frac{5}{8}$ mile west of Stevenson they strike northwest and are also vertical. Near Tobin north-south vertical cross joints form practically the only joint system. At Waters quarry $1\frac{1}{4}$ miles east of Pikesville a major system varies in strike from 150 to 20 degrees. From the strike and pitch of linear parallelism it seems likely that cross joints strike 10 to 20 degrees and dip 50 to 60 degrees west. North-south steeply dipping cross joints are abundant in the small quarry $\frac{3}{8}$ mile southwest of Mount Wilson.

In the Towson dome cross joints do not seem to dominate over other systems. In the Rustic quarry near Oakleigh (fig. 25) those joints which strike northeast and dip 60 degrees may be cross joints, judging from the strike and pitch of linear structures. Likewise, at Cromwell Bridge (fig. 26) cross joints should strike northeast and dip 50 degrees east. At Long Green Creek north-south vertical joints seem to be cross joints. Along the southeast flank of the dome cross joints which strike northwest are locally common. At Gunpowder Falls the vertical system which strikes northwest and dips steeply northeast seems to represent cross joints.

A radial arrangement of cross joints around the eastern rim of the

Woodstock dome is indicated by many joints 1 mile southwest of Randallstown. Along the western flank of the dome cross joints bend around from a north-northeast direction on the north to north-northwest on the south. At Blunt's quarry near Hernwood Post Office a very prominent

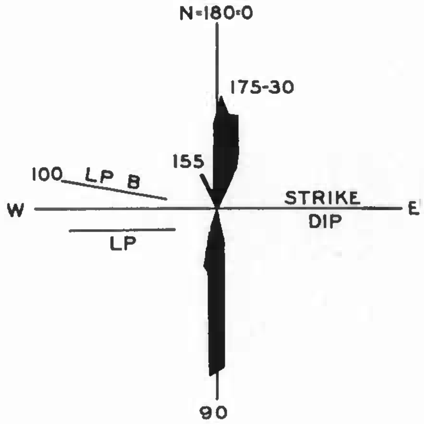


FIG. 23

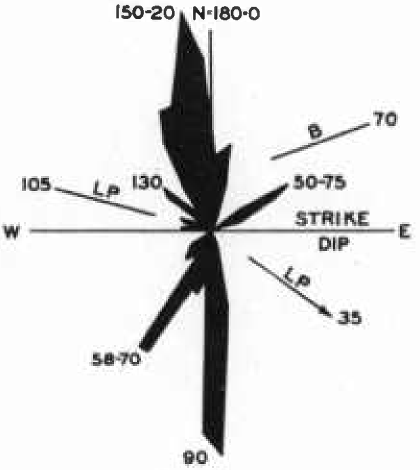


FIG. 24

FIG. 23.—Joints in Setters quartzite. Quarry one-quarter mile east of Tobin.
FIG. 24.—Joints in quartzite. Waters quarry.

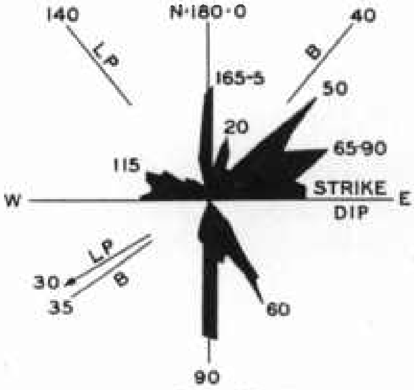


FIG. 25

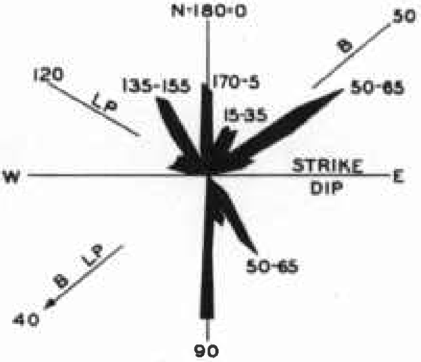


FIG. 26

FIG. 25.—Joints in quartzite. Rustic quarry.
FIG. 26.—Joints in quartzite quarry at Cromwell Bridge.

vertical system strikes north-south. One-quarter of a mile west of Knopf's quarry vertical cross joints strike 10 to 25 degrees. Three-eighths of a mile southwest in Jones' quarry a major system varies in strike from 165 to 25 degrees and dips steeply east to vertical. This system represents in part cross joints because a faint linear parallelism pitches 25 degrees west. At the Patapsco stone quarries at the North Branch of the Patapsco River relations are clearly defined since good axes of folds and strong linear stretching occur. Cross joints strike north-south and dip 60 to 70 degrees east. At Flynn's quarry, $\frac{1}{4}$ mile northeast of Marriottsville cross joints strike north-northeast and dip 60 to 75 degrees east.

Cross joints are very abundant along the limbs of the narrow anticlines southeast of the Woodstock dome between Alberton and Davis. They range in strike from north to northeast and dip steeply to vertical. At Feeney quarry $\frac{1}{8}$ mile southeast of Davis a dominant north-south system which dips steeply east probably represents cross joints.

Flow cleavage parallel to the axial planes of isoclinal folds is common throughout the area. It is conspicuous in only one locality.

Fracture cleavage in the quartzite was observed only along the north limb of the Towson dome at Long Green Creek, along the northeast side of the Texas dome, and south of Phoenix. In these localities the cleavage planes dip gently to horizontal.

THE COCKEYSVILLE MARBLE

Bedding in the marble parallels that of the Setters formation along the flanks of domes and anticlines but in the broader synclines no relation seems to exist for it is frequently on end and is folded independently. However, linear structures parallel those in the Setters formation. Along the southeast flank of the Chattolanee dome axes of folding strike east-west and pitch gently east. The same conformity is seen along the northwest rim of the Woodstock dome, in the syncline west of Clarksville and along the east and south sides of the Texas dome.

Cross joints are prominent along the southeast flank of the Chattolanee dome. They strike 160 to 180 degrees and dip steeply west. Steeply dipping cross joints which strike northeast are common in a quarry $\frac{1}{2}$ mile southwest of Alberton.

THE WISSAHICKON SCHIST

Axes of folding, cross joints, and axes of crinkling in the schist largely conform to structures in the above rock types. An exception was noted $\frac{3}{4}$ mile east of Alberton where axes of crinkling strike north-south and pitch gently north.

STRUCTURES IN IGNEOUS ROCKS WHICH PENETRATE THE UNCONFORMITY

All igneous rocks occurring in the region with the exception of the Hartley augen gneiss penetrate the unconformity. The Gunpowder granite and the Woodstock granite were studied and will be discussed below.

THE GUNPOWDER GRANITE

Throughout the northeastern portion of the Towson dome the Gunpowder granite has intruded the Baltimore gneiss and Hartley augen gneiss as well as the quartzite and schist along the southeastern flank. "Lit-par-lit" injection prevails although locally cross cutting relations occur. Along Gunpowder Falls near Harford Road the granite is locally folded along with the quartzite, and schist with flow cleavage is developed. Granite gneisses which appear in the central portion of the Texas dome have been considered as Gunpowder granite by Knopf and Jonas and others. The writer believes that a part of the core is Baltimore gneiss and Hartley augen gneiss as shown by exposures along the periphery.

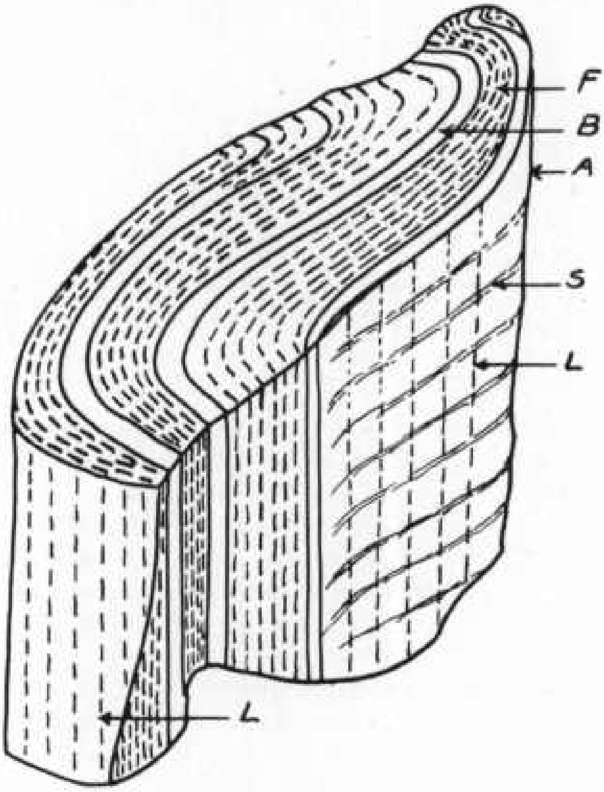


FIG. 27.—Structural elements in folded ribbon gneiss near Clarksville. The horizontal plane is a cross joint. F = foliation, B = banding, A = axis of folding, S = slickensides, L = linear stretching. The horizontal plane is a cross joint.

THE WOODSTOCK GRANITE

A slightly metamorphosed granite has intruded the Baltimore gneiss and Glenarm Series in the northern portion of the Woodstock anticlinorium between Hernwood and the Old Frederick Road. The intrusive in the center of the Woodstock dome is the only large body. Hundreds of small dike-like bodies of granite intrude the Baltimore gneiss and Setters quartzite in the vicinity of Dorseys Run. The dikes are largely concordant although locally they cut across the foliation and include fragments of the gneiss (Pl. XXV, Fig. 2). In the Setters quartzite and Wissahickon schist they are mostly concordant. Two narrow dikes of granite cut the quartzite, one at Blunt's quarry and another at Jones' quarry. South of Dorseys Run a series of small and larger dikes of granite parallel the strike of the schist. In the larger dikes the schist forms inclusions in or interfingers with the granite. Locally, numerous fragments of mica gneiss occur within a complex of schist and granite resembling what Sederholm called eruptive breccias.

THE INTRUSIVE AT GRANITE

In the southwestern portion of this intrusive several large areas of Baltimore gneiss with irregular trends were found. Because of the parallelism of linear structures in the areas with that of the country rock (gneiss) it seems likely that they are in place and the granite has intruded around them. The northwestern and southern contacts of the body conform to the general trend of the surrounding gneiss while its eastern and western contacts seem to be intertongued with it. A long arm of gneiss penetrates the southwestern portion as far east as Granite.

Foliation in the granite seems to strike prevailingly eastward and dip moderately north throughout the greater portion of the intrusive. This trend seems to conform to that in the surrounding gneiss and indicates a sheet-like body which dips northward.

Flow lines strike west-northwest and pitch moderately in the same direction (20 to 50 degrees) in the southwestern portion of the intrusive; as for instance at Fox Rock quarry ¼ mile west of Granite. Several hundred joints were measured in the Fox Rock and Walkersville quarries as well as other small openings in an attempt to determine the joint system. It was found that no regularity existed. Joints varying in strike from north to northeast were most abundant and consistent. These joints roughly coincide in strike with that of cross joints in the surrounding gneiss. They dip, however, steeply west to vertical and show no relation to the flow lines in the granite.

Linear parallelism in the areas of gneiss within the intrusive strikes

Fig. 1.—Vertical bedding in Setters quartzite. Horizontal fracture cleavage parallel to hammer head. One and a half miles northeast of Warren.

Fig. 2.—Inclusion of Baltimore gneiss in aplite granite. The banding in the gneiss xenolith parallels that in the adjacent gneiss. Three-eighths mile northwest of Dorsey's Run.

prevailingly west-northwest and dips gently in the same direction. Along the contact of these areas gneiss xenoliths occur in the granite; as for example, ⅛ mile northeast of Fox Rock quarry. Linear parallelism in the xenoliths strikes west-northwest and pitches 10 to 15 degrees west thus coinciding with flow lines in the granite. Linear elements in a small inclusion of gneiss along the west wall of the Fox Rock quarry also strike west-northwest and pitch 25 degrees west.

DIABASE DIKES

These dikes are the youngest intrusives in the region and are considered Triassic. They follow the trend of jointing characteristic of this period. Only one exposure was found, ¾ mile east of Davis. The dike at this point was 30 feet wide and its strike 15 degrees and dip 75 degrees east. From the distribution of diabase boulders it seems that all of the dikes trend roughly 20 to 30 degrees in the Chattolanee and Woodstock domes.

From the marked coincidence in the trend of these dikes in the vicinity of Dorseys Run and the western end of the Chattolanee dome with that of cross joints, it seems likely that they have in part followed this direction.

FAULTING

RUXTON FAULT

Normal faults, which transect the unconformity, the gneiss complex, and the Glenarm Series, belong to the youngest structures of the region. The Ruxton fault, which can be traced from Mount Washington to the northwest end of the Texas dome, was traced by E. B. Mathews in 1904. (See geologic map of Baltimore County). It is considered by Mathews, Knopf, and Jonas to be a thrust which dips east and along which the Towson and Texas domes have moved westward and partly overridden the marble and Wissahickon schist. Their conclusion is based on the general structural relations within the Piedmont, the apparent abnormal thickness of the marble at Lutherville, and the lack of certain formations; as for instance, quartzite and marble. This thrust was projected from Baltimore to the southeastern flank of the Phoenix dome.

The writer is of the opinion that the Ruxton fault is a normal fault for reasons elaborated below:

The fault is accompanied by a breccia which is locally exposed along the western ends of the Towson and Texas domes. Near Hollins Station this breccia dips west at angles varying between 60 and 80 degrees. It can be traced here with interruptions for approximately a half mile. East of Texas it also dips 60 degrees west.

The fault parallels cross joints in the Baltimore gneiss. In the vicinity of the fault these joints are very numerous and have a persistent strike and steep to vertical dip. The fault seems to follow an old pre-existing direction.

A well drilled immediately east of the fault near Lake Station remained in gneiss to a depth of 3200 feet, thus indicating a normal fault. Another well at Lutherville encountered 3000 feet of marble which is an abnormal thickness for this formation. This may, however, be due to an abnormal accumulation of marble due to folding. Experience in the entire region shows that the Cockeysville marble varies greatly in thickness.

Slickensides on a joint plane parallel to a banding in the breccia one mile east of Texas dip west and indicate a downward movement of the western block in relation to the Texas dome.

In a preliminary report E. Cloos described radio reception experiments near Riderwood. He found that the fault occurs in two steps and dips steeply. Since gently dipping contacts or boundaries did not result in radio reception disturbances he concluded that the fault is a steeply dipping normal fault.

The relation of the fault with the axes of the domes, minor axes of folding within the domes, and cross joints indicated that it is probably of the nature of a large cross fault. In many regions in which thrusting and faulting occurs thrusting seems to follow the major axes of folding and parallel the regional strike. Faults which occur in the same regions cross the regional strike as is shown in the Jura Mountains. Examples of this relationship can be found in hundreds of overthrusts in the Alps; the Moine thrust; the Scandinavian thrust; the thrusts in the southern Appalachian region, and maybe the Martic overthrust. Normal faults, which are found in the same area, transect the thrusts at large angles and in many cases are younger.

LOCAL FAULTS

The occurrence of breccia in other localities; as for instance, the south flank of the Chattolanee dome combined with the interruption of the normal trend of the Setters quartzite, lead the writer to the belief that normal faulting is common (Plate XXXI). The lack of good exposures made a thorough investigation impossible.

Good evidence of faulting was observed in the diabase belt in the vicinity of Dorseys Run. Here the quartzite ridges seem to be offset several hundred yards or more at several localities. This is well shown $\frac{3}{4}$ of a mile west of Wrights Mill Road along the north limb of the Brice Run syncline and $\frac{5}{8}$ of a mile west-southwest of Dorseys Run along the south limb of the Highland-Alberton anticline. No attempt was made to

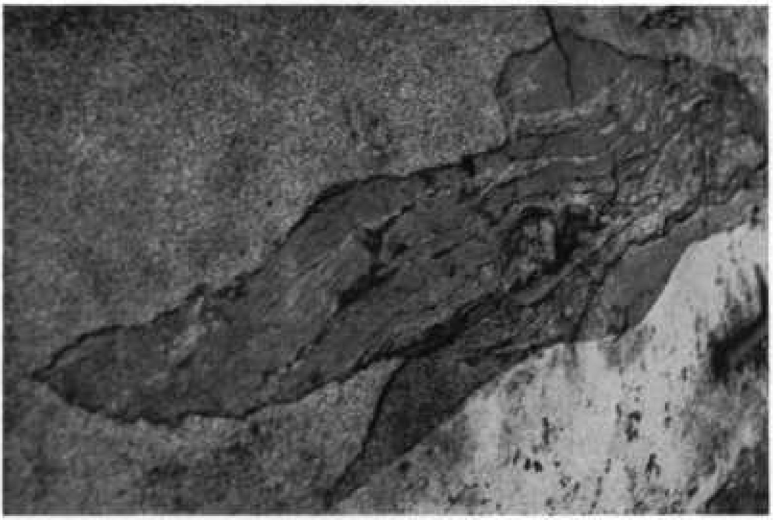


Fig. 1.—Inclusion of Wissahickon schist in Woodstock granite. One-half mile Southwest of Dorseys Run

Fig. 2.—Strong linear parallelism in Baltimore gneiss. One-half mile east of Alberton.

represent these offsets in Plates XXXII and XXVIII. These two displacements parallel the diabase dikes and may be due to Triassic faulting. The ridges are offset to the south on the west side of this break. A similar offset of quartzite seems to occur near Dorseys Run along the north limb of the Highland-Alberton anticline.

THRUSTING

The cross sections and maps (Plates XXVIII–XXXII) show clearly that thrusting occurs in many parts of the region, especially in closely folded anticlines and synclines. Minor thrusts may account for relations between Setters quartzite and marble in sections 4, 5, 9, and 10. In nearly all these localities the quartzite is flanked by marble within sharply folded synclines. The writer believes that the quartzite is here thrust over the marble. The distribution of different formations of the Glenarm Series along the flanks of anticlines indicates thrusting of a similar type; as for instance, the southeastern flanks of the Towson dome and Woodstock anticlinorium where the marble and the Setters formation are partly lacking. In all cases the strike of the thrusts is parallel to the general strike of the region and may have resulted from sharp overfolding.

Thrusts seem to be confined to the southeastern and southern flanks of uplifts. This indicates forces in a southeast-northwest direction and may result from movement against the more rigid and resisting gneiss domes.

The rapid thinning of the quartzite ridges to the east along the southeastern flank of the Chattolanee dome seems to indicate thrusting. It is also possible that the south limb of the Mount Wilson syncline is a thrust, since the Setters formation shows a normal width and marble seems to be locally absent. However, this structure was interpreted as a sharp fold in Plate XXXII section 6.

Some thrusting is necessary to explain relations at the southern end of the Bens Run anticline as well as south of Alberton.

The apparent absence of marble in many of the narrow overturned anticlines and synclines southeast of the Woodstock dome may be due to thrusting or squeezing out of the marble.

METAMORPHISM AND DEPTH OF FORMATION OF THE DOMES

There appears to be a definite relation of metamorphic intensity in relation to the domes and igneous intrusions. The Baltimore gneiss with its crystalline texture shows the maximum intensity of metamorphism, having been produced by dynamic metamorphism modified by contact action of igneous injection at considerable depth. Knopf and Jonas (64) point out that the high degree of metamorphism of the gneiss shows no evidence that it is the result of several periods of metamorphism, having remained inert since its formation due to its prolonged deep-seated position. The lower formations of the Glenarm Series including the quartzite, marble, and eastern facies of schist show a high degree of metamorphism while the upper formations of the Glenarm Series, the Peters Creek formation, in the Peach Bottom syncline as well as the western facies of schist show less metamorphism. Knopf and Jonas consider this situation as due to diapthoritic changes. The difference in intensity between the eastern and western facies may be explained by the numerous igneous intrusions in the former facies which may have produced a regional contact metamorphism. Also the eastern facies may be at a deeper level of erosion than the western facies. The intrusion of a large body of granite (Sykesville granite) in the Peach Bottom syncline has, however, not increased appreciably the degree of metamorphism of the sediments.

The problem of the highly metamorphosed sediments which surround the Mine Ridge anticline in Pennsylvania contrasted with the low intensity in the Glenarm formations to the south lead Knopf and Jonas (65) to the conclusion that the dominant metamorphism in both Paleozoic and Glenarm strata was subsequent to an overthrust which brought the Glenarm Series over the Paleozoic sediments (Martic overthrust). They state that depth of burial with load metamorphism alone is insufficient to produce crystalloblastic textures. They suggest a rise of geothermal gradient from an igneous source and together with the increased load of the overthrust block would be sufficient to account for the high metamorphism of the Paleozoic rocks.

It seems more likely to the writer that this difference in degree of metamorphism is a function of the depth of formation of these structures previous to uplift in the eastern portion of the Piedmont.

SUMMARY AND CONCLUSIONS

As a general rule the axes of major and minor folds are parallel in the entire region. In spite of this fact these structures can not be ascribed to the same period of deformation. The folds in the Baltimore gneiss complex seem to determine the trend of the domes. In the anticlinal domes the axes plunge towards their ends and parallel their flanks, roughly outlining the trend of the domes as primary structures. The shape of the domes, however, is superimposed on the older structures which have been formed before the Setters quartzite has been deposited. The blunt endings of circular domes and the semicircular arrangement of internal dome structures strongly suggests that the superposition of post-Glenarm doming was guided by earlier structural lines.

The semicircular arrangement is followed by the structures in the marble and Wissahickon schist which run around these blunt ends. In this way the structure of the marble and schist seem to parallel the structures in the gneiss. Considering the major axes of uplift, the minor structures in the marble and schist cross these axes at right angles.

The presence of the unconformity between the Baltimore gneiss with its primary structure and the Glenarm Series which have suffered from later periods of deformation renders a simple connection between the two units unlikely. The deformation of the Glenarm Series may have affected the Baltimore gneiss complex only to the extent of intensifying the older dome structures.

The deformation of the unconformity, to which the Setters formation seems closely attached, is of very much larger order of magnitude than minor folding in the gneiss complex below or in the marble and schist above. Major folds are overturned toward the north as well as to the south and toward the west as well as to the southeast. This lack of a uniform direction of folding and movements renders a simple explanation difficult.

The writer believes that an explanation of the structures in the crystalline rocks of Maryland and probably of the Piedmont in general hinges on a consideration and careful study of the Gneiss-Glenarm unconformity and its deformation. Uniform movements seem to comprise all formations above the Setters quartzite. The relatively incompetent Wissahickon schist is closely folded but its formational boundaries probably dip gently. Its flow cleavage is steep and its fracture cleavage seems to dip uniformly northwest over a large area. Fracture cleavage developed in the Setters mica schist is probably directly related to this fracture cleavage in the Wissahickon schist complex. The deformation of the unconformity and the attached Setters indicate folding by bending. The shear planes have never been observed to penetrate the unconformity or the Setters formation. It is therefore most surprising to observe the lack of uniformity in folding between the major folding of the Baltimore gneiss surface and the Setters formation in contrast to the prevailing minor folding of the marble and Wissahickon schist. The writer believes that the only explanation for this discrepancy lies in a deformation of the marble and schist which affected only comparatively slightly the gneiss complex and Setters formation. In this deformation the latter seems to have been protected and its deformation guided by its close connection with the gneiss. It is only in a few localities that the quartzite leaves its position as the next neighbor of the gneiss; for example, where thrusts may be present.

It seems possible that the deformation of the Wissahickon schist found its lower limit approximately in the very incompetent marble which facilitated the separation of the schist from the competent gneiss-quartzite unit. This would explain the discrepancy between the typical minor folding in the incompetent marble-schist unit and major folding of the gneiss surface and quartzite. The relative competence and incompetence of formations is therefore an important factor.

During the folding of the unconformity the marble may have acted as a lubricant for the close folding of the Wissahickon schist. The intense deformation which must have accompanied uplift of the gneiss surface and the closely attached Setters formation might explain the considerable variation in thickness and frequent absence of the marble. Its relative incompetency would explain the discrepancy in type of folding above and below the unconformity.

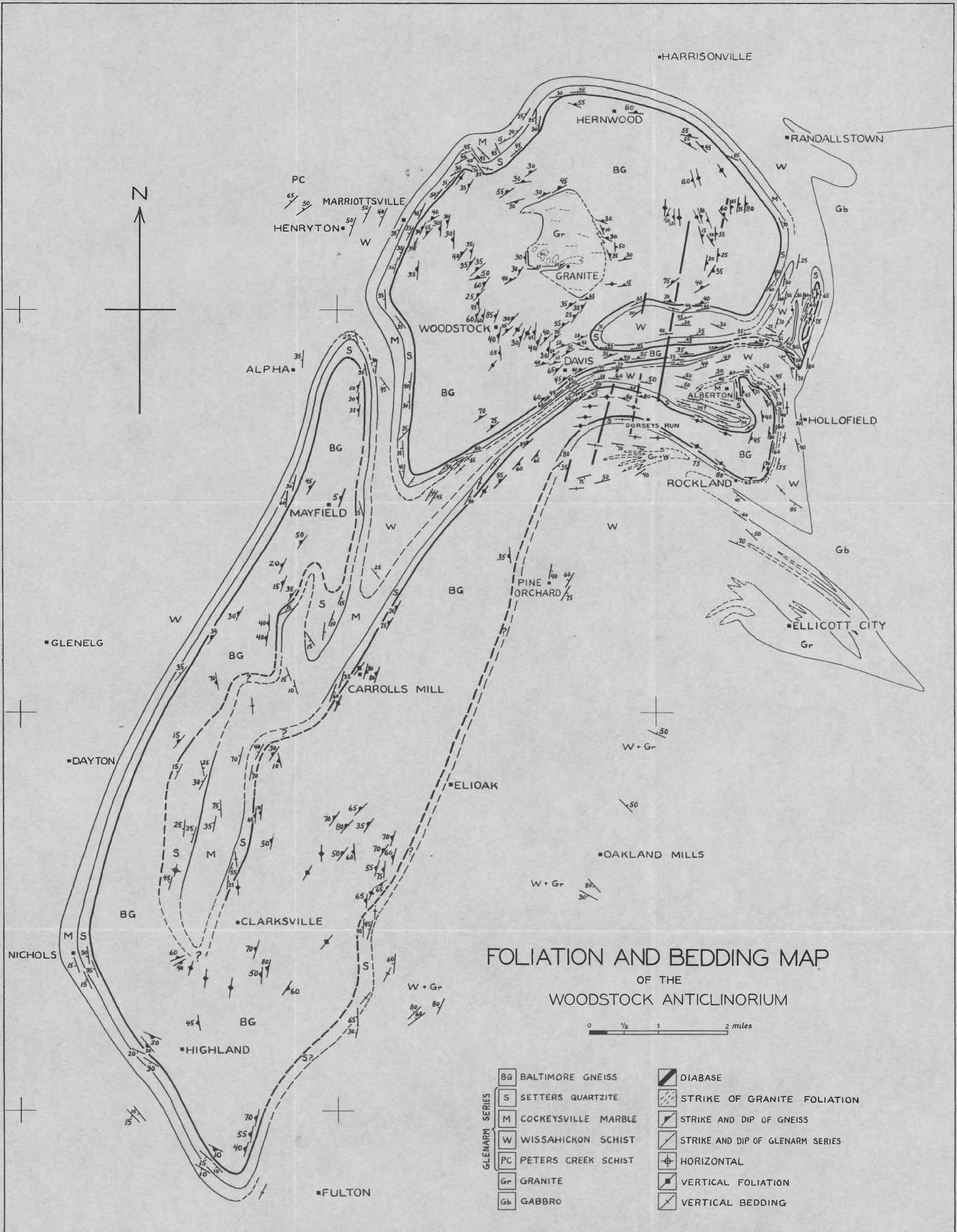
Conditions may have been similar to the folding of the Swiss Jura above the Triassic. Here Triassic salt beds have obviously served as a lubricant during a rather shallow folding process (51). Since there is no uniform direction of overturning and folding within the gneiss domes, the writer does not believe that a uniform pressure through thrusting could have produced these structures. The older internal structure of the gneiss domes in combination with igneous intrusions may have influenced their formation.

The oval to almost circular outline of the Woodstock and Texas domes makes the introduction of vertical uplifting forces almost inevitable. Lateral compression alone could not explain the semicircular arrangement of structures which run around these domes. Such structures are most abundant in all regions in which one considerable vertical component of uplift or subsidence is proven; as for instance, in all laccolithic and many batholithic domes as well as in basins and depressions. The writer, however, does not intend to infer a batholithic origin for the gneiss domes.

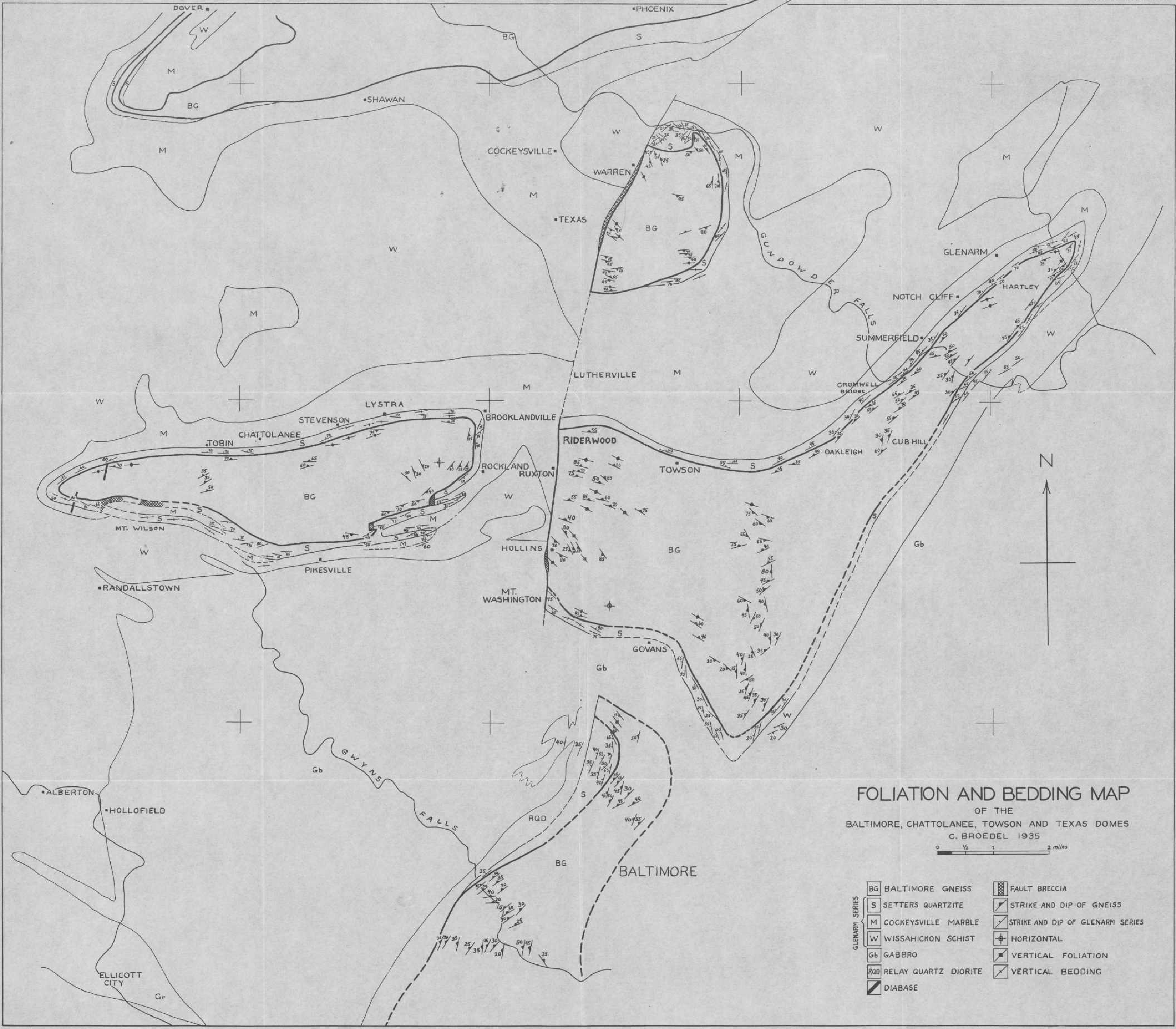
The lack of any uniform overturning of the gneiss domes and associated anticlines seems to argue against large overthrusts. The general relations indicate local thrusting associated with the gneiss domes during deformation of the unconformity.

The writer believes that the shape of the domes has been determined by pre-Glenarm structures and that they have been partly upfolded and partly upthrust into the Glenarm Series during post-Glenarm deformation. Normal cross faults and cross joints transgress the major and minor axes at large angles while reverse faults and thrusts parallel these axes and are confined to the flanks of the domes and associated anticlines. The gneiss complex and Setters quartzite may have taken an active part in the production of thrusts while the marble and schist appears to have played a passive rôle in the deformation of the region.

STRUCTURAL CONTOUR LINES
DRAWN ON THE
SETTERS QUARTZITE
IN THE BALTIMORE, TOWSON, CHATTOLANEE AND WOODSTOCK DOMES



FOLIATION AND BEDDING MAP
OF THE
WOODSTOCK ANTICLINORIUM

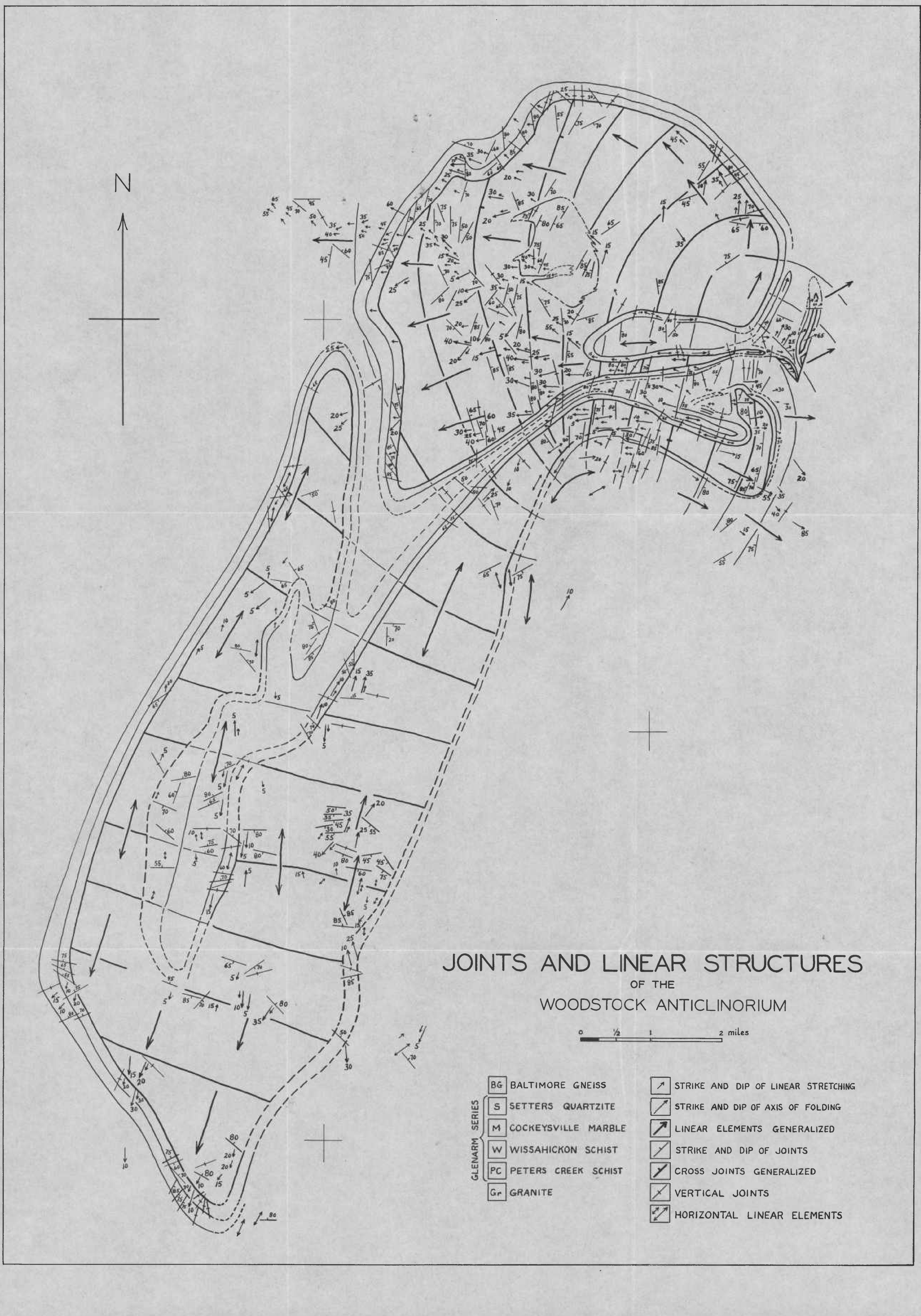


FOLIATION AND BEDDING MAP

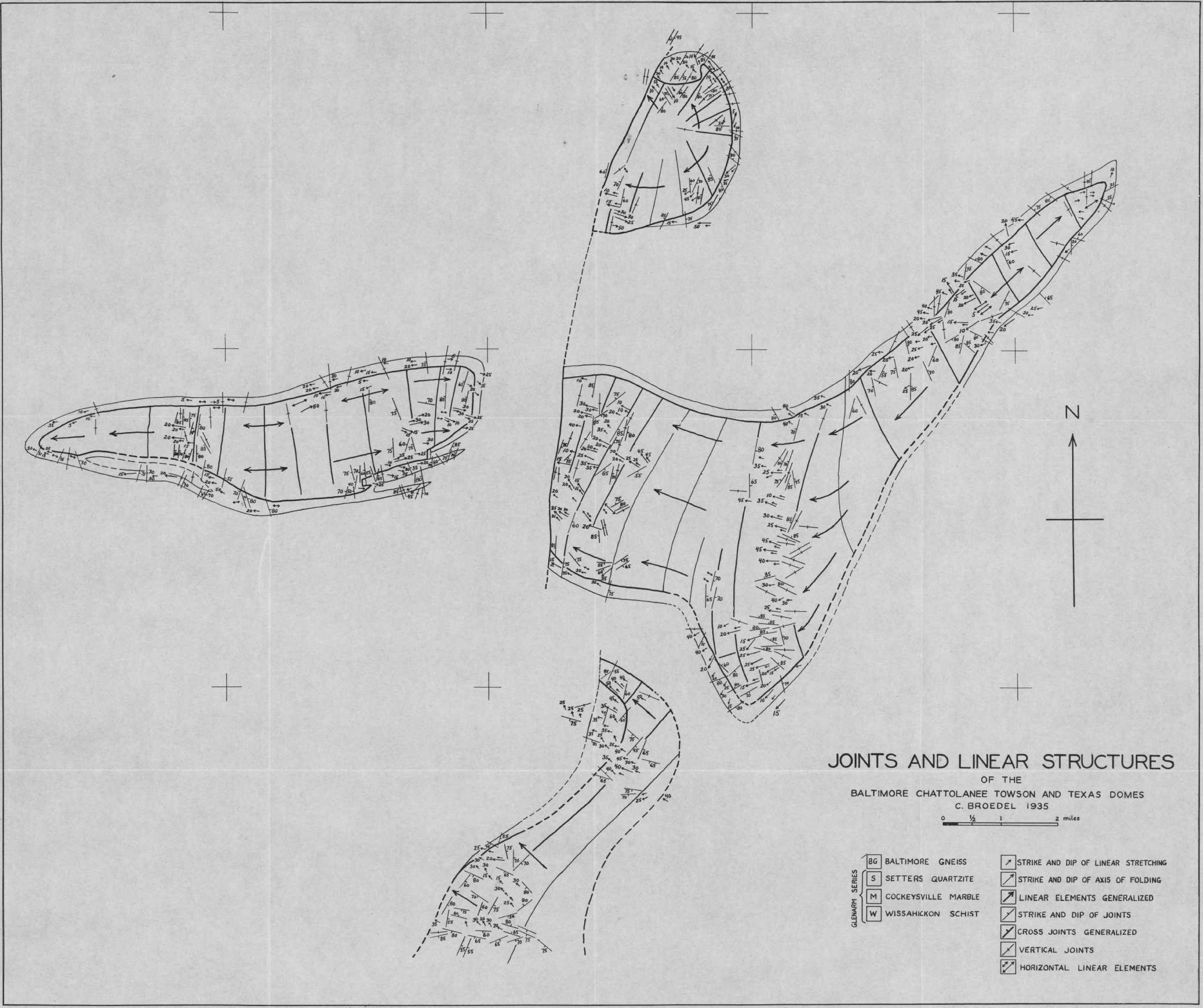
OF THE

BALTIMORE, CHATTOLANEE, TOWSON AND TEXAS DOMES

C. BROEDEL 1935



JOINTS AND LINEAR STRUCTURES
OF THE
WOODSTOCK ANTICLINORIUM



JOINTS AND LINEAR STRUCTURES

OF THE

BALTIMORE CHATTOLANEE TOWSON AND TEXAS DOMES

C. BROEDEL 1935

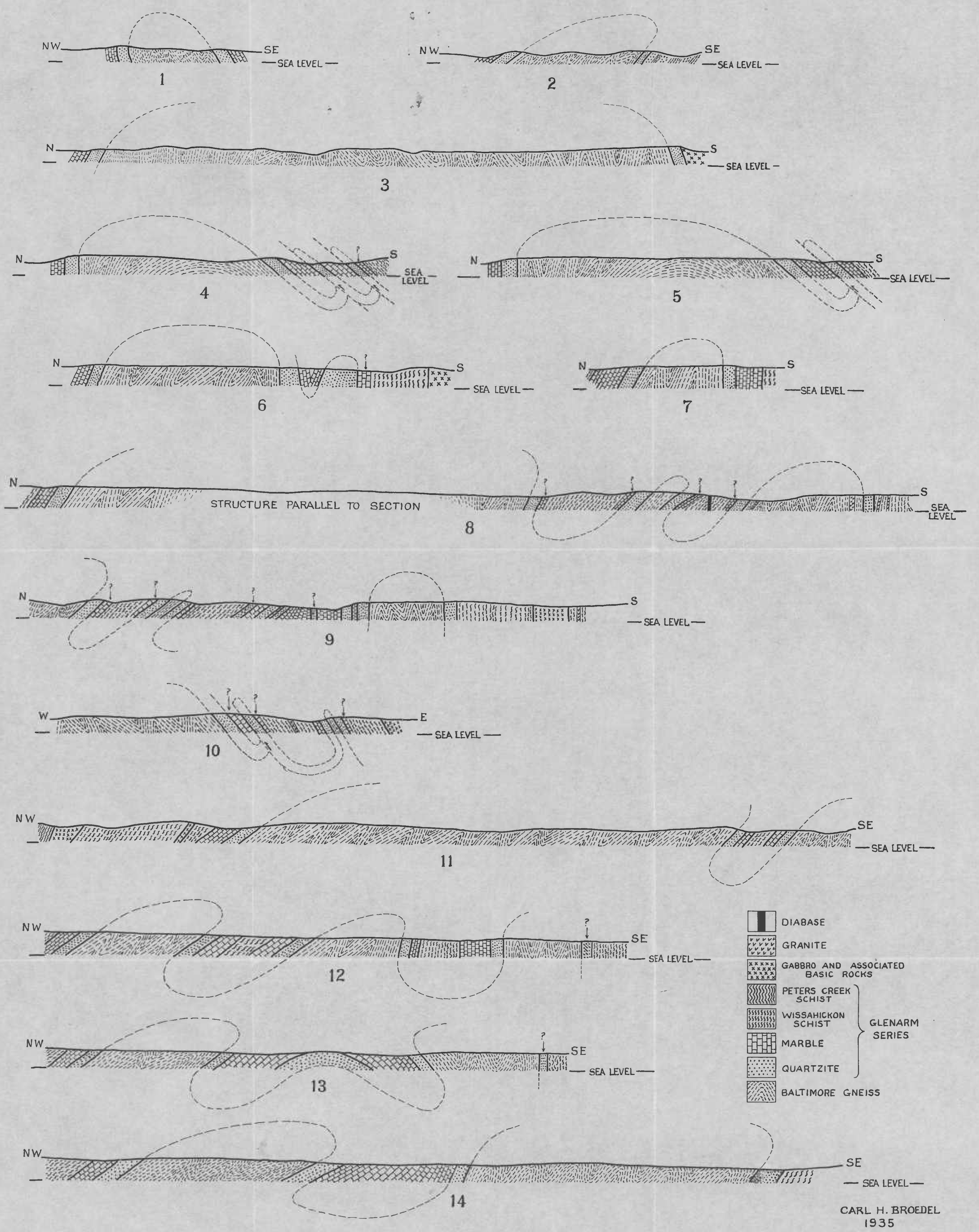
LOCATION OF CROSS SECTIONS

(On plate XXXII)

Towson dome:
   1. Long Green Creek.
   2. Gunpowder Falls.
   3. Western portion of dome.

Chattolanee dome:
   4. Green Spring Avenue
   5. Three-quarters of a mile west of section 4.
   6. Section through Tobin and Mount Wilson.
   7. Western portion of dome.

Woodstock anticlinorium:
   8. Harrisonville to Old Frederick Road.
   9. From Dogwood Road through Alberton to Sucker Branch.
   10. From Brice Run across Bens Run Anticline
   11. From Henryton to ¾ mile southeast of Davis.
   12. From Alpha to 1 mile south of Pine Orchard.
   13. One-half mile north of Carrolls Mill.
   14. One mile north of Clarksville.



CARL H. BROEDEL
1935

PART IV

THE STRUCTURES AND AGE OF THE VOLCANIC COMPLEX OF CECIL COUNTY, MARYLAND

BY

JOHN MARSHALL

THE STRUCTURES AND AGE OF THE VOLCANIC COMPLEX OF CECIL COUNTY, MARYLAND

INTRODUCTION

The region described in the subsequent pages lies in the central part of Cecil County, Maryland, and extends toward the southwest across the Susquehanna River into Harford County. The area is nearly two miles wide and a little more than twelve miles long. As shown on the map (pl. XXXV) the belt of volcanic rocks varies in width and is widest where it approaches the Susquehanna River. The region is a part of the great Piedmont complex of crystalline rocks which lies between the sediments of known Paleozoic age in Pennsylvania and western Maryland and the unconsolidated deposits of the Atlantic Coastal Plain. The rocks are highly metamorphosed and bear little resemblance to the igneous intrusions which have invaded them.

The peculiarities of the volcanic rocks have been briefly described by several workers. G. P. Grimsley (44) in 1894 described the material as diorite and thought it was probably a dynamically metamorphosed gabbro. Bascom made a more detailed study in 1902 and considered it a later intrusion into the granite. She recognized the more acid character of the rock and, concluding it was a metamorphosed rhyolite, applied the term metarhyolite to the rocks of an area roughly coinciding with that shown in plate XXXV. In 1920 (12), working in the eastern part of the region, Bascom concluded that the material was not so acidic and named it metadacite, which term has also been applied in a later paper (11).

AGE RELATIONS

The age and sequence of the rocks of the complex has been determined by various workers but their results vary widely. Keyes (60) concluded that the granites are the youngest intrusives and may be anything from pre-Cambrian to epi-Carboniferous. Grimsley (44) concludes that the granites are older than the gabbro and that the volcanics, which he called diorite, are intrusive into the granite. In the published version of the paper (44) he concludes that the gabbro is the older rock. Bascom in the Cecil County report (1902) considers the sequence from older to younger to be: basic biotite-granite, metarhyolite, basic hornblende-granite, quartz-biotite-hornblende-gabbro, quartz-hornblende-gabbro, hornblende norite and quartz norite, norite and hypersthene gabbro, pyroxenite, and peridotite. In the Elkton-Wilmington Folio (12) Bascom gives the same sequence and considers the volcanics as intrusive into the granite. The age is determined as post-Glenarm and either pre-Cambrian or Upper Silurian. In the latest paper (11) the sequence of intrusives is given as the same, but the volcanics are called extrusives and correlated with those of western Maryland described in several earlier papers (14, 15) but no age is given. Cloos and Hershey (26) have shown that the age of the intrusive rocks of the region is post-Conestoga and hence at least Lower Paleozoic, if not later, but they do not mention the volcanic complex.

The age of the Glenarm Series is still a subject of controversy. Some writers (72, 78) deny the presence of the Martic overthrust suggested by Knopf and Jonas (65) and believe the series to be Paleozoic; while others accept the hypothesis of an overthrust and consider the Glenarm Series as pre-Cambrian.

The age relations of the rocks of the complex were determined by structural methods: truncation of foliation, inclusions of older rock engulfed in intrusives, intrusive relationships of younger rocks, and contact phenomena of various kinds.

PETROGRAPHY

Most of the rock types found in the complex have been previously described. Many of the descriptions lack detail, however, and none gives the locality of the specimens so that one is never sure which type is given a certain name, especially since there is in each case more than one type of the same general composition and texture although they differ in occurrence and sometimes in age. For this reason the locality of the following specimens described will be given in some detail.

SCHIST

Of the rock types found in the complex one of the oldest is the schist which is probably of Glenarm age. This rock is well exposed at only one locality, on Principio Creek about 600 feet downstream from the Baltimore and Ohio Railroad bridge. The rock in the stream is a fine-grained, compact, chlorite schist which is worn to very smooth rounded forms by the water in spite of the softness of the material. In this respect it is in marked contrast to other schist exposures which have a ragged appearance where subjected to stream erosion. The compact structureless character of this rock is probably caused by the gabbro dikes by which the schist is intruded. In the old channel of the spillway of an abandoned mill to the east of the stream the rock resembles the Peters Creek schist as exposed in the neighborhood of Peach Bottom station along the Susquehanna River. The material is not exposed in place but is scattered along the ditch. This schist is more foliated than that in the creek and has a strong fracture cleavage with a second less intense fracture cleavage superimposed on the first one. This fracture cleavage produces crinkles on the planes of the first at an angle of about 30 degrees to the trace of the schistosity which is almost obliterated by fracture cleavages.

Specimen of Glenarm schist from south side of spillway about 50 feet north of exposure in creek:

Megascopically the rock appears as a soft chlorite schist of pale brownish-green color. Specimens break out along the fracture cleavage rather than along the schistosity, owing to the sharp crinkling of the folia.

Microscopically the rock consists of finely-laminated colorless chlorite with fine-grained epidote in nearly equal amount between the folia. Occasional larger grains of epidote cut off the cleavage traces of the chlorite. Secondary magnetite occurs both in thin lenticles between chlorite plates and as bunchy aggregates cutting across the foliation.

VOLCANICS

The volcanic rocks of the area show considerable variation, megascopically grading from massive amygdaloids and even-textured volcanics through schistose amygdaloids to fine-grained hornblende schists which at times are indistinguishable from sheared gabbro except by microscopic examination. In thin sections these variations may be described as representing three types although they grade into each other. These are: a massive amygdaloid with hornblende varying from a few per cent to more than half of the rock and, as a rule, with a weak foliation; a schistose amygdaloid carrying more hornblende than the average massive type; and a schistose rock composed mostly of hornblende without apparent amygdules in the hand specimen. The minerals of all types are the same but vary in proportion according to the development of the schistosity. The primary minerals seen in thin sections are: quartz, plagioclase of a composition Ab_8An_2 to Ab_7An_3, and green hornblende with a pleochroism from light green to deep blue-green and acicular habit. The stronger the shearing the rock has undergone the greater is the proportion of hornblende. Quartz and feldspar occur in about equal proportion. Secondary minerals are usually epidote or clinozoisite and magnetite.

MASSIVE AMYGDALOIDS

Of the volcanics the most easily recognized is the massive amygdaloid. This material differs from the more schistose type in the larger proportion of quartz and feldspar and its less intense schistosity. However, the types may grade into one another and are even found in alternating bands. Besides the inclusions of feldspar in the rock which are largely altered to epidote, there are also larger structures, up to one foot or more in diameter, composed of epidote and sometimes also of feldspar or chlorite around which the foliation is bent. Where these bodies are entirely replaced by epidote no clue as to their origin remains but in several exposures they were found in all stages of replacement with a few which were unaltered. In all such cases the amygdules have a typical structure (pl. XXXIII, fig. 1). In thin sections they are indistinguishable from the rest of the rock except for a slight increase in grain size and a somewhat lower proportion of mafic constituents. These inclusions are marked out on the periphery by a narrow zone of fine hornblende needles which decrease in number away from the inclusion to the normal amount for the inclosing rock at that place. These needles are oriented parallel to the foliation of the rock and appear to be part of it since the sharp border of the inclusions is inside this hornblende zone. Immediately inside the hornblende-rich margin the material is lighter and carries little if any hornblende. Pabst (82, p. 341) notes similar phenomena in autoliths in the Sierra Nevada granite. In most cases there is a darker zone within the light border carrying more hornblende which shows some parallelism to the foliation. The center of the inclusion is again light colored with hornblende crystals considerably larger than the others and without orientation.

Inclusions very similar to this type are found in schist of Glenarm age on the Susquehanna River to the north of the area. In the schist and in some cases in the volcanics these inclusions show a marked resemblance to the pseudo-diorite at Ducktown, Tennessee, described by Keith (58), Ross (85) and others.

Other cases were found in which these zones were lacking. The contacts in these are sharp and the material inside the hornblende-rich border is similar to the inclosing rock but entirely devoid of any foliation. In others the centers carry more mafics than the inclosing rock. Another type is nearly spherical with a well-marked dark border around a lighter colored center. The appearance of the rock suggests that these inclusions were formed while the material was still flowing since the structures do not transgress the flow lines and the platy and linear minerals within them are unoriented. Where these structures are abundant there is a certain resemblance to the pillow lavas described by Sederholm (95) in southwestern Finland. F. Corin has suggested that these inclusions may represent volcanic bombs caught in the lava.

These structures and the amygdaloidal textures are the most easily recognized features of both the massive and schistose types of volcanics.

Specimen from Stony Run 600 feet north of the Baltimore and Ohio Railroad:

Megascopically this rock is very dark gray, fine-grained, and without visible foliation either in the amygdules or the groundmass. It differs from the typical massive amygdaloid in its darker color. The rock is crowded with amygdules of feldspar and epidote which have a tendency toward a concentric structure with the feldspar in the middle. The epidote shows a radiating growth inward from the borders of the amygdules.

Microscopically the material is holocrystalline, fine-grained, with amygdules up to several millimeters in diameter in a felt of green hornblende crystals with a fine feldspar groundmass. The hornblende shows a decussate structure and, due to its prismatic character, gives the feldspar the superficial appearance of intersertal structure of a basalt. Hornblende forms over 50 per cent of the groundmass; the remainder is feldspar. This is the only specimen of the volcanic series in which quartz is not an essential constituent.

The feldspar was determined as oligoclase-andesine ($Ab_{72}An_{28}$). No orthoclase was found. The average size of the feldspar grains is about 0.1 mm. and the hornblende about 0.3 by 0.1 mm. There are a few anhedral stumpy hornblende grains of slightly larger size.

The amygdules are composed of feldspar of the same composition as that in the groundmass, partially or wholly replaced by epidote. The epidote has a weak pleochroism. It shows a radiating structure growing toward the center of the amygdule from a point slightly inside the border around the epidote and often the center of the amygdule is also a feldspar remnant. (pl. XXXIII, fig. 1).

Secondary minerals are small magnetite metacrysts less than 0.1 mm. and the epidote of the amygdules. Epidote is rare and fine-grained in the groundmass. This rock is apparently an unaltered andesite but is indistinguishable in the field from those amygdaloids which carry considerable quartz.

Specimen from the south end of Keystone quarry along the Columbia branch of the Pennsylvania Railroad:

Megascopically this rock is a medium gray, fine-grained material with discontinuous black platy streams of hornblende, giving a distinct linear and platy structure but not strong enough to develop a good cleavage. The rock therefore breaks with an uneven fracture. Epidote-bearing amygdules about 2.0 to 3.0 mm. are sparingly present.

Microscopically the material is holocrystalline, amygdaloidal, with a fine-grained groundmass and a fairly strong linear foliation due to acicular green hornblende averaging about 0.5 by 0.05 mm. The groundmass is a fine-grained mosaic of quartz and feldspar averaging less then 0.1 mm.

The amygdules are of feldspar some of which at least is orthoclase partly or wholly replaced by epidote which occurs as unoriented inclusions in the feldspar and as radial aggregates replacing it. The hornblende occurs mostly in needles but also as anhedral masses of larger size and makes up about 33 per cent of the slide. It partly bends around amygdules and is partly cut off by them.

The feldspar of the groundmass occurs as anhedral grains of less than 0.1 mm. but larger than the quartz. It was determined as an acid plagioclase, probably oligoclase-andesine.

The quartz, in somewhat smaller grains than the feldspar, shows no strain shadows and is hence probably recrystallized since the rock has undergone strain. Quartz is more abundant than feldspar. Apatite is questionably present in very small quantity as an accessory.

Secondary minerals are the epidote which occurs in fine aggregates and small crystals in the groundmass as well as in the amygdules and magnetite metacrysts occurring in the amygdules.

SHEARED AMYGDALOIDS

The schistose type of amygdaloid is so intimately mixed with the massive type that the two can not be separated in mapping. The amygdules are no more elongated than in the massive type and either remain as eye-shaped inclusions in the schist or are broken and stretched out. They do not show evidence that the vesicles were more elongated in the parent rock. Hence the schistosity of this type seems to be due to later metamorphism of parts of the volcanic rather than an original difference in the two types.

This second type carries a larger proportion of hornblende than the first and has a much more pronounced schistosity. Both the amygdules and inclusions are completely altered to epidote with occasional hornblende and magnetite. The hornblende of the groundmass is usually segregated in bands alternating with bands of quartz and feldspar, giving the rock the appearance of a flow banded lava with the flow planes bending around the amygdules. These bands vary in width from one millimeter to over a centimeter but in any one specimen are of about the same width. With a higher degree of metamorphism the banding is destroyed and the rock grades into an amygdaloidal hornblende schist, which in turn grades into a schist in which the amygdules are no longer visible megascopically although remnants of the structure may be seen under the microscope.

Specimen of schistose amygdaloid from Principio Creek about 5000 feet north of Philadelphia Road:

Megascopically this rock is dark-gray, fine-grained, and highly stretched. It is banded with alternating black layers of hornblende and gray layers of quartz and feldspar. These layers have a wavy structure and bend around the amygdules which are composed of quartz and epidote somewhat fractured and rolled out. In weathering the amygdules stand out as lumps on the surface of the rock. The hornblende

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FIG. 1.—Photomicrograph of amygdaloidal structure in metaandesite. Parallel nicols, specimen 145.

FIG. 2.—Photomicrograph of schistose volcanics. Parallel nicols, specimen 9.

FIG. 3.—Photomicrograph of basal sections of tremolite in granulose rock. Parallel nicols, specimen 29.

FIG. 4.—Photomicrograph of myrmekitic intergrowth in granite. Crossed nicols, specimen 17.

FIG. 5.—Photomicrograph of porphyritic texture of contact phase in granite. Crossed nicols, specimen 46.

FIG. 6.—Photomicrograph of linear structure in hornblende granite. Parallel nicols, specimen 125.

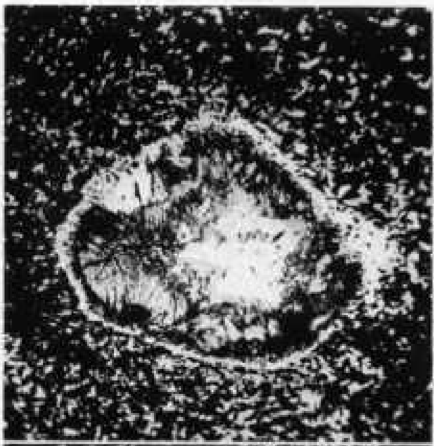

Fig. 1

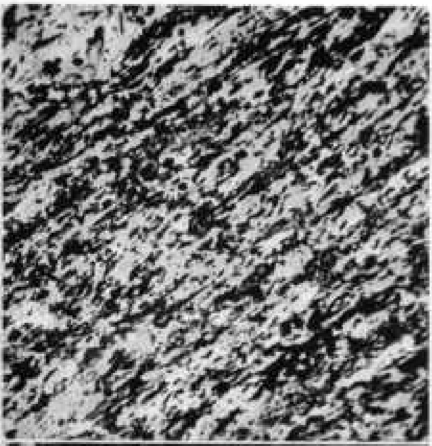

Fig. 2

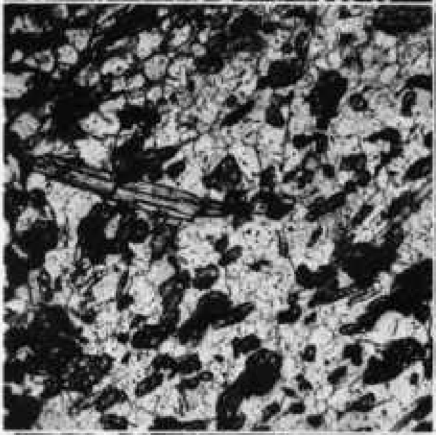

Fig. 3

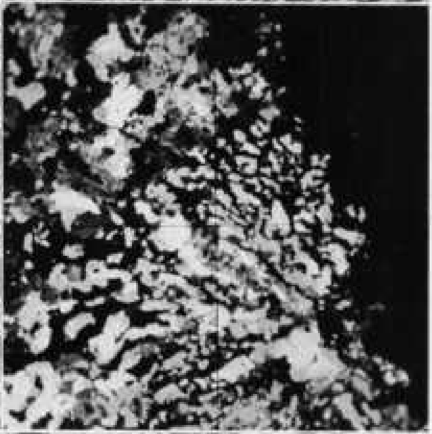

Fig. 4

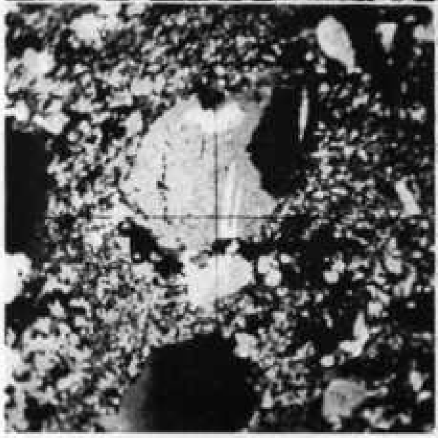

Fig. 5

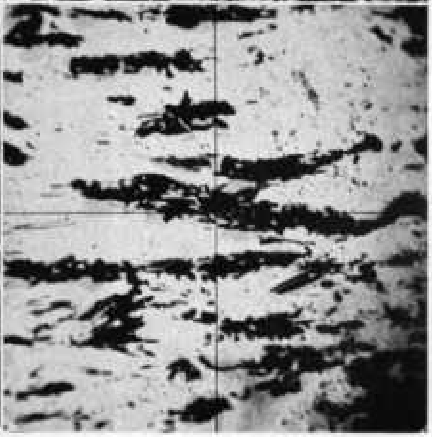

Fig. 6

layers are more resistant than the others, resulting in a series of black ridges and gray depressions on the weathered surface. The outstanding characteristic of the fresh material is its extreme stretching.

Microscopically this specimen shows bands composed mostly of hornblende needles about 1.5 by 0.05 mm. separated by a crushed amygdule of quartz and epidote in a band of fine-grained quartz and feldspar. The rock is holocrystalline, almost schistose. Hornblende is the most abundant mineral, constituting about 50 per cent of the rock. It occurs in the dark bands in small acicular crystals embedded in a fine-grained groundmass of quartz and feldspar and in the more acidic layers as poikiloblastic anhedral masses. It is partly altered to chlorite. Quartz is next in abundance to hornblende, occurring in the groundmass in fine anhedral grains less than 0.1 mm. and in the amygdules as grains with sutured boundaries about 0.3 mm. showing no strain shadows. Feldspar is slightly less abundant than quartz. It was determined, in some cases at least, to be about oligoclase-andesine. The grains are slightly larger than the quartz and contain many fine inclusions of epidote. In the groundmass it is very similar in size and appearance to the quartz. Epidote is rare in the groundmass but makes up over half of the amygdules, occurring as a finely granulated mass. Magnetite occurs in the amygdules in octahedra less than 0.1 mm. and as fine disseminated grains in the groundmass. It is apparently secondary.

SCHISTOSE VOLCANICS

The schistose type of volcanics is at the end of the series of increasing schistosity. Amydules no longer are visible in the field and the rock has a laminated structure and much more perfect cleavage than the two preceding types. The color is distinctly green in the fresh material due to the abundance of green hornblende and a certain amount of chlorite. The Bayview greenstones exposed on Northeast Creek near Bayview fall into this class although in many cases the schistosity is almost lacking. They are composed mainly of hornblende, chlorite, and epidote. Although somewhat massive they grade imperceptibly into the truly schistose type to the south. The most typical examples of these schistose amygdaloids are confined to contacts and shear zones, a circumstance suggesting that the increased schistosity of various types is a local and secondary feature. While the rocks show no evidence of amygdaloidal structure in the field, in thin sections traces of amygdules are frequently noted (pl. XXXIII, fig. 2).

Specimen from Susquehanna River ⅜ mile north of Frenchtown, inclusion in granite porphyry dike in stream bed:

Megascopically the rock is apparently included in the dike but the body is large enough not to have been altered much more than the other rocks of the type found near contacts. It is a dark gray, fine, even-grained rock with a distinctly laminated structure and very regular cleavage. The lamination is caused by light and dark layers less than 0.1 mm. thick.

Microscopically the material is holocrystalline, fine-grained nearly equigranular and schistose. The lamination is due to a higher concentration of green hornblende crystals in the darker layers with a nearly perfect linear orientation. In the lighter layers quartz and feldspar are more abundant than hornblende. Occasional larger grains of feldspar are crushed and partly granulated. Secondary growths of magnetite and chlorite are also larger than the average grain size. Hornblende is the most abundant mineral, making up about half of the rock. It is acicular in habit, green with a pleochroism from light yellowish-green to deep blue-green and an average size of 0.8 mm. by less than 0.1 mm. A mosaic of quartz and feldspar makes up most of the remainder of the rock. The grains are about 0.1 mm. but longer than wide and have their long dimension parallel to the foliation. The feldspar was determined as oligoclase, about Ab_8An_2. Quartz and feldspar are about equal. The larger feldspar grains, about 1.0 mm., are granulated and show orientation at small angles to the foliation as if they have been rotated by shearing in the rock. Secondary minerals are irregular magnetite-chlorite aggregates up to 0.5 mm. transgressing the foliation, fine disseminated magnetite in the groundmass, and a few small anhedral grains of epidote.

Specimen from east side of the Susquehanna River about 30 feet south of the north volcanic-granite contact:

Megascopically this rock closely resembles the previous specimen and also occurs near the contact of a granite porphyry dike. In hand specimens it is almost black with a laminated structure due to finer darker layers. The grain is fine and even with a good cleavage parallel to the schistosity.

Microscopically the rock is holocrystalline with a schistose texture caused by biotite plates in a fine-grained groundmass of quartz and feldspar. Elongated lenticular bodies of quartz and feldspar with little biotite are apparently crushed and rolled out amygdules. The felsic minerals of the groundmass are slightly elongated and oriented parallel to the schistosity. Poikiloblastic hornblende up to 0.2 mm. occur, usually parallel to the foliation but sometimes at an angle to it.

Biotite makes up somewhat less than 50 per cent of the rock and reaches an average size of 0.2 mm. in its greatest dimension. Quartz is slightly more abundant than feldspar. It shows no strain shadows and is clear. The average dimensions are about 0.1 by 0.07 mm. The felspar grains are slightly larger and a few crushed individuals of greater dimension are present. It is crowded with fine inclusions of epidote. The composition was determined by extinction angles as oligoclase-andesine, Ab_7An_3 to Ab_6An_4. Secondary minerals beside the few green hornblendes are magnetite, chlorite aggregates up to 0.1 mm. which transgress the foliation, fine anhedral magnetite, and the epidote inclusions in the feldspar.

Specimen from Susquehanna River, Keystone quarry, at the contact of a gabbro dike:

Megascopically this material is a very light gray, fine, even-grained rock with larger crystals of magnetite scattered through it in the fresh material. In weathering it turns brown and develops a much more ready cleavage. The platy cleavage of the fresh material is poor but it has a distinct linear structure due to fine colorless acicular minerals up to a millimeter or so in length which have an almost parallel alignment. This rock resembles the inclusions of arenaceous sediments in the granite south of Conowingo dam (26) more than any other rock found in the area but is probably a contact metamorphic phase of the volcanics.

Microscopically this specimen is holocrystalline, fine-grained granulose with only a faint suggestion of foliation since it is cut normal to the linear minerals nearly all of which are parallel. The slight foliation is cut normal to the linear minerals nearly all of which are parallel. The slight foliation is due in part to linear minerals at an angle to the majority and to the longer dimensions of the felsic constituents which lie almost in the same plane (pl. XXXIII, fig. 3).

The essential minerals are tremolite, quartz, and feldspar. The tremolite for the most part shows basal sections due to the orientation of the slide in the rock, but occasional crystals are cut parallel to the length. The average cross section is a little over 0.1 mm. and they range up to 1.0 mm. in length. Slight alteration to chlorite is present. The tremolite constitutes somewhat under 30 per cent of the rock. Feldspar is slightly more abundant than quartz and occurs in grains from 0.3 to 0.1 mm. It is oligoclase, about Ab_8An_2, in part at least. Quartz is less abundant, smaller in size 0.1 mm., and shows no strain shadows.

Secondary minerals are clinozoisite in subhedral grains about 0.1 mm., magnetite in octohedra and anhedral grains of about the same magnitude, and magnetite chlorite aggregates up to 2 mm.

GABBRO

The gabbroic rocks of the area have been described in Harford County as metagabbro and in Cecil County as gabbro. The only difference is a variation from a massive type to a highly stretched type, a phenomenon which appears to be local and due to shearing and contact action rather than to an original difference in the rock.

MASSIVE GABBRO

The massive gabbro occurs in dikes in the volcanics and is the more common one in Cecil County. In most places it shows a weak flow structure thus grading over to the second type but occasionally it is found without any foliation. The material is medium grained with the mafic constituents usually green hornblende, showing greater size. The foliation, when present, is caused by the parallel alignment of these minerals. Analyses of gabbros from the area in question are not available but those to the north, which have been carefully studied, do not differ except that they show somewhat less alteration. These gabbros to the north are both normal and quartz-bearing (11 and 54). The gabbros associated with the volcanic complex usually carry considerable quartz but in at least one case it is lacking. Alteration in the gabbro has been discussed by Insley (54), Bascom (1902), Jonas and Knopf (64), and Watson (102).

Specimen of gabbro near contact, southwest side of Keystone quarry, Susquehanna River:

Megascopically the rock is mottled dark-green and white with a medium coarse, even grain. It has a fair foliation due to the parallel alignment of the mafic constituents but has no regular cleavage.

Microscopically the rock is holocrystalline hypidiomorphic with a medium and uneven grain. Larger stumpy hornblende crystals are embedded with little parallel orientation in a fine groundmass of feldspar and quartz.

Essential minerals are hornblende, feldspar, and quartz. The hornblende constitutes slightly over 50 per cent of the rock. It has a characteristically broad stumpy habit and is only partially idiomorphic. Its color is light green and the pleochroism is much less marked than in the hornblende of the volcanics. The feldspar was determined as bytownite Ab_1An_9. In most cases, however, the borders of the grains are altered to albite and some are entirely replaced. Quartz is about equal to feldspar in abundance and shows no strain. The grain size of the groundmass averages about 0.1 mm.

Epidote in fine grains in the groundmass is the only important secondary mineral. Magnetite is rare.

Specimen from Northeast Creek along the southern volcanic-granitic contact 1 mile southeast of Bayview:

Megascopically this rock is dark greenish-gray with dark green equant phenocrysts of hornblende about 1 mm. in size. It shows no foliation at all in the specimen although there is an indefinite banding of finer grained streaks in the outcrop. The groundmass is fine-grained. It is dark gray and weathers to a greenish-gray.

Microscopically the rock is holocrystalline inequigranular. Both the feldspar of the groundmass and the hornblende phenocrysts show cataclastic effects, the hornblende in particular. In many cases it is bent and in one place in the slide one of the crystals is rolled almost into a circle, the effects figured by Harker (48, p. 354) as typical of cataclastic metamorphism.

The essential minerals are green hornblende and feldspar. The hornblende constituting over 50 per cent of the slide reaches a size of about 1.5 mm. and is nearly equant. Its pleochroism is weaker than in the volcanics; yellowish to yellow-green. Partial alteration to chlorite is present. The feldspar is largely replaced by epidote and is fine grained, about 0.1 mm. The few grains on which measurements were possible seem to fall between andesine and labradorite, according to extinction angles normal to 010 and index of refraction. Quartz was not found.

Secondary minerals are clinozoisite in anhedral grains of about 0.05 mm. making up about 30 per cent of the slide, and irregular masses of magnesite associated with chlorite as filling in cracks in the hornblende. It is partly altered to brown hydrous iron oxides.

STRETCHED GABBRO

The more highly stretched type of gabbro differs from the massive variety in its more intense foliation and tendency to a finer grain. With decreasing grain size the stretched gabbro becomes exceedingly difficult to distinguish from the schistose type of volcanics and even in thin section there is no marked difference. The volcanics are slightly finer in grain and the habit of the hornblende is somewhat different. The hornblende of the volcanics is acicular and more or less idiomorphic with a strong pleochroism. In the gabbro it is also acicular but shows less developed crystal form, is more fractured, and has usually a weaker pleochroism. The feldspars of the gabbro are so extremely albitized that they can not be used for determination of gabbroic character.

Specimen from the east side of the Susquehanna about 500 feet south of Keystone quarry:

Megascopically the material is dark greenish-gray with a speckled appearance due to the hornblende and feldspar. It has a slight brownish stain from weathering. Linear stretching is pronounced with a rigid parallel alignment of the hornblende. A dike of aplitic material about 1 cm. thick runs through one corner of the specimen and is probably derived from the granite which is exposed a short distance to the south.

Microscopically the thin section of this specimen shows a rock of holocrystalline, nearly equigranular character. Its texture is medium-grained gneissose. The hornblendes are larger than the rest of the grains and are nearly parallel.

The essential minerals are hornblende, making up about 50 per cent of the rock, and feldspar and quartz in nearly equal amounts. The hornblende grains tend to be shorter and wider than those of the volcanics and some show a poikiloblastic structure. These are fractured and stretched out in the line of foliation. Pleochroism is fairly strong yellow-green to blue-green. The average size is 1 mm. by 0.5 mm. The feldspars range in size from 1.0 to less than 0.1 mm. The larger individuals show Carlsbad twinning and oriented inclusions of hornblende, the structure to which Sederholm (96, p. 45) gives the term symplectite. The feldspar was determined as having the composition of oligoclase Ab_8An_2. Quartz is nearly as abundant as feldspar. The average size is 0.2 mm. It shows a tendency to segregation in irregular bands and in some cases shows undulatory extinction. A few grains of magnetite are associated with the hornblende.

GRANITE *

Later than the gabbro is the granite complex in which the following three types may be distinguished in larger bodies and three other types in dikes: Port Deposit granite, massive granite, hornblende granite, granite dikes, granite porphyry, and aplite dikes.

The *Port Deposit granite* is intrusive discordantly into both gabbro and volcanics, transecting the foliation of the older rocks. In addition xenoliths of gabbro are found locally torn off the walls near the contact with the granite. Larger bodies of volcanics are found in the granite near contacts and are apparently loosened from larger masses of wall rock.

The *massive hornblende granite* is found in dikes intrusive into the volcanics. These are abundant on Stony Run and Northeast Creek. On Stony Run, south of the railroad, inclusions of gabbro occur in this granite.

The *hornblende granite* is not found in association with gabbro. However, its relations to the volcanics are clear. Xenoliths of volcanics occur in Principio Creek and the granite is found intrusive into the volcanics in small stringers. Along contacts the volcanics are quite schistose and the granite fine grained with a strong linear flow structure.

The *granite porphyry* differs from the other granitic dikes in color and

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* Ed. Note: The term "granite" is here used loosely as a group name for the rocks of the granodiorite complex described in part II of this volume.

texture. Microscopically, it is finer grained and the feldspars have a different habit. The occurrence of the dikes is similar to that of the granite dikes described above and in addition the granite porphyry forms plug-like intrusions. In a few cases it cuts the wall rock foliation at a high angle. Inclusions of the volcanics are found locally. This material shows intrusive relationships to all the older rocks except the schist. It is common as dikes in the gabbro, granite, and in the volcanics.

The *granite dikes*, which are distinguishable in the field from granite porphyry by their lighter color and large quartz grains, nearly parallel the schistosity of the wall rock. They are intrusive into the volcanics. On Northeast Creek east of Leslie, this rock has soaked into a banded and crinkled material which is probably a schist member of the Glenarm Series. Little altered inclusions of schist showing a distinct fracture cleavage occur in the granite.

The *aplite dikes* are intrusive into the granite, gabbro, and volcanics. Within the granites their foliation is parallel to that of the granite although the dike contacts maybe at an angle to it. This would seem to indicate that the dikes were probably formed during a late stage of the granite intrusion. In the volcanics the foliation of the dikes parallels their contacts though the dikes may be at any direction in the country rock. In the gabbro the aplites occur in tiny stringers without foliation and are oriented in all directions.

The youngest intrusive rock is a hornblende lamprophyre. It occurs in small dark fine-grained dikes in all the rocks of the region except the schist. The larger dikes generally strike parallel to the schistosity of the wall rocks. Smaller stringers may transect the country rock in any direction.

The age of various types of veins found in the region is mostly uncertain but some small pegmatites are associated with the granite porphyry. They were not found in the lamprophyres.

Dikes of diabase correlated with the Triassic intrusions to the north and

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FIG. 1.—Photomicrograph of porphyritic texture and zonal growth. Crossed nicols, specimen 57.

FIG. 2.—Photomicrograph of bending in hornblende in massive gabbro. Parallel nicols.

FIG. 3.—Photomicrograph of granite porphyry. Crossed nicols, specimens.

FIG. 4.—Photomicrograph of cataclastic structures in sheared granite porphyry. The fractures in the large garnet crystal are walled by quartz. Crossed nicols, specimen 63.

FIG. 5.—Photomicrograph of mylonitic granite porphyry. Parallel nicols, specimen 36.

FIG. 6.—Photomicrograph of hornblende lamprophyre from south face of Keystone quarry. Parallel nicols.

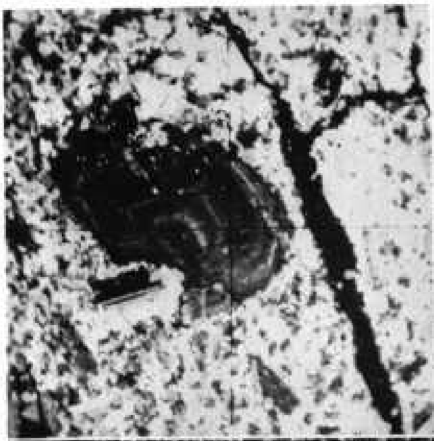


Fig. 1

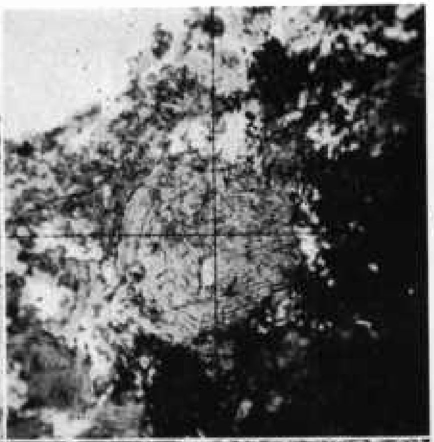


Fig. 2

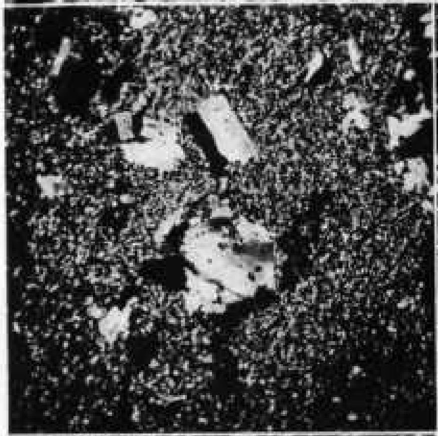


Fig. 3

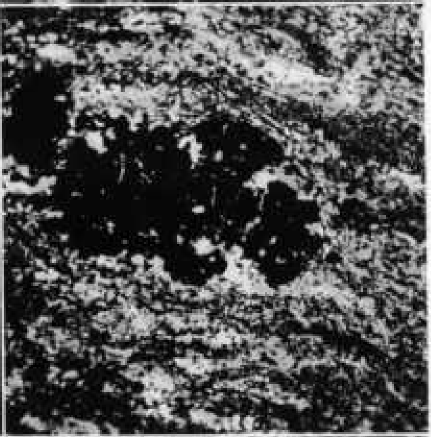


Fig. 4

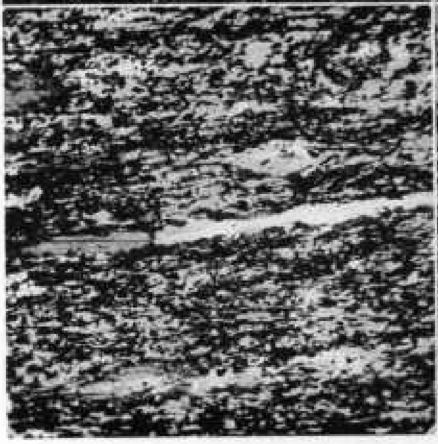


Fig. 5

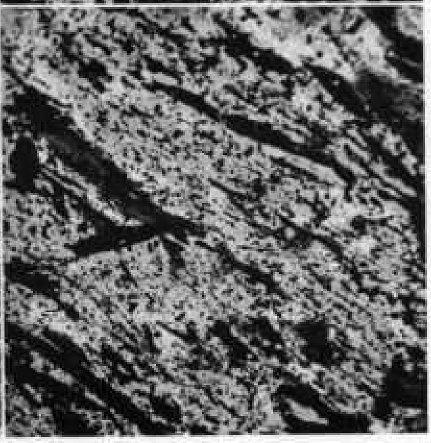


Fig. 6

west occur in the granite near Port Deposit and at other localities but none was found in the area covered by this paper.

STRUCTURE

ELEMENTS OF FLOW

Under elements of flow are included both primary structures due to movement of plastic material during intrusion and secondary schistosity due to metamorphism which has, in many cases, obscured the primary structures that were present. The degree of metamorphism varies with the different rock types but in no case were rocks found that were free from all evidence of deformation. Flow structure and allied phenomena of the rocks of the region will be discussed with the rock types in which they are developed.

THE GLENARM SCHIST

The Glenarm schist was found in only one small outcrop. Near the inclosing gabbro it loses its characteristic fracture cleavage and becomes more dense. The rock is a highly foliated chlorite schist with a strong fracture cleavage, transgressing the flow cleavage at about an angle of 45 degrees. The closeness of the cleavage planes and the amount of displacement along them has almost obscured the schistosity and fracturing takes place along the fracture cleavage planes rather than along the schistosity. The development of fracture cleavage in the Glenarm Series on the Susquehanna River has been discussed by Cloos and Hershey (26). The schist on Principio Creek shows great similarity to the schist of the Glenarm Series except that the flow cleavage is more intense. In addition there is a second fracture cleavage developed which produces fine crinkles on the planes of the first one.

The schist is intruded by small dike-like bodies of dark fine-grained rock. These resemble the hornblende lamprophyre but may be aphopyses of the gabbro which borders the schist on the north and south sides. The gabbro to the south becomes strongly foliated and gneissic near the contact though apparently not sheared. This probably is a primary border gneiss of the gabbro formed during a late stage of intrusion. Away from the contact the gabbro is more massive though there is a tendency to banding and other flow structure.

VOLCANICS

Flow structures in the volcanics are largely secondary. All alignment of the minerals must be due to secondary processes since the minerals themselves are secondary. Knopf and Anderson (61) describe similar textures in andesite roof pendants at Engels, California, as secondary and due to metamorphism. Traces of primary structures, however, are preserved in the shape and orientation of amygdules and inclusions which are mostly parallel to the later schistosity. The shape of both amygdules and inclusions is, as a rule, lenticular but without an excessive length-width ratio; an indication that flow was not strong in the primary lava. There has been little stretching of these bodies since. No cases were found in which amygdules had been either broken and pulled apart or stretched into elongated bodies as have, for instance, the pebbles of the Cardiff conglomerate near Whiteford in Harford County. Where the amygdules are deformed they are crushed and rolled out into lenticular streaks of fragments to such an extent that the amydgaloidal character has been lost. As noted earlier, this extreme deformation seems to be limited to zones of shearing or contacts and is not due to regional metamorphism. Other exposures show amygdaloids without any deformation although the rock is thoroughly recrystallized. Additional evidence of the restriction of the deformation to local zones is furnished by the wide variations in strike of the schistosity over short distances. Later intrusions in the form of plugs or dikes seem to have bent and deformed the older rock to conform to their contacts. Where straight dikes occur bending of the wall rock schistosity is rare. This, however, may be due to the small angle between the dikes and the general strike of the country rock.

Actual contacts in the region are rarely exposed and hence mapping must be done by distribution and structural features of outcrops interpreted in the light of their behavior where contacts can be seen. Exposures of strikingly discordant contacts between the volcanics and later rocks are few. The exposed contacts are generally conformable to the foliation of the volcanics. Where later intrusions cross the strike of the volcanics they do so by interfingering and "lit-par-lit" injection. This manner of intrusion has resulted in the splitting off of small bodies of volcanics which are found as dike-like bodies outside the main mass. This "lit-par-lit" type of contact is somewhat similar to that described by Cloos (28) between the Ellicott City granite and the Wissahickon schist.

The original nature of the volcanic complex has been obscured by the later intrusions and their shattering of the volcanic rocks. However, while the large structural features have been largely obliterated, smaller structures often remain. The most important of these is the amygdaloidal character of the material. The development of this structure is so widespread and characteristic that there can be little doubt that the original rock has been vesicular. According to Bowen vesiculation in a rock of any thickness can be developed only in a flow but not in dikes. These rocks are, as a rule, several hundred feet thick and, except for a few later dikes which cut them, may attain thicknesses of more than a mile. Therefore they must have been formed as flows and not as dikes, as suggested by previous workers (44). Since flows do not form with dips from 70 to 90 degrees these must have been tilted or folded into their present position. If the body is a fold the folding, like that of the Peach Bottom syncline, is isoclinal but no general change in the dip or strike indicating a fold is recognizable.

The strike readings given in the following pages are simplified as follows: readings are taken in degrees from 0 to 180 degrees clockwise with 0–180 degrees at the north. Thus a reading of 45 degrees represents a direction 45 degrees east of north and one of 135 degrees a direction of 45 degrees west of north.

The general strike of the volcanics changes gradually from west to east, the banding in the flow structures showing a tendency to form a fan pattern opening to the east. On both sides of the Susquehanna River the strike is uniformly about 40 to 50 degrees. On Mill Creek it is about 55 to 60 degrees. This strike persists through the central part of the volcanic complex. In the southern half the strike shows a tendency to swing more to the east and in the northern half it tends more northward.

In the eastern portion of the area there is little change in the general strike of the foliation but there is a marked flattening in the dip both in the granite and the volcanics.

GABBRO

In the large body of gabbro in Harford County, to the southwest of the volcanic complex, the foliation is parallel to the schistosity of the volcanics where it joins them near the Susquehanna River. West and south of this region the strike bends to the north, following roughly the outline of the granite body which partly underlies the town of Havre de Grace.

The gabbro dikes within the volcanics are extremely variable. Their foliation may or may not parallel the schistosity in the wall rock or the contacts of the dike. As a rule, however, the dikes are parallel to the schistosity of the volcanics or cut it at a low angle and the foliation of the dike is parallel to the contact. Many of these dikes are exposed along the Susquehanna River and a few along other streams.

The contacts of gabbro and volcanics are always sharp and usually mark a zone of shearing accompanied by a development of strongly schistose and crushed rocks in the volcanics. These zones are in several localities the channels for later intrusives.

GRANITE

The character of the granite foliation varies with the rock type. Port Deposit granite, in which the mafic constituents are mostly mica, has a well developed platy foliation with a weaker linear direction due to the shape of the mica folia (p. 42). In the hornblende and massive granites, on the other hand, the shape of subparallel hornblende crystals favors strong linear flow lines with a weaker planar structure due to a slight deviation from a parallel alignment of the hornblende in the plane of the foliation. Inclusions in all the granites parallel the foliation when the shape of the inclusions is elongate or tabular. Equidimensional inclusions show no orientation (26). These inclusions are both autoliths and xenoliths in all three granites. According to Hershey (Part II of this volume) the directions expressed by the foliation and inclusions are lines of primary flow and not due to subsequent metamorphism. In this case it is to be expected that granite will cut off structures in older rocks where the two are not parallel.

Contact relations between the volcanics and granite are poorly exposed and in most of the localities studied the structures of both rocks are parallel. Locally, however, the contact is discordant and the structure of the granite parallels the contact while the schistosity of the volcanics is truncated. This is well shown by the "closing in" of the granite foliation on either side of the nose of the volcanic complex at its northeastern end. The intertonguing relationships where the contact crossed the strike of the volcanics has been described. This same type of contact occurs apparently between gabbro and granite, as is shown on the contact of the two south of the Keystone quarry north of Havre de Grace. Here the contact is parallel with the granite foliation and cuts that of the gabbro about 30 degrees. However, the distribution of the granite is such that, if the contacts are parallel with the foliation, the granite and gabbro must be intertongued. The same type of contact relations are clearly shown between gabbro and volcanics about 200 feet north of this locality.

That intertonguing contacts are not always developed on a small scale is shown by the bending of the strike of the volcanics around the nose of a granite body several hundred feet in width on the little stream three-eighths of a mile north of Frenchtown.

In the granite dikes the structures are quite simple and uncomplicated. There is a fairly distinct linear orientation and at times a weak planar foliation due to a majority of the hornblende crystals lying in the same plane. The foliation in all observed cases is parallel with the contacts. The contacts do not always parallel the foliation of the volcanics though they were not observed to cut the wall rock foliation at very high angles.

In the aplites, which occur only as small dikes, there is some variation in the intensity of foliation depending on the occurrence of the material and the parent granite with which it is associated. The aplites in the Port Deposit granite carry biotite and muscovite in tiny flakes and are quite massive. In the hornblende granite the aplites contain acicular hornblende with a fairly good foliation parallel to that of the inclosing granite regardless of the direction of the dikes. Where aplites are intrusive into the wall rock they have a fairly strong foliation, which is parallel to the walls of the dike, whether this direction cuts the foliation of the inclosing rock or is parallel to it.

The granite porphyry, while probably related to the granodiorite intrusions, is later and intrusive into them. It occurs in dikes from a few inches to about 75 feet thick. These dikes are most abundant along the Susquehanna River and the lower part of Principio Creek but are found also over the whole area. Along the Susquehanna River in Harford County they strike parallel to the wall rock structure. On Principio Creek where the strike of the volcanics swings more to the east they cut it, striking roughly parallel to the dikes at the river. On Stony Run the strike of both volcanics and porphyry is extremely irregular. One exposure shows a curving dike with the foliation of the volcanics following its contact. Probably the great variation in readings is due to the valley of the creek cutting across these curved dikes. Another type of variation is due to plug-like intrusions of the porphyry. Farther to the east the dikes are fairly regular and intrude the volcanics nearly parallel to their schistosity. The exposed contacts are sharp and the foliation of the dike, where it is developed, is parallel to the contacts except in cases of plug-shaped intrusions. The foliation of the wall rock is never cut at a high angle but is usually nearly parallel, apparently due to bending around of the wall rock schistosity since a short distance away there may be considerable difference between the strikes of the foliation of wall rock and dike. No dikes were found with exposed terminations but the frequency of exposures showing "lit-par-lit" injections of porphyry into volcanics seems to indicate that in most cases the dikes feather out into the wall rock.

The foliation of the porphyry can vary between a very weak and a very strong linear or planar structure. The latter occurs in dikes which have undergone considerable deformation. Shear zones of granite or gabbro are frequently marked by dikes of porphyry in the central portion. These dikes show strong cataclastic structures and schistose margins. The dike contacts have apparently been lines of weakness along which later movements have taken place. Contacts of other types are also loci of movement and in several cases have been the spaces into which the porphyry found its way. Inclusions in the porphyry are rare and in all cases are schistose volcanic rocks.

HORNBLENDE LAMPROPHYRE

The structures in the basic dikes in the region vary between a rather strong linear foliation with a weaker planar one due to the alignment of hornblende and a material in which no foliation is visible megascopically. Under the microscope all specimens show at least a trace of parallel hornblende crystals.

Where the foliation is visible it is usually parallel to the contacts. In the small irregular dikes in the gabbro the lamprophyre is generally too fine grained and massive to show any arrangement of minerals. The larger dikes have a fairly strong foliation in the central portion. The margins of these show chilled borders, finer grained and darker than the rest of the rock.

The dikes are mostly intruded parallel to the schistosity of the wall rock. Exceptions are found striking at a low angle to the foliation of gabbro, granite, and volcanics. In addition to these larger dikes there are small injections in the gabbro which are extremely irregular and have no relation to the foliation of the inclosing rock. These are well developed along the west side of the Susquehanna River. A dike of the same rock, but with a more pronounced planar foliation, occurs here intrusive into granite porphyry and cutting it at a small angle. The planar foliation in this dike, and also occasionally found in others, is due to the development of mutually parallel chlorite crystals. At least one case has been observed in which the strike of the lamprophyre is controlled by the schistosity of the wall rock. On the small stream three-eighths of a mile above Frenchtown a dike of the lamprophyre occurs in the volcanics which are here bent arount the end of a tongue of granite. The dike follows the foliation of the volcanics and its strike changes from 60 to 50 degrees within a distance of about 100 feet.

JOINTING

Jointing is abundant in the area. In all the rock types there are two dominating joint systems and others that are less widespread and some which are peculiar to certain rock types.

The two most important sets are those joints parallel to the strike and dip of the foliation and those nearly at right angles to the first and with a nearly vertical dip. The first set is present in all the rock types of the region but varies greatly in different rock types. They are most frequent and closely spaced in the volcanics, displaying considerable movement. In the gabbro and granite they are more widely spaced and in the dike rocks are usually inconspicuous although generally present. These joints are of considerable extent and more conspicuous than any other system.

Slickensiding is practically always present and indicates normal faulting. The set is later than the intrusion of the youngest rocks. Shear zones occur frequently in the same direction. Every gradation between the joints and shear zones is represented. In the volcanics zones of intense deformation, with the production of crush rocks and mylonite, die out into closely spaced planes of movement in solid rock which become more widely spaced farther away. Rarely are these joints more than a few feet apart in the volcanics. In the granite and gabbro they are less numerous but also grade into zones of shearing. The shear zones are frequently marked by dikes of granite porphyry which is intensely sheared along the margins and shows a strong foliation in the center. These sheared dikes are common in granite and gabbros. In the volcanics the dikes are little altered but the adjoining wall rock is highly sheared.

In addition to the slickensiding, indicating normal faulting on the strike joint faces, there is in places a second weaker direction of slickensiding which shows nearly horizontal movement. This is later than the regional tension joints and offsets them to a considerable extent. In one locality the offset has been about 2 feet on each joint, where they are about 2 feet apart. This movement appears to be local and has been effective over a small area. Where the rocks are exposed considerable creep is developed, producing an appreciable change in dip of both the foliation and joints.

The second important joint system is extremely uniform over the entire area. The joints are large, even, fairly widely spaced, and vary little in strike and dip over considerable distances. Except in one case where there are slickensides showing a nearly horizontal displacement, they show no evidence of movement. They tend to be slightly open and their surfaces are often coated with calcite or zeolite. However, no instances of dikes filling the openings were observed. Along the Susquehanna River they strike uniformly about 140 to 150 degrees with a very nearly vertical dip. Farther eastward the strike swings to the east but beyond Stony Run it swings back again toward the north. The average strike on Mill Creek is about 160 degrees; on Principio Creek it is about the same; while on Stony Run it is nearer 165 degrees. Exposures are too poor to record very many readings but these are probably close to the average. Beyond Stony Run the strike swings more westward and on Northeast Creek readings of about 110 degrees are usual where these joints are exposed. Most of these joints are nearly at right angles to the strike of the foliation but the dip is nearly 45 degrees to that of the linear schistosity; also they are developed equally in all rocks, hence they can not be primary cross joints. They have, however, the appearance of tension joints. The uniformity over a wide area and their other characters suggest that they are regional tension joints formed after the intrusion of the granites.

Another set of joints which is well developed both in volcanics and gabbro, and to lesser extent in other rock types, is composed of horizontal joints. These are common but rarely of large extent with great variation in strike and changing in dip from 0 to about 20 degrees except where they are developed on a hill side. Here the jointing often follows the topography. The number of these joints decreases with depth. Leith (68) describes joints of this type as being due to compression, the jointing being developed with removal of load by erosion. It seems reasonable to interpret these joints as exfoliation joints, since they remain always parallel with the present surface.

Another system of joints is sporadically well developed over this area. This set has a strike slightly south of east, with little variation over the region, and a dip from 60 to 70 degrees south. On a joint-strike diagram they show as a slightly variable group of joints striking at about 30 degrees east of the regional tension joints.

Primary jointing, except for the widespread strike joints, is not common. The only good examples noted in the area are in the granite porphyry dikes. These show both cross joints and diagonal joints in a few instances. The cross joints are developed in a plane normal to the orientation of the flow lines. They do not extend into the wall rock. These characters fit the definition of cross joints, that is primary joints due to tension during intrusion. They have very plane surfaces and show no evidence of movement.

The diagonal joints occur also in granite porphyry but not together with the cross joints. They are small, closely-spaced, and tight. Except where weathering has stained the surfaces they are often blind joints; that is, they are not visible but the rock will break along them. The traces of these joints on the platy foliation is normal to the linear foliation with an angle of about 45 degrees between the plane of the planar structure and the joint surface. The tightness of these joints and their development near the centers of the dikes is evidence that they are not feather joints, which are due to tension. The number of these joints, in the few localities in which they occur, is small.

Joints of origins besides those already described are few and small. Feather joints (29), that is open diagonal joints due to tension along a plane of movement with the acute angle between the joint and the fault plane pointing in the direction of movement, are found along small faults in several places. Neither the fault nor feather joints are of any great extent. The faults rarely show displacements of more than a few feet, and have apparently little relation to the structure. A few larger movements occur in the granite in a few cases with displacements in tens of feet.

One exception to normal faulting was noted. Here a small thrust is developed striking parallel to the foliation but dipping at a lower angle. Slickensiding shows that a reverse movement has taken place. The strike joints cross this thrust plane and offset it. Hence it must be older than the joints. The slickensides indicate a movement parallel to the linear foliation of the gabbro; that is, pitching about 50 degrees east. Small feather joints also indicate reverse faulting. A thin film of mylonitic material occurs on the plane of the thrust.

TABLE OF AGE RELATIONS

Rock Type	Inclusions	Intruded by
Hornblende lamprophyre	*Younger*	
Aplite		
Granite porphyry	Volcanics	Lamprophyre
Granite dikes	Glenarm schist	
Hornblende granite	Volcanics	Aplite Granite porphyry
Massive granite	Gabbro	
Port Deposit granite	Gabbro	Lamprophyre Granite porphyry Aplite
Gabbro		Lamprophyre Granite porphyry Aplite Pegmatite
Glenarm schist		Gabbro Granite dikes
Volcanics	*Older*	Lamprophyre Aplite Granite porphyry Granite dikes Hornblende granite Massive granite

SUMMARY AND CONCLUSIONS

In the course of the present investigation it was found that the area is not composed entirely of one rock type as it had been mapped. Several of the other rock types which are present in other parts of the Piedmont

Province were found in the area and are apparently of Glenarm age which had not been previously recognized.

There are at least seven rock types which vary rather markedly. The oldest of these are the schists. They bear a close resemblance to those of the Glenarm Series which are well exposed on the Susquehanna River at Peach Bottom station, north of the Pennsylvania line, and which are also found as inclusions at Conowingo Dam (p. 119). These schists show well developed fracture cleavage and in all respects resemble those of the Peters Creek formation. Apparently of about the same age are the volcanics, the diorite of Grimsley, or the metarhyolite and metadacite of F. Bascom. Into the volcanics is intruded a gabbro which has been described by Leonard (70), Insley (54), and F. Bascom (11). The gabbro has been separated into gabbro and metagabbro. In this area the gabbro shows a strong linear structure while the metagabbro is rather massive. Both are altered. These have been intruded by several granites which range in composition from biotite to hornblende granite. The granites in turn are intruded by dikes of granite porphyry and later by hornblende lamprophyre. The granite porphyry was recognized by Bascom and called "micro-granite." Within the granite are small aplite dikes later than the granite but of uncertain relations to the other rocks. There are also probable apophyses of the main granite mass.

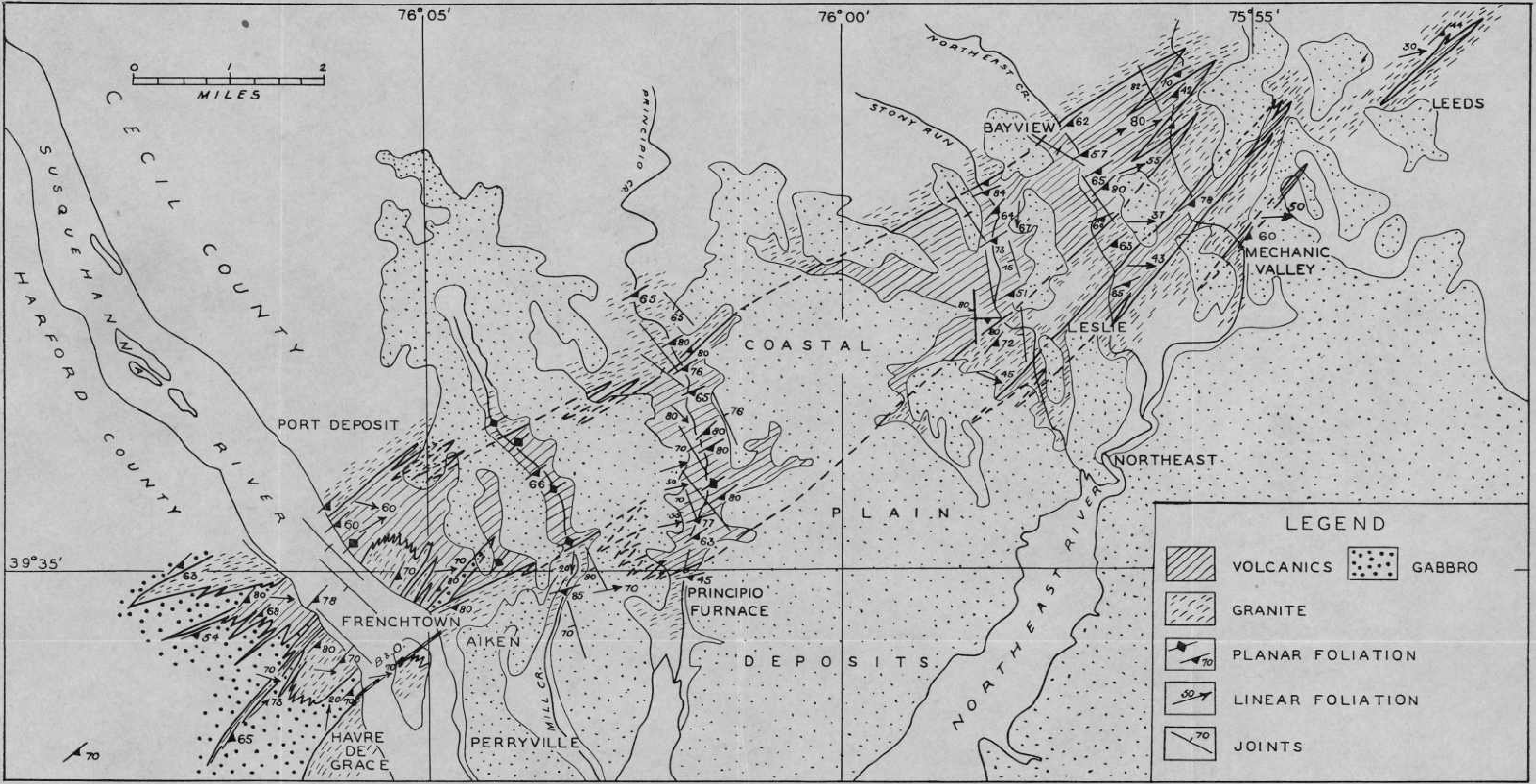
The structure of the volcanics apparently indicates the trough of an isoclinally folded syncline remaining as roof pendant in the surrounding Port Deposit granite complex. In this case the schist occurring in the central portion of the belt of volcanics must originally have overlain them. This would make the volcanics Peters Creek in age or older. Volcanics of the same type are common in the limestones of Carroll County, Maryland, and it seems probable that the Cecil County volcanics are to be correlated with them. In this case the Wissahickon formation is missing, but this is true in other localities and may be so in Cecil County. Whatever the actual position may be there can be little doubt that the volcanics belong to the Glenarm Series and that they have been folded into their present position.

The intrusion of the Port Deposit complex has taken place after this folding into the position it now occupies. These inclusions are believed to have taken place during post-Conestoga times.

The rocks of the region have been considered by many workers as highly metamorphosed and the foliation described as secondary, but the only highly metamorphic rocks are the volcanics and schists of Glenarm age and portions of the Baltimore gneiss. The structures of the intrusives are largely primary. The gabbro shows considerable alteration but largely dependent on local movements such as shear zones.

The metamorphism of all the later rocks of the area consists in a moderate cataclastic deformation. Locally it increases in intensity with the production of mylonite along zones of shearing. These shear zones show normal faulting.

The history of the region may be summarized as follows: Glenarm volcanics and schists were folded into isoclinal folds, slightly overturned to the northwest. Fracture cleavage developed after folding. The gabbro was then intruded largely following structures in the older rocks, mostly in small dikes. The gabbro apparently did not split up the volcanics or stope off blocks from the walls. The following intrusion of the Port Deposit igneous rocks broke up the edges of the volcanics, intruding them "lit-par-lit" and splitting off long narrow fragments. The direction of the flow of the granite was very nearly parallel to the strike of the fold. The dikes intruded after the granite followed these lines and intruded both volcanics and granite about parallel to their foliation. Veins and pegmatites formed after the dike intrusion. After the last intrusion there was sufficient deformation to form shear zones along the lines of foliation and develop cataclastic structures in varying degrees throughout the area.



Structure map of the area of volcanic rocks in Cecil County, Maryland

PART V

STRUCTURE OF THE METAMORPHOSED GABBRO COMPLEX AT BALTIMORE, MARYLAND

BY

CHARLES J. COHEN

STRUCTURE OF THE METAMORPHOSED GABBRO COMPLEX AT BALTIMORE, MARYLAND

INTRODUCTION

The subject of this investigation is a complex of basic and ultrabasic rocks which are metamorphosed in various degrees. The area lies in the Piedmont of Maryland west and northwest and in part within the city limits of Baltimore and occupies approximately 50 square miles. The rocks were made famous by the petrographic studies of G. H. Williams (104–110) fifty years ago. He was concerned primarily with the alteration processes. His report published in 1886 (108) has made the area a classic illustration of uralitization.

The present study was undertaken upon the suggestion of Dr. Ernst Cloos in the hope of discovering the mode of emplacement of the rocks. It was thought that the intense and conspicuous foliations of the rocks could be a primary flow structure. The investigation demonstrated, however, that the principal structure may not be primary, but a result of partially intense metamorphism, and that the primary structures are transected and have in part been obliterated by secondary structures. These structures prove of great interest.

The descriptive part of this report deals with the geologic setting, the contact phenomena, and the structures of the gabbro complex. The internal structures are outlined in two parts: (1) petrographic and (2) structural, supplementing the descriptive part of the structure and the history of the complex.*

GEOLOGIC SETTING

The Baltimore gabbro occurs in a peneplained area. The investigation was somewhat hampered by lack of good exposures. The best ones are in

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* Ed. Note: At the end of this report are supplementary notes by the editor. Since the investigations have been continued by other workers it has become necessary to incorporate newer findings and to outline the history of the region in the light of new results. The author, who has been in Rhodesia for several years, would most likely have expanded his views somewhat if he had had the new results available. The great distance and cumbersome correspondence between Baltimore and Rhodesia made a discussion impossible. The editor has therefore added his comments for which the author is not responsible.

the valleys of three southeast draining streams entrenched in the old peneplain: Jones Falls, Gwynns Falls, and the Patapsco River.

The details of the geologic setting are described in other papers of this volume (pt. III) and brief remarks here will suffice. The gabbro body forms a bulge in a belt of basic rocks extending northeast from Virginia through Maryland and into Pennsylvania and Delaware. The country rocks are the Baltimore gneiss , the Relay quartz diorite and the Glenarm Series. The gabbro bulge occupies a structural basin in the Glenarm Series and the Baltimore gneiss. The outer margin of the basin closely adjoins the gabbro and is marked by four major domes of Baltimore gneiss overturned to the south and southeast. The gabbro is intruded by several granitic intrusions.

PETROGRAPHY

THE PRINCIPAL ROCK TYPES

G. H. Williams (108) in his well known paper on the alteration processes in the Baltimore gabbro and in other papers has given a very thorough petrographic description of most of the rock types. His collections of rocks and thin sections are still available.

The rocks may be divided into two principal types: basic and ultrabasic. Ultrabasic rocks underlie 15 per cent of the area. In the following discussion the rock names will be defined as employed in this paper. Principally four rock types are distinguished, two igneous and two metamorphic ones.

1. *Pyroxene gabbro* refers to pyroxene, basic plagioclase rocks. The pyroxene gabbro consists of roughly equal amounts of feldspar and pyroxene. The feldspar is Ab_{15} An_{85}—a bytownite. The pyroxene is both orthorhombic and monoclinic. Accessories are magnetite, apatite, rarely olivine, and indeterminate inclusions in the minerals. The pyroxene-feldspar ratio is rather high locally and the pyroxene gabbro grades into pyroxenite. The grain size varies between one millimeter and three millimeters, except for coarse gabbro pegmatite. The minerals are hypidiomorphic equant. The pyroxene generally has rounded edges while the feldspar is more often indented. The texture is practically always massive. In sharp contrast with the gabbro, fresh specimens show cleavage faces of feldspar.

2. *Hornblende gabbro* is likewise a pyroxene, basic plagioclase rock, but containing brown hornblende in addition to the gabbro minerals. The type was recognized by Chester (24) in Delaware. The refractive indices of the hornblende are not quite high enough to warrant the term basaltic hornblende. The mineral occurs in compact grains with sharp boundaries

against pyroxene and feldspar. The latter minerals are as fresh as in pyroxene gabbro and the pyroxenes generally have the same hypidiomorphic form in the rounded edges. The hornblende boundaries in contrast are generally concave. Hornblende may poikilitically enclose rounded pyroxene and feldspar grains. It is also found in cracks in pyroxene. It is clearly younger than pyroxene but is older than uralitization. It may be regarded as a pyrogenic reaction mineral. The rock is further characterized by a foliation in contrast with the massive pyroxene gabbro. Slightly tabular pyroxene, feldspar tabular parallel to 010, and elongated irregular shaped brown hornblende contribute to the foliation. The presence of a primary foliation in the younger magmatic phase agrees with the relation noted by Balk (8) in the structure of the Peekskill norite body.

3. The term *metagabbro* refers to uralitized gabbro and consists essentially of pyroxene, uralite, and basic plagioclase. As shown by Williams, a green hornblende, basic plagioclase rock is the end member of the series of uralitized rocks. Uralite is an aggregate of microscopic fibers of amphibole derived by alteration from pyroxene (107, p. 52). All transitional types between a pyroxene rock and green hornblende-bearing rock are present. All uralitized gabbros with pyroxene relicts are massive, except for a few specimens derived from foliated hornblende gabbro. Mineral alignment of hornblende needles does not necessarily accompany uralitization.

4. The term *amphibolite* is used to denote a rock composed essentially of basic plagioclase and green hornblende, the latter aligned in varying degrees. The hornblendes are elongated prisms roughly bounded by cleavage planes and have ragged edges. The texture is therefore crystalloblastic. Feldspar too has rarely been noted aligned. Epidote is an important constituent.

Ultrabasic rocks. A wide range of ultrabasic rocks occur and these likewise together with the alteration processes, have been studied by Williams. The group includes varieties of periodotite, pyroxenite, serpentine, talc schist, and amphibole schist.

The usage of *peridotite* is conventional and unambiguous. The pyroxenites consist essentially of orthorhombic and aluminum-bearing monoclinic pyroxenes. They are generally medium grained and have a massive texture. The individual crystals are hypidiomorphic, equant. In the more calcic pyroxenites, particularly, the rock approaches a saccaroidal character due to the ease with which the individual pyroxene grains break out.

The rocks are unusual in that olivine is interstitial to large pyroxene crystals, contrary to the general rule. It may be noted that incongruent partial melting of a pyroxene rock followed by filter pressing is a process which can produce this unusual feature. Only the edges of the pyroxene grains would fuse and olivine alone would be left in the interstices.

The term *pyroxenite* is used in the conventional sense.

The ultrabasics which have been shown to be derived from pyroxenites and peridotites are far more abundant than the primary rocks. They comprise serpentine, amphibolite, chlorite, and talc schists and soapstones. Of these amphibole schists are the most common and serpentines comprise most of the remaining rocks.

The term *serpentine* is used conventionally. Serpentine and not hornblende has been derived from pyroxene in cases where the original proportion of olivine was large. An unusual serpentine (Plate XXXVI, fig. 2) adjoining some large boulders of quartz was found near a small stream one mile north of Union Dam. It consists of slender fibrous sheaves up to one inch long of chrysotile embedded in a groundmass of antigorite with a "feathery" texture.

Talc schists occur both massive (soapstones) and schistose, indicating perhaps hydrothermal *and* dynamic alteration.

Amphibole schist is used to denote a metamorphic ultrabasic rock consisting essentially of amphibole. It is in many cases a monomineralic rock and the amphibole a member of the tremolite-pargasite series. Less commonly the amphibole schists are massive.

CONTACT AND LOCAL ALTERATIONS

The principal mineralogic contact effect lies in the Wissahickon schist. *Garnets* are abundantly developed and at Sudbrook Park well formed equant garnets reach a size of one and one-half inches in diameter. Garnets are found also in the gabbro close to the schists at Hollofield, south of Rockland, and at Sudbrook Park. *Epidote* is also abundant in the amphibolites of the mixed gabbroic-Wissahickon rocks south of Bare Hills as to suggest it as an endomorphic contact mineral. It occurs in streaks, knobs, and nodules two feet in diameter.

The amphobolites in the southeastern portion of the area near the intrusion of the Relay quartz diorite have been extensively *saussuritized.* The rock weathers rapidly and is frequently rusty looking and fractured. The fractures are filled with thin sheets of felsic material. Saussuritization has affected only the feldspar but the hornblende folia are as in other amphibolites. This alteration indicates a low grade dynamic metamorphism subsequent to the formation of the amphibolite, and it may be attributed to the intrusion of the quartz diorite.

Chloritization of amphibolite is common in a small area one and one-half miles southeast of Hollofield. It is confined to irregular zones extend-

FIG. 1.—Foliation cutting bands in the Baltimore gneiss. South bluff of Lake Roland.

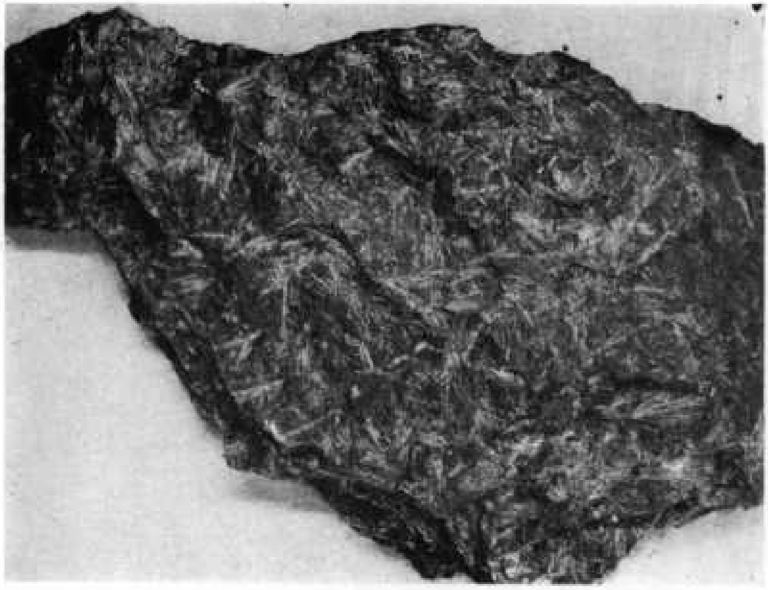


FIG. 2.—Feathery serpentine, natural scale. One mile north of Union Dam.

ing up to a few inches from a strong set of cross joints. The alteration is a replacement of hornblende by chlorite. It is remarkable in that feldspar is unaffected, an immunity which must be attributed to low temperature.

Minor *assimilation and solution effects* have been noted at the contacts with felsic veins. Examples are hornblende needles and epidote in Relay quartz diorite aplite, gabbro ghosts in Port Deposit granite aplites, and relative enrichment in mafic constituents of the gabbroic rocks at the border of felsic veins, as by selective solution.

"Honeycomb ironstone" is a term which has been used to denote chunks of a cellular iron-stained silicious rock generally found as float. The septa are of chalcedony, terminated quartz, interlocking quartz, and hematite—material evidently deposited from a colloidal suspension. The rock, as is generally recognized is a concomitant of the weathering of serpentines. That serpentine occupied the cells is shown by a single specimen, found in Cedar Branch, some cells of which are still filled by serpentine (Plate XXXVII Fig. 1b). The occurrences at Baltimore indicate that the cellular rock does not form in country undergoing rapid erosion. It is abundant on the old peneplain surface, near serpentines, and rare in dissected regions. A process leading to a similar product may, however, be seen in rocks so recently exposed as in railroad cuts. The weathered surface in such cases is cut by numerous such septa resulting in very much smaller cells and these are still filled with serpentine. It is suggested that when weathering extends deep beneath the rock surface, as during long exposures on a peneplain, the honeycomb ironstone with its relatively coarse dimensions forms through the same process.

DISTRIBUTION AND RELATIONS OF THE ROCKS

DISTRIBUTION IN THE MAIN BODY

The basic rocks are approximately five times as abundant as the ultrabasic ones. Of the basic rocks probably nine-tenths are amphibolites. Metagrabbro and gabbro are roughly equally abundant and hornblende gabbro is known from just four occurrences. Of the ultrabasic rocks the most abundant are likewise the metamorphic ones, principally serpentine and amphibole schist.

The distribution of the types is unsystematic. In particular the marginal distribution of ultrabasic rocks, typical of undeformed gabbro lopoliths, is lacking. It is true that talc, amphibole, and chlorite schists are common at the contacts, for example the western contact, that at Sudbrook Park, those of the Rockland tongue. These, however, are very small bodies of ultrabasic rocks. Many of the large ones are near the margin, but many are also away from it. In the center of the complex there are, for example along Gwynns Falls, feldspathic and magnetic serpentines, northwest of Forest Park Avenue, and amphibole schists to the southeast. When closely studied it seems that ultrabasics occur within a mile of every point within the complex.

A minor exception to the random distribution is the common presence of talc or chlorite schist at the margin of the less hydrated ultrabasic rocks. In particular, marginal talc schist completely surrounds the Bare Hills serpentine.

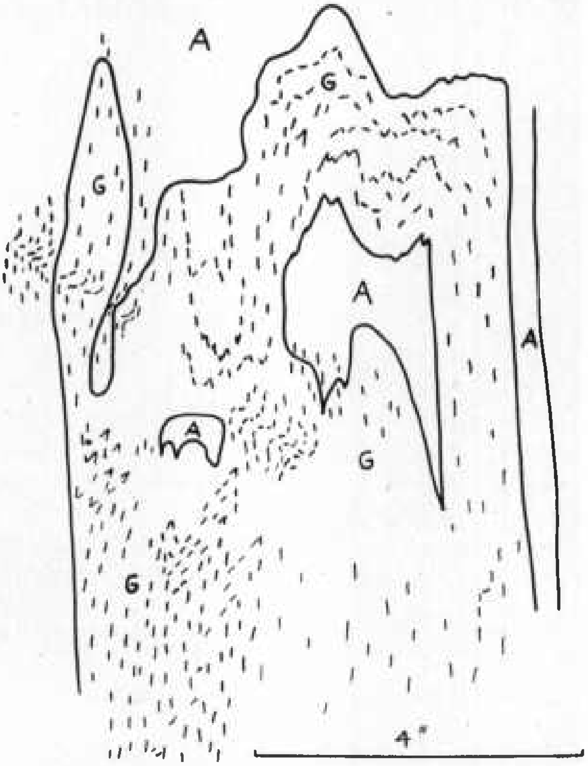


FIG. 28.—Contact of amphibolite (G) with amphobolite schist (A). Forest Park Avenue at Hillsdale.

True gabbro is most common in the northern and northwestern portion of the complex. It is, however, found principally on the peneplain and as boulders. Its relative abundance may therefore be due to concentration during peneplanation because it is extremely resistant to weathering.

Regarding distribution it can further only be added that there are random areas of mixed unaltered types and areas of mixed metamorphic types and that each igneous type is associated with its metamorphic equivalent.

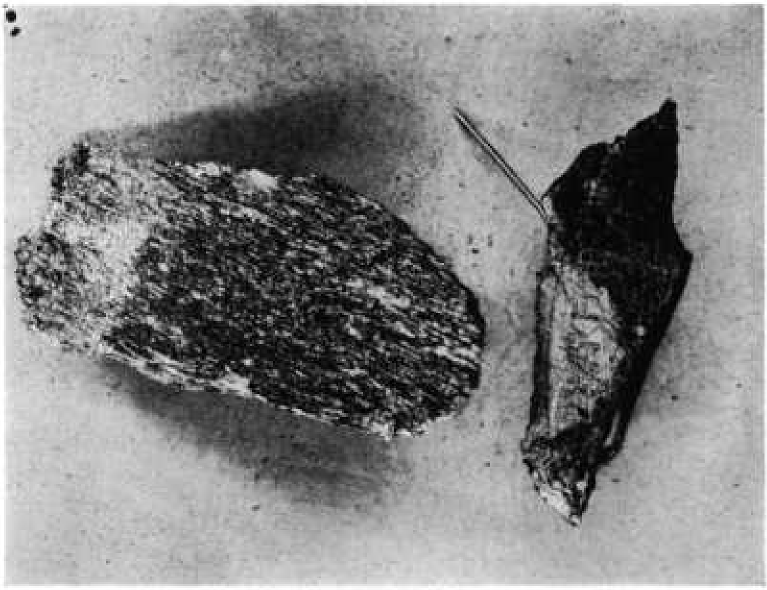


FIG. 1A.—Specimen of chloritized amphibolite. Patapsco River southeast of Hollofield.

FIG. 1B.—Honeycomb ironstone with residual serpentine. Cedar Branch. Natural size.

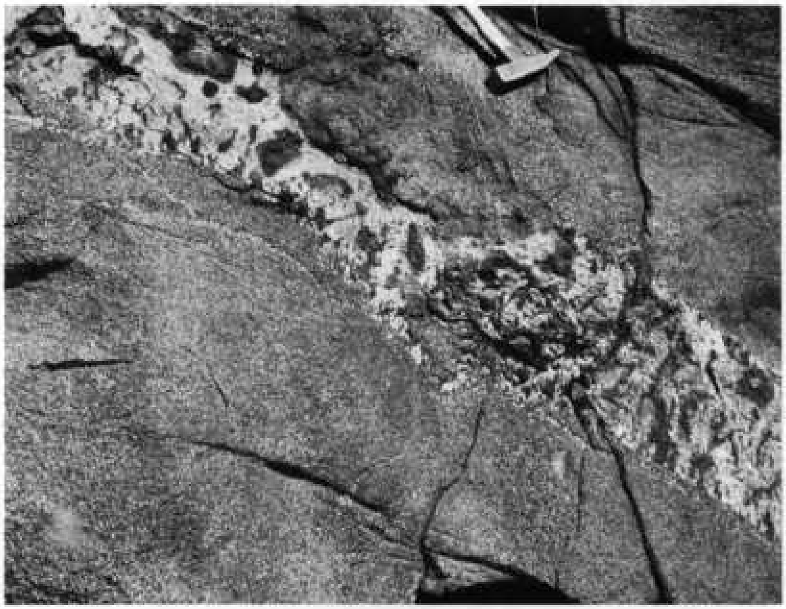


FIG. 2.—Gabbro pegmatite north of Union Dam.

FORM OF OCCURRENCE OF ULTRABASIC ROCKS

The outlines of the larger masses of ultrabasic rocks generally can not be mapped precisely for want of exposures. The Bare Hills serpentine is exceptional because of the thin soil. It is readily delimited and has an oval outline. Of the smaller masses from an inch to 20 feet across, many are tabular and all have sharp contacts with the basic rocks. Others have very irregular boundaries probably in part due to later deformations.

Williams and all subsequent writers have referred to the ultrabasic bodies as dikes. The only possible suggestion of a dike is the tabular shape of the smaller bodies and the invariably sharp contacts. The data themselves do not suggest dikes because many basic intrusions are now known with bands of ultrabasics as integral parts of the bodies (e.g. the Bushveld complex). For such an occurrence diking is an untenable hypothesis and the idea of differentiation by crystallization, which leads to the early segregation of olivine-bearing and pyroxenite rocks, is hardly challenged. A difficulty of the dike hypothesis is seen in the Baltimore area itself where basic and ultrabasic rocks are associated in and confined to a narrow tongue extending 2 miles from the main body south of Rockland. The ultrabasic rocks of this tongue are not dikes. A segregation hypothesis seems more plausible. It may be added that gabbroic veins, of uncertain provenance, are locally found cutting amphibole schist.

AMPHIBOLITES OF THE BALTIMORE GNEISS AREA

The Baltimore gneiss dome southeast of the main gabbro mass contains considerable quantities of amphibolite. Various lines of evidence lead to conflicting estimates of their age. They might have been formed before or after the deposition of the Glenarm Series. On the geologic map of 1892 Williams (105) classed the amphibolites of the Baltimore gneiss with those of the main gabbro complex. Jonas and Knopf followed this plan and in their 1929 report did not refer to the problem (64).

The gneiss dome at Baltimore is bounded concordantly on the northwest and west by a mica schist considered part of the Setters formation. This schist belt is only a few hundred feet wide at Gwynns Falls but gradually widens to the northeast. At Gwynns Falls the gabbro complex is separated from the Baltimore gneiss only by a thin sheet-like body of Relay quartz diorite. On the north the dome is bounded by amphibolites, ultrabasic rocks, and metagabbro. Mica gneiss was reported in a Maryland Geological Survey well record as far north as Canterbury Road and Highfield north of University Parkway.

The phase of the Baltimore gneiss quarried in Gwynns Falls and Jones Falls is a banded gneiss in which the bands have great persistence. The strike is consistently N 40°–70°E, 35°N, southwest of Jones Falls. On Stony Run south of University Parkway it has veered to N 10°W, 90°. No ultrabasic rocks have been found by the writer in this area though to the northeast, in Harford County, they are associated with the Baltimore gneiss. The basic rocks are amphibolites none of which quite satisfy the description of those of the gabbro complex. They differ in (1) the frequent presence of important quantities of biotite and (2) a much more intense planar foliation accompanied by only a faint linear foliation. The habit of the hornblende is often tabular parallel to a cleavage rather than the linear arrangement which is common in amphibolites.

At Gwynns Falls where the amphibolites are closest to the gabbro complex they are not at all altered like the rocks of the complex in contact with the Relay quartz diorite. Moreover they are isoclinally folded, also unlike the rocks of the gabbro complex (Plate III Fig. 1).

The distribution of the amphibolites in the Baltimore gneiss is not systematic. They are particularly dominant over the Baltimore gneiss at the contact with the mica schist both on Gwynns Falls and Stony Run, and are somewhat less important on Jones Falls at this contact. Though the exposures in the railroad cuts are good, basic rocks are nowhere found within the belt of mica schist. It is highly probable that the basic rocks have been interbanded with the Baltimore gneiss before the mica schist came into contact with the gneiss.

Metagabbro is not present in the Baltimore gneiss area though but slightly schistose amphibolite is well exposed in the center of a large mass of amphibolite 1000 feet across outcropping on the Pennsylvania Railroad just east of Union Station. It contains swirling bands (bed of Jones Falls before entering Fallsway aqueduct) typical of gabbros and suggestive of the igneous origin of the amphibolites.

Aside from such large bodies the amphibolites are in persistent sheets and thicker masses conformable in the Baltimore gneiss. The sheets vary in thickness from a millimeter up to 100 feet. The arguments favoring the pre-Glenarm age of at least some of the Baltimore gneiss are:

1. Petrographic differences: a. Frequent presence of biotite, b. Different habit of hornblende.

2. Where occurring close together the gabbro is altered and intensely fractured while the Baltimore gneiss amphibolites are folded and unfractured.

3. Amphibolites are not present in the Glenarm mica schist adjoining the amphibolite-bearing Baltimore gneiss.

The problem is not peculiar to this region. It has been encountered and left unsettled in the eastern United States by the workers in the gneisses of western North Carolina and of Virginia, by the authors of the Phila-

FIG. 1.—Thin acid bands in amphibolite. Patapsco River one mile southeast of Hollofield.

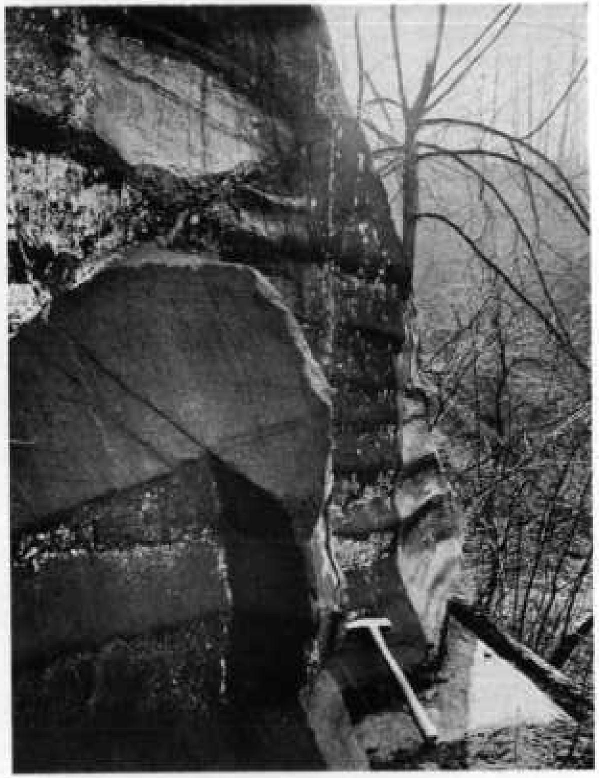


FIG. 2.—Joints refracted by banding. Baltimore and Ohio Railroad, south of Hollofield.

delphia Folio, Jonas and Knopf in the Quarryville quadrangle, the students of the oldest gneisses in southeastern New York, by Alling, Balk, Cushing, Martin, Newland, and Smyth in the Adirondacks, and other localities in the Canadian Shield.

DIRECTED STRUCTURES IN THE GABBRO MASS

BANDING

A striking feature of all the basic rock types is banding (Plate XXXIX, Fig. 1). It consists of an alteration of tabular shaped bodies of rock which have different relative amounts of the constituent minerals with or without a variation in grain size. The contacts often have knife-edge sharpness. The thickness of a band is quite variable, ranging from a quarter of an inch up to 2 feet. A determination of the lateral extent of a band depends on the presence of large continuous exposures. One hundred feet is the maximum found (Hillsdale Quarry), but there is no reason to believe that they may not be very much longer. In general very acid bands are more persistent than very basic ones. Bands have been found to terminate by wedging out and by lateral variation in composition until they grade into the adjacent bands.

All the bands of a group usually have the same mineral facies. That is, a group may be pyroxene gabbro; it may be metagabbro; or it may be amphibolite. Exceptionally, foliated amphibolite and massive metagabbro may be interbanded in which case the amphibolite is more melanocratic. This is significant, showing the greater ease with which the more basic and ultrabasic rocks react to dynamic metamorphism. Bands crossing one another have not been found.

SCHISTOSITY IN AMPHIBOLITES

According to the usage here adopted amphibolites are by definition schistose. The schistosity is due to subparallel elongated or flattened folia, no longer than the average feldspar, consisting of more or less aligned hornblende grains. The number of grains in a patch varies from perhaps 1000 down to one and the shape of the hornblende is most elongated in the most compact folia. The hornblende crystals have the shape of cleavage prisms with jagged terminations. A linear schistosity appears when the prism axes alone are subparallel, a planar schistosity when the axis lie at random but within a plane. In the case of planar schistosity the *b* (crystal) axis as well as the *c* (prismatic) axis tends to lie in the plane. This was found in oriented thin sections from localities where the structures were quite different (a. Herring Run, and b. Union Dam on the

Patapsco). Generally feldspar alignment is not present or can not be recognized.

CROSS JOINTS IN AMPHIBOLITE

A set of joints transects the linear schistosity of the amphibolites approximately at an angle of 90 degrees. These cross joints are smooth, plane, subparallel, and persistent in their direction. Their frequency, parallelism, and persistence depends on the intensity of linear schistosity of the amphibolites.

No other set of joints except a weak fracture cleavage (Plate XL, Fig. 2) is sufficiently developed to be of value in a structural analysis.

OTHER DIRECTED ELEMENTS

Foliation in gabbro.—Pyroxene gabbro has a massive texture. However, hornblende gabbro is foliated and its foliation is primary. Because of its rarity it is not important as a structure element.

Fracture cleavage in serpentine.—The serpentines are massive in texture and flow cleavage has not been found. A fracture cleavage has been found but it is not common. It consists of small, subparallel fractures from a fraction of an inch to several inches and, as an average, about one-quarter of an inch apart but with zones of closer spacing. Feldspars are dimensionally aligned in a serpentine outcropping near Gwynns Falls and Forest Park Avenue. Joints, rendered conspicuous by the familiar form of weathering of serpentines, show random orientation and are of little structural significance.

Schistosity in amphibolite schists.—The amphibole schists are frequently massive and schistosity is ordinarily much less developed than in the amphibolites. The structure consists primarily in a linear mineral arrangement. Some very fine grained amphibole schists with a silky luster show an intense planar cleavage.

Refracted joints.—An interesting feature of jointing, shown at only one locality, is the refraction of steep joints cutting flat-banded amphibolite (Plate XXXVIII, Fig. 2). The joints are vertical in the less basic bands and less steep in the more basic bands. Elsewhere all joints cut the banding without refraction.

Schistose zones.—Zones from one to six inches thick of intensely schistose amphibolite have been noted. The zones (Plate XXXIX, Fig. 2) are not rectilinear but bulge, narrow, curve, and even fork. Generally banding is displaced slightly and drags on planes of displacement have been observed. Less intensely schistose amphibolite zones transect massive gabbros. The age and significance of these structures has not been positively established. Some have an orientation and linear schistosity parallel to the linear structure in the amphibolites and have probably been formed at the same time.

Flexures of schistosity.—The attitude of schistosity is generally uniform on a small scale. However, in places it is flexed. These flexures consist in small zones perhaps an inch wide and a foot long. A relatively intense schistosity is oriented parallel to the plane of the disturbance. The regional orientation of these flexures is irregular.

Remarkably sharp and minute folding of linear schistosity in amphibolite was noted in a boulder. The two limbs of a fold are equally schistose and rectilinear. The crest is sharply pointed. Limbs wedge out by the tapering of the equally rectilinear axial planes (Plate XL, Fig. 1). A similar type of folding of planar schistosity was found on a somewhat larger scale in amphibolite north of Oella.

Quartz veins.—Quartz veins are numerous. Usually they consist only of quartz. Schistose and flexed zones are generally followed by these veins. They frequently parallel the schistosity and north of Oella a well developed set of veins paralleled the linear schistosity, the veins themselves being cylinders of irregular section.

DIRECTED STRUCTURES

THE CONTACTS

PRIMARY CONTACTS

The boundaries of the gabbro body against country rock are remarkably conformable and concordant.

The only country rock formation which is definitely cut by the gabbro is the Wissahickon schist of the Glenarm Series. The contact is exposed in the northeast corner of the area near Bare Hills, on the north border at Sudbrook Park, and on the western border on Bens Run at the Patapsco River. Here the boundary is a zone of intertonguing amphibolite and Wissahickon schist (Fig. 29). It is widest approximately 2 miles south of Bare Hills. The planar and linear schistosities in the intrusive is parallel with that in the country rock. The contact and the schistosity are either vertical or dip under the gabbro. The dip is between 40 and 75 degrees south at Bare Hills, vertical at Sudbrook Park, 45 degrees at Bens Run near Dogwood Road, and vertical south of Hollofield. Banding near the contact is not parallel with the contact. For example, at Hollofield banding in the serpentine quarry is flat and the contact is vertical only 200 yards away (Plate XLI).

Two dikes of amphibolite approximately one foot thick have been noted within a half mile of the boundary in Wissahickon schist. One is south of Hollofield, the other on Bens Run at Ridge Road. Both appear to be greatly deformed; one being bent and the schistosity crinkled, the other bulging, pinching, and fraying. The southeastern contact of the gabbro, against Relay quartz diorite, dips 45 degrees north and northwest and under the gabbro.

FAULT CONTACTS

The northern part of the eastern boundary is a fault. It is marked by a recrystallized breccia (p. 160) which is approximately 100 feet wide at Hollins Station. Similar breccia, perhaps its southern extension, was found within the gabbro on the creek entering Jones Falls from the northwest at Melvale. The cleavage trends in the amphibolite and Wissahickon schist on the one side and the Baltimore gneiss on the other are highly discordant.

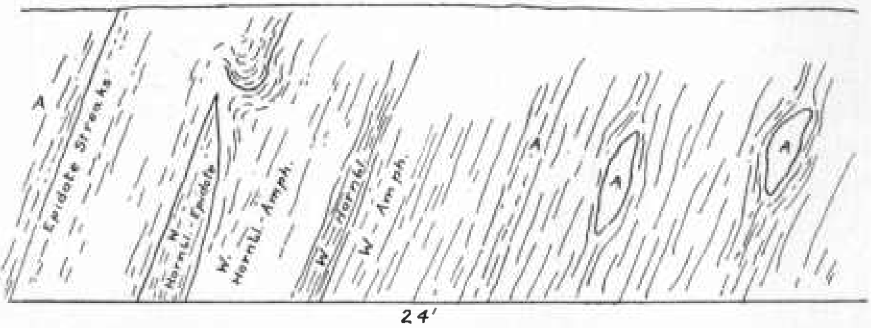


FIG. 29.—Section of mixed Wissahickon schist (W) and amphibolite (A). Pennsylvania Railroad at Mount Washington.

CONTACTS WITH YOUNGER INTRUSIVES

Intrusives into the gabbro are the Relay quartz diorite, the Port Deposit granite, the Ellicott City granite, and possibly the gneissic granite at Ilchester. All are conformable, intertonguing with the gabbro rocks. For this reason the age relations are not evident and the following detailed evidence is offered. Offshoots of the Relay quartz diorite intrude the gabbro discordantly. Moreover, the amphibolites in the contact zone have been saussuritized and otherwise altered. The Port Deposit granite cross-cuts the abnormally flat banding in gabbro at one place on Gwynns Falls (See also p. 127). Aplitic and alaskitic dikes with a peripheral distribution about the granite also cut the gabbro. The Ellicott City granite

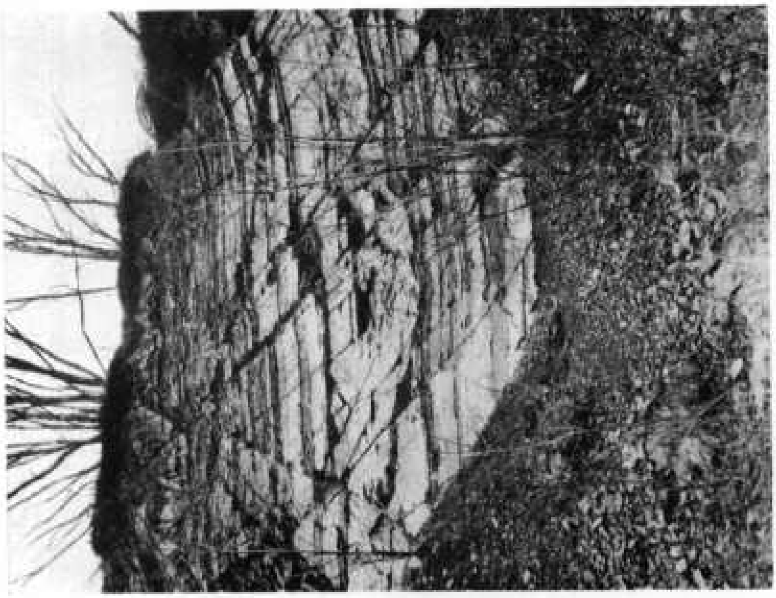


Fig. 1.—Banded ultrabasics. Northeast of Western Maryland Railroad and Gwynns Falls Parkway.

Fig. 2.—Schistose zone in gabbro. Western Maryland Railroad at Sudbrook Park.

is younger than the gabbro because associated pegmatites cut the gabbro. The granite itself cuts the amphibolite and its cleavage near Ilchester. Inclusions of banded gabbro in random orientation at Gray and of amphibolite near Oella have been found. The relative age of the Ilchester granite remains undetermined.

RELATIONS OF BANDING TO SCHISTOSITY

As a general rule banding and schistosity are parallel. This rule is confirmed in many exposures and exceptions are too rare to be discovered by other than a thorough and methodical search. Exceptions do exist, however. Along the Patapsco River between Hollofield and Union Dam weak but systematic cross-cutting is developed. Here the banding assumes various attitudes, one of which is parallel to the prevailing planar cleavage. Only where banding parallels the cleavage is planar schistosity well developed. If banding is at an angle to the cleavage the latter is very weak or absent. Its orientation is, however, represented by a set of joints or by weak fracture cleavage. Traces of schistosity were megascopically noted paralleling the joints and cross-cutting the bands. In

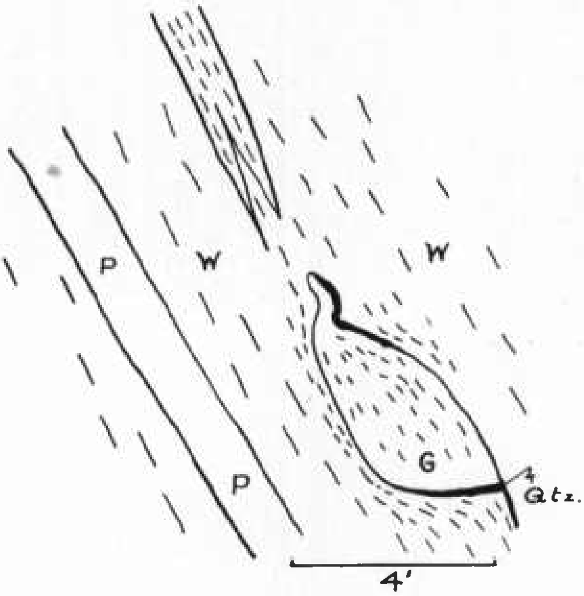


FIG. 30.—Amphibolite (G) in Wissahickon schist (W). Baltimore and Ohio Railroad south of Hollofield; P = pegmatite; Qtz. = quartz veins.

one instance alignment was masked by the fracture cleavage but was determined in thin section with the help of pleochroism of the hornblendes. The alignment likewise paralleled the fracture cleavage and cut banding. In the one outcrop where banding was actually seen curving into the plane of schistosity, a schistose zone intervened at the beginning of the curve (Fig. 31). A further feature of this Patapsco district is a beautifully developed strong and invariant linear schistosity with complementary cross-joints. The various attitudes of banding are all parallel to the linear structure and the intensity of this schistosity is uniform and independent of the direction of banding.

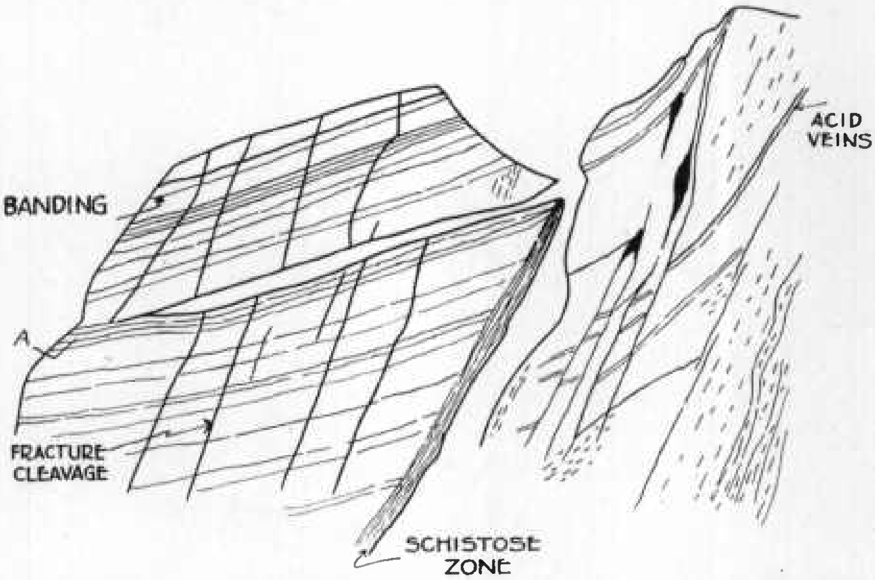


FIG. 31.—Relation of secondary structure to banding, one mile southeast of Hollofield.

Another relation of banding and schistosity is important. Banding may be flat but schistosity is rarely flatter than 20 degrees. It follows from this and the rarity of cross-cutting cleavage that flat banded rocks are generally massive. Flat banded metagabbro may be observed where it grades into amphibolite with steeply dipping linear schistosity on Gwynns Falls 1000 feet southeast of Windsor Mill Road. The bands swirl, steepen, and thin out into cylinders whose axes are parallel to the linear structure. A similar gradation from metagabbros into amphibolite was noted a quarter of a mile southeast of Dogwood Road and Belmont Avenue. In one case of flat banding a plunging linear schistosity was found close to the

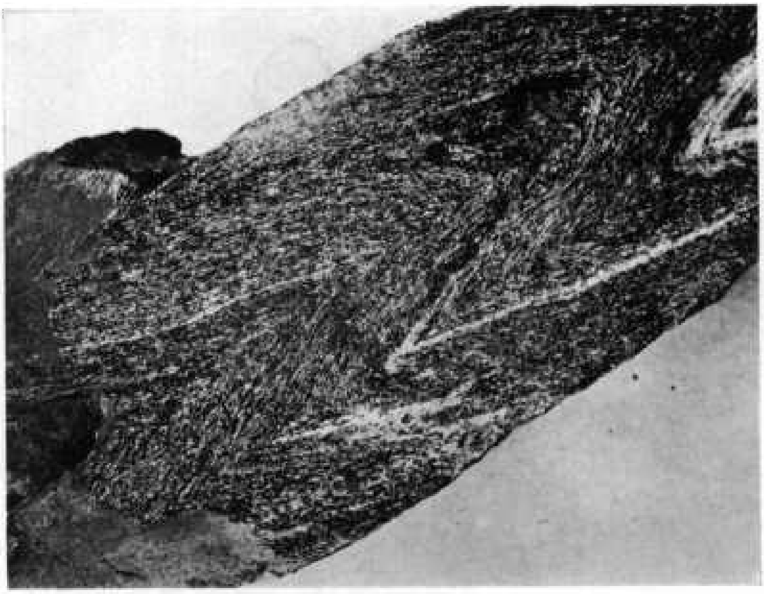


FIG. 1.—Sharply folded linear foliation of amphibolite. Specimen from south of Union Dam, Baltimore County. Natural size.

FIG. 2.—Cross jointing. Patapsco River, one mile southeast of Hollofield.

contact along the Baltimore and Ohio Railroad one mile south of Hollofield. It is another of the rare exceptions to the rule of parallelism.

THE TREND LINES

The trends of the elements are shown on the accompanying map (Plate XLI). The salient features of their distribution and orientations may be summarized as follows:

The trend is parallel to the contacts at the few exposures along the northern contact; along the entire length of the southeastern contact; and along the contact with the Wissahickon gneiss in the vicinity of Ellicott City, Oella, and north of Hollofield. However, the trend between Hollofield and Oella varies from N 10° W through northeast to east while the contact remains N 10° W approximately. The Ruxton fault cuts the flow elements at an angle of 90 degrees.

The dip when the strike parallels the contact is either vertical or toward the center of the gabbro complex. It dips under the complex at Bare Hills and along the southeastern contact.

The trend within the complex is northeast with a steep dip generally to the northwest.

Secondary planar schistosity embracing amphibole foliation and fracture cleavage is in part followed by acid veins. Everywhere the trend parallels the contact of the complex with the older rocks, even between Hollofield and Oella where the primary foliation is not always parallel to the contact.

Like the primary foliation it is vertical around the western and part of the northern contacts but dips about 50 degrees under the gabbro complex at Bare Hills and along the southeastern contact. Also like the primary foliation it has a northeast trend and a steep dip in the interior of the complex.

The foliation is never flat. It is always as steep as, or steeper than, the primary flow elements.

At the southwest corner of the complex the secondary planar foliation does not close around from the western to the southeastern contact, but it converges and continues on to the southwest.

The structure in the eastern part of the complex is still obscure. The southward continuation of the Ruxton fault (See p. 181) has not been definitely located and the few readings found in the area are not consistent enough to give a reliable picture.

The strike varies considerably. It is quite common to find strikes differing by 45 degrees from the mean in a relatively small area.

South of Bare Hills most bearings are nearly east-west and parallel to the northern contact.

The secondary structures in the country rocks are parallel to the contacts of the complex. Hence the gabbro is conformable.

The strike of the horizontal projection of linear elements is sometimes parallel and sometimes perpendicular to the contact. It is decidedly away from the contact south of Bare Hills and along the southeastern border. It consistently parallels the western contact, especially between Oella and Hollofield.

Within the complex the linear elements plunge in a northerly direction except in the vicinity of Mount Washington. The dip is rarely flatter than 25 degrees. It is generally between 40 and 70 degrees and is vertical near Thistle. It is nearly down the dip of the platy foliation except on the western contact.

The direction of the linear elements is far more consistent than that of the platy foliation and the banding.

In the southeastern Baltimore gneiss area the linear elements parallel that of the adjacent gabbro complex. In the northeast Baltimore gneiss area, where a fault intervenes between the gabbro and the gneiss area, the linear elements are at right angles. The linear foliation in the Wissahickon schist areas of the complex south of Bare Hills is parallel to that in the amphibolites.

JOINTS AND DIKES

The only significant joint system of the gabbroic rocks is a set roughly perpedicular to the linear foliation (Plate XL, Fig. 2). It is best developed in the exposures along the Patapsco River both south of Hollofield and on Bull Branch near Glenartney. It is confined almost entirely to amphibolites of the gabbro complex.

In the vicinity of Orange Grove most of the pegmatite dikes dip about 20 degrees east, which is roughly perpendicular to the very steep linear foliation.

INTERPRETATION OF THE STRUCTURE

Except for discussions in the section dealing with petrography of the rocks, the foregoing pages have been devoted to a presentation of observations. In the following section the significance of the directed structures will be discussed. Attention is focused on the metamorphic structure. An attempt will be made to show first that the cleavage is of metamorphic origin. Second, the significance of the orientation of planar and linear schistosity will then be discussed independently and the character of the deformation will be deduced forthwith.

METAMORPHIC ORIGIN OF THE AMPHIBOLITES

The most remarkable structural feature is the conformity of the amphibolite foliation with the boundary of the gabbro mass. Such conformity of foliation in an igneous mass has generally been regarded as evidence of the primary origin of that foliation. In the present instance, however, this foliation is believed to be secondary. The following facts attest to its metamorphic origin:

1. In terrains which have not been dynamically metamorphosed subsequent to intrusion, intrusives are unknown as amphibolite but are rather gabbros and diabases and related pyrogenic rocks. Further, primary foliation is known to accompany the typical pyrogenic facies, as for example, in the brown hornblende-bearing gabbro and the Peekskill norite (8).
2. The texture of the amphibolites is crystalloblastic (Page 219).
3. Primary banding and a later cleavage are not always mutually parallel. Though rarely, they differ in strike and dip and the cleavage as a rule is steeper than the banding. Exposures have been found in which the cleavage transects the bands.
4. The author believes that the relation between primary banding and secondary cleavage in the gabbro complex is paralleled by a similar relationship between primary and secondary structures in the adjacent wall rocks. Within the gabbro complex banding is a highly irregular structure; being bent, folded, flexed, generally with a great freedom of orientation. The direction of cleavage, on the other hand, is much more persistent over larger areas. Irregularities in the banding are furthermore transgressed by cleavage. This is comparable with the highly irregular orientation of folded bedding or of folded gneissic bands. Cleavage clearly transects bedding and gneissic foliation and maintains a much more consistent orientation over a large area. Banding in gabbro and bedding or gneissic foliation seem therefore comparable primary structures, all of which are transected by a later and much more consistent cleavage.

The above comparison is not meant to imply that banding and bedding are of similar origin or that they have been formed at the same time. They are merely both primary structures transected by similar later ones. In addition, these later structures are parallel inside and outside of the gabbro complex and it seems therefore suggestive of a similar origin, and they may even have been formed at the same time.

5. It has been outlined above that primary and secondary structures within the gabbro complex are mostly conformable. In the sediments and gneisses of the adjacent wall rocks primary banding and bedding are also predominantly conformable because of intense folding. Since this folding is isoclinal the schistosity parallels the primary structures more often than

it transgresses it. Transgressions are rarely exposed but have been observed, clearly indicating that the schistosity is later than bedding or gneissic banding. Since banding in the gabbro is also folded, it seems very probable that this conformity can be explained in a similar way and it does not necessarily mean that the schistosity is a primary structure.

INTERPRETATION OF PLANAR SCHISTOSITY

The orientation of planar schistosity parallel with primary structures is highly significant. In the gabbro complex schistosity mostly parallels both primary banding and the contacts of the complex. In the country rocks it frequently parallels bedding, gneissic banding, formational boundaries, and the contact between the Baltimore gneiss and the Glenarm series. The area in which this relation prevails is considerably larger than the gabbro complex and includes in Maryland the entire area in which Baltimore gneiss occurs, a strip at least 20 miles wide and 80 miles long in a northeast-southwest direction (see Parts II, III, and IV of this volume). The dynamic conditions in this area seem to be, as the grade of metamorphism and the uniformity of structures indicate, an accentuated form of the conditions governing Appalachian deformation. Between the open folds of the western Appalachians and the strip of crystalline schists containing the gabbro and basement gneiss is a belt of slates, phyllites, and other low-grade metamorphosed rocks in which the folds are isoclinal and the limbs are nearly parallel to one another and to a flow cleavage. Intensity of folding, it may therefore be inferred, has aligned bedding and flow cleavage planes with banding and schistosity in the highly crystalline rocks. Folding of such intensity is best described as flow and the planes of greatest dilation, which are planes of alignment, may be termed flow planes (flow cleavage). The planes of schistosity in the gabbro complex, as well as in the country rocks, are thus interpreted as flow planes.

INTERPRETATION OF LINEAR SCHISTOSITY

Linear schistosity (stretching in sediments or flow lines in igneous rocks) are coupled with cross joints (see Pt. I of this volume). The joints may therefore frequently furnish the clue to the interpretation of such linear structures. The cross joints in the amphibolites are closely related to the linear structure and of the same nature as those described in the Setters quartzite, the Port Deposit granite, and many other localities (see Page 74 of this volume). They could conceivably be a response to thermal dilation, the orientation of the most elongated fibre having been determined by the aeolotropic character of the amphibolite rock. However, such thermal strains are small in comparison with the dynamic conditions which induced flow and schistosity. Linear schistosity and the greatest elongation during deformation are both perpendicular to the cross joints and therefore parallel.

ORIGIN OF SECONDARY STRUCTURES

The author believes that the secondary structures in the gabbro complex have been superimposed on primary flow structures during a period of general regional metamorphism of the crystalline rocks of the Piedmont Province.

The alignments are due to unequal yielding of different rock masses to the deforming forces. Thus tongues or sheets flowed at different rates and past each other. Primary structures may have been rotated until they became parallel to the secondary ones, comparable to the rotation of bedding planes into subparallel positions, and the formation of a cleavage parallel to these bedding planes.

The parallelism of primary and secondary structures in the Baltimore gabbro and the surrounding rocks is interpreted to indicate a strong secondary flow motion with intense shearing between the different portions of the rock masses.

The basin-like arrangement of the cleavages and the convergence of linear schistosity towards a central area is believed to be due to an adaption of the gabbro mass to the available space. Large, very resistant domes of Baltimore gneiss surround the gabbro on all sides. If these domes were being moved toward each other, for instance by lateral compression of the entire area, the gabbro and its parts would be squeezed upward and outward. The lines of greatest elongation—as shown in the linear schistosity—would then point the way of easiest escape.

The contact of the gabbro mass dips inward on three sides towards a central opening. From here the gabbro may have entered its present chamber between the gneiss domes. The shape of the primary intrusive was determined by the shape of the space of its chamber. Later orogeny has then most likely modified the shape somewhat and has tended to squeeze the gabbro upward. Lateral squeezing is indicated by the overturned folds in the Baltimore gneiss to the southeast (Part III) and toward the gabbro mass. During this period of deformation the secondary structures may have been produced.

Primary structures indicate that the gabbro has been a conformable intrusion into a synclinal area of the Glenarm series. It may be called a synclinal pluton (33). Its shape may be that of a sill or basin-like body, narrowing downward from the south, east, and north sides—wherever the Baltimore gneiss domes are nearest. At its west side the contact against the Wissahickon schist is vertical and in part the gabbro has been intruded by a later granite (Ellicott City granite). All later deformation could only serve to modify its primary outlines slightly and to produce secondary structures which now predominate and have to a large extent obliterated the earlier ones. The secondary structures clearly indicate the directions in which the gabbro masses flowed during their metamorphism; that is, during the latest period in which it participated passively in the deformation of the crystalline rocks of the Piedmont area.

Editor's Note: The author's original manuscript has been edited to conform more closely with the later results of Broedel and Hershey in the adjacent regions.

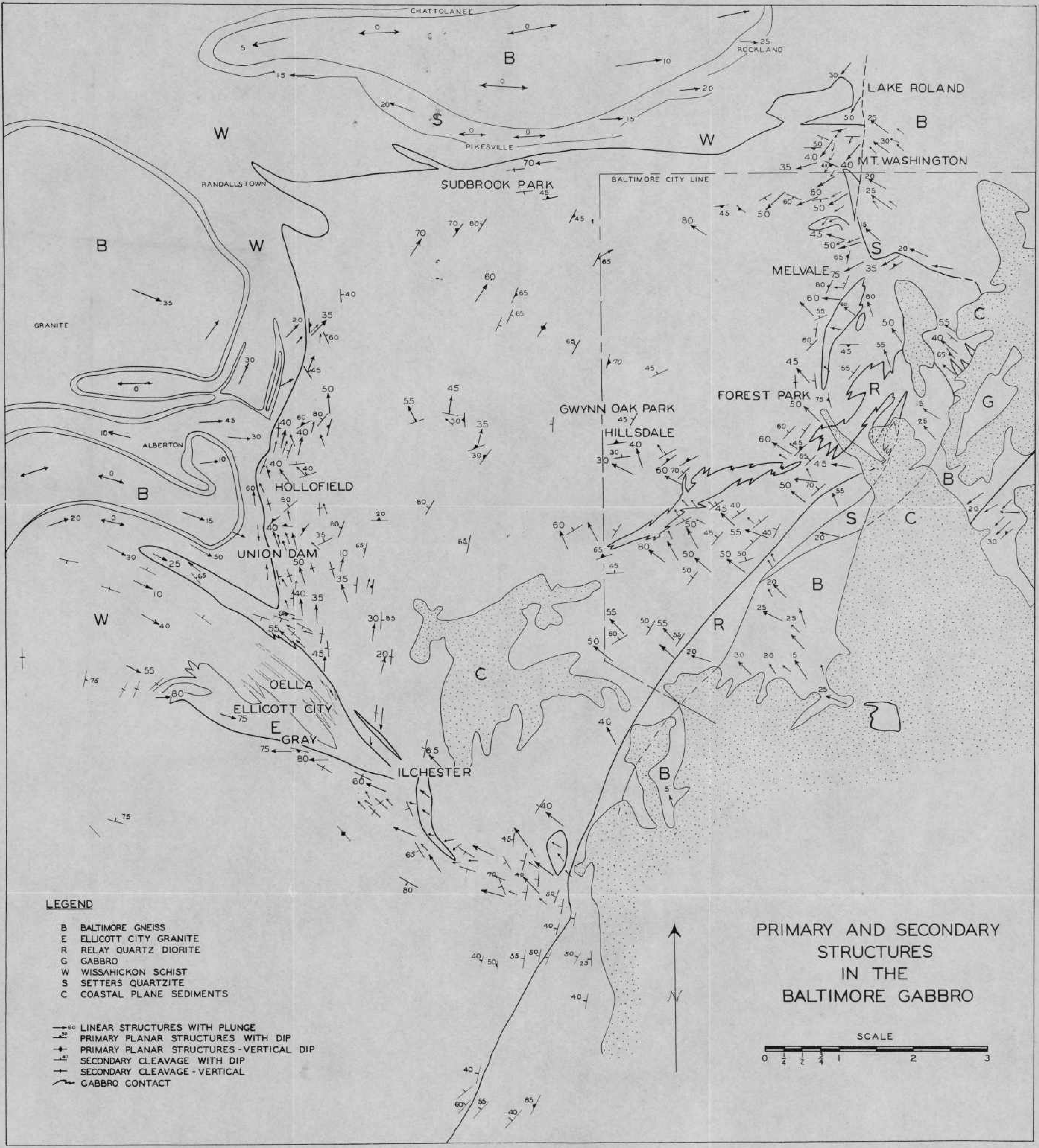
The Baltimore Gneiss Domes and the Setters formation show abundant structures which are not parallel to those in the gabbro area (see Plates XLI, XXIX-XXXI). The planar schistosity of the gabbro and wall rocks are as a rule conformable, but locally the gabbro clearly cuts across them. The linear structures however are unconformable. This is shown on the west and north side of the gabbro complex and it is evident that the gabbro intrusion has invaded already schistose Glenarm sediments. This has been outlined by Hershey and Marshall (Pts. II and IV). Not all the structures within the gabbro and outside of the gabbro are due to *one* act of deformation.

The Editor believes that metamorphism and deformation subsequent to the gabbro intrusion followed local directions and probably old, preexisting lines, and not a general regional direction. The linear structures of the gabbro point inward from the northeast, east, and south sides which cannot be due to regional metamorphism alone. Schistosity does not transect the gabbro contact. This should also occur if a circular body is subjected to a regional deformation, accompanied by complete recrystallization.

In spite of the fact that a large portion of the gabbro structures has the appearance of secondary structures, all structures are locally related to the shape of the gabbro mass and in no way to a general regional direction.

It seems therefore most likely that the gabbro mass was deformed during a late stage of its intrusion, thus becoming a "primary gneiss," or during a later phase. If the gabbro structures are secondary, as discussed by the author, they may have been formed during a period which affected the entire Piedmont Province, but in close adherence to local conditions, as is indicated in the arrangements of structures seen on Plate XLI.

For these reasons the editor has changed Mr. Cohen's conclusions somewhat, however, without the author's permission, who could not be reached on time. The editor is certain that the author would have modified his conclusions if the newer material had been available to him. The major portion of the paper is in no way affected by the newer findings or the conclusions derived from them.



PRIMARY AND SECONDARY STRUCTURES IN THE BALTIMORE GABBRO

LEGEND

B	BALTIMORE GNEISS
E	ELLICOTT CITY GRANITE
R	RELAY QUARTZ DIORITE
G	GABBRO
W	WISSAHICKON SCHIST
S	SETTERS QUARTZITE
C	COASTAL PLANE SEDIMENTS

→60	LINEAR STRUCTURES WITH PLUNGE
⊥50	PRIMARY PLANAR STRUCTURES WITH DIP
✦	PRIMARY PLANAR STRUCTURES - VERTICAL DIP
⊥40	SECONDARY CLEAVAGE WITH DIP
+	SECONDARY CLEAVAGE - VERTICAL
~	GABBRO CONTACT

SCALE

0 ¼ ½ ¾ 1 2 3

PART VI

THE UPPER CRETACEOUS DEPOSITS OF THE CHESAPEAKE AND DELAWARE CANAL OF MARYLAND AND DELAWARE

BY

CHARLES WILLIAM CARTER

THE UPPER CRETACEOUS DEPOSITS OF THE CHESAPEAKE AND DELAWARE CANAL OF MARYLAND AND DELAWARE*

INTRODUCTION

The data used in this paper were obtained by the author as a result of researches carried on under the auspices of the United States Geological Survey, along the route of the Chesapeake and Delaware Canal. The incentive for the undertaking was the opportunity afforded by the widening and deepening of the canal, a Government project now in progress, to study the stratigraphic relations and the paleontology of the formations cut by the canal.

The investigations were begun in September, 1935, and were continued at sufficiently close time intervals to keep pace with the work of excavating and dredging. The geologic units previously recognized along the canal were the Raritan, Magothy, Matawan and Monmouth formations. The present studies have demonstrated the feasibility of subdividing the Matawan into smaller units and of correlating these units with corresponding formations of the Matawan group of New Jersey. The Matawan unit of the canal area is therefore raised to the rank of group, to correspond to the New Jersey classification, and its subdivisions are classed as formations. The Monmouth group of New Jersey was found to be represented along the immediate banks of the canal only by the Mount Laurel sand, the lowest formation of the group in New Jersey. In extending the application of the name Mount Laurel to the canal area, it becomes necessary to raise the Monmouth unit also to the rank of group.

Large and varied invertebrate faunas were collected in both the Matawan and the Monmouth groups, including mollusks (abundant), foraminifers, ostracods, brachiopods (rare), crinoids (rare), and echinoids (rare). Many of the specimens are in a poor state of preservation. Preliminary lists of fossils, many only generically determined, are included, but only those of particular interest because of their abundance or because of their importance in correlation are discussed.

The author wishes to express his thanks to the geological faculty of the Johns Hopkins University under whom he has received his training,

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and especially to Dr. E. W. Berry, through whose teachings he first became interested in the study of paleontology; to Dr. Julia A. Gardner of the United States Geological Survey for her many kindnesses in fostering this interest; and to Dr. L. W. Stephenson, also of the Geological Survey, under whose immediate supervision this work was conducted, and whose criticisms and suggestions have aided greatly in the preparation of this paper.

Grateful acknowledgment is made to Dr. R. S. Bassler, Head Curator of the Department of Geology of the United States National Museum, for placing the collections and facilities of the Museum at the author's disposal.

The Chesapeake and Delaware Canal is a Government owned sea-level ship canal connecting the Chesapeake Bay with the Delaware River. It is 14 miles long and extends from Chesapeake City, Maryland, situated on Back Creek, a tributary of Elk River, one of the headwater estuaries of Chesapeake Bay, eastward to Reedy Point, Delaware on the Delaware River. The original canal was built as a private project more than a century ago and was operated by means of a series of locks. In 1922 the United States Government took over the canal and converted it into a sea-level waterway, widening it to 90 feet at the bottom, and deepening it to 12 feet at mean low tide. The present project to enlarge the canal to accommodate large sea-going vessels was begun in August, 1935, and when completed in the fall of 1937 the canal will be 27 feet deep at mean low tide and 150 feet wide at the bottom.

The topography of the region traversed by the canal is essentially flat, nowhere exceeding an altitude of 80 feet above sea level. On the Delaware end and extending westward for 3 miles the canal cuts the low-lying deposits (20 feet or less above sea level) of the Talbot formation (Pleistocene) except here and there where patches of swamp and marsh (Recent) intervene. Underlying Cretaceous deposits are reached by the dredge below sea level throughout this stretch. Beginning in the vicinity of St. Georges, Cretaceous deposits are exposed in the banks of the canal westward nearly to Chesapeake City, Maryland. The Cretaceous deposits rise well above water level but are overlain by the surficial Wicomico terrace deposits (Pleistocene), which reach a maximum measured thickness of 30 feet, and whose upper surface averages about 60 feet above sea level. In the vicinity of Chesapeake City the surface again descends to the low-lying Talbot formation, beneath which at a few places the Raritan formation is exposed above water level.

The divide between the streams flowing eastward into Delaware Bay and those flowing westward into Chesapeake Bay is in the vicinity of Summit Bridge where the maximum altitude of 80 feet is attained; the canal excavation through the divide has been called the "Deep Cut".

Although the various excavations made from time to time in connection with the canal have afforded excellent opportunities for making valuable collections of fossils, no one prior to the present project ever actually camped on the site and systematically collected as the work progressed. The records show that relatively few fossils of the great number possible of recovery have been described, some of them inadequately, and frequently with no label other than "Chesapeake and Delaware Canal".

The earlier collections, beginning with those recorded by Morton in 1829 were small and sporadic. Systematic collections were made by Dr. Julia Gardner in 1915, when no excavations were being made and when the exposures did not afford a complete section; her collections were recorded in 1916. An attempt has been made to determine the type localities of the indefinitely described species of earlier authors and to collect topotypes.

The major problem of this paper concerns not the systematic paleontology, for this is a voluminous task in itself, but rather the determination of the stratigraphic relationships of the several formations revealed by this giant exposure 14 miles long and 20 to 80 feet in height.

It is the hope of the author in the light of the new data, and as a sequel to this report, to conduct field investigations farther south in the Maryland area with a view to subdividing the Matawan group there, as has been done in the canal area.

A map (Figure 32) indicates the region investigated in the prosecution of this work.

HISTORICAL SKETCH

The first geologic work on the Chesapeake and Delaware Canal was done in 1829 by Morton, who published a series of short papers describing the few fossils which he collected there. Although one of the papers included a section of the Deep Cut, still his work was essentially paleontologic. His first paper appeared in 1829.

In 1832 Durand wrote concerning the green color of the water in the canal near Chesapeake City. This paper, though of historic interest, contains no geological data.

The only memoir of the Geological Survey of the State of Delaware, that of Booth, was published in 1841 and contained a general soil analysis and an estimation of the mineral wealth of the State of Delaware. Several interesting references are made to the canal.

The next publication concerning Delaware geology appeared in 1884, by F. D. Chester. It contained preliminary notes on the geology of the Laurentian, Paleozoic and Cretaceous areas.

In 1886 McGee wrote on the geography and topography around the head of the Chesapeake Bay.

The publications of Clark and of Roberts about 1895, on the correlation of the Cretaceous formations, refer to the canal area in their consideration of the Maryland Eastern Shore formations.

Fossil plants from the canal were described by E. W. Berry and appeared in the New York Botanical Garden Journal for 1906.

In a paper published in 1904 by the Johns Hopkins University press, W. B. Clark discusses the Matawan group of the canal and suggests that the chocolate colored marls and black micaceous sandy clays present in the Deep Cut at Summit Bridge are equivalents of the Crosswicks clays of New Jersey.

Other papers by Clark appeared in 1905 and later. These treated chiefly of the correlation of the Upper Cretaceous formations of the New Jersey-Delaware-Maryland region and referred to certain features of the canal cut.

Until 1916, when the Maryland Geological Survey, directed by W. B. Clark, published the work of Berry, Gardner, Goldman and others, no very detailed investigation had been made of the geology of the canal proper. At this time Doctor Gardner made a study of the deposits and in her discussion of their correlation pointed out the similarity of the fauna found at Summit Bridge to that of the Merchantville and Woodbury clays of New Jersey, and suggested the probability of their being of the same age. She also suggested that the general aspect of the fauna found 1⅝ miles west of St. George's Bridge, Delaware, is very similar to that of the Marshalltown of New Jersey.

Shortly after the work of the Maryland Survey, Bascom and Miller made a study of the region in connection with the Elkton-Wilmington folio of the United States Geological Survey, which was issued in 1920. Their interpretation of the canal section conformed to the findings of Doctor Gardner and therefore no formal subdivision of the Matawan or Monmouth formations was attempted.

In 1932 L. W. Stephenson and others prepared a guidebook of the Chesapeake Bay Region in connection with a field excursion participated in by the members of the Sixteenth International Geological Congress. This excursion passed through the Chesapeake and Delaware canal and made stops at several of the more interesting localities.

The United States Government made an appropriation in 1934 for the widening and deepening of the canal. This cutting offered an unusually good opportunity for a detailed geologic study of the area, for the cutting of the banks and the lowering of the canal bottom afforded new exposures and fossiliferous dredgings from deeper levels. The present investigations were begun in September, 1935, and have been continued intermittently

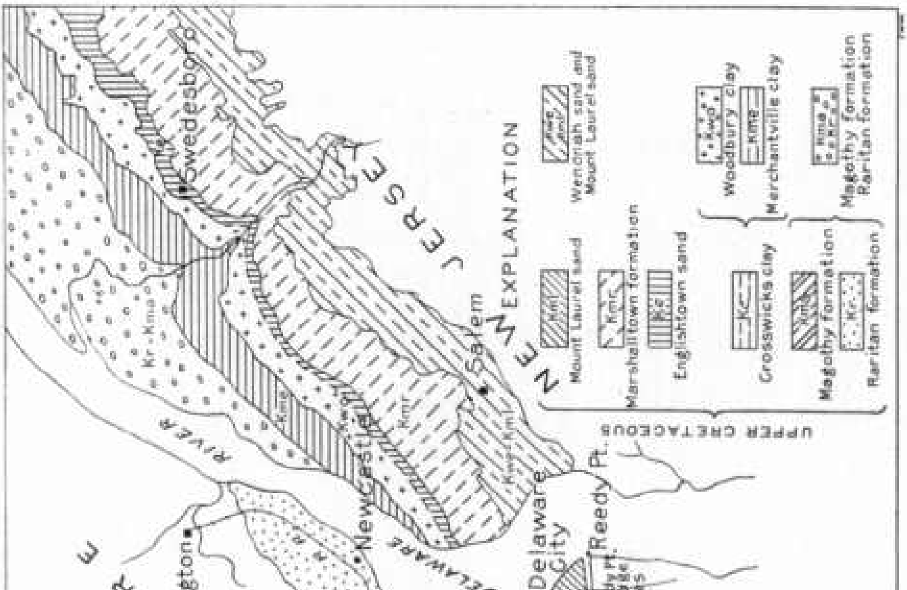


FIG. 32.—Belt of Upper Cretaceous outcrops in the Chesapeake and Delaware Canal region.

until the present. It is hoped that plans for collecting and keeping pace with the dredging operations may be carried forward and the work continued until the winter of 1937, at which time the dredging operations are scheduled to reach completion.

GENERAL GEOLOGY

The State of Delaware and adjacent portions of Maryland comprise parts of two of the major physiographic provinces that parallel the generally northeast-southwest striking Atlantic coast line. The smaller of these parts, the Piedmont region covering several hundred square miles in northern Delaware and northeastern Maryland, is underlain by a complex of igneous and metamorphosed sedimentary rocks including the Baltimore gneiss and some interbedded limestones, intruded by pegmatite dikes and by gabbro. The gabbro occurs mainly as a band of intrusives along the southern border of the Baltimore gneiss at the edge of the Coastal Plain. The rocks of the Piedmont province and of the associated Blue Ridge province farther to the west, have been the source of the widely differing sediments that underlie the adjoining Coastal Plain province to the south. In northeastern Maryland and northern Delaware the surface of these older crystalline rocks dips gently to the southeast and passes beneath the sedimentary formations of the Coastal Plain.

All of Delaware and the Eastern Shore of Maryland south of the Piedmont province are included in the Coastal Plain province, which is underlain by sedimentary formations ranging in age from Upper Cretaceous to Recent.

In general these formations dip gently toward the southeast, the older ones appearing at the surface along the border of the Piedmont province, and the younger ones forming bands of outcrop successively farther to the southeast. In the interstream areas the Cretaceous and Tertiary formations are largely covered by superficial terrace deposits of Pleistocene age; Recent sediments are sparingly present closely bordering the streams and estuaries. In the canal area the Pleistocene surficial sediments belong to the Talbot formation (20 feet or less above sea level) and to the Wicomico formation whose upper surface lies 60-80 feet above sea level.

The Upper Cretaceous formations of the Coastal Plain strike northeastward across the nearly east-trending canal at an angle of approximately 45°. The apparent thickness of the beds exposed along the canal is therefore a slight exaggeration. The dips grow progressively flatter southeastward as the younger beds come in, decreasing from 25 feet to the mile at the west end of the canal to 12 feet at the east end.

The strike of the beds is shown on Figure 32 which indicates the south-

FIG. 1.—The canal west of Summit Bridge, Delaware before the recent dredging operations.

FIG. 2.—The canal east of Summit Bridge, Delaware, during the recent dredging operations. M = Marshalltown; E = Englishtown; Cr = Crosswicks.

westward continuation of certain of the New Jersey deposits across the Delaware River into the canal area. Contacts that can not be seen and are inferred are represented on the map by dashed lines. The formations as they have been differentiated in the canal area are listed below.

- Upper Cretaceous series
    - Monmouth group
        - Navesink marl (presence inferred in area south of the canal)
        - Mount Laurel sand
    - Matawan group
        - Marshalltown formation
        - Englishtown sand
        - Crosswicks clay = in New Jersey $\left\{\begin{array}{l}\text{Woodbury clay}\\ \text{Merchantville clay}\end{array}\right.$
    - Magothy formation
    - Raritan formation

No physical evidence has been found for separating the Merchantville clay from the Woodbury clay in Delaware and the term Crosswicks clay, a name formerly applied to these combined units in New Jersey, is here revived and applied to these Delaware equivalents.

In New Jersey the separation of the two formations was made mainly on paleontologic evidence, although the Woodbury is said to be less glauconitic than the Merchantville.

The contacts of the Englishtown sand are clearly seen in the canal exposures, where the formation is well developed; this unit has not lost its identity to the southwest as was thought by Knapp, Weller, and others of the New Jersey Geological Survey (1907, Weller, p. 79).

The Marshalltown formation can be traced for several miles along the canal; it was mapped as part of the Monmouth formation by Bascom and Miller in the Elkton-Wilmington Folio of the United States Geological Survey. The top of the formation is exposed continuously along the canal from a point 2100 feet west of Summit Bridge eastward to about $\frac{1}{4}$ mile east of St. Georges Bridge, where it sinks below water level; the exact place at which it disappears can not be seen and can only be approximated. The Mount Laurel sand is incompletely exposed in the eastern canal section where its presence and extent must be deduced from a few small exposures, and from dredgings and test borings. It is best seen exposed in the bank at St. Georges Bridge.

The Mount Laurel sand and Wenonah sand are mapped as a unit on the New Jersey State geological map. In Delaware the Mount Laurel sand rests unconformably on the Marshalltown formation, and the Wenonah sand is wanting. The relationship is well substantiated by the presence in the Mount Laurel of *Exogyra cancellata* Stephenson and its associated characteristic fauna, immediately above the contact with the Marshalltown. The Navesink marl is not exposed along the canal but is believed to be present farther south in Delaware and Maryland beneath the nearly universal covering of Pleistocene terrace deposits; this is suggested by the southwestward strike of these formations in adjacent parts of New Jersey.

THE RARITAN FORMATION

NAME, AUTHOR AND TYPE LOCALITY

The Raritan formation is typically developed along the Raritan River in New Jersey. The name Raritan was first used by Conrad (1869, p. 360) for the lowermost division of the New Jersey Cretaceous, but he assigned no definite upper limit to the formation. Clark in 1893 was the first to apply the name to a unit with accurately defined boundaries. Later studies by Clark in association with others lead to the recognition of the formation southward in Delaware and Maryland where it had previously been partly or wholly included in the Potomac group of the Lower Cretaceous by Uhler, McGee, Ward and others. E. W. Berry (1916, p. 329) pointed out the similarity of this formation to the Dakota sandstone of the Western Interior. He suggested that the similar stratigraphic and floral relations of the two, while not sufficient to determine their equivalency, yet serve to show conclusively the Upper Cretaceous rather than the Lower Cretaceous age of the Raritan.

AREAL EXTENT

The upper part of the Raritan formation crops out at a few places along the canal (see section I) from Chesapeake City Bridge eastward to a quarter of a mile east of Bethel (site of old Pivot Bridge), Maryland, where its line of outcrop disappears beneath water level. At one or two isolated points, however, where the Raritan is particularly high, it reappears in the canal banks; it is seen for the last time at a station 2200 feet west of Summit Bridge (section VI). The Raritan is also exposed at several places along the south bank of Back Creek west of the bridge at Chesapeake City.

LITHOLOGIC CHARACTER

The Raritan formation, though poorly exposed in the canal area, may be distinguished with ease wherever it can be seen, because of its white to yellow sands and its white and pink tinted clays containing intermingled masses of brown plastic clay and fine comminuted plant remains (section I).

The rapid change from pure sand to admixed sand and clay, to pure clay, together with the tendency of the clay to slump in exposures, make difficult the accurate description of sections.

The coarse sandy portions of the formation are in places strongly cemented with iron oxide, forming hard crusts and pipe-like concretions locally known as "pipe-ore". A mass of this kind was contacted by the dredge drill 15 feet below water level at a station half a mile east of the Chesapeake City Bridge; it was so resistant to the powerful steel blades (3 inches thick and 7 feet in diameter) of the steam driven suction pump of the dredge that serious damage and expensive delays were caused by it.

The dip of the beds and the thickness of the formation are not determinable from the few poor exposures along the canal. The place at which the contact of the formation with the overlying Magothy formation passes beneath water level was very closely estimated by examining the material thrown out onto the disposal area west of the point at which the Magothy was first recognized in the canal.

STRATIGRAPHIC RELATIONS

The Raritan formation unconformably overlies the Patapsco formation of the Lower Cretaceous and though this contact is not seen in the immediate canal area, it may be found to the northeast in Delaware along Red Lion Creek, Christiana Creek, and along the sides of small tributaries entering Elk River. Its unconformable contact with the overlying Magothy formation may be seen in the banks of the canal just west of the site of Pivot Bridge (Bethel). This is an unusual exposure, however, for Pleistocene deposits are generally found unconformably overlying the Raritan and generally obscure it considerably.

FOSSIL CONTENT

Though fossil remains of both plants and animals have been reported from the Raritan of Maryland and of New Jersey, none have been found in the immediate canal area. The very poor, disturbed and slumped condition of the exposures reduces the chances of finding fossils, and may have been responsible for the negative results obtained.

CORRELATION

On the basis of its contained flora, E. W. Berry (1910, p. 258) correlates the Raritan formation approximately with the Dakota sandstone of the Western Interior; he feels, however, that the former is a little the older. He considers the Raritan to be equivalent to the Tuscaloosa formation of Alabama. It is placed in the Cenomanian of the European section.

THE MAGOTHY FORMATION

NAME, AUTHOR AND TYPE LOCALITY

The name Magothy was proposed by Darton (1893, pp. 407–419) for certain distinctive clays and sands exposed along the banks of the Magothy River in Maryland. Later the name was employed for the extension of the formation northward into Delaware and New Jersey.

AREAL EXTENT

The banks of the Chesapeake and Delaware Canal present a particularly fine section of this formation (Plate XLV, figure 1). It is exposed nearly continuously for a distance of 3¼ miles beginning at a point 4,000 feet east of the Chesapeake City Bridge, Maryland, and extending eastward to approximately 1,900 feet west of Summit Bridge, Delaware, where it dips beneath the surface of the water. The continuity of outcrop is interrupted at a few places where the new canal penetrates formerly dredged material and at one place, a mile west of Summit Bridge, where a slight slump has caused the section to be lowered several feet from its true position. The conditions at these places, however, can be clearly seen and understood and cause but slight chance of misinterpretation.

LITHOLOGIC CHARACTER

The materials composing the Magothy formation are of three more or less distinct kinds and can be arranged roughly into three members one above the other (Section II). The first and lowermost member is a fine, yellow, iron-stained to buff, micaceous, compact sand containing variable proportions of clay of the same color, plus additional small patches or lenses of black sticky clay up to 1 foot in length and 1 inch in thickness. This sand makes up an average of more than half the thickness of the Magothy formation throughout its extent of 3¼ miles along the canal. The second or middle member consists of white sand and clay. The bedding is very irregular for the sand may rapidly grade into clay within less than 3 inches of vertical thickness; it may gradually grade into the clay giving all proportions of admixed clay and sand; or it may be distinctly laminated and sharply interbedded with the clay. The sand of this member is most unique and differs so widely from all the other sands seen along the canal that it is recognizable at sight. It is coarse, sharp and "sugary" grained, and is composed largely of pure quartz with a small content of mica. The third or upper member is black clay also possessing characteristics that permit of its immediate recognition. It is dark blue to black, massive clay of sticky, slippery character, containing much lignitized plant material and some grains of amber. Near its top are to be found many very hard rounded and variously shaped masses of gray siderite up to 15 inches in length. These undoubtedly are the objects referred to by early naturalists as coprolites, but their massiveness, large size, and fortuitous shape negative this identification. Amber grains and the lignite with its associated marcasite are useful in identifying the formation (sections II–IV).

The Magothy may be distinguished from the underlying Raritan formation not only by its lithologic characteristics and the presence of lignitized trunks and other vegetable matter, but by the absence of pink and related colors. The formation may be distinguished from the overlying Matawan group by the plasticity of its clays, by the presence in the extreme upper part of irregular, solid masses of gray siderite of various sizes, and by the comparatively small mica content.

THICKNESS

The thickness of the formation was not accurately determined. Each of the three members is irregular in thickness from place to place along the canal. The iron-stained sand below never exceeds 25 feet; the intermediate white sand and clay does not exceed 18 feet, and the maximum observed thickness of the black clay at the top is 15 feet. The maximum observed combined thickness of the three members is about 34 feet.

STRATIGRAPHIC RELATIONS

The Magothy formation lies between the Raritan formation below and the Crosswicks clay of the Matawan group above, the relationship to each being that of unconformity. Each of the contacts is extremely irregular and represents a long period of erosion. At several places the Crosswicks clay fills pockets in the upper surface of the Magothy.

FOSSIL CONTENT

Weller (1907, 33–44) has described a fairly large invertebrate fauna from the Magothy formation at Cliffwood Point and vicinity. Repeated search in the Magothy sands and clays along the canal failed to disclose any fossil animal remains other than borings of mollusks, Teredos, and worms, all encased in marcasite.

With the exception of lignite, few identifiable fossil plant remains were found in the exposures along the canal; some of the material was washed and yielded seeds of *Chara* and other objects which suggested seeds and seed coats. However, E. W. Berry (1916, pp. 102–104) described about

35 species of plants from this formation in the Deep Cut 0.7 mile west of Summit Bridge.

CORRELATION

The Magothy formation of the canal area is, as described by Gardner (1916, pp. 61–64), a northeastward extension of the typical deposits of the formation on Magothy River, Maryland. The formation continues northeastward as an intercalation within the Upper Cretaceous series to Raritan Bay, New Jersey.

On the basis of an unpublished correlation chart prepared by L. W. Stephenson of the United States Geological Survey, the Magothy formation is correlated with the lower part of the Senonian division of the European section. In his opinion the fauna recorded by Weller from Cliffwood Point and vicinity contains no elements that justify an age assignment older than Senonian.

THE MATAWAN GROUP

The name Matawan was first applied by W. B. Clark (1894, pp. 161–177) to a geologic unit extensively exposed along Matawan Creek, a tributary of the Raritan Bay, New Jersey. The unit consists of glauconitic sands and clays which had previously been known to New Jersey geologists as the "clay marl series". The Matawan was later traced into Maryland as an undivided unit, and was there known as the Matawan formation.

When first named, the Matawan unit in New Jersey was classed as a formation. Subdivisions recognized at the time, and during subsequent years, were classed as members. Eventually the members were raised to formation rank, and the Matawan was treated as a group. In the 1910–1912 and the 1931 editions of the geological map of New Jersey the group name was not used and only formation names appear in the legend.

The classification of the Matawan as now accepted by the United States Geological Survey is as follows:

- Matawan group
    - Wenonah sand
    - Marshalltown formation
    - Englishtown sand
    - Woodbury clay
    - Merchantville clay

The five formations of the Matawan group appear in a continuous band in New Jersey, extending from the shore of Raritan Bay on the northeast to the Delaware River in Salem County on the southwest. The formations parallel each other, the oldest on the northwest side of the band and the younger ones in successive belts to the southeast. The strata dip gently to the southeast, the older passing beneath the younger. The band is 25 miles wide at its northeast end but decreases to a width of 10 miles in Salem County.

In the canal area in Delaware and in adjacent parts of Maryland the Matawan unit has been mapped heretofore as an individual formation; previous investigators have not considered it practicable to subdivide it (1916, Gardner; 1920, Bascom and Miller). The fresh exposures afforded by the recent diggings along the sides of the canal have made it possible to subdivide the Matawan there, although it has not been deemed feasible to separate the Merchantville and Woodbury clay units, which are therefore treated as a combined unit under the old name Crosswicks clay. The Wenonah sand is wanting in the canal area for, as will be shown later, the Mount Laurel sand of the overlying Monmouth group, rests directly on the Marshalltown formation.

One of the fossil localities (Briar Point, Post 156) referred by Dr. Julia Gardner (1916, pp. 90–101) to the Monmouth formation is in this report included in the Marshalltown formation. It is now known that some of the collections made by Dr. Gardner near and within 3 miles west of St. Georges, comprise mechanically mixed faunas derived in part from the Marshalltown formation and in part from the overyling Mount Laurel sand; these she referred to either one or the other of the two formations. This explains why she listed the restricted Mount Laurel species, *Exogyra cancellata*, from both the Matawan and the Monmouth units.

CROSSWICKS CLAY (=COMBINED MERCHANTVILLE AND WOODBURY)

In New Jersey the Merchantville clay and the Woodbury clay have been mapped as separate formations and Weller records differences in the contained faunas; he noted an absence of glauconite in the Woodbury clay, except in its basal part, but glauconite is present throughout the unit here under consideration in Delaware, where no physical basis has been found for distinguishing the two formations with any degree of accuracy. They appear to be essentially alike in their lithologic characters. The "cinnamon brown" of the Merchantville clay of New Jersey has been observed along the canal, but this is a feature that may result from the weathering of any part of the unit. A systematic study of the ranges of the old and of the new species collected in Delaware might yield data for making a faunal separation.

NAME, AUTHOR, AND TYPE LOCALITY

The names Merchantville and Woodbury were derived from towns respectively of these names, at which the formations are well developed. George N. Knapp used them in 1895 in his field notes though they did not appear in print until 1896.

The term Crosswicks clay was derived from the village of Crosswicks on Crosswicks Creek, New Jersey, and was proposed by W. B. Clark in 1897 for the clays composing the combined Merchantville and Woodbury units exposed near that place.

AREAL EXTENT

The Crosswicks clay is exposed in the banks of the Chesapeake and Delaware Canal for a distance of 4 3/16 miles. The clay, in contact with the underlying Magothy formation, first appears in the canal area at a point 2400 feet east of Bethel (site of Privot Bridge), Maryland. From there eastward the formation is conspicuous and easily traceable to a station 1800 feet east of the Philadelphia, Baltimore and Washington Railroad bridge where its top disappears beneath water level.

LITHOLOGIC CHARACTER

The Crosswicks unit consists almost entirely of massive, dark blue to black, very glauconitic, micaceous, soft "mealy" clay with but little admixed sand except at its upper contact where it grades into the Englishtown sand above; the clay is nowhere plastic. The transitional sand at the top weathers to a yellowish "iron rust" color, is slightly iron-cemented and contains external molds of fossils. (Sections V–IX.)

In the vicinity of Station 53+300 one-fifth of a mile west of Summit Bridge on the north side, the Crosswicks clay unit, as there preserved, contains in its upper part cinnamon-brown patches of weathered material like that which characterizes the Merchantville clay of New Jersey and this bed may represent the Merchantville.

Interspersed throughout the clay are round, oval, and irregular concretions composed of an amorphous calcium phosphate mineral, identified as collophane by W. F. Foshag of the United States National Museum. These concretions, distinctive markers of the formation in this region and in New Jersey, serve the useful purpose of preserving the fauna of early Matawan time, for at least half of them bear the imprints of more or less perfectly preserved fossil invertebrates.

The base of the formation is marked at most places by a thin layer of sparsely scattered pebbles averaging one-fourth of an inch in diameter;

this is in the nature of a basal conglomerate. In places this layer contains siderite concretions reworked from the underlying Magothy formation. The formation differs markedly from the overlying Englishtown sand in its physical and faunal characteristics and the two are easily separable.

THICKNESS

The thickness of the Crosswicks clay in the canal area is approximately 50 feet. This is 50 feet less than the thickness given for the Crosswicks equivalent in Salem County, New Jersey.

STRATIGRAPHIC RELATIONS

The Crosswicks clay, as already pointed out, unconformably overlies the Magothy formation and is itself overlain conformably by the Englishtown sand.

FOSSIL CONTENT

The Crosswicks clay contains an abundance of invertebrate fossils which are generally distributed through the clay; fossils were present at every locality examined. Most of the fossils occur in concretions in which the external ornamentation is perfectly preserved. A plaster or clay squeeze serves to bring out the minute details of the exterior of the shell and generally permits an accurate specific determination. The disposal areas upon which the dredged material was pumped were excellent sites for collecting the fossiliferous concretions.

For over a mile along the south bank beginning at, and extending 1700 feet east of, the Philadelphia, Baltimore & Washington Railroad bridge a layer of yellowish brown sandy clay 1 to 2 feet thick near the top of the formation is very fossiliferous and yielded a large collection of forms most of which were external molds.

The fossil lists of the Crosswicks clay include forms found both in place and on the disposal areas. The list, including only the forms identified to date, is given below; those marked with an asterisk (*) are recorded by Weller (1907, pp. 57–75) from the Merchantville and Woodbury of New Jersey (=Crosswicks):

Vermes:
    Serpula sp.
    Hamulus major Gabb
    Hamulus sp.
Echinodermata:
    Family
    Plicatocrinidae cf *Hyocrinus*

Mollusca:
- Pelecypoda:
  - *Nuculana* sp.
  - *Nemodon* n. sp. (a)
  - *Nemodon* n. sp. (b) cf. N. *neusensis* Stephenson
  - *Cucullaea vulgaris* Morton (?)
  - *Breviarca haddonfieldensis* Stephenson
  - **Pinna laqueata* Conrad
  - *Inoceramus* sp.
  - *Pulvinites* sp.
  - *Ostrea falcata* Morton
  - *Ostrea* sp.
  - *Exogyra ponderosa* Roemer
  - *Pecten bellisculptus* Roemer
  - **Pecten conradi* (Whitfield)
  - **Pecten* cf. *quinquecostatus* Sowerby
  - *Pecten simplicius* Conrad
  - *Pecten* n. sp.
  - **Anomia argentaria* Morton
  - **Paranomia scabra* (Morton)
  - **Pholadomya occidentalis* (Morton)
  - *?*Liopistha* sp.
  - **Cymella bella* (Conrad)
  - **Veniella conradi* (Morton)
  - *Etea* cf. *carolinensis* (Conrad)
  - *Crassatellites carolinensis* (Conrad)
  - *Crassatellites* sp.
  - **Cardium spillmani* Conrad
  - **Cardium* cf. *ripleyanum* Conrad
  - *Cardium* sp. ind.
  - **Cardium* (*Criocardium*) *dumosum* Conrad
  - *Cardium* (*Criocardium*) cf. *kummeli* Weller
  - *Cardium* (*Criocardium*) n. sp.
  - *?*Isocardia* sp.
  - *Cyprimeria* n. sp.
  - *Legumen* n. sp.
  - *Legumen concentricum* Stephenson
  - *?*Solyma* sp.
  - *Linearia* n. sp.
  - *Linearia contracta* Whitfield
  - **Linearia metastriata* Conrad
  - **Corbula crassiplica* Gabb
  - **Corbula* cf. *swedesboroensis* Weller
  - *Corbula* sp. A
  - *Corbula* sp. B
  - *Corbula* sp. C
  - **Panope decisa* Conrad
- Scaphopoda:
  - **Dentalium subarcuatum* Conrad
  - *Dentalium* sp.
  - **Cadulus obnotus* (Conrad)

Gastropoda:
- *Paladmete* sp.
- *Odontofusus* sp.
- *?*Anchura* sp.
- *Anchura johnsoni* Stephenson
- *?*Anchura rostrata* (Gabb)?
- *Cerithium* n. sp.
- *Epitonium* sp. A
- *Epitonium* sp. B
- **Laxispira lumbricalis* Gabb
- **Turritella quadrilira* Johnson
- **Turritella merchantvillensis* Weller
- *Turritella* n. sp. A
- *Turritella* n. sp. B
- *Turritella* n. sp. C
- *Turritella* sp. ind.
- *Turritella* sp. ind.
- *Xenophora leprosa* (Morton)
- *Gyrodes supraplicatus* (Conrad)
- *?*Gyrodes* sp.
- *Calliomphalus* n. sp.

Cephalopoda:
- **Placenticeras placenta* (DeKay)
- *?*Baculites* sp.
- *Scaphites* cf. *aquilensis* Reeside
- *?*Scaphites* sp.

The present available evidence indicates that the marine organisms of Crosswicks time lived under approximately constant ecologic conditions throughout that period. At no time were there any changes in these conditions such as would cause important differences in the faunal assemblages.

The fossil lists indicate a more extended range of some of the forms that had previously been recorded. The genus *Pulvinites*, for example, has not been known northeast of the Mississippi Embayment; it is known from the Owl Creek formation at Owl Creek, Tippah County, Mississippi, and Wade (1926) records it from Coon Creek, Tennessee; both of these localities are stratigraphically higher than the Crosswicks clay in Delaware. The species *Legumen concentricus* Stephenson has not heretofore been reported north of North Carolina.

Several small crinoid calyces were taken from one of the phosphatic concretions. Dr. Edwin Kirk of the United States Geological Survey examined and identified the specimens and found them closely related to the genus *Hyocrinus* of the family Plicatocrinidae; the nearest known relatives occur in the Jurassic and in the Recent.

Other interesting finds included *Chara* seeds, small seed coats, fish scales and bones, shark teeth, and several as yet unidentified fragmentary reptile bones.

CORRELATION

The Crosswicks clay corresponding as it does in lithologic character, faunal content, strike, dip and alignment with the Crosswicks clay (= combined Merchantville and Woodbury formations) of New Jersey, is considered to be a southwestward extension of the Crosswicks into the canal area. With the European Upper Cretaceous it correlates approximately with the lower part of the Senonian (but not the lowermost) according to an unpublished correlation chart by Dr. L. W. Stephenson.

THE ENGLISHTOWN SAND

NAME, AUTHOR, AND TYPE LOCALITY

The Englishtown sand, formerly called Columbus sand, was named by Dr. H. B. Kümmel (1907, p. 17), State Geologist of New Jersey, after the village of Englishtown, near which the sand is characteristically developed. Kümmel proposed the name to replace Columbus which was preoccupied, having been used for a Devonian formation in Ohio.

AREAL EXTENT

According to New Jersey reports and maps, the Englishtown sand, where it intersects Raritan Bay, has a width of outcrop of about 3 miles, and is over 100 feet thick. It extends southwestward thinning along the way until at a place near Swedesboro, New Jersey, it is reported to be only 20 feet thick. This thinning-out southward is shown to be true by the evidence in the canal exposures for its observed thickness there is only 6 to 16 feet and it may be nearly or completely overlapped by the overlying Marshalltown formation between 2100 and 2900 feet west of Summit Bridge, where the relations are obscured by the slumping of the banks.

LITHOLOGIC CHARACTER

The Englishtown is a soft, yellow to buff micaceous, fluffy, fine-grained quartz sand containing very thin ferruginous clay laminae. It is replete with tubular objects to which the name *Halymenites major* Lesquereux has been given. (Sections VI–IX.)

In New Jersey the Englishtown sand presents precisely the same lithologic characters as in Delaware and contains *Halymenites major*.

THICKNESS

In the vicinity of Swedesboro, New Jersey, the thickness of the Englishtown is, according to Weller (1907, p. 79), approximately 20 feet. In Delaware the thickness as seen in the exposures ranges from 6 to 16 feet.

STRATIGRAPHIC RELATIONS

The Englishtown sand lies between the Crosswicks clay below and the Marshalltown formation above (Plate XLII, Figure 2). It can be separated from the underlying Crosswicks clay into which it grades through a thickness of about 2 feet by its very different lithologic character, and by its lack of fossils other than the problematical forms described below. The Englishtown sand may be separated from the Marshalltown formation, which unconformably overlies it, by its distintive lithologic characters and by the presence at many places of a thin pebble layer at the base of the Marshalltown. This contact marks an erosion interval which may not have been of long duration in a geologic sense.

FOSSIL CONTENT

The known fossil remains of the Englishtown sand include only doubtful bryozoans and *Halymenites major* Lesquereux (Plates XLIII and XLIV). The questionable bryozoans occur near the upper contact of the bed; they are very fragile sand casts that have been etched out on the surface of the sand by weathering. Their small branching shape suggests their affinity to the bryozoans. The friable casts fall apart when touched and render a detailed examination impossible. Better material must be obtained before their true nature can be determined. They may be allied to the sponges.

Halymenites major was originally described in 1873 by Leo Lesquereux (1873, p. 373) from the Raton Mountain area near Trinidad, New Mexico being included in his, "Enumeration and Descriptions of Fossil plants from The Western Tertiary Formations" (1873, p. 371). He called it a marine alga of the Fucaceae family, but its plant origin may be seriously questioned. It is a long, branching cylindrical object of varying diameter from 1/16 up to 2 inches, and attains a length of 3 feet or more. The outer surface of the tubes is regularly papillated with round tubercles, up to 0.2 inch in diameter; the tubes are found in both upright and recumbent positions in the sand. The largest ones observed (1½ inches in diameter and 3 feet long) were in place half a mile west of St. Georges Bridge where the top of the Englishtown is within 1 foot of the water level; here they lie horizontally one upon another in a sort of matted network.

In New Jersey *Halymenites major* was observed well developed in the Englishtown sand along U. S. Highway 206, at a place 2.2 miles south of the crossing of Blacks Creek, 3 miles south of Bordentown, New Jersey. At this and other New Jersey localities visited the tubes are typical but are less abundant in individuals than in the canal exposures.

Berry (1921, pp. 55–72) mentions *H. major* at two Upper Cretaceous localities in Tennessee, one in the Coffee sand at Coffee Bluff on Tennessee River, and the other in the McNairy sand member of the Ripley formation near Camden. In the Western Interior the species is recorded from Colorado, Wyoming and New Mexico in beds of Upper Cretaceous age. Dr. L. W. Stephenson in a personal communication states that *H. major* is common in the glauconitic sands of the Upper Cretaceous series of the Gulf region, and he has seen it in marine Tertiary sands of both the Eocene and Miocene epochs.

A closely allied form is *Halymenites minor* Fischer, described from Europe. This species as far as available records show, has not been recorded from America. From figures and descriptions of the type it seems probable that *H. minor* occurs here also though this is stated with reservation for it has been noted that *H. major* has quite a considerable range in size. This being the case, it is possible for the *H. minor*—differentiated more or less on its smaller size—to be in reality a small *H. major.* R. W. Brown, in a paper now in press as United States Geological Survey Professional Paper 189-I, considers *H. minor* a synonym of *H. major*; he is of the opinion that the tubes of *Halymenites major* may have been constructed by a boring marine organism, probably a crustacean, rather than that they are the impressions of seaweeds (fucoids).

CORRELATION

The correspondence in lithologic character of the sands, the common and abundant presence of *Halymenites major*, the essential agreement in strike, dip, thickness, and alignment, indicate that the sand unit in Delaware here under consideration is the southwestward extension of the New Jersey Englishtown sand.

The Marshalltown Formation

NAME, AUTHOR, AND TYPE LOCALITY

The name Marshalltown formation was used in field notes by G. N. Knapp in 1895, though not recorded in print until 1898 (1898, pp. 3–41), for the sands and clays characteristically developed near the old town of that name in Salem County, New Jersey.

AREAL EXTENT

The Marshalltown formation of New Jersey extends from Sandy Hook Bay, an arm of the Raritan Bay, southwestward to the Delaware River. It gradually thins southwestward along its strike and its width of surface outcrop in the vicinity of the Delaware River is about 1.1 miles.

The formation can be traced in the banks of the canal a distance of approximately 5 miles from 2100 feet west of Summit Bridge to one-fourth mile east of St. Georges Bridge where it disappears beneath water level. Its width of surface outcrop, disregarding the surficial covering of Pleistocene terrace deposits, is estimated to average about 2 miles.

LITHOLOGIC CHARACTER

The Marshalltown formation in Delaware is a dark green to black, soft, slightly micaceous, heavily glauconitic, calcareous, sandy clay containing many fossils; many of the fossils are in the form of molds. Near its top the formation is more sandy and less fossiliferous. It preserves its lithologic character throughout its extent along the canal changing only locally by weathering to a faded gray color. It is lithologically identical with the Marshalltown at its type locality in New Jersey. (Sections VI–IX.)

THICKNESS

The thickness of the Marshalltown formation in Salem County, New Jersey, is recorded as 30–40 feet; the formation thins to the southwest, the maximum thickness recorded in the canal area being 16 feet. The thickness is nearly constant along the canal with, however, a slight and gradual increase down the dip.

The dip of the Marshalltown has been calculated to be 14 to 18 feet per mile to the southeast.

STRATIGRAPHIC RELATIONS

The Marshalltown formation is separated from the underlying Englishtown sand by a gently undulating erosional unconformity. The contact is marked at many places by a thin line of tiny pebbles. The two formations are markedly different in their lithologic characteristics and are easily separated.

The contact of the Marshalltown formation with the overlying Mount Laurel sand was seen in a bluff on the south side of the canal at a station 1½ miles west of the St. Georges Bridge. The profusion of fossil remains, the dark green color and the weathered and somewhat sandy top of the

Marshalltown, serve to disinguish it from the white sandy marl of the Mount Laurel. The contact is an unconformable one and represents a considerable time interval, for the Wenonah sand, which in New Jersey is the uppermost formation of the Matawan group, is wanting. Paleontologically the Marshalltown can be distinguished by the presence of the shells of _Exogyra ponderosa_ Roemer and other associated fossils, in contradistinction to the ever present _Exogyra cancellata_ Stephenson in the Mount Laurel.

FOSSIL CONTENT

A conspicuous feature of the Marshalltown fauna in Delaware is the difference between it and the fauna of the Crosswicks clay; in passing upward in the section the fauna changes from the numerous small gastropods and pelecypods so characteristic of the Crosswicks clay, to a group of large, ponderous oysters in the Marshalltown. This change is not confined to the canal area, for it also takes place in the corresponding section in New Jersey, that is in the passage from the Merchantville and Woodbury clays to the Marshalltown formation above.

A list of Marshalltown forms found along the Chesapeake and Delaware Canal is only partially complete at this date; the species marked by an asterisk (*) are recorded by Weller from the Marshalltown formation of New Jersey. The partial list is as follows:

- Echinodermata:
  - _Cassidulidae_ n. gen.? and n. sp.
  - _Echinoid spines_
- Mollusca:
  - Pelecypoda:
    - _Nucula slackiana_ Gabb
    - _Cucullaea_ sp.
    - *_Ostrea falcata_ Morton
    - *_Ostrea plumosa_ Morton
    - *_Gryphaea convexa_ Say
    - *_Gryphaea mutabilis_ Morton
    - *_Exogyra ponderosa_ Roemer
    - *?_Exogyra ponderosa erraticostata_ Stephenson
    - _Trigonia_ sp.
    - *_Pecten_ cf. _quniquecostatus_ Sowerby
    - *?_Pecten bellisculptus_ (Conrad)
    - _Pecten_ cf. _mississippiensis_ Conrad
    - _Pecten simplicius_ Conrad
    - *_Anomia argentaria_ Morton
    - *_Paranomia scabra_ (Morton)
    - *_Veniella conradi_ (Morton)
    - _Crassatellites_ sp.

- **Unicardium umbonata* Whitfield
- *Cardium* cf. *eufaulense* Conrad
- **Cardium tenuistriatum* Whitfield
- **Cyprimeria excavata* (Morton)
- **Linearia metastriata* Conrad
- *Panope decisa* Conrad

Gastropoda:

- *Avellana bullata* (Morton)
- *Epitonium* sp.
- *Cypraea* n. sp.
- **Turritella marshalltownensis* Weller
- *Turritella* sp.
- *Turritella* sp. ind.
- *Pyropsis* sp.
- *Gyrodes supraplicatus* (Conrad)
- *Gyrodes petrosus* (Morton)

Many other species of Mollusca previously unrecorded from the Chesapeake and Delaware Canal are being studied and when the dredging of the canal is concluded at the end of the present year the writer hopes to have the opportunity of systematically describing them.

CORRELATION

The marked similarity between the unit under consideration in Delaware and the Marshalltown formation of New Jersey is brought out in many ways. The identical lithologic, faunal and stratigraphic characters of the beds together with the alignment along the strike, all point to their identity and lead to the conclusion that these Delaware beds represent the southwestward extension of the Marshalltown formation of New Jersey into the Chesapeake and Delaware Canal area.

THE MONMOUTH GROUP

The name Monmouth was proposed by W. B. Clark (1897, pp. 331–336) for a unit typically developed in Monmouth County, New Jersey. He subdivided the formation into three members, in ascending order: The Mount Laurel sand, the Navesink marl, and the Red Bank sand. Subsequently, the Monmouth was raised to the rank of group and each of the three members to the rank of formation. This is the classification now recognized by the United States Geological Survey. Weller states that he fails to see any faunal characters upon which to separate the Mount Laurel from the Navesink but the boundary between the two units has been drawn on several maps. In the later editions of the geological map of New Jersey the name Monmouth is omitted, and the Wenonah sand, the uppermost formation of the Matawan group, and the Mount Laurel sand, the lowermost formation of the Monmouth group, are mapped together.

In the immediate canal area only the Mount Laurel sand of the Monmouth group is represented. There are a few outcrops at high points along the banks 2 to 3 miles east of the Philadelphia, Baltimore & Washington Railroad bridge, and one at the water's edge $\frac{1}{10}$ mile east of St. Georges Bridge, Delaware. Additional data are, however, afforded by the dredged material, including fossils, thrown onto the disposal areas. The Navesink marl, one of the other two formations of the Monmouth group, is believed to be present within a few miles south of the canal, under cover of surficial Pleistocene deposits, but it is not included in the present investigation.

THE MOUNT LAUREL SAND

NAME, AUTHOR, AND TYPE LOCALITY

The Mount Laurel sand was so named in 1897 by W. B. Clark. The name is derived from Mount Laurel, a small, round hill about 7 miles southwest of Mount Holly, Burlington County, New Jersey. The sand is present in the body of this hill but is not now well exposed.

AREAL EXTENT

The Mount Laurel sand is traceable from the shore of Sandy Hook Bay in Monmouth County, New Jersey, to Delaware River in Salem County; the present investigations have shown that it extends across the Delaware and is present along the canal for a distance of $1\frac{7}{8}$ miles at its eastern end. With the exception of a few sparsely scattered exposures along the canal sides the formation is known only from dredged materials thrown up from below water level. This lack of exposures is due to the general low-lying topography of this part of Delaware, and to the disturbed condition of the canal banks.

LITHOLOGIC CHARACTER

The Mount Laurel sand consists of iron-stained, spotted, light-brown to white, coarse, glauconitic, calcareous sand with subordinate amounts of sandy clay; in places it is strongly ferruginous. Cook (1868, pp. 241–283) called it "sand marl".

THICKNESS

The Mount Laurel sand is largely obscured along the part of the canal where it is known to be present, by levelling effected by excavating carried on in former years and by the plant growth that subsequently took possession of the levelled areas. One exposure (at St. Georges Bridge) reveals 8½ feet of the formation above water level. It is doubtful if the full thickness of the formation is cut by the canal.

STRATIGRAPHIC RELATIONS

The Mount Laurel sand unconformably overlies the Marshalltown formation. The contact between the dark green heavily glauconitic materials of the latter, and the lighter calcareous materials of the former, is fairly sharp and easily recognizable at the few places where the formation was seen in place. The unconformity is of considerable importance for the hiatus recorded by it includes the time interval of the Wenonah sand, which is wanting in the canal section. (Section X.)

The formation is unconformably overlain along the canal by the deposits of the Wicomico and Talbot formations (Pleistocene) at their respective elevations above sea level.

FOSSIL CONTENT

The Mount Laurel sand was seen best exposed at a place 1.5 miles west of the St. Georges Bridge on the south side of the canal where it is in unconformable contact with the underlying Marshalltown formation. Here a wealth of fossil material from both formations, in an excellent state of preservation, was weathered out and lay scattered on the beach. The contact was rather sharply defined both lithologically and faunally. *Exogyra ponderosa* and its Marshalltown associates were found about 4 feet below the contact. Above the contact in the Mount Laurel the stratigraphically important *Belemnitella americana*, *Exogyra cancellata*, *E. costata*, and *Anomia tellinoides* were present. Many other fossils of interest but of wider vertical range were recorded from this place.

The formations from which the fossils at the disposal areas came could in most cases be distinguished by the matrix associated with them. The shells from the Marshalltown generally contained dark green clay solidly imbedded in the shell cavities, or the shells themselves were contained in a lithologically identifiable lump of clay. Similarly shells from the Mount Laurel were identifiable by their lighter colored sand matrix. With few exceptions the fossils could be instantly assigned to their respective formations. One suite of microfossils from the Marshalltown and one from the Mount Laurel were retrieved from characteristic matrices taken from shells.

Exogyra cancellata is found in abundance at the few Mount Laurel outcrops and upon every disposal area along the canal where the lithologically characteristic "sand marl" is observed. On the disposal area on the north side 1.2 miles east of the St. Georges Bridge *E. cancellata* associated with *Gryphaea* sp., *Anomia tellinoides*, *Belemnitella americana*, and a host of other Mount Laurel forms are present. At Reedy Point, Delaware, an old disposal area on the north side east of the bridge, consists of material dredged in 1925 from a depth of not more than 12 feet below tide level; it contains a similar assemblage of many individuals of *E. cancellata*, *Pecten quinquenarius*, *Belemnitella americana* and numerous other new and otherwise interesting species. The finding of *E. cancellata* and *B. americana* on the old disposal area at the very east end of the canal means that the Mount Laurel sand is the youngest of the Upper Cretaceous formations to be found along the canal.

A list (only partially complete at this date) of the fossils identified from the Mount Laurel sand is given below; those marked with an asterisk (*) were recorded by Weller from the combined Mount Laurel sand and Navesink marl in New Jersey:

- Echinodermata:
  - *Echinoid spines*
- Brachiopoda:
  - *Terebratulina* sp.
- Mollusca:
  - Pelecypoda:
    - *Nucula slackiana* Gabb
    - *Nucula* sp.
    - *Nuculana* n. sp.
    - *Nuculana* sp.
    - **Cucullaea antrosa* (Morton)
    - *Nemodon* cf. *N. cecilius* Gardner
    - **Ostrea falcata* Morton
    - **Gryphaea convexa* Say
    - **Exogyra costata* Say
    - *Exogyra cancellata* Stephenson
    - *Trigonia* sp.
    - **Pecten simplicius* Conrad
    - **Pecten quinquenarius* Conrad
    - **Anomia tellinoides* Morton
    - **Anomia argentaria* Morton
    - **Liopistha protexta* (Conrad)
    - **Veniella conradi* (Morton)
    - *Corbula* n. sp.
    - *Corbula* sp.
  - Scaphopoda:
    - *Dentalium* sp.
  - Gastropoda:
    - *Anchura* sp.
    - *Turritella* sp.
  - Cephalopoda:
    - **Belemnitella americana* (Morton)

Weller believed that the Mount Laurel sand and the Navesink marl contained indistinguishable faunal assemblages, but it is now known that the Mount Laurel contains several species that do not range upward into the Navesink. Two of the most important of these are *Exogyra cancellata* Stephenson and *Anomia tellinoides* Morton. These species have been recorded from the Mount Laurel sand and equivalent beds throughout the Atlantic and Gulf Coastal Plain; in New Jersey and in Delaware they are restricted to the Mount Laurel sand. Stephenson (1914; 1933, pp. 1351–1361) pointed out the far reaching significance of these species in papers published in 1914 and in 1933. According to Weller the most diagnostic forms in the Mount Laurel sand and the Navesink marl are *Belemnitella americana* and *Terebratella plicata.* The former is now known to be present in both formations and the latter is restricted to the Navesink. *B. americana* has been found in great numbers in both formations in New Jersey, and is present in the Mount Laurel sand in New Jersey; *T. plicata* is not known from the canal area. Gardner (1916, p. 73) reports *B. americana* from Maryland with the suggestion that the containing beds are very probably equivalent to the Mount Laurel and Navesink of New Jersey. Stephenson (1923, p. 401) records the species from North Carolina where it occupies a slightly higher position in the *E. costata* zone.

In Europe a close analogue of *Belemnitella americana* is *B. mucronata* (Schlotheim) from beds assigned to the uppermost Senonian which may be a little higher stratigraphically than the Navesink marl.

CORRELATION

The data presented on preceding pages indicate that the geologic unit now under consideration is the southwestward continuation of the Mount Laurel sand of New Jersey. The principal basis for the correlation is the presence of *Exogyra cancellata* and *Anomia tellinoides,* two associated species that have been shown by Stephenson to be restricted to a narrow zone throughout the Atlantic and Gulf Coastal Plain.

The canal is too far north in Delaware to transect the Navesink marl, the next higher formation of the Monmouth group. This leaves the Mount Laurel sand as the sole representative of the group along the canal. The Navesink has not been recognized in Delaware south of the canal, but it is believed to be present there beneath the surficial covering of Pleistocene terrace deposits.

DETAILED DESCRIPTIONS OF ELEVEN SELECTED SECTIONS

Upper Cretaceous deposits are exposed nearly continuously along the canal, except at a few places where rerouting of the canal for the purpose of eliminating certain bends necessitated cutting in formerly dredged material. Eleven sections are described at significant places beginning near the west end of the canal and proceeding eastward.

The station markers erected by the United States Engineers along the canal route are placed at intervals of 1000 feet, beginning in the Delaware River 4500 feet east of Reedy Point, Delaware, and ending with 100 in Elk River west of the Chesapeake City entrance. The letter "N" for north or "S" for south, is placed after the station numbers, to indicate on which side of the canal the sections are exposed. The datum for the base of the sections is medium tide level.

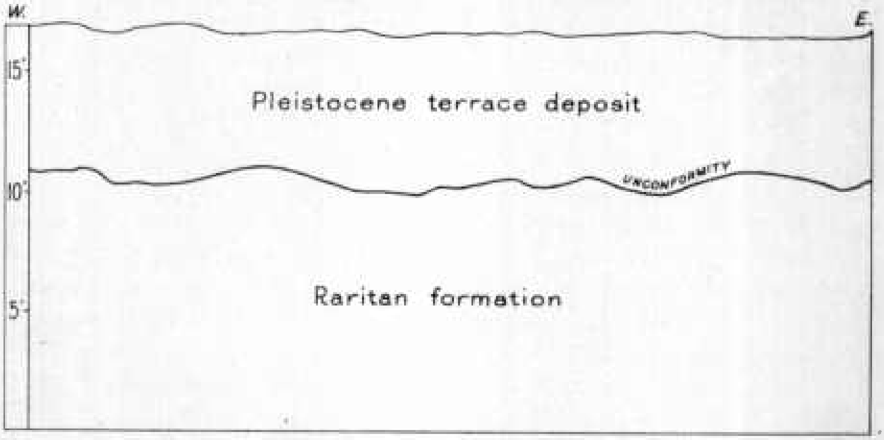


FIG. 33.—Section accompanying Plate XLIII, Fig. 1.

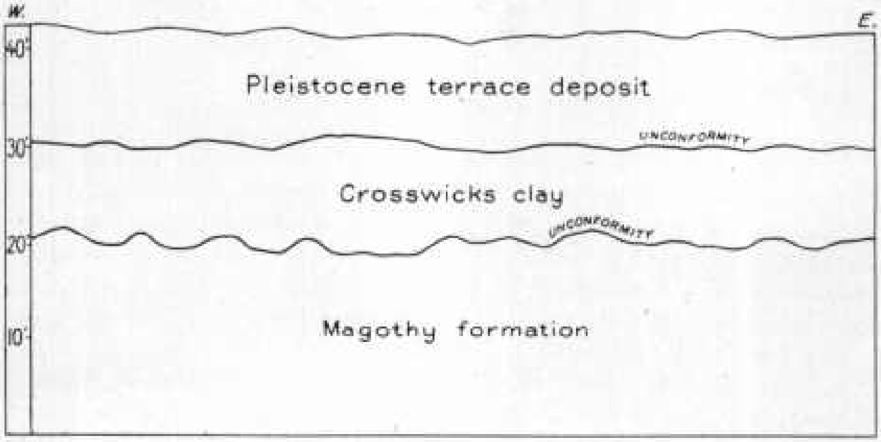


FIG. 34.—Section accompanying Plate XLV, Fig. 1.

FIG. 1.—The Pleistocene overlying the Raritan formation 1200 feet east of Chesapeake City bridge, station 76 + 400 N.

FIG. 2.—*Halymenites major* in Englishtown sand 50 feet east of the Philadelphia, Baltimore, and Washington Railroad bridge, station 45 + 280 S.

Section I, 1200 feet east of the Chesapeake City Bridge, Maryland, at station 76 + 400N

	Feet
Pleistocene series:	
Talbot formation:	
Mixed, coarse, feldspathic, iron-stained sand and gravel; the largest pebbles are near the base and do not exceed 1½ inches in diameter..	6
Unconformity.	
Upper Cretaceous series:	
Raritan formation:	
Buff to white, gray, pink and variegated clay mixed and interbedded with white, light gray, fine-grained sand; the change from clay to sand is rapid and the layers are thin and numerous; these closely spaced clay layers contain large amounts of finely divided, macerated plant particles; exposed to water level	11
Total	17

Section II, 400 feet west of Bethel (old Pivot Bridge) at Station 69S

	Feet
Pleistocene series:	
Talbot formation:	
Heterogeneous assortment of brownish sand and yellow fine clayey sand at the top, gradually grading down into a more or less banded and iron-cemented mass of highly feldspathic, coarse, iron-stained sand and pebbles	12
Unconformity.	
Upper Cretaceous series:	
Magothy formation:	
Gray clayey sand intertongued with fine sharp sand	2½
Sharp, sugary, white sand interspersed with black specks of mica that gives the whole bed a "salt and pepper" appearance; there are also fine laminae of the black sticky, plastic clay, such as are usually found with the sand of the Magothy formation	3½
Very coarse, white, iron-stained sand becoming almost pebbly at the base where it becomes iron-cemented into large, loosely united conglomerate	2½
Raritan formation:	
White, pink, drab and variegated clay changing rapidly in color from place to place	3½
Total	24

Section III, 1600 feet east of Maryland-Delaware line at Lighthouse No. 2, Station 66 + 300S

	Feet
Pleistocence series:	
Talbot formation:	
Sharp, coarse, buff, iron-cemented sand and gravel with cobbles interspersed	5

Section III continued

	Feet
Unconformity.	
Upper Cretaceous series:	
Matawan group:	
Crosswicks clay:	
Dark blue to black, micaceous, glauconitic, brittle clay with admixed sand appearing in the section here for the first time	2
Unconformity.	
Magothy formation:	
Black, sticky, tough clay, typical of the Magothy and appearing in the section as lenses and thin tongues interstratified with sugary white to iron-stained sharp sand; contains biotite mica that gives to it a "salt and pepper" appearance	12
Total	19

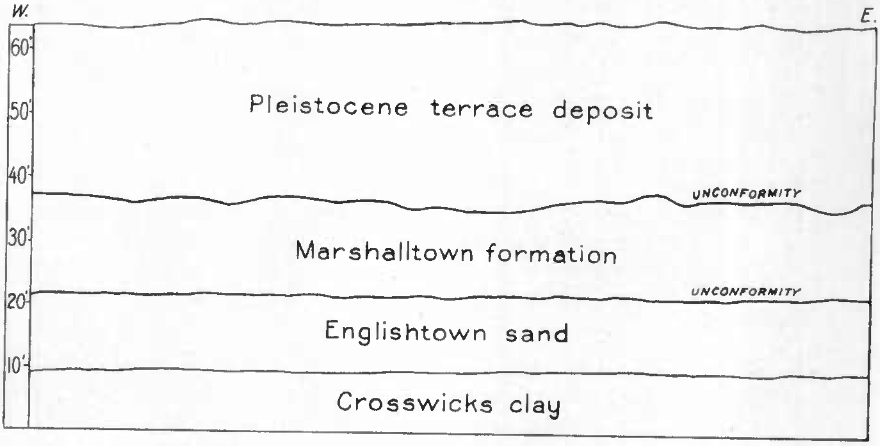


FIG. 35.—Section accompanying Plate XLIV, Fig. 1.

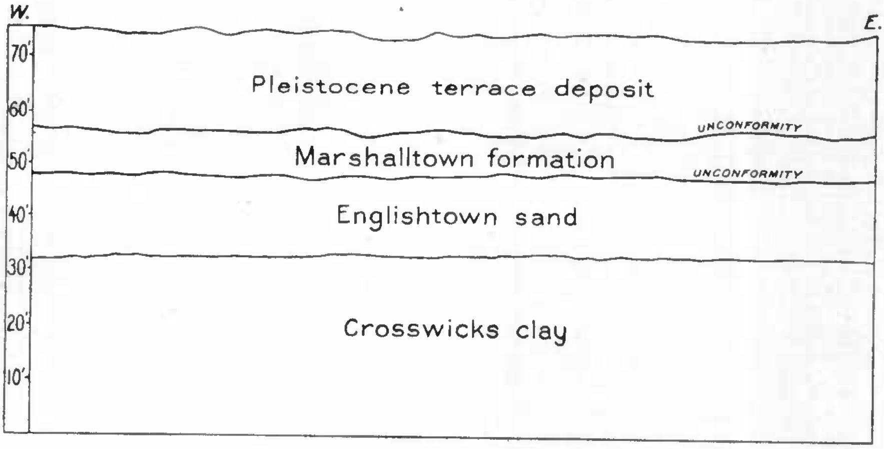


FIG. 36.—Section accompanying Plate XLV, Fig. 2.

Fig. 1.—The Englishtown-Marshalltown contact at station 52 + 150 S. The Englishtown contains *Halymenites major*.

Fig. 2.—*Halymenites major* in Englishtown sand at above station.

Section IV, 4100 feet east of the Maryland-Delaware line at Station 64 + 200S

	Feet
Pleistocene series:	
Wicomico formation:	
Loose, coarse, iron-stained, feldspathic sand containing numerous pebbles, cobbles and boulders scattered throughout the bed	37
Fine, clayey, brownish to yellow sand	1½
Unconformity.	
Upper Cretaceous series:	
Magothy formation:	
The black, sticky, tough clay, typical of the Magothy, is found in the section as a bed here for the first time; it is replete with plant material; at its top there is a platy swamp deposit that suggests a filling in an erosion basin in the upper part of this formation	3
White, sugary, sharp sand with admixed biotite mica which gives to it a characteristic "salt and pepper" appearance; it contains many fine lenses of black clay (each about ½ inch thick and several feet long) which become increasingingly numerous and more closely spaced until they grade into the clay bed of the Magothy above	7½
Total	49

The Crosswicks clay which is present in the section west of this place (see Section III) is wanting in this section and may indicate a slight upwarp between stations 65 and 64.

Section V, 1 mile west of Summit Bridge Station 57 + 480N

	Feet
Pleistocene series:	
Wicomico formation:	
Coarse, iron-stained, micaceous, feldspathic sand with intermixed gravel; somewhat iron-cemented at the base	12
Unconformity.	
Upper Cretaceous series:	
Matawan group:	
Crosswicks clay:	
Dark blue, glauconitic, heavily micaceous, sandy clay containing phosphatic concretions	10
Unconformity.	
Magothy formation:	
Black sticky, tough, marcasitized clay containing considerable lignite and macerated plant material; lignitized logs have been bored by *Teredo*	3
Loose, white to buff, coarse, sharp, sugary, micaceous sand containing thin interbedded black clay layers and lignitized plant fragments	19
Total	44

Section VI, 2000 feet west of Summit Bridge at Station 54 + 200N

	Feet
Pleistocene series:	
Wicomico formation:	
Coarse, feldspathic, buff colored sand with pellets of brown clay; the sand is micaceous, in part glauconitic, and is iron-cemented at many places; the glauconite was probably derived by mechanical reworking from the underlying Marshalltown formation	20
Gray to yellow sand, coarse in texture and containing well banded iron-cemented layers of gravel and cobbles, especially at the base	8
Unconformity.	
Upper Cretaceous series:	
Matawan group:	
Marshalltown formation:	
Somewhat faded dark green, glauconitic, micaceous, soft sand containing numerous pebbles about ¼ of an inch in diameter, which become abundant toward the base of the formation; contains fossil molds of gastropods and pelecypods	6
Unconformity.	
Englishtown sand:	
Light gray and buff to yellow, fluffy, soft, fine sand gradually grading up into orange colored sand of similar lithologic character, but containing slightly more clay; the base of the formation contains thin iron cemented layers about ¾ inch in thickness; this formation is here, as everywhere, literally packed with tubes of *Halymenites major* Lesquereux	11
Crosswicks clay:	
Light bluish gray sand which forms a transition from this formation into the overlying fine sand of the Englishtown; contains no fossils of any sort	1
Weathered rusty brown sandy clay; resembles the weathered top of the Merchantville clay of New Jersey, but is not a continuous feature	5
Typical dark blue to black, micaceous, glauconitic, sandy, non-sticky clay containing scattered hard calcium phosphate concretions, many of which contain more or less well preserved fossil molds; poorly preserved fossils not in concretions are dispersed throughout the clay; the fossils collected include cephalopods, gastropods, pelecypods and scaphopods	26
Magothy formation:	
Black, sticky, tough clay to water's edge	1
Total	78

Two hundred feet west of Section VI a high place in the uneven contact separating the Magothy formation from the underlying Raritan formation, brings the latter slightly above water level, exposing a lens of typical pink clay; the appearance of the Raritan this far east may be further evidence of the previously suggested upwarp.

FIG. 1.—The irregular contact between the Magothy formation (M) and the overlying Cross wicks clay, one mile west of Summit Bridge, at station 57 + 480 N.

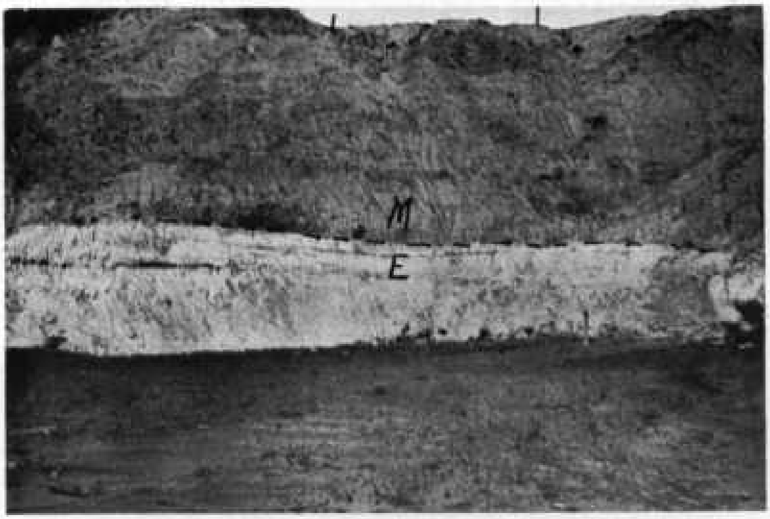


FIG. 2.—The Englishtown-Marshalltown contact 100 feet west of the Philadelphia, Baltimore, and Washington Railroad bridge, station 45 + 450 S.

Section VII, 50 feet east of Summit Bridge, Delaware, at Station 52 + 150S

	Feet
Pleistocene series:	
Wicomico formation:	
Sharp, feldspathic, argillaceous, iron-stained, coarse sand and gravel; grades into bed below	6
Indurated and iron-encrusted masses of sand; the sandy matrix surrounding the pebbles and boulders in the lower part, contains reworked glauconitic sand from the underlying Marshalltown formation	10
Unconformity.	
Upper Cretaceous series:	
Matawan group:	
Marshalltown formation:	
Bluish gray, weathered and partly leached, heavily glauconitic clay, separated from the Englishtown sand below by a thin layer of pebbles up to a fourth of an inch in diameter; contains an abundance of poorly preserved fossil molds of which *Exogyra, Cucullaea, Trigonia* and other genera were collected	11
Unconformity.	
Englishtown sand:	
Yellowish buff and gray, soft, micaceous, fluffy, extremely fine-grained sand, containing at its top a layer approximately 8 inches thick, composed literally of millions of gently curving tube-like smooth-sided crusts ⅛ to ¼ inch in diameter and varying in length from 6 to 10 inches; these are etched out on the surface by weathering and are poorly held together with iron oxide cement; their interiors are usually filled with dark greenish, glauconitic sand derived from the Marshalltown above; it was not found practicable to collect them but their appearance suggested the possibility of their being bryozoans	⅔
Fine, gray, soft sand like that above but filled with numerous tubes of *Halymenites major* Lesquereux, weakly iron-cemented and very fragile	10⅓
Rather hard, bright yellow to orange red, argillaceous sand grading down into the sandy top of the dark blue Crosswicks clay	5
Crosswicks clay:	
Dark bluish-black, argillaceous, micaceous, sandy clay, quite sandy at the top where it grades into the overlying Englishtown sand, but soft and somewhat spongy, though never sticky or plastic, below	32
Total	75

Section VIII, 100 feet west of the Philadelphia, Baltimore & Washington Railroad bridge, Delaware, at Station 45 + 450S

	Feet
Pleistocene series:	
Wicomico formation:	
Compact, coarse, feldspathic, iron-stained and hardened clay carrying pebbles and cobbles, particularly near its base; the sand in places has a yellow spotted appearance	11

Section VIII continued **Feet**

Brownish green, coarse, feldspathic, glauconitic, micaceous sand, pebbly at the top where thin bands of sand cemented with iron oxide run very irregularly through it; contains patches of gray-green, glauconitic sand, mottled where weathered; the glauconitic sand has been derived from the underlying Marshalltown formation; wherever seen the contained iron crusts and gray sand patches make its identification certain 16

Unconformity.

Upper Cretaceous series:

Matawan group:

Marshalltown formation:

Dark green, soft, heavily glauconitic, micaceous, sandy clay, weathering to a lighter color but easily identifiable by its contained fauna and its unmistakable lithologic character; the bed is more argillaceous below than above; the lower part is very fossiliferous; the fossils are poorly preserved, some of them leached to a yellowish, floury material which gives to the clay a spotted appearance; *Exogyra ponderosa*, *Trigonia*, *Cucullaea*, *Unicardium*, and other forms were collected; phosphatic casts of a very interesting species of sponge, provisionally referred to the genus *Cliona*, are found in the thick shells of mollusks into which the sponge bored, the casts forming a closely spaced network of branches in the shell; in some specimens the shell substance has been completely dissolved away, leaving the form of the shell faithfully preserved by the dense network of casts. 14⅚

At the base of the Marshalltown and separating it from the underlying Englishtown, is two inches of gray clay containing abundant macerated plant material .... ⅙

Unconformity.

Englishtown sand:

Fine, fluffy, gray to buff, micaceous, slightly glauconitic sand replete with tubes of *Halymenites major* Lesquereux; the lower and upper contacts are easily identifiable and traceable 13

Crosswicks clay:

Typical dark blue, glauconitic, heavily micaceous, sandy clay containing the characteristic hard more or less fossiliferous, phosphatic concretions which yielded many described and undescribed species of gastropods, pelecypods, and crab remains; the top of this formation presents a dark brown zone transitional into the Englishtown sand; this zone is very fossiliferous and contains characteristic Crosswicks forms preserved as external molds 10

Total 65

Section IX, 1700 feet east of the Philadelphia, Baltimore & Washington Railroad bridge, at Station 43 + 600N

Feet

Pleistocene series:

Wicomico formation:

Sharp, coarse, buff to yellow, cross-bedded sand 4½

Section IX continued	Feet
Indurated band of pebbles and cobbles cemented by iron oxide, in a matrix of sharp, yellow feldspathic sand; the largest cobbles are 5 inches in diameter	11
Unconformity.	
Upper Cretaceous series:	
Matawan group:	
Marshalltown formation:	
Soft, dark green, heavily glauconitic sand containing irregular, flattened pellets of clay and small, irregular, subangular quartz pebbles; contains molds of *Unicardium umbonata* (Whitfield), *Trigonia, Pecten, Turritella,* and other forms including a new genus (?) and species of the family Cassidulidae	11
Unconformity.	
Englishtown sand:	
Fine, soft, fluffy, yellow to light gray, very micaceous sand; the sand is packed with the characteristic fragile tubes of *Halymenites major* Lesquereux	16
Crosswicks clay:	
Dark blue to light gray, micaceous, somewhat glauconitic sand, containing some clay and forming a transition zone from this formation to the soft Englishtown sand above	2
Total	44½

Section X, 1½ miles west of St. Georges bridge, Delaware, at Station 36 + 720S

	Feet
Pleistocene series:	
Talbot formation:	
Coarse to fine-grained, feldspathic, iron-stained, buff to yellow sand with iron-cemented pebbles and cobbles at the base	5½
Unconformity.	
Upper Cretaceous series:	
Monmouth group:	
Mount Laurel sand:	
Brown, micaceous, glauconitic, medium-grained sand grading downward into rather coarse sand at the base; contains a large number of small, yellowish spotted areas that mark the positions of fossils now completely leached out and removed	6
White to buff, mealy, rather compact, glauconitic, micaceous marly clay containing a wealth of fossil material, among which are *Exogyra cancellata, Anomia tellinoides* and *Belemnitella americana*	2½
Unconformity.	
Matawan group:	
Marshalltown formation:	
Dark green to blue, yellow spotted, micaceous, compact, heavily glauconitic, mealy clay containing many fossils including *Exogyra ponderosa, Gryphaea, Anomia argentaria,* and other forms	6
Englishtown sand:	
Fine, soft, fluffy, yellow, micaceous sand containing *Halymenites major*	½
Total	20½

Section XI, 25 feet west of St. Georges bridge at Station 28 + 825S

	Feet
Pleistocene series:	
Talbot formation:	
Coarse, brown, iron-stained, feldspathic, micaceous, pebbly sand containing irregular, sparsely placed, thin laminae of iron, particularly at the base	6
Unconformity.	
Upper Cretaceous series:	
Monmouth group:	
Mount Laurel sand:	
Brown, micaceous, medium-grained sand containing a large number of yellowish spotted areas	11
White, mealy, rather compact, marly clay containing a wealth of fossil material	3
Unconformity.	
Matawan group:	
Marshalltown formation:	
Dark green to dark blue, yellow-spotted, micaceous, compact glauconitic, marly clay	6
Total	26

The exposures east of Section XI show that the formations present in that section maintain a uniform thickness and gentle dip until they sink from view beneath water level. The banks of the canal to the east of St. Georges bridge are in the main very low-lying, composed for the most part of swamp and bog deposits. The easternmost exposure in the canal was seen at a point 2000 feet east of the St. Georges bridge where 4 feet of Mount Laurel sand is overlain by several feet of sand and gravel belonging to the Talbot formation.

Excavations yet to be made on the north bank halfway between the Philadelphia, Baltimore & Washington bridge and St. Georges bridge should bring to view the whitish marly sand of the Mount Laurel that is now so poorly exposed beneath slumped and formerly dredged material. The formation can not be accurately described until the "draglines" and "scoops" have completed their work along this stretch. However, wherever exposed, the Mount Laurel sand may be distinguished from the Marshalltown formation below by its lithologic character and by the presence of the diagnostic *Exogyra cancellata*, *Anomia tellinoides*, and associated fossils. Along the swampy part of the canal from St. Georges bridge eastward to Reedy Point the dredges have pumped onto the disposal areas large lumps of clay from below water level which, from their lithologic character and fossil content, can be identified with the formations from which they came. Materials from both the Marshalltown and Mount Laurel were recognized. On the north side at the east end of the canal there is a

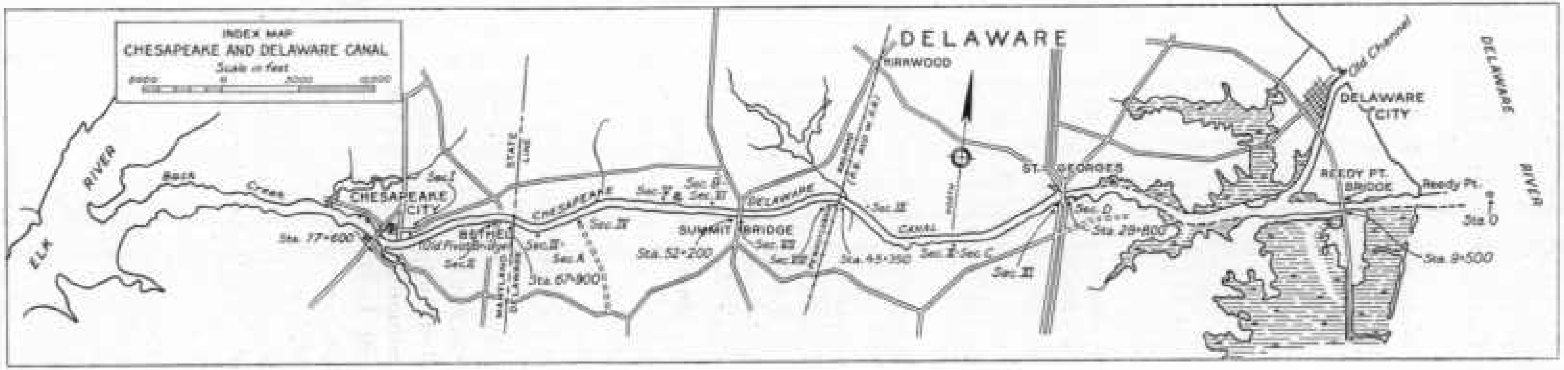


FIG. 37.—Index map showing location of sections along the canal.

remnant of an old disposal area dredged in 1925; it contains a profusion of the typical *Exogyra cancellata* "the finger post" of the Mount Laurel sand and other fossils from that formation. This old dredging was done to a depth of only 12 feet below mean low tide and the fossils indicate that the Mount Laurel sand is the highest and youngest Cretaceous formation present in the immediate canal area.

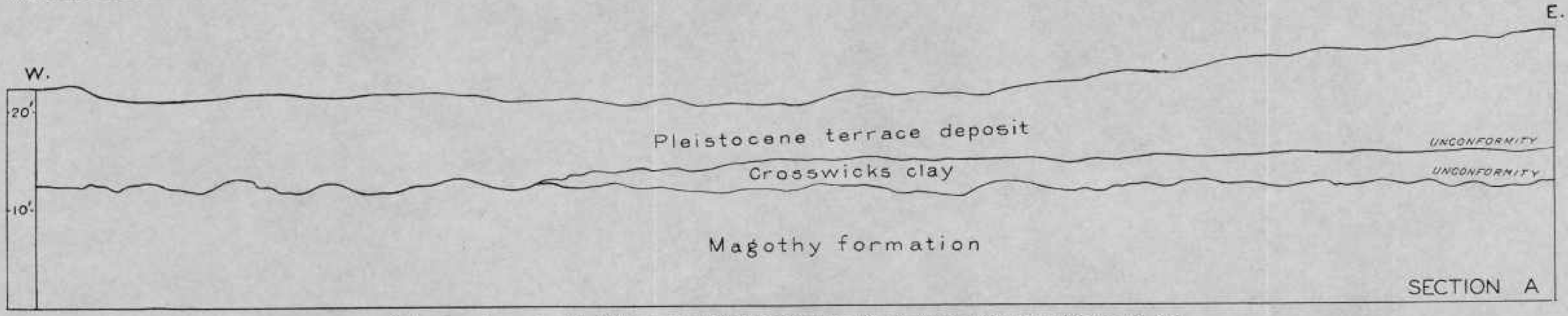
CONCLUSIONS

The present Government-sponsored project to widen and deepen the Chesapeake and Delaware Canal to accommodate large sea-going vessels has provided an excellent opportunity to restudy the Upper Cretaceous formations exposed along the canal banks.

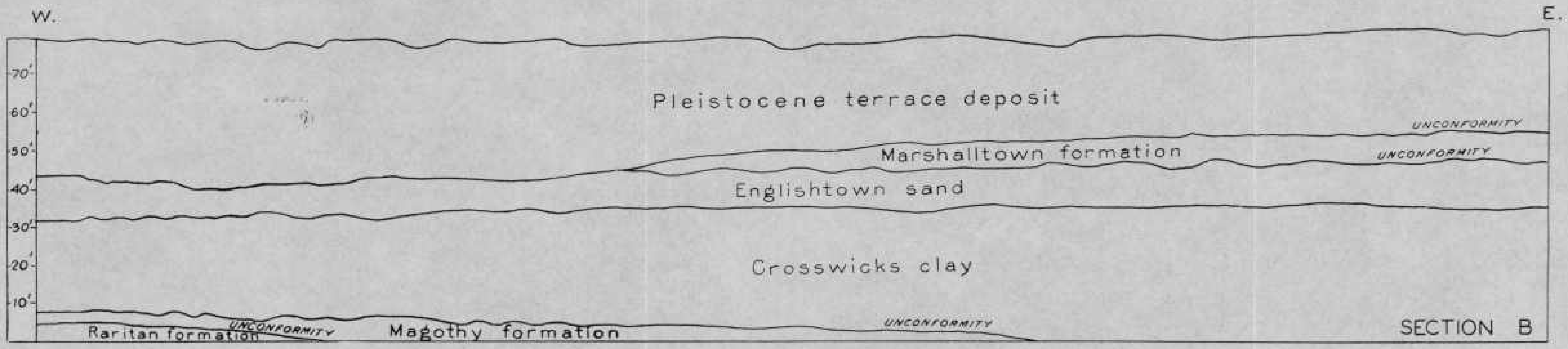
No change is made in the classification of the Raritan and Magothy formations each of which has heretofore been treated as an independent formation.

It is found that the geologic unit to which the name Matawan group is applied in New Jersey, but which has been treated as an indivisible formational unit in Delaware and Maryland, can be readily subdivided in the canal area on the basis of both physical and paleontological criteria into at least three lesser units corresponding to formations of the Matawan group in New Jersey. These are in ascending order, the Crosswicks clay (= the combined Merchantville clay and Woodbury clay of New Jersey), the Englishtown sand, and the Marshalltown formation. The Wenonah sand, the uppermost formation of the Matawan group in New Jersey, is wanting in the canal area, having been cut out by a transgressive overlap of the overlying Mount Laurel sand. The Matawan unit is raised to the rank of group and the three subdivisions are classed as formations. Crosswicks is an old name applied by W. B. Clark to the combined Merchantville and Woodbury units in New Jersey; it is a convenient term for use in the canal section because there it has not been found practicable to differentiate the Merchantville and Woodbury into separate clay units.

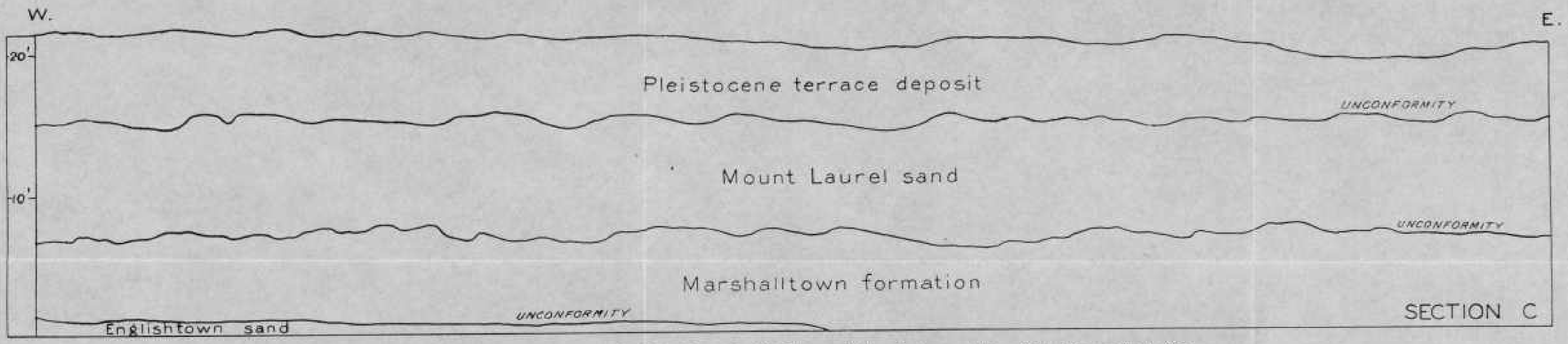
In New Jersey the Monmouth group includes three formations, named in ascending order, Mount Laurel sand, Navesink marl and Red Bank sand (including the Tinton sand member). Of these only the lowest formation, the Mount Laurel, is exposed in the canal banks; it is easily recognizable both on the basis of its lithologic character and its contained fossils. The term Monmouth is raised to the rank of group and the Mount Laurel is treated as a formation of that group in the canal area.



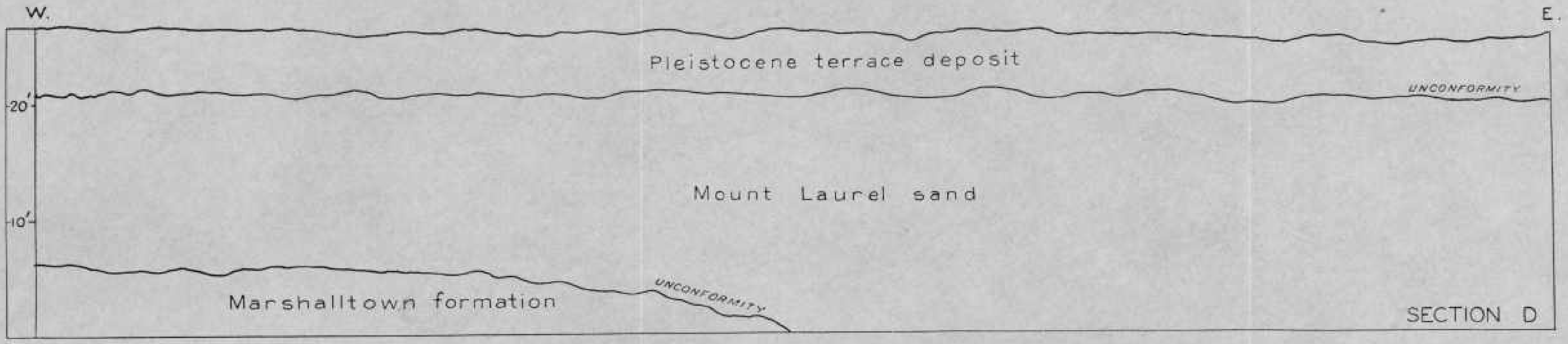
Bank of canal approximately 1600 feet east of Maryland-Delaware line (between stations 66 + 375 and 66+ 225)



Bank of canal approximately 2000 feet west of Summit Bridge (between stations 54 + 450 and 54 + 050)



Bank of canal approximately one and a half miles west of St. Georges bridge (between stations 36 + 776 and 36 + 665)



Bank of canal approximately one-quarter mile east of St. Georges bridge (between stations 28 + 865 and 28 + 735)

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* The following abbreviations indicate the County, City, or State in which a locality is situated: (B) = Baltimore County; (BC) = Baltimore City; (C) = Cecil County; (Co) = Carroll County; (Del) = Delaware; (F) = Frederick County; (Ha) = Harford County; (Ho) = Howard County; (M) = Montgomery County; (Miss) = Mississippi; (NJ) = New Jersey; (NM) = New Mexico; (NY) = New York; (Pa) = Pennsylvania; (Tenn) = Tennessee.

Roman numbers indicate references to plates.