Delaware Piedmont Geology

including a guide to the rocks of Red Clay Valley

By Margaret O. Plank
and William S. Schenck

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Contents

Foreword

The Red Clay Creek Valley traverses geologic features that have long been recognized as important to science, industry, and history. The reader will note that within the text "Piedmont," and "Atlantic Coastal Plain" are capitalized. This is because these are formal geologic provinces. The "Fall Line" or "fall zone" is also an important geologic area. The Fall Line is the the contact where the hard crystalline rocks of the Piedmont dip under and disappear beneath the sediments of the Coastal Plain. The fall zone is a narrow zone that parallels the Fall Line where rapids and waterfalls are common. The landscape and rock types shown in northern Delaware are classical examples of the larger geologic features that dominate the geology of eastern North America.

There are reasons why the major cities line up parallel to the coast and in accordance with the trend of the mountains. The fall zone was the limit of navigation to the European explorers. This and the availability of fresh water suggested the location of the initial settlements. Earth materials in the region—stone, sand and gravel, brick and china clay, mica, and feldspar—sustained economic development for several hundred years. Waterpower provided energy essential to the Industrial Revolution. Commerce and communication by ship benefited by access to tidewater. Northeast-southwest land travel and communication benefited from the relatively flat topography of the inner Coastal Plain. No wonder that our initial population concentrated along the fall zone.

A trip through the Red Clay Creek Valley provides outstanding illustrations of the influence of geology on our history and society. Our forebears lived close to the land and understood its basic dictates. Pressures of land use and environmental protection now prompt us to rediscover the essentials of geology and apply modern science to advance applications appropriate to today's needs.

You will undoubtedly appreciate the scenery and history of the Delaware Piedmont as you travel in the Red Clay Creek Valley (or Brandywine or White Clay valleys as well). We hope that you will also enjoy something of the underlying geology and a billion years of earth history that have formed and now support this land.

Robert R. Jordan, *Director and State Geologist*
Delaware Geological Survey

Introduction

The Red Clay Creek has flowed through the rolling hills of northern Delaware for many thousands of years, cutting a deep valley into the old deformed rocks of the Appalachian Piedmont. This publication describes the rocks of the Red Clay Valley and the geologic history of the Delaware Piedmont. It has been written for those who would like to know more about rocks, for students and teachers of earth science who would like to know more about Piedmont rocks and what they look like outside the classroom, and for geologists who may be familiar with Appalachian geology, but are curious about the Delaware Piedmont.

The first section, "Basic Facts About Rocks," is a brief overview of geology organized to help in understanding the rocks of the Delaware Piedmont. Basic concepts are described, and some of the terminology used by geologists is defined. The second section, "Reading the Rocks: History of the Delaware Piedmont," is a summary of the geology of the Delaware Piedmont. The third section, "A Guide to the Rocks Along the Track," is a railroad log along the tracks of the Wilmington and Western Railroad. It describes the rocks you can see from the train as you travel the Red Clay Valley from Greenbank Station to Hockessin.

In preparing this publication, we have borrowed freely from the geologists who have worked previously in the Piedmont, including the first State Geologist, James C. Booth, who described the rocks of Delaware in an 1841 Memoir; Florence Bascom and her co-workers, who carefully mapped the area in the 1920s and '30s for the U. S. Geological Survey; Bruce K. Goodwin, who wrote a 1964 Guidebook to the Geology of the Philadelphia Area; Richard F. Ward and Johan J. Groot, (1957), who studied the rocks of Delaware for their engineering properties; Kenneth D. Woodruff and Allan M. Thompson, who published the 1972 and 1975 geologic maps that include Delaware's Piedmont; Allan M. Thompson, who wrote the first summary of the geology of the Piedmont in Delaware for the 1976 edition of the Transactions of the Delaware Academy of Science; and the geologists at the Delaware Geological Survey who, along with the many students and faculty of the local universities, have courageously attempted to understand the local geology from the widely scattered surface exposures. We have listed additional sources of information at the end of the publication for anyone interested in learning more about the geology of the Delaware Piedmont.

Acknowledgments

The idea for this publication came from Robert W. Wilhelm, who approached the Delaware Geological Survey and asked for assistance in preparing a publication to describe the rocks that can be seen from the Wilmington and Western trains. The publication has grown from his initial suggestion of a simple railroad log to include a summary of the geology of the Delaware Piedmont.

We would like to thank Robert R. Jordan, director of the Delaware Geological Survey, for his encouragement and support, reviewers Richard N. Benson and Nenad A. Spoljaric of the Delaware Geological Survey, and Karen Barker of Tatnall School for their comments and suggestions that helped to improve earlier versions of the manuscript.

The layout for the publication was completed by Connee W. McKinney, editorial coordinator, University Publications. We appreciate her professional knowledge and cheerful assistance during the publishing process.

In addition, we would like to express our appreciation to the owners of the property next to the track for allowing us access: Hercules Inc., Mrs. Lammont du Pont Copeland, Mr. Henry B. du Pont IV, Delaware Nature Society, Mrs. Eleanor M. Reynolds, Mr. & Mrs. John Biggs III, Roger Murray and Kaye Murray, Mr. & Mrs. K. Edward Lefren, Mr. & Mrs. Wales Craven, and the NVF Co.

Cover photo: Photograph of the large boulder in the Delaware Geological Survey lobby. The boulder was removed from the "The Ridge", a development constructed near the intersection of Paper Mill Road (Route 72) and Limestone Road (Route 7), and taken to the site of the new Delaware Geological Survey building in 1988. The boulder was positioned on the concrete pad, and the building was built around it. The boulder is a metamorphic rock from the Wissahickon Formation called an amphibolite. It is composed of the minerals hornblende and plagioclase feldspar.

Basic Facts about Rocks

■ Our Earth

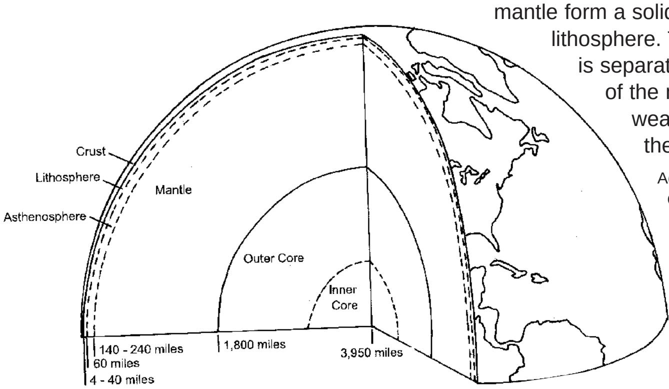
Our Earth is a wondrous place, ever evolving, ever changing. It formed along with the rest of the solar system, approximately 4.6 billion years ago by the collection of clumps of matter spinning around the Sun after it had condensed from an interstellar cloud. As the Earth evolved into a sphere with a radius of about 3,950 miles, it separated into three distinct layers: a crust, a mantle, and a core (Figure 1).

It is an exciting time to study our planet, as new technologies allow us to see the Earth from space, compare it with other bodies in the solar system, map its landforms, examine its internal structure, and study the ocean floors. With the new knowledge comes an increased perception of how the Earth is continually changing, and, equally as important, a fresh awareness of how fragile our planet truly is.

The Crust

The crust on which we live is a thin layer of cool solid rocks. Its thickness ranges from less than 4 miles under the oceans to over 40 miles under the highest mountain ranges. Within the crust there are two principal regions, continents and ocean basins. The rocks of these two regions differ from one another in almost every way, including elevation, density, chemical composition, age, and history.

Figure 1. The Earth consists of three distinct layers, a core, a mantle, and a brittle crust. The crust plus the cool uppermost mantle form a solid layer called the lithosphere. The lithosphere is separated from the rest of the mantle by a soft, weak layer called the asthenosphere.



Adapted from Continents Adrift and Continents Aground," 1963, *Scientific American, Inc.*

Beneath the crust is the mantle. Both the crust and the mantle are made up of similar rock-forming minerals, but the minerals of the crust tend to be richer in lighter elements such as sodium, calcium, and potassium, whereas the minerals in the mantle are richer in heavy elements such as magnesium and iron. The boundary between the crust and the mantle represents a chemical change, and is marked by a sharp seismic discontinuity, called the Mohorovicic discontinuity or "Moho."

The Mantle

The mantle is the thickest layer of the Earth. It extends from the base of the crust to a depth of approximately 1,800 miles (Figure 1). The top part of the mantle consists of two distinct layers, an upper layer that is relatively cool and brittle, and a deeper weak layer that is molten.

The rocks in the uppermost layer are like the rocks of the crust, they are rigid and will crack when stressed. This uppermost layer of the mantle together with the crust is called the lithosphere. It extends from the surface of the Earth to an average depth of 60 miles.

Lying between the lithosphere and the rest of the mantle is a weak layer called by the cumbersome name of the asthenosphere. Its temperature and pressure are in a delicate balance, so most of the material is near the melting point. It is partly molten, structurally weak, and capable of flowing. This weak layer is responsible for most of the volcanic activity and is the layer over which Earth's tectonic plates ride and create the crustal deformation observed on the Earth's surface. It is most easily identified beneath the oceans, where it is about 80 miles thick, but it has also been recognized beneath the continents, where it may extend to depths of up to 240 miles.

The Core

The core is a dense, hot, mass of iron and nickel. The temperatures in the core are thought to reach approximately 12,000°F, about the same temperature as the surface of the sun. The core has a solid inner core and a liquid outer core. The rotation of the Earth probably causes the liquid core to circulate and generate the Earth's magnetic field.

Plate Tectonics

The Earth's crust, although solid, is continuously in motion. Sometimes the movements are quick and easily observed, such as erupting volcanoes or earthquakes. Sometimes the changes are slow and more difficult to recognize, such as uplift and erosion.

For many years geologists recorded and dated these changes, but they could not explain how or why they occurred. Not until a new technology, developed during World War II and based on echo sounding (sonar), allowed geologists to map the ocean floor. The new maps revealed amazing features! They showed the world's ocean basins contain a system of mountain ridges some six to ten thousand feet tall. Moreover, in the center of the ridges there is a narrow valley where the ocean floor is splitting apart and erupting hot molten lava. The new map also showed that the deepest parts of the ocean occur in narrow trenches beside rows of active volcanoes.

As geologists compared their new maps with the locations of earthquakes, they found that earthquakes almost always occur either along ridges or near trenches. They recognized the ridges and trenches as zones of active deformation.

Additionally, as they used newly designed dredges and drill rigs to bring up bits and pieces of the ocean floor, they found that the oceanic crust lying beneath ocean sediments is composed of dense black rock called basalt, a rock that is very different from the light granitic rock typical of the continents. Even more surprising, radiometric dating found these ocean floor basalts get steadily older away from the ridges, and to be never older than 200 million years! The ocean crust is young when compared with continental rocks that may be as old as four billion years.

Armed with the new maps of the ocean floor and the new information on the composition and age of the sea floor, geolo-

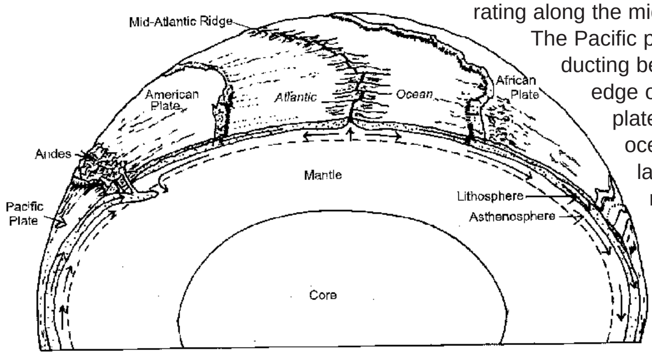


Figure 2. Cross section of the Earth as it is envisioned in plate tectonics. The African plate and American plate are shown separating along the mid-Atlantic Ridge. The Pacific plate is shown subducting beneath the western edge of the American plate to form a deep ocean trench and a large mountain range, the Andes.

Adapted from "Continents Adrift and Continents Aground," 1963, *Scientific American, Inc.*

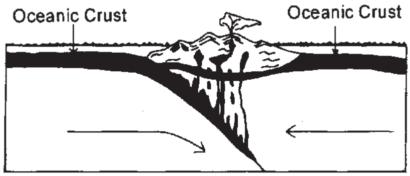


Figure 3. A schematic cross section of a converging plate margin illustrating an oceanic plate subducting beneath an oceanic plate.

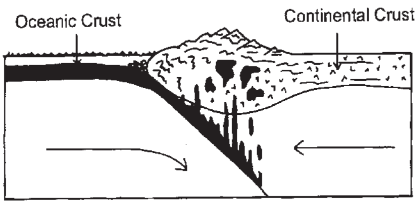


Figure 4. A schematic cross section of a converging plate margin illustrating an oceanic plate subducting beneath a continental plate.

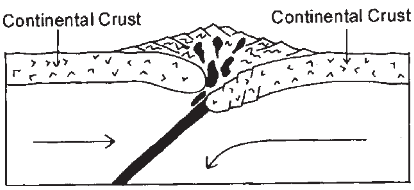


Figure 5. A schematic cross section of a converging plate margin illustrating a continental plate colliding with a continental plate.

gists developed a theory to explain the changing Earth. According to this new theory, called plate tectonics, the Earth has a thin outer shell that is broken into twelve or more plates. The plates are in constant motion as they glide slowly over the weak layer in the mantle (asthenosphere). They move away from each other along the mid-ocean ridges where lava from the mantle flows into the gap and forms new oceanic crust. Where plates collide, deep sea trenches form as one plate subducts beneath the other and eventually sinks into the mantle (Figure 2). Thus new crust is constantly formed where plates pull away from each other, and old crust is constantly consumed into the mantle where they collide. Along other boundaries, the plates slide past one another causing earthquakes, such as those along the San Andreas fault in California.

Although seafloor is consumed at subduction zones, these regions are also the sites of the generation of new crust in the form of volcanoes. At depths of approximately 60 miles, melting occurs above the subducting plate, and blobs of newly melted magma rise slowly through the overlying mantle and crust to erupt as volcanoes. Over time magmas rising from a subducting slab form an arc-shaped chain of active volcanoes such as the Aleutian Islands off the coast of Alaska (Figure 3). If the crust above the subducting slab is continental, it will be crumpled into a linear mountain range capped by volcanoes as in the Andes of South America and the Cascades of the United States (Figure 4).

If two plates both carry continental crust, the continental masses may crash into one another and push up an enormous mountain range. A continental collision of this type is happening today as India and Asia grind into one another and push up the Himalayan Mountains (Figure 5). Similarly, millions of years ago, collisions between the North American, African, and European plates formed the Appalachian Mountains.

Minerals

At some time almost everyone has picked up and examined a rock. It may have been round and smooth and you liked the way it felt; it may have been just the right size to skip across a pond; or it may have been beautiful or unusual. Whatever your reason for picking up a rock, we hope you observed that it was made up of many small individual grains. These small grains are minerals. Most common everyday rocks, such as granite, slate, or gneiss, are made up of several different minerals, but it is possible for a rock, such as quartzite, to be composed of only one mineral. The dictionary broadly defines a mineral as a naturally occurring solid with a definite chemical composition and an ordered (crystalline) atomic arrangement.

Minerals can form in many ways, such as crystallization from a lava or magma, by recrystallization when a rock is heated or compressed, or by precipitation from water. Usually new minerals

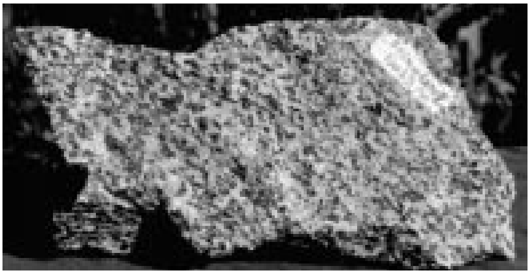


Photo credit: Frank McRight

A

Photo credit: Frank McRight

B

Figure 6. (A) A rock made up of two minerals, feldspar and pyroxene. When this rock crystallized the two minerals grew at the same time and formed interlocking grains. This rock is from Bringhurst Woods Park, Delaware.

(B) Rock made up of only one mineral, stibnite. The stibnite crystallized without competition from other minerals. This is a mineral specimen prized by collectors.

crystallize in a medium where they are competing for space with other minerals that are forming at the same time, and they end up as a maze of interlocking grains (Figure 6 A). However, if the minerals are allowed to crystallize without competition, such as in water or molten magma, the minerals will crystallize into geometric shapes that are strikingly beautiful and often valued by collectors (Figure 6 B). There are thousands of different minerals that form in the Earth, but only a few are found in the Red Clay Valley (Table 1).

■ Rocks

Rocks are made up of minerals. They have names such as limestone, shale, granite, gneiss, marble, and quartzite. Geologists have classified all rocks into three major groups: igneous rocks, sedimentary rocks, and metamorphic rocks.

Igneous Rocks

Igneous rocks are those that form by the crystallization of a hot molten liquid called magma or lava. We can see igneous rocks form today where lava erupts from volcanoes and cools to form solid rock. If it was not for volcanoes, it might be difficult to convince anyone that rocks can form from molten lava. Igneous rocks that form on the Earth's surface are called volcanic rocks or extrusive igneous rocks (Figure 7).

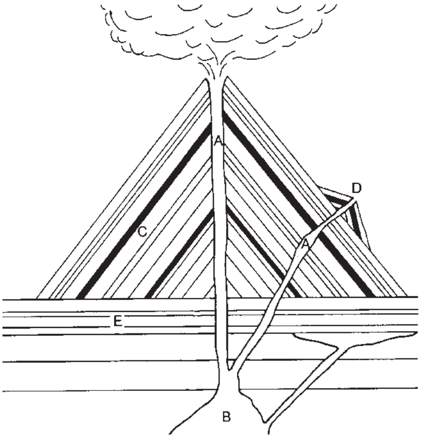


Figure 7. Cross section of a volcano showing (A) vents for magma as it rises to the Earth's surface where it erupts as gas, ash, and lava, (B) a magma chamber, (C) alternating layers of ash and lava, (D) parasitic cone of ash and lava, (E) crust, either oceanic or continental.

Not all molten rock rises from deep within the Earth to erupt in a volcano. Sometimes the molten rock, or magma, does not reach the surface, but is held in big underground chambers where it slowly solidifies to form intrusive igneous rocks. We can see this type of igneous rock only where erosion has removed the overlying rocks.

Table 1. Common Minerals of the Red Clay Valley

Quartz	A glassy, transparent to translucent mineral that breaks and fractures like glass. Its color is usually white to gray. Quartz is present in almost all Piedmont rocks.
Feldspar	In weathered rocks or granitic pegmatites, feldspars occur as milky white or pink porcelain-like minerals that often break into rectangular shapes with shiny flat surfaces. In fresh, unweathered amphilbolites or gneisses, the feldspars are glassy and transparent. In the 18th and 19th centuries, feldspar was quarried in the Red Clay Valley for use in porcelain, china, and glazes. Orthoclase and plagioclase are two types of feldspar found in the Delaware Piedmont.
Mica	A mineral with perfect basal cleavage that easily separates into sheets. The varieties are black biotite, white muscovite, bronze phlogopite, and green chlorite. Micas are common in all Piedmont rocks except the high-grade gneisses of the Wilmington Complex.
Garnet	Most Piedmont garnets are a dark-red, iron-rich variety called almandine. They usually occur as 12-sided crystals that vary in size from crystals so small they can be seen only under a microscope to crystals of an inch or more across. Garnets are considered semi-precious stones, but in the highly deformed rocks of the Piedmont they are usually fractured and not suitable for jewelery. Garnet is also used as an abrasive.
Sillimanite	Sillimanite, or fibrolite as it is commonly called, occurs as aggregates of thin fibers, nodules, or veins. Its color is either gray blue or dull white. It is a high-grade metamorphic mineral that occurs in the gneisses and granitic pegmatites. Sillimanite is the Delaware State Mineral.
Calcite and Dolomite	The major minerals in marble. In the Delaware Piedmont they occur in the Cockeysville Marble as blue-white, coarsely crystalline interlocking grains. Years ago the marble was quarried, converted into quick lime, and used as a soil conditioner.
Serpentine	A secondary mineral that forms by the alteration of magnesium-rich minerals. Serpentines are always shades of green, they are soft, and have a slightly soapy or greasy feel.
Amphibole	A large family of minerals. In the Delaware Piedmont, they are usually black or dark green. Amphiboles usually have one good cleavage that will sparkle on fresh surfaces. A rock containing around 50% or more amphibole is called an amphibolite.
Pryoxene	A group of dark minerals that are common in the Piedmont rocks. They usually occur as interlocking grains in the highest-grade gneisses, amphibolites, and gabbros.

Table 2. Igneous Rocks of the Red Clay Valley	
EXTRUSIVE	
Basalt	A fine-grained, dark-colored, extrusive igneous rock that forms by the crystallization of lava flows. Most basalt flows in the Red Clay Valley have been metamorphosed to amphibolites and are now composed of plagioclase, pyroxene, and amphibole.
INTRUSIVE	
Granite	A coarse-grained, light-colored rock composed of quartz and two feldspars (plagioclase and orthoclase), with lesser amounts of mica or amphibole.
Gabbro	A coarse-grained rock composed of greenish-white feldspar (mostly plagioclase) and pyroxene. Gabbro is usually very dark in color. It is the intrusive equivalent of basalt.
Pegmatite	An igneous rock with very large (usually > one inch), well-formed crystals. A granitic pegmatite has the mineralogy of a granite and abnormally large grains, whereas a gabbroic pegmatite has the mineralogy of a gabbro and very large grains.
Diorite	A coarse, uniformly grained rock composed of a feldspar and less than 50% amphibole or pyroxene. A quartz diorite has the composition of a diorite plus quartz and biotite, whereas a granodiorite has the composition of a diorite plus quartz and two feldspars.

Extrusive and intrusive igneous rocks can be distinguished by the size of their mineral grains. If the individual crystals are too small to be seen without magnification, the rock is fine-grained and probably extrusive. If you can easily differentiate the grains, it is considered coarse-grained and intrusive. Extrusive rocks are fine-grained because lava cools quickly and large grains do not have time to form. Intrusive rocks cool slowly deep inside the Earth and have time to grow large mineral grains.

The igneous rocks exposed in the Red Clay Valley are mostly coarse-grained, intrusive rocks that are named granites, granitic pegmatites, diorites, and gabbros. These rocks form in large masses usually without the layering that is characteristic of sedimentary and metamorphic rocks (Table 2).

Sedimentary Rocks

Sedimentary rocks are made up of the debris from weathering and erosion of rocks, from chemical precipitates, or from the remains of living things. Most sedimentary rocks are formed from particles of older rocks that are carried by rivers and streams to lakes or oceans where they are deposited, deeply buried, and then consolidated into solid rock. They cover most of the ocean floor and three-quarters of the land. The most common solid sedimentary rocks are shale, sandstone, conglomerate, and limestone.

The only sedimentary rocks in Delaware's Piedmont are modern sediments (sand, silt, and clay) that are being eroded, transported, and deposited in the local streams as the rocks within the watersheds weather and erode. The Piedmont has been a source of sediment that is deposited elsewhere, and has been for a long part of geologic time.

Metamorphic Rocks

Metamorphic rocks are sedimentary or igneous rocks that have been changed. These changes usually occur deep within the Earth, by processes we cannot observe; however, we do know that under the lithosphere the mantle is a slowly churning reservoir of fiery hot rock. Thus, when rocks are deeply buried, they are heated from the reservoir below and squeezed from above by the overlying rocks. At these high temperatures and pressures, some minerals will become unstable and change into new minerals. For example, clay will change into mica, mica plus quartz will change into sillimanite, and chlorite will change into garnet. The mineral changes that occur in solid rocks as they are heated and deeply buried are known as metamorphism.

The new minerals that form during metamorphism depend upon (1) the original composition of the rock; (2) the temperature to which the rocks are heated; and (3) the pressure (amount of

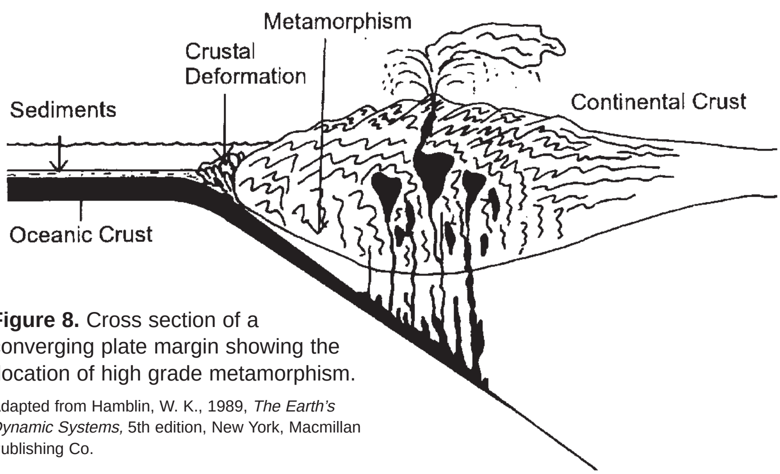


Figure 8. Cross section of a converging plate margin showing the location of high grade metamorphism.

Adapted from Hamblin, W. K., 1989, *The Earth's Dynamic Systems,* 5th edition, New York, Macmillan Publishing Co.

Table 3. Metamorphic Rocks of the Red Clay Valley	
Gneiss	A course-grained rock commonly having imperfect, but prominent light-dark layering. In the Delaware Piedmont the light layers are composed of feldspars and quartz and the dark layers of mica, garnet, sillimanite, amphiboles, and pyroxenes. Gneisses are formed by the high-grade metamorphism of either igneous or sedimentary rocks.
Schist	A sharply layered, commonly crinkle-folded rock, that can easily split into flakes or slabs due to a well developed parallelism of platy minerals such as micas or amphiboles. Schists commonly form by the medium-grade metamorphism of igneous and sedimentary rocks.
Amphibolite	A rock composed primarily of amphibole and feldspar. The amphibole grains are commonly elongated with long axes parallel. In the Delaware Piedmont most amphibolites are formed by the metamorphism of igneous rocks.
Serpentinite	A greenish-yellow, greasy soft rock composed essentially of the mineral serpentine. It may be soft enough to carve with a pocketknife. Serpentenites are formed by the metamorphism of ultramafic (iron-magnesium rich) rocks. Ultramafics originate deep in oceanic crust and occur on land only as slivers of rock that have been thrust faulted onto the continental margin.
Quartzite	A massive rock composed essentially of interlocking quartz grains. Quartzites are formed by metamorphism of sand or sandstone.
Vein Quartz	A rock composed of sutured quartz crystals that formed by precipitation from a solution or melt. In the Piedmont vein quartz commonly fills ancient fractures.
Marble	A massive, coarse-grained sparkling blue-white rock composed mostly of calcite and/or dolomite. Marble forms by the metamorphism of limestone.

squeezing) to which the rock is subjected. Because there are minerals that are characteristic of low, medium, and high temperatures, and low and high pressures, it is possible to estimate the temperature and pressure of metamorphism by identifying the minerals present in a metamorphic rock. These estimates allow the geologist to determine the depth of burial and the temperature of the rocks during a metamorphic event.

The highest metamorphic temperatures and pressures occur near subduction zones where large bodies of magma rise through the crust and transport heat. This heat, together with the normal heat from burial, produces the extremely high temperatures (up to

1,600°F) that are recorded by rocks metamorphosed within the margins of colliding plates (Figure 8).

Common metamorphic rocks are slate, schist, gneiss, quartzite, marble, and amphibolite. The dominant rocks in the Delaware Piedmont are gneisses and amphibolites, rocks that were highly metamorphosed by heating deep within a subduction zone (Table 3).

■ Deformation

Imagine that you can see sand, clay, seashells, bones, or fish teeth being deposited in a lake or an ocean basin. You would see these as sediments being deposited in nearly horizontal layers that are parallel to the surface on which they are dropping. However, you may notice that the layered Piedmont rocks that occur along the highways, railroad tracks, or stream beds tip at various angles to the horizontal. These rocks have been deformed.

The forces that deform rocks are compression and tension. Compression squeezes or pushes rocks together, causing them to thicken. If the rocks being compressed are cool and brittle, they will break along faults and slide on top of one another. If the rocks are soft and ductile, they will fold and buckle. On the other hand, tension will pull rocks apart and cause brittle rocks to break and separate, whereas soft ductile rocks will thin and stretch (Figure 9).

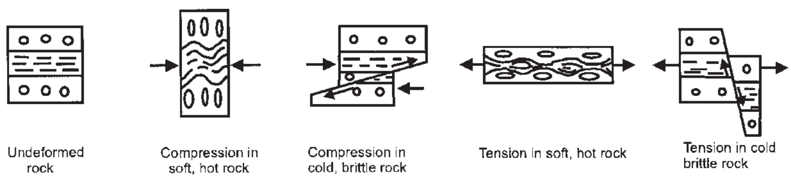


Figure 9. Diagrams showing the effects of compression and tension on rocks.

The most important forces that deform rocks are those produced by the movement of tectonic plates. Each plate boundary is characterized by different large-scale tectonic forces. At divergent boundaries, such as those along the mid-ocean ridges where the seafloor is being pulled apart, the forces are tensional. At subduction zones, where plates collide, the forces are compressional. At other boundaries, where the plates simply slide past one another, the forces cause shearing and faulting. As a result, different deformational features are associated with each type of plate boundary.

The common deformational features that can be observed in rocks are folds, faults, and joints. **Folds** are bends in rocks that usually form as the result of compression. They occur in all styles from broad gentle warps to complex refolded folds. Folding normally takes place over long periods of time in rocks at high temperatures and pressures. However, folds can form at shallow depths even at the Earth's surface where temperatures are low.

If rocks are cool and brittle, they will respond to compression or tension by breaking to produce faults or joints. **Faults** are breaks or fractures in rocks along which movement has occurred. The distance the rocks on opposite sides of a fault have moved is called slip. In many cases, a fault exists as a single fracture; however, in very large faults with hundreds of feet of slip, the movement takes place in a zone of several faults.

Joints are fractures or breaks in rocks along which no movement has occurred. Joints are so common in surface rocks that they occur in almost every outcrop. Commonly they will occur as a set of two fractures that intersect at a high angle. Joints result from a number of causes, such as broad regional upwarps, cooling and contraction, compression, tension, or erosional unloading.

The deformational features that are common in the highly metamorphosed Delaware Piedmont are folds, reverse faults, and joints. The folds and reverse faults are compressional features and suggest formation in a subduction zone.

■ Time

Measuring time is important to geologists because rocks record time. To measure processes such as the motion of the sun, weather, floods, volcanic eruptions, and earthquakes geologists can use calendars and clocks. For the age of rocks, or the slow processes such as the movement of continents, or the formation of mountain ranges, processes that require time periods in millions or even billions of years, geologists must use relative time or absolute time.

Relative time is based upon the order in which geologic events occur. No absolute number of years is deduced, only that one event occurred earlier or later than another. The sequence of geological events is usually presented in the form of a chart and can be constructed for any area by arranging the rock units in a column, with the oldest units at the bottom and progressively younger ones toward the top.

Absolute time is measured using radioactivity and is called radiometric age dating. This process is used to determine the years in which geological events occurred. For example the age of the Earth has been determined using radioactivity, and it is found to be about 4.6 billion years old. The tectonic activity that built the Appalachian Mountains began about 543 million years ago, and was mostly finished by 250 million years ago. These dates are expressions of absolute time in years.

Reading the Rocks: A History of the Delaware Piedmont

■ Geologic Setting

Piedmont

The State of Delaware is located within two provinces, the Atlantic Coastal Plain and the Piedmont (Figure 10). Most of the state lies within the Coastal Plain; it is only the hills of northern New Castle County that lie within the Piedmont. Piedmont means foothills. Delaware's rolling hills, which rise to over 400 feet above sea level, are a part of the foothills of the Appalachian Mountains.

The rocks at the surface in the Piedmont today are old, deformed, metamorphic rocks that were once buried in the core of an ancient mountain range. This range formed early in a series of tectonic events that built the Appalachians between about 543 and 250 million years ago. During an early event, called the Taconic orogeny, an offshore chain of volcanoes collided with the ancient North American continental margin to push up a gigantic mountain range that was as tall as the Alps or the Rockies of today. Geologists date the Taconic orogeny between 470 and 440 million years ago.

The Taconic orogeny is important to our understanding of the geology of Delaware, because during this event, the rocks of Delaware's Piedmont were deeply buried under miles of overlying rock

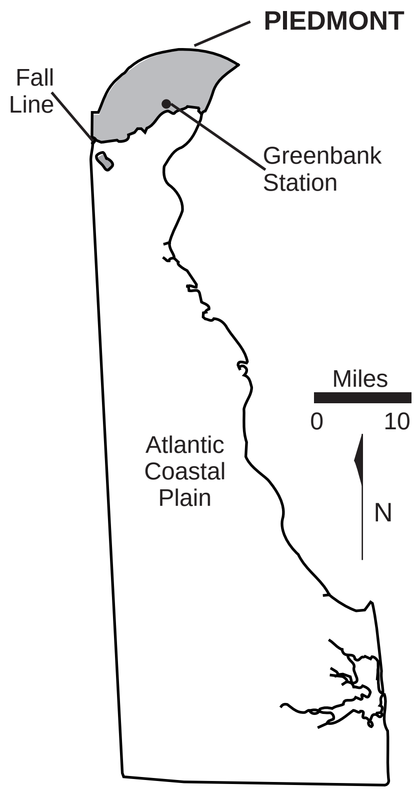


Figure 10. Map of Delaware showing the location of the Piedmont Province, Atlantic Coastal Plain, Fall Line, and Greenbank Station.

and metamorphosed by heat from the underlying mantle. Since that time, rivers and streams have carried the erosional products, mostly sand, clay, and gravel, from the mountains onto the Atlantic Coastal Plain and continental shelf. As the mountains wear down, the buried rocks rebound and rise to the surface. Thus what we see in the Piedmont today are old deformed metamorphic rocks that were once buried deep within an ancient mountain range.

The oldest rocks in Delaware also preserve the history of an earlier mountain-building event called the Grenville orogeny. This event occurred approximately one billion years ago.

Within Delaware's Piedmont, five distinct rock units can be recognized: (1) rocks of the volcanic arc, (2) rocks formed from the mud and sand deposited in the deep ocean that existed between the volcanic arc and the ancient continental margin, (3 & 4) rocks that were once sand and carbonates (calcite and dolomite) lying on the shallow shelf of the ancient continental margin, and (5) rocks of the ancient North American continent. The names given to these units indicate the geographic area where they were first identified.

Table 4. Geologic Units of the Delaware Piedmont

Geologic Setting	Rock Unit	Area where first identified
1. Volcanic arc	Wilmington Complex	City of Wilmington, Delaware
2. Deep basin	Wissahickon Formation	Wissahickon Creek, Philadelphia, Pennsylvania
3. Shelf sand	Setters Formation	Setters Ridge, Maryland
4. Carbonate bank	Cockeysville Marble	Cockeysville, Maryland
5. Ancient continent	Baltimore Gneiss	Baltimore, Maryland

Because of the total absence of fossils, determining the age of the Piedmont rocks has always been a problem. Age must be determined either by correlation with units elsewhere in the Piedmont, or by calculating radiometric ages from measurements of radioactive elements and their decay products (usually uranium-lead). Table 5 lists the geologic events important in eastern North America correlated with major events in the history of life on Earth. Delaware's Piedmont rocks were formed during Proterozoic through Ordovician times.

Fall Line

Delaware's Piedmont ends at the Fall Line where the metamorphic rocks dip under and disappear beneath the sediments of the Coastal Plain. The Fall Line roughly follows Kirkwood Highway, Route 2, across the state between Newark and Wilmington (Figure 10). Parallel to the Fall Line is a narrow zone where rapids and waterfalls are common. Delaware's early settlers built near the rapids using the energy generated from the falls to power their mills.

Explorers and sea captains of the colonial period found the bays, rivers, and streams of the Coastal Plain navigable until they reached the fall zone. Here it was necessary to dock their ships, unload the cargo, and move it inland by rail or road. Many of the settlements that grew around these unloading sites later became large cities. Richmond, Washington, Baltimore, Wilmington, and Philadelphia are cities built around ports located along the fall zone.

Atlantic Coastal Plain

Delaware's Coastal Plain rises to about 100 feet above sea level. Its streams drain into the Delaware River or Bay, and for much of their length they are tidal. The Coastal Plain is made up of sediments, mostly silt, sand, and gravel, that have been eroded off the Piedmont and adjacent Appalachian Mountains. In cross section (Figure 11), these sediments form a southeastward thickening wedge that increases from 0 feet at the Fall Line to over 10,000 feet along Delaware's coast. Offshore, on the continental shelf, the sediments become even thicker with reported thicknesses of 8 to 10 miles. In the 1970s and 1980s, exploratory drilling in this thick pile of sediments found no commercial deposits of gas or oil, although one noncommercial gas deposit was discovered.

Underlying the sand, silt, and gravel of the Coastal Plain lie consolidated rocks that geologists refer to as the basement (Figure 11). Test drilling into the basement near the Fall Line found metamorphosed and deformed rocks similar to those of the Piedmont. Hence, the basement is probably a subsurface extension of the Piedmont.

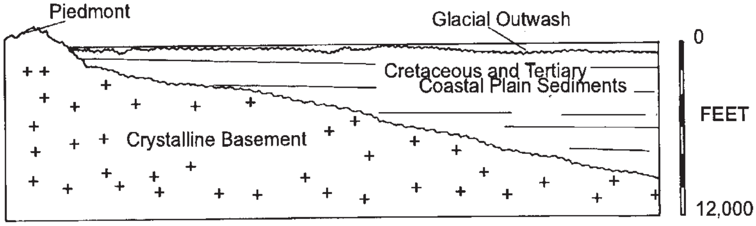


Figure 11. Generalized cross section of Delaware from north to south showing the relationship between the crystalline basement and the sediments of the Coastal Plain.

The contact between the sediments of the Coastal Plain and the basement is called an unconformity. An unconformity represents an interval of time during which no sediments are preserved to record geological events. In the Coastal Plain, the oldest sedimentary rocks beneath Delaware's coast are of Late Jurassic to Early Cretaceous age (140–150 million years), and the basement rocks they overlie are of Paleozoic age, older than 245 million years. During the time represented by this unconformity, the rocks we see in the Piedmont today reached the earth's surface as approximately 7 to 13 miles of overlying rock were removed by erosion allowing the buried rocks to rise to the surface in compensation.

The oldest Coastal Plain sediments observed in Delaware are river-deposited sediments. These sediments were eroded from the Appalachian Mountains to the west, transported to the southeast by rivers, and deposited where the rivers met the ocean to form a delta. On top of the river sediments a sequence of marine silt and sand deposits records the rise and fall of the sea level many times during a period of over 80 million years, from the Late Cretaceous until the end of the Tertiary Period, about 2 million years ago (Table 5).

On top of all of these sediments is a thin veneer of young sand and gravel that was carried into Delaware by glacial outwash during the Ice Age (Table 5). Glacial ice did not advance into Delaware, but melt-water pouring off the glacier fronts carried great quantities of sand, silt, and gravel over southern Pennsylvania and Delaware. Today Delaware's largest mineral resource is the sand and gravel deposited from the glacier outwash.

Table 5. Geologic Events in Eastern North America

AGE*	ERA	PERIOD	GEOLOGIC EVENTS: History of Life	GEOLOGIC EVENTS: Eastern North America
	CENOZOIC			Ice Ages
1 .8	CENOZOIC	QUATERNARY	Rise of Man	Glacial outwash deposits sand and gravel over Delaware
65	CENOZOIC	TERTIARY	Mammals become dominant	Marine deposits of sand and silt predominate Sealevel rises and falls
144	MESOZOIC	CRETACEOUS	Mass extinction and dinosaurs disappear Dinosaurs abundant, first mammals	Rivers deposit sediments eroded from the Appalachians onto Coastal Plain followed by marine deposits of sand and silts
201	MESOZOIC	JURASSIC		Rifting of Pangea as today's continents separate
245	MESOZOIC	TRIASSIC	First dinosaurs	Rift basins develop
290	PALEOZOIC	PERMIAN	Earth's greatest mass extinction	Final assembly of the super continent Pangea
363	PALEOZOIC	CARBONIFEROUS	Great coal forests	Appalachian Mountains completed
408	PALEOZOIC	DEVONIAN	First amphibians	
439	PALEOZOIC	SILURIAN	First land plants	
510	PALEOZOIC	ORDOVICIAN	First fish	Taconic orogeny, volcanic arc collides with North America, metamorphism and deformation Appalachian mountain building begins
543	PALEOZOIC	CAMBRIAN	First organisms with shells, trilobites dominant	Subduction begins offshore of ancient North American continent
570	PROTEROZOIC	LATE PROTEROZOIC	First multi-celled organisms	Erosion of Grenville Mountains, sediments deposited on ancient North American continental margin
900	PROTEROZOIC	MIDDLE PROTEROZOIC		Grenville mountain building event
1600	PROTEROZOIC	EARLY PROTEROZOIC		

*Beginning of each period, millions of years before present

■ Rock Units of the Delaware Piedmont

Wilmington Complex

The Wilmington Complex is a diverse association of metamorphic rocks that formed in an offshore volcanic setting. Although originally igneous and sedimentary, most of the exposed rocks have been buried, heated, and changed into metamorphic rocks. Geologists estimate these rocks were buried to depths of 11 to 13 miles, and heated to temperatures as high as 1,600°F. These are among the highest metamorphic temperatures recorded in the entire Appalachian system. Mixed with the metamorphic rocks are various intrusive igneous rocks, such as gabbros, diorites, and granites. These igneous rocks may represent the crystallized remains of magma chambers or vents (Figure 7), or pockets of rock melted during metamorphism.

The age of the Wilmington Complex is controversial; however, a large mass of granitic rock, exposed in the community of Arden, was radiometrically dated and found to be approximately 500 million years old. This date suggests the Wilmington Complex may represent the root zone of the volcanic arc that existed off the ancient North American continent during Cambrian and Early Ordovician time, between 543 and 480 million years ago (Table 5).

The most extensive and well-known rock in the Wilmington Complex is a light-dark banded gneiss, known locally as the "blue rocks." Large boulders of this rock can be found in stream beds, parks, and lawns throughout Wilmington and Brandywine Hundred. The light-colored bands, which may be many feet thick, are quartz-rich (usually 30 to 40% quartz). The quartz contains inclusions that give it a bright blue cast when freshly broken. Once the rock is exposed at the surface it loses its blue color and becomes dark gray. The dark bands, usually only inches thick, contain mostly pyroxene and feldspar with almost no quartz. Because the gneisses look bright blue on fresh broken surfaces, quarry workers called these rocks the Brandywine blue granite. This rock is a gneiss and not a granite, nevertheless the nickname is still used.

Wilmington's original minor league baseball team thought they were as solid and resilient as the local rocks and called themselves the Blue Rocks. Recently the name has been revived, and Wilmington's new baseball team is also called the Blue Rocks.

The banded gniesses are extremely hard, so hard, in fact, that they rapidly wear rock crushers and cannot economically be used for road ballast. They make excellent building stones, and many of the old buildings and fences around northern Delaware are made from these beautiful rocks.

In addition to the banded gneiss, a number of metamorphic and igneous rocks with unfamiliar names, such as norites, charnokites, anorthosites, diorites, granodiorites, gabbros, and amphibolites, have been recognized within the Wilmington Complex.

Most of the city of Wilmington and its older suburbs are built on the gently rolling upland supported by these rocks.

Wissahickon Formation

In the northwestern half of the Piedmont, the gently rolling uplands of the Wilmington Complex give way to a more rugged terrain of steep slopes and sharp valleys, often referred to casually as "Delaware's chateau country." Underlying this terrain is the Wissahickon Formation, an array of metamorphosed sedimentary and igneous rocks that were once deposited in a deep ocean basin.

Originally, the oceanic sediments were sand and clay, but during the Taconic event, these sediments, along with any igneous rocks that invaded the ocean basin, were dragged into a subduction zone, metamorphosed, and deformed. The rocks of the ocean basin became a jumbled mass of gneisses and amphibolites today called the Wissahickon Formation.

Although the Wissahickon is complexly folded, four rock types can always be recognized (1) gneiss; (2) amphibolite; (3) pegmatite; (4) serpentinite.

The gneiss was formed by the metamorphism of oceanic sediments, primarily sand and clay, and always contains the minerals quartz, feldspar, and black mica. In addition the minerals, staurolite, sillimanite, garnet, and white mica may be present. It is these additional minerals that vary systematically with increasing metamorphic grade and can be used to track the intensity of metamorphism as it increases from west to east across Delaware's Piedmont. The peak temperatures reached by Wissahickon rocks, while buried under a pile of rocks 7 to 11 miles thick, have been estimated to be between 1,200° and 1,400°F, several hundred degrees lower than the temperatures reached by the Wilmington Complex.

Interlayered with the metasedimentary gneisses are black metaigneous rocks called amphibolites. Because of the metamorphism, the origin of these igneous rocks is not well understood. Today they are amphibolites, but years ago they may have been lava flows, ash falls, or magma that intruded into the ocean basin sediments.

Serpentinite occurs along the northwest shore of Hoopes Reservoir, where small areas of soft, greenish-yellow rock are exposed when the water level is low. Serpentinite was once valued as a beautiful building stone, but today air pollution causes it to weather and disintegrate quickly.

Granitic pegmatites are coarse-grained igneous rocks composed of mica, two feldspars, and quartz. They are extremely common in the Wissahickon because the high temperatures of metamorphism caused partial melting of the gneisses. The melted rock segregated into pods and veins, where it cooled and crystallized into coarse-grained pegmatites. In the eighteenth and nineteenth centuries, local residents quarried these pegmatites for large crystals of white and pink feldspar that they shipped to England and Philadelphia for use in manufacturing fine china and porcelain.

Setters Formation and Cockeysville Marble

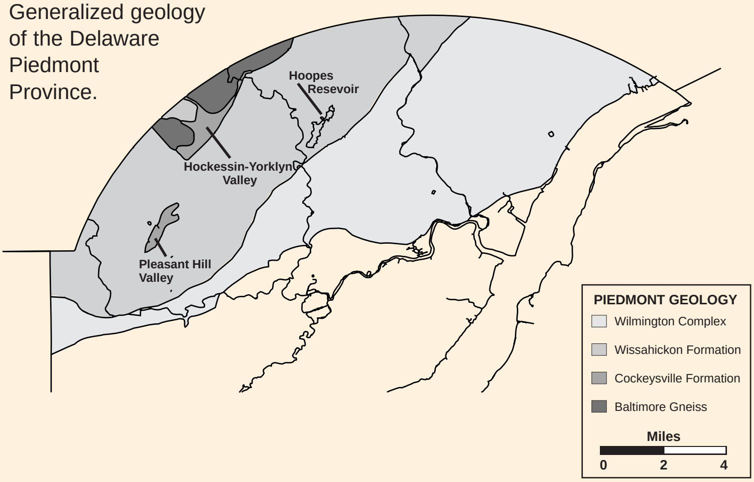
The Setters Formation and Cockeysville Marble are also metamorphosed sedimentary rocks; however, the sediments that formed these rocks were deposited in the shallow waters of the continental shelf of ancient North America. The Setters represents the sandy beaches of the ancient continent, whereas the Cockeysville represents a carbonate reef or bank made up of minerals precipitated from sea water mixed with the shells and/or skeletons of marine organisms. During the Taconic orogeny, high metamorphic temperatures and deep burial changed the sand into an impure quartzite and the carbonate bank into coarse-grained, blue-white marble, destroying all fossils. Where the marble is exposed at the ground surface it weathers easily and forms broad flat valleys, such as the Hockessin-Yorklyn and Pleasant Hill valleys (Figure 12). There are no natural exposures of the marble in Delaware, but the lack of surface exposure and scarcity of loose rock on valley floors is usually evidence of underlying marble. Limited exposures do exist in several of the old abandoned quarries located in the Hockessin-Yorklyn and Pleasant Hill valleys.

The Setters Formation is volumetrically an insignificant unit in Delaware; however, large quarries just north of the Delaware border produce a light-brown building stone known locally as “Avondale stone.” Delaware’s one outcrop of Setters rocks is in Eastburn’s Quarry where it lies on top of the marble.

The Cockeysville Marble, although also limited in extent, has always been a commercially important rock unit. Early settlers in Delaware searched diligently for marble in order to convert it to

■ Geologic Map

Figure 12.
Generalized geology of the Delaware Piedmont Province.



When geologists study an area, they identify the rock types, group them into mappable units, and prepare a map that portrays the surface extents of the units. Figure 12 is a simplified geologic map of the Delaware Piedmont. Each geologic unit is indicated by a different pattern to illustrate where it forms the bedrock.

Wilmington Complex—represents a volcanic arc; rocks are gneisses, amphibolites, diorites, gabbros, and granitic intrusives.

Wissahickon Formation—-represents deep ocean sediments; rocks are interlayered gneisses and amphibolites with numerous pegmatites and minor serpentinite.

Cockeysville Marble—represents a carbonate bank; rocks are blue-white dolomitic marble interlayered with calcite-rich schists.

Setters Formation—represents a sandy beach; rocks are feldspar-rich quartzites and gneisses.

Baltimore Gneiss—represents the ancient North American continent; rocks are interlayered granitic gneiss, biotite gneiss, pegmatite, and amphibolite.

quicklime and use as a soil conditioner on their fields. Their abandoned quarries and lime kilns still dot the Hockessin and Pleasant Hill landscape.

Today the marble is an important aquifer. Marble is easily dissolved by acidic ground water to form large solution channels or caves. The channels collect ground water and act as large reservoirs. Wells drilled into the marble provide almost 1.5 to 2 million gallons of water each day to the residents of northern Delaware. It is a surface recharge unit, which means the water in its reservoirs is renewed from rain falling in the marble valleys and from streams flowing over the marble. In recent years, the increasing development in the marble valleys has caused concern about maintaining the Cockeysville Marble as a source of water for New Castle County.

Baltimore Gneiss

The oldest rocks in the Delaware Piedmont are billion-year-old gneisses that support the hills north of the Hockessin-Yorklyn valley. They form the core of the Mill Creek Nappe, one of eleven dome-like structures cored by billion-year-old rocks that crop out between Baltimore and Philadelphia. These rocks, thought to be remnants of the ancient North American continent, are named the Baltimore Gneiss. The Baltimore Gneiss was metamorphosed and deformed during at least two mountain building episodes, the Grenville orogeny and the Taconic orogeny.

In Delaware, the Baltimore Gneiss is a contorted mixture of granitic gneisses, biotite gneisses, amphibolites, and pegmatites.

■ Deformation in the Delaware Piedmont

All the rock units in Delaware's Piedmont are highly deformed. Deformational features, such as folds, faults, and/or joints, are present in almost every outcrop.

The folds are a remarkable assortment of sharp folds, angular crinkle folds, and round gentle folds that may be upright, inclined, or turned upside down. The variety can be attributed to several distinct episodes of folding, and to the different mechanical properties of the rocks. For example, the soft mica-rich gneisses of the Wissahickon were crinkle-folded (Figure 13 A and C), whereas during the same deformation the more rigid amphibolites were bent into rounded folds (Figure 13 B). Overall, the folds in the Piedmont suggest a long compressional event in soft rocks that were hot and deeply buried.

Although folding styles in the rocks vary dramatically, the trend of the folds is remarkably consistent across the Piedmont, and parallels the trend of the Appalachians as a whole, which is northeast-southwest.

Folds permit determination of tectonic trends and are convenient indicators of crustal movements. Thus the folds in the Piedmont suggest a geologic setting at colliding plate boundaries, and the orientation of the folds indicates convergence from the southeast.

Today in the Delaware Piedmont there are no large active faults. Delaware is positioned on the trailing edge of the North American plate in a moderately active tectonic area. Several hundred million years ago, when Delaware was caught between two colliding plates, deep earthquakes were frequent and probably violent as regional faults stacked the various units in the Piedmont into a high mountain range. These ancient faults are difficult to identify, having been largely obscured by metamorphism and deformation.

Faults in cool brittle rocks may offset folds or layering across the fault surface, form a smooth slick surface called a slickenside, or grind

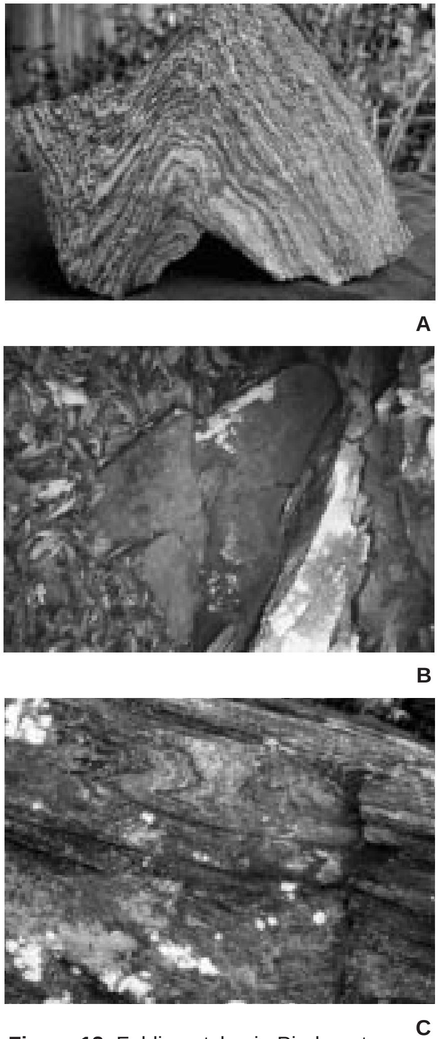


Photo credit: Frank McRight

Figure 13. Folding styles in Piedmont rocks:

(A) crinkle folds in mica-rich gneiss, Wooddale Quarry;

(B) rounded folds in amphibolite, Mount Cuba;

(C) drag fold in quartz-rich gneiss, Burrows Run.

up the rocks to produce fault gouge. These indicators of brittle faulting are present in the Piedmont rocks, but they are less common than folds and joints, and are younger features.

Almost all the rocks exposed in Delaware's Piedmont are broken and fractured to form joints. If joints form in deeply buried rocks, they are normally healed with vein material, such as quartz or mixtures of quartz and feldspar. Because the Piedmont rocks were once deeply buried, healed veins are a prominent feature of these rocks. Most of these veins were healed before the major deformational events, and are now folded, stretched into thin layers, or pulled apart into segments.

A

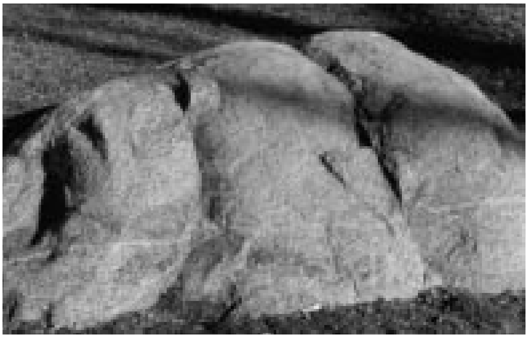


Photo credit: Frank McRight

B

Figure 14. Joints in Piedmont rocks:

(A) Wissahickon rocks with horizontal and vertical joints, Wooddale Quarry;

(B) rounded rocks of the Wilmington Complex, Tatnall Preschool.

Surface exposures of Wissahickon and Baltimore Gneiss rocks are riddled with very young horizontal and vertical joints, most likely the result of unloading and expansion as the overlying material is removed by erosion (Figure 14 A). Wilmington Complex rocks will joint and weather by peeling off a curved shell leaving round rocks. This jointing and weathering style is typical of massive, unlayered rocks. Thus, to a first approximation, it is possible to distinguish the rocks of the Wilmington Complex from those of the Wissahickon by the shape of the rocks at the surface. The Wissahickon rocks are angular and sharp whereas the Wilmington Complex rocks are round (Figure 14 B). The brittle fractures in the Piedmont rocks are important because they provide storage reservoirs for ground water. To produce water, the wells in northern Delaware must tap a fracture zone.

■ The Piedmont and Plate Tectonics

The Delaware Piedmont is but a small part of the Appalachian Mountain system that extends from Georgia to Newfoundland. This mountain system is the result of tectonic activity that took place during the Paleozoic era, between 543 and 245 million years ago. Since that time, the mountains have been continuously eroding, and their deep roots slowly rising in compensation as the overlying rocks are removed. It is surprising to find that although the Delaware Piedmont has passed through the whole series of tectonic events that formed the Appalachians, the mineralogy and structures preserved in Delaware were formed by the early event that occurred between 470 and 440 million years ago, called the Taconic orogeny.

This event was triggered by the formation of a subduction zone off the coast of the ancient North American continent that slid oceanic crust on the ancient North American plate beneath oceanic crust on the overriding plate, produced magma, and fueled an arc-shaped chain of volcanoes. This volcanic arc existed in the late Precambrian-early Paleozoic along most of the eastern margin of the ancient North American continent (Figure 15 A). In Delaware, there is some evidence in the Wilmington Complex to suggest that the overriding oceanic plate included a small island cored by continental crust.

As convergence continued, most of the sediments deposited on the subducting plate were scraped off to form a thick pile of deformed and metamorphosed rocks. In Delaware this accreted pile of sediments became the Wissahickon Formation. The many amphibolite layers in the Wissahickon suggest that these sediments may have been mixed with ash falls, basalt flows from the volcanoes, or slivers of underlying oceanic crust that were broken off during scraping (Figure 15 B).

Eventually, continued convergence dragged the ancient North American continent into the subduction zone where it collided with the volcanic arc and pushed up a gigantic mountain range (Figure 15 C). The creation of this range signified the end of the Taconic orogeny along the Appalachians. Today the once lofty mountains have eroded away leaving their roots exposed in the rolling hills of Delaware's Piedmont. The intense metamorphism that occurred when the root zone was deeply buried in the base of the mountain range has obscured most of the rocks' original features; however, careful study has recognized a series of rock units that represents the ancient continental margin. The amphibolites and "blue rocks" of the Wilmington Complex were formerly a volcanic island that existed seaward of the ancient North American continent about 500 million years ago. The gneisses of the Wissahickon Formation represent sediments deposited in a deep ocean basin between the volcanic island and the continental shelf. The pure white crystalline marble of the Cockeysville Marble is the metamorphosed equivalent of a carbonate bank or reef that formed just off the ancient shoreline. The impure quartzites of the Setters Formation were certainly dirty beach sands, and the Baltimore Gneiss that forms the basement under the Setters and Cockeysville

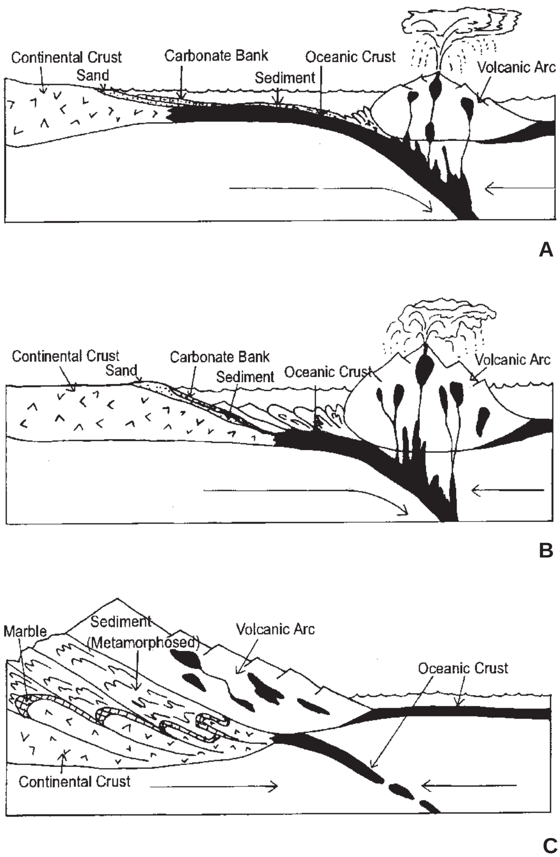


Figure 15. Cross sections of eastern North America as it may have looked (from top to bottom):

(A) 543 million years ago, active volcano is offshore;

(B) 500 million years ago, volcano and pile of sediments scraped off the subducting slab are larger than in (A); and

(C) 440 million years ago, collision between the volcanic islands and the ancient continent has formed a tall mountain range.

formations is billion-year-old rock, assumed to be a remnant of the ancient North American continent (Figure 15 A, B, and C).

The rocks in the Delaware hills are still eroding; their surfaces are fractured, broken, and covered with moss and lichen. As the rocks disintegrate, small pieces wash into the creeks and rivers to begin a journey that may take them to the Atlantic Ocean where they will be buried on the continental margin. Millions of years from now subduction may begin again off Delaware's shore, and these sediments will be caught in another cycle of mountain building and erosion.

A Guide to the Rocks along the Tracks

■ Before We Begin

The Wilmington and Western Railroad follows the Red Clay Creek as it winds its way through the rolling hills of northern Delaware. The Red Clay Creek has flowed through these hills for many thousands of years, cutting a deep valley into the bedrock. Because of this valley, passengers on the Wilmington and Western trains can see the old deformed rocks of the Appalachian Piedmont. This guide describes the rocks that can be seen from the train and recounts the geological events that occurred hundreds of millions of years ago as subducting tectonic plates and volcanic activity shaped them. Reviewing the two previous sections, “Basic Facts About Rocks” and “Reading the Rocks: A History of the Delaware Piedmont,” before riding the train will make the trip more interesting.

The geology adventure on the Wilmington and Western Railroad begins at Greenbank Station in the gently rolling hills of northern New Castle County. These hills are a part of the foothills of the Appalachian Piedmont Province (Figure 10). Piedmont means foothills, hence these hills are a part of the foothills of the Appalachian Mountains which lie to the west. The rocks exposed in the Delaware Piedmont are metamorphic and igneous rocks that are approximately half a billion to 1.2 billion years old. They have an interesting story to tell of the collision between the ancient North American continent and offshore volcanoes, the upheaval of an enormous mountain range, prolonged erosion, and the deposition of sediments onto the continental shelf as the mountains became hills.

Southeast of the station there is a distinct drop in the land surface, as the foothills give way to the flat land of the Atlantic Coastal Plain. The Coastal Plain is composed of a thick pile of clay, silt, sand, and gravel eroded from the Appalachian Mountains. At Delaware’s coast, these sediments are all younger than about 150 million years. Near the Fall Line, the Coastal Plain rocks are younger than 100 million years. The rock record between the formation of the Piedmont and Coastal Plain rocks is missing. Any rocks formed during this more than 300 million-year interval have been removed by erosion.

The interface between the Piedmont and the Coastal Plain is called the Fall Line. Delaware's Fall Line trends northeast across the state and roughly follows Kirkwood Highway. It is but a small part of a continuous zone that extends from Georgia to New York and marks the contact between the hard metamorphic rocks of the Appalachian Piedmont and the soft sediments of the Atlantic Coastal Plain. Although the Fall Line marks their eastern exposed limit, the Piedmont rocks extend underneath and are buried by the sediments of the Coastal Plain.

Delaware's history has been profoundly influenced by these two provinces, the interface between them, and the underlying rocks that they expose. Our train ride originates near the Fall Line and traverses the Piedmont. We hope you will be interested in the various rocks exposed along the track, but we also encourage you to note how the shape of the land has affected the way we work, live, and play in the Red Clay Valley.

The block diagram in Figure 16 shows the Red Clay Creek flowing across the Piedmont onto the Coastal Plain. If you were able to cut a slice through the Red Clay valley, we think you would see the rocks stacked and folded as in the block diagram. Sediments of the Coastal Plain are shown overlapping a southeast dipping stack of Piedmont rocks including, from top to bottom:

(A) the *Wilmington Complex*, an assortment of metamorphic and igneous rocks that are the remains of a once active volcanic system,

(B) the *Wissahickon Formation*, intensely deformed gneisses and amphibolites that were, many years ago, deposited as sediments in a deep ocean that existed between the volcanos and the ancient continental margin,

(C) the *Cockeysville Marble*, a dolomitic marble, that was originally a shallow water carbonate (limestone) reef or bank composed primarily of shells, skeletal remains, and precipitates that formed on the ancient continental shelf,

(D) the *Baltimore Gneiss*, a billion-year-old rock unit that was the eastern part of the ancient North American continent.

These are the rocks that we will see along the track of the Wilmington and Western Railroad. It is important to note that the interesting features of these rocks, such as the mineralogy, folding, and layering, formed hundreds of millions of years ago.

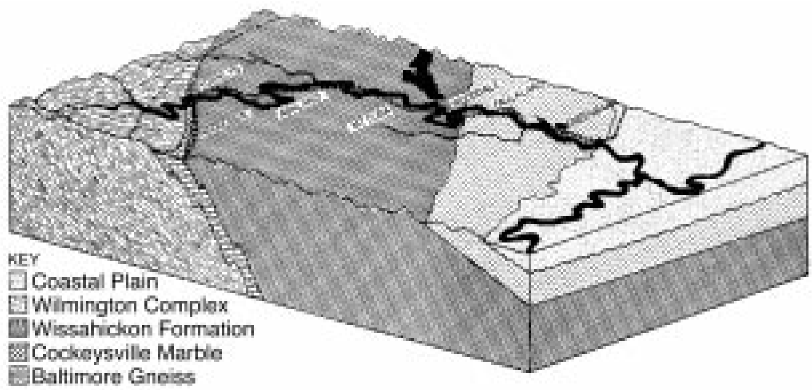


Figure 16. Block diagram showing the Red Clay Creek as it flows across the various rock formations of the Delaware Piedmont.

Referring to the block diagram (Figure 16) during the train ride will help you to identify the geologic units and to understand their relationships to each other. All the outcrops described in the text are located on the map in Figure 17, and on the small maps that accompany the text.

In-depth descriptions of some interesting features that you can see along the track are inserted in boxes. It is not necessary to read the information in the boxes to understand the geology, they are included in case the trip piques your interest, and you want to know more about the rocks. Geological terms that may be unfamiliar are defined in a glossary at the end of this section.

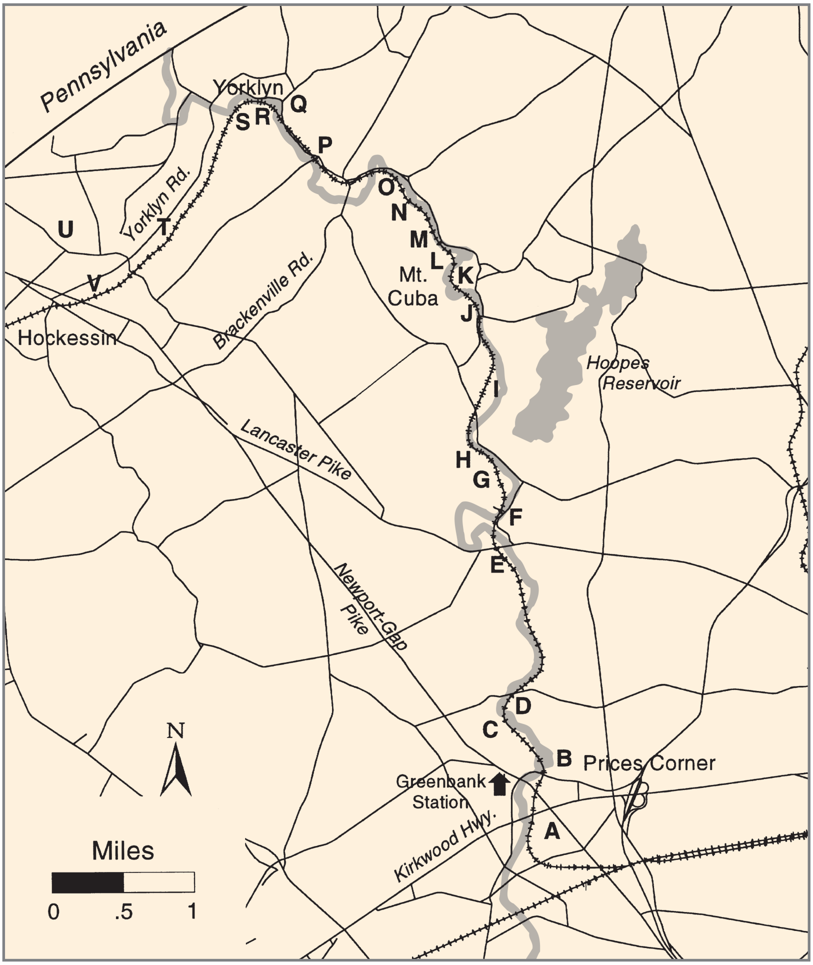
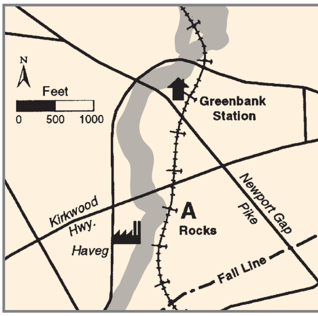


Figure 17. Index map denoting the small maps used to show the locations of the described geologic features.

See also inside back cover for a fold-out version of this map.

Caution: *With the exception of the Brandywine Spring Park and the Delaware Nature Center, all of the outcrops described in the rail log are on private property. Please do not trespass on the track, the right of way, or the adjoining privately-owned property without permission. Trespassing on any railroad is a federal offense and is prosecuted by the Federal Railroad Administration.*



A ➧ *Southeast of Greenbank Station*

South of the Greenbank Station, between the station house and the Fall Line, metamorphosed igneous rocks are exposed along the track. These rocks are not on the standard train trip, but are excellent exposures of amphibolites in the Delaware Piedmont. The rocks are broken by numerous fractures (called joints by geologists) and are round on the surface. These features are the result of expansion and weathering as the overlying rocks are removed by erosion. The round surface that forms as the outer weathered layer peels off into curved sheets is a distinguishing characteristic of the metamorphosed igneous rocks.

If you look closely at the rocks, you will see that the individual mineral grains in the rocks are large enough to be identified with the naked eye. The minerals are black, sparkling amphiboles, dull black pyroxenes, and opaque white feldspars.

Look carefully at the rock and you will see the individual grains of amphibole occur as tiny elongate prisms that are aligned with their long directions parallel to one another. The alignment of these grains indicates these rocks were squeezed (compressed) while they were soft and hot (Figure 18 A and B).

Old fractures that formed while the rocks were buried are now filled with white quartz. These quartz-filled fractures are either folded into tight folds or stretched into thin veins (Figure 19). The folds and veins also indicate compression in soft rocks.

"Bright eyes," which are small black grains of magnetite surrounded by halos of white feldspar, are sprinkled throughout the

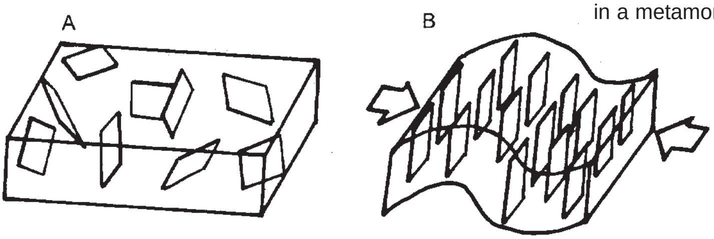


Figure 18.

(A) Random arrangement of mineral grains as they occur in igneous rocks.

(B) Mineral grains aligned by compression in a metamorphic rock.

Photo credit: Frank McRight

Figure 19. Rounded boulder with quartz-filled fractures.

outcrop. This texture frequently occurs in rocks metamorphosed at high temperatures and moderate pressures.

These amphibolites were once igneous rocks, possibly ash falls, lava flows, or intrusive dikes or sills, that formed in an active volcano (Figure 7). Any original igneous textures that formed in these rocks have been erased. What we see today, the mineralogy, the arrangement of the amphibole grains, the thin folded quartz veins, and the “bright eyes,” are due to intense metamorphism and compression generated by the collision of tectonic plates many millions of years ago (Figure 8).

B ➧ *Workhouse Quarry at Greenbank*

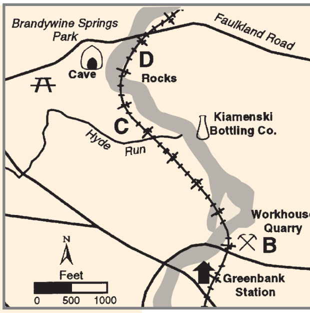
North of Greenbank Road, there is an overgrown parking lot that is bounded on its northeast side by the remains of the old Workhouse Quarry. Years ago convicts were brought down the hill from the New Castle County Workhouse and forced to work in this quarry. We have no doubt these prisoners were sentenced to hard labor, because our energetic blows with a five-pound sledge hammer only bounce off these hard rocks.

These rocks are gneisses and amphibolites assigned to the Wilmington Complex.

C ➧ *Red Clay Creek & Brandywine Springs Park*

In Brandywine Springs Park, you will notice there are many large round boulders in the stream bed and along the banks. These boulders are gneisses and amphibolites, and if you could see them up close, you would find that many of them are spotted with large olive-green grains of pyroxene, a mineral commonly found in igneous and high-grade metamorphic rocks.

The hills that enclose both the Red Clay Creek and its tributary Hyde Run are riddled with fresh water springs. The springs occur at the contacts between rock units and are probably abun-



Wilmington Complex (Volcanic Arc) Rocks

The minerals in the rocks are various assemblages of pyroxene, quartz, feldspar, and amphibole. These minerals suggest to geologists that the gneisses were deeply buried and heated to temperatures in excess of 1,600°F. Recrystallization of the original minerals is complete and there is little evidence to indicate what these rocks were before they were metamorphosed. These rocks are among the most intensely metamorphosed in the entire Appalachian Range.

In the back of the quarry, wedged between layers of a pyroxene-bearing amphibolite is a six-foot layer of crinkle-folded schist. This rock was most likely a sedimentary (muddy) layer that was incorporated into the igneous rocks, and later metamorphosed to a schist. Although the schist is crinkle folded and the black amphibolites are gently folded, the folds are parallel suggesting that two units were folded together.

dant here because of the interlayering of rock units (gneisses, schists, amphibolites, and pegmatites) in these hills. Early in this century the Kiamensi Bottling Company bottled and sold fresh spring water from these springs. The most famous spring located in Brandywine Springs Park spewed brown water charged with iron. Renowned in the nineteenth century for its health restoring qualities, this spring attracted the very wealthy from Philadelphia and Baltimore. A grand hotel was built on the hill above Hyde Run to house the guests, who walked twice each day to the spring to drink the foul tasting water. After a disastrous fire destroyed the hotel, enthusiasm for the spa waned. In 1886 the area was restored as an amusement park, complete with rides, picnic areas, and a trolley. Today Brandywine Springs is still a park operated by New Castle County, but without the attraction of mineral springs or amusements.

Within the park, mineral collectors have found large boulders of sillimanite (Figure 20). Sillimanite is a common mineral in highly metamorphosed rocks, but its occurrence as large boulders of

Figure 20. Boulder of sillimanite from Brandywine Springs Park. Bundles of coarse fibers are clustered together to form this boulder.

coarse fibrous crystals is extremely rare. Because of these unusual boulders, sillimanite was chosen by Delaware's General Assembly as the state mineral.

The Delaware State Mineral

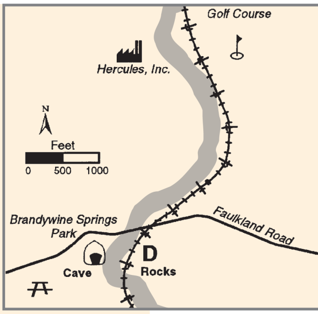
Sillimanite (Al_2SiO_5) was named for Benjamin Silliman, the founder of Yale University's geology department. It is a common mineral in aluminum-rich rocks that have been buried and heated to temperatures greater than 1,100°F. The metamorphic event that produced the sillimanite at Brandywine Springs occurred hundreds of millions of years ago during an early phase of mountain building in the Appalachian Range.

The boulders of sillimanite may have formed in the schists near the contact with the pyroxene-bearing gneisses, but no one has found a boulder of sillimanite imbedded in bedrock, so we are not sure precisely how or where these boulders formed at Brandywine Springs.

D ➧ *South of Faulkland Road*

Along the track of the Wilmington and Western Railroad, between the trestle and Faulkland Road, are some good exposures of a massive garnet-bearing quartzite. The quartzite is easy to recognize because it always has a rounded surface, and if you hit it with a sledge hammer, it will ring, just as annealed metal or fine crystal will ring. At the northern end of the outcrop, a light-colored, crinkle-folded layer of mica schist lies on top of the quartzite. This interlayering is typical of this area.

The Cave



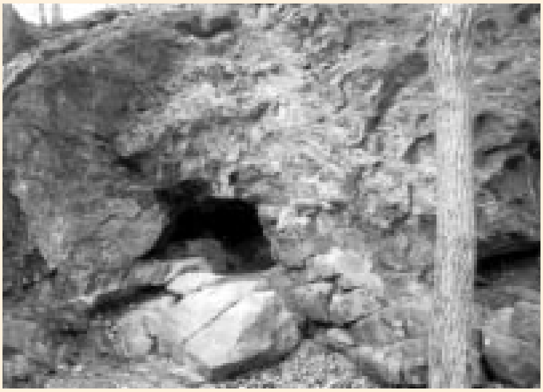
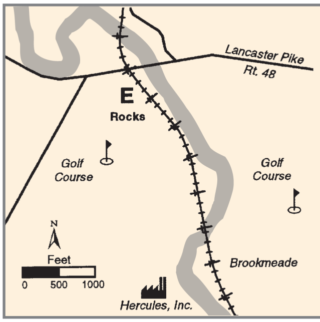


Figure 21. Picture of the "cave" at Brandywine Springs Park. A micaceous schist overlies a thick layer of garnet and pyroxene bearing quartzite. Folds in the yellow-weathering schist are sharp and crinkled, while in the solid massive quartzite the folds are gentle.

Approximately 100 yards east of the tracks is one of the largest outcrops in the state. Here along the hillside, a thick layer of crinkle-folded, yellow-weathering schist overlies a layer of garnet-bearing quartzite and amphibolite. At the contact between the quartzite and the schist, the mica schists are eroded to form a small cave (Figure 21). Maybe Indians used this cave, but it is not very inviting. If you hit the black rocks with a hammer they will ring. Look for the tiny lavender garnets in the quartzite.

E ➧ *Hercules Golf Course*



Along the track next to the Hercules Golf Course are some good (for Delaware) exposures of bedrock. The rocks are a jumble of black amphibolite, gneiss, and schist (Figure 22). In the center of the outcrop there is the trace of a fault delineated by a milky-white quartz vein. This assemblage of rock units probably represents a mixture of igneous and sedimentary

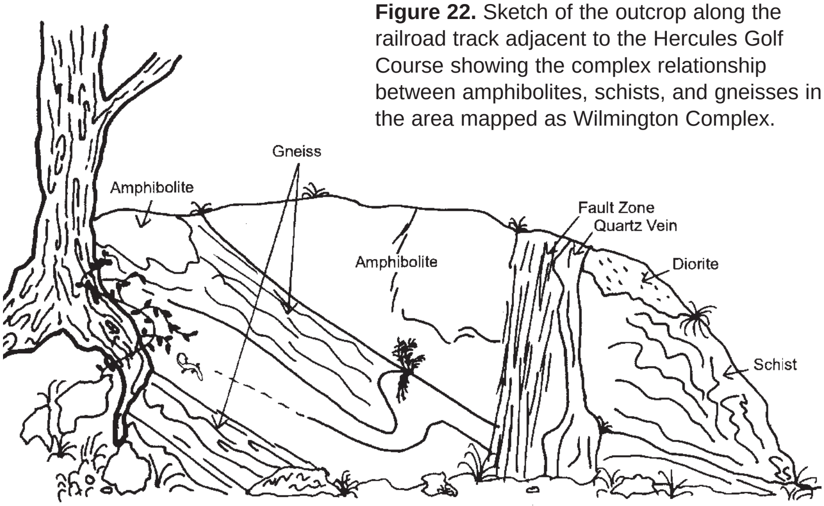


Figure 22. Sketch of the outcrop along the railroad track adjacent to the Hercules Golf Course showing the complex relationship between amphibolites, schists, and gneisses in the area mapped as Wilmington Complex.

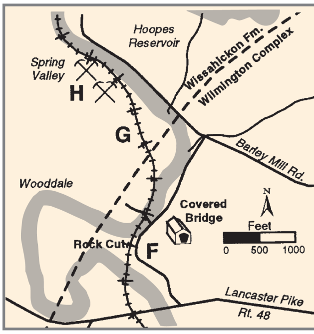
rocks formed within a volcanic arc. The strong metamorphic overprinting in all of these units makes them extremely difficult to interpret.

Amphibolites and Other Amphibole-bearing Rocks

In this outcrop there are three rock types that contain amphiboles. Type I is an extremely coarse-grained, monomineralic rock that consists solely of black amphibole (hornblende). These monomineralic rocks are exposed along the track as float, but nearby at the Hercules pilot plant, they occur as bedrock. Type II, a true amphibolite, is composed of almost equal amounts of two minerals, amphibole and feldspar. Type III has the composition of a quartz diorite, and consists of amphibole and/or black mica with up to 75 % feldspar and quartz.

F ➧ *Rock Cut at Wooddale*

At Wooddale the Red Clay Creek takes a sharp turn westward and loops around a small hill. During the construction of the railroad, the engineers elected to blast through the hill rather than follow the loop of the creek, thus providing another “window” into rocks of the Piedmont. The rock in the cut is light-gray,



because it contains mostly quartz and feldspar with lesser amounts of amphibole and black mica. This association of minerals suggests these rocks were once quartz diorites, intrusive igneous rocks that are common in mountain ranges. These gray rocks contain pods and stringers of black amphibolite (Figure 23). Deformation has orientated the pods and stringers into parallelism with one another and with the overall northeast-southwest trend of Delaware Piedmont.

The most notable feature in the cut is the trace of a brittle fault that extends up the west wall. The rocks within the fault zone have been ground-up and some of the minerals altered to vermiculite, a gold-colored mica. Along the fault, rocks slid past each other to produce a smooth polished and striated surface called a slickenside. This fault can be recognized by its smooth surface and by the many grains of shiny gold mica lying along the trace of the fault (Figure 24). We do not know when this fault was active, but because it formed in brittle rocks, we know it formed when the rocks were cold, probably sometime within the last one hundred million years.

Figure 23. Wooddale railroad cut, diorite with (darker) pods and stringers of amphibolite.

Figure 24. Wooddale railroad cut, steep fault surface on the west wall of the cut.

Layering in the Wissahickon Formation

Wissahickon rocks always show two types of layering that are parallel to each other: (1) a gross layering between the rock units (e. g., between the gneisses and amphibolites) and (2) a fine light-dark compositional layering within each rock unit (Figure 25 A and B). The gross layering is presumed to be parallel to the original sedimentary beds, and the fine compositional layering is thought to be a result of a process called metamorphic differentiation. During metamorphic differentiation the light minerals, quartz and feldspar, migrate to form a light layer, while the dark minerals, garnet, biotite and sillimanite, form a dark layer. Thus the overall composition of the rock remains the same, but the individual bands have strongly contrasting compositions that are completely different from the original rock.

Figure 25. Layering in the Wissahickon Formation:

(A) Gross layering between black amphibolite and light-colored gneiss.

(B) Fine compositional layering in the gneiss, Wooddale Quarry; note the cross cutting pegmatite pods.

G ➧ *Wissahickon Formation at Wooddale*

North of the second trestle at Wooddale, is the contact between the rocks of the Wilmington Complex (volcanic arc) and the Wissahickon Formation (deep ocean sediments). The gently rolling hills of the eastern Piedmont will give way to the steep slopes and deeply incised valleys that are characteristic of the Wissahickon Formation. All the rocks you will see along the track are intensely folded, highly metamorphosed, originally sedimentary rocks that are mixed with thin layers of amphibolite and pegmatites. Wissahickon rocks are layered, sharply folded, and usually exposed as jagged, angular rocks.

H ➧ *Quarries at Wooddale*

The old quarries at Wooddale were operated in the early years of the twentieth century to supply ballast stone for the B&O Railroad system, which owned the Wilmington & Western between 1882 and 1982. If the leaves are off the trees, you can see the back wall of the quarry where the vertical layering and upright folds typical of the Wissahickon Formation are spectacularly displayed (Figure 26). The light layers are large masses of granitic pegmatite that have flowed between the layers of gneiss and amphibolite.

Photo credit: Frank McRight

Figure 26. Upright folds in amphibolite on the back wall of Wooddale Quarry. Light rock on the left of the fold is a granitic pegmatite.

Migmatites

The Wissahickon rocks exposed in the Wooddale Quarry are a mixture of igneous rocks (pegmatites) and metamorphic rocks (gneisses and amphibolites) that are called migmatites. Migmatites actually bridge the gap between true igneous rocks and ultra-metamorphic rocks and are the result of heating rocks to temperatures near their melting points. At these temperatures some of the quartz and feldspar in the rock will melt, form a magma, and flow upward through weak zones in the rocks. This leaves behind a residue of unmelted minerals, primarily black mica, sillimanite, and garnet. During metamorphism, when these rocks were deeply buried and heated to temperatures above 1,300°F, much of the quartz and feldspar melted. The melted fraction then migrated along the layering and collected. It slowly cooled and solidified to form the migmatite exposed in this quarry.

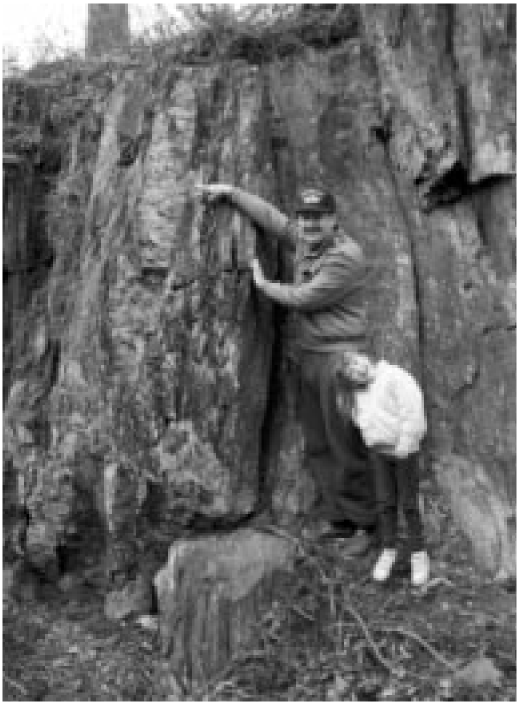
I ➧ *Red Clay Creek Flood Plain*

North of the Wooddale quarries and the development of Spring Valley, is a broad flood plain filled with modern sediments. The sediments are a mixture of clay, fine sand, and tiny flakes of mica that were deposited on the flood plain each time the Red Clay Creek flooded. If you look at the sediments through a magnifying glass, you can see the grains are tiny and angular. Angular grains suggest to geologists that the source of the sediments is nearby, and that the grains have not been rolled or transported very far by a stream. The source of these sediments is most likely the weathered Wissahickon rocks of the Red Clay watershed.

Because a much larger stream is necessary to produce a flood plain of this size, the Red Clay Creek is considered an “underfit” stream. It is too small to have enlarged this valley, or even to have meandered across its flood plain. Sometime in its geological past the Red Clay Creek was a much larger stream.

J ➧ *Mount Cuba*

Along the tracks at Mount Cuba there are several outcrops of Wissahickon gneisses. The gneisses are fractured and broken into blocks. The fractures are considered joints rather than faults



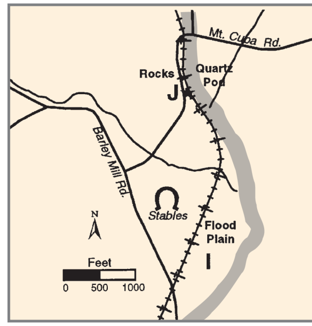


Figure 27. Large quartz pod in gneiss along railroad track at Mount Cuba.

because there has been no movement along the fractures. Joints are a common feature of buried rocks that have been uplifted and eroded. Erosion of the overlying rock releases the confining pressure and allows the rocks to relax, expand, and fracture.

If you "look through" the jointing and weathering, you will see a fine gneissic layering that is slightly tilted to the southeast. Additionally there are large quartz pods and numerous veins of granitic pegmatites (Figure 27).

Quartz Pods in Metasedimentary Rocks

Pods and veins of "bull quartz" are common within the Wissahickon rocks (Figure 27). They probably represent channels for hot fluids that escaped during metamorphism. The process of metamorphism in sedimentary rocks is generally accompanied by dehydration and the production of superheated fluids. These superheated fluids are usually saturated with dissolved silica, and as they seep upward through fractures in the rocks, they cool and fill the fractures with "bull quartz."

K ➧ *Mount Cuba Picnic Grove*

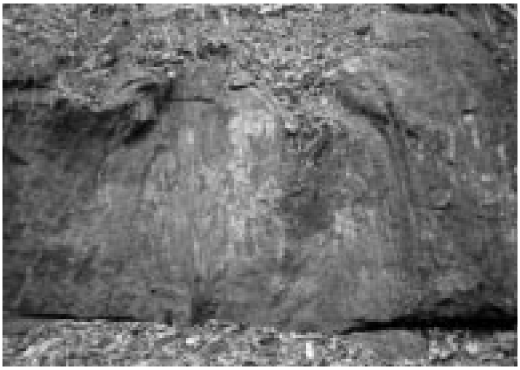


Figure 28. Upright folds in gneiss at Mount Cuba picnic grove.

The rest stop at the Mount Cuba Picnic Grove provides an opportunity to look closely at the gneisses and amphibolites of the Wissahickon Formation. The large boulders of gneiss lying beside the steps are peppered with dark-red garnets and elongated nodules of dull-white sillimanite. These sillimanite nodules (1/4 in. to 3/4 in. in length) are abundant in the gneisses at Mount Cuba and are an interesting feature of highly metamorphosed sedimentary rocks in many parts of the world.

Alternating layers of gneisses and amphibolites crop out on the east side of the track. Much of the amphibolite layer is covered with soil (weathered rock), but the gneisses are better exposed and show some typical upright folds and fractures (Figure 28). Contacts between the layers trend northeast, parallel to the regional trend of the Appalachians.

Across the creek from the picnic grove are several old quarries. The rock exposed in the quarries is a typical Wissahickon gneiss. It is similar to the rock in the Wooddale quarries, and was also used for railroad ballast.

Folds

The folds preserved in the gneisses along the track are upright with rounded crests, sharp troughs and axes that plunge steeply northeast. These folds suggest horizontal compression in ductile rocks; therefore, folding must have occurred when the rocks were still hot and buried. Geologists recognize that small scale folds commonly mimic large scale folds; thus these folds at Mount Cuba mimic the large regional folds that have folded the rock units.

L ➧ *Rock Cut at Mount Cuba*

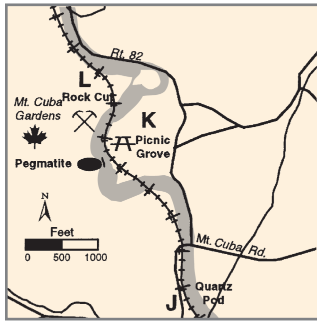


Figure 29. Folds in amphibolite at north end of Mount Cuba railroad cut.

The Mount Cuba railroad cut is narrow and deep, and much of the rock is covered with dirt and soot from the train. The rocks are interlayered gneisses and amphibolites, with gneisses predominating in the south end of the cut and amphibolites in the north end. Folding here is well developed, but the angle of the sunlight as it shines on the walls of the cut will determine which of the folds will be the easiest to see (Figure 29). Wonderful examples of the effects of rock type on folding styles can be seen in the cut and in many of the rocks piled north of the cut (Figure 30).

Figure 30. Rock illustrating the effect of rock type on folding style. Weak layer at top of rock responds to compressive stress by intense folding. Stronger layer in center of rock responds by thickening.

Granitic Pegmatites

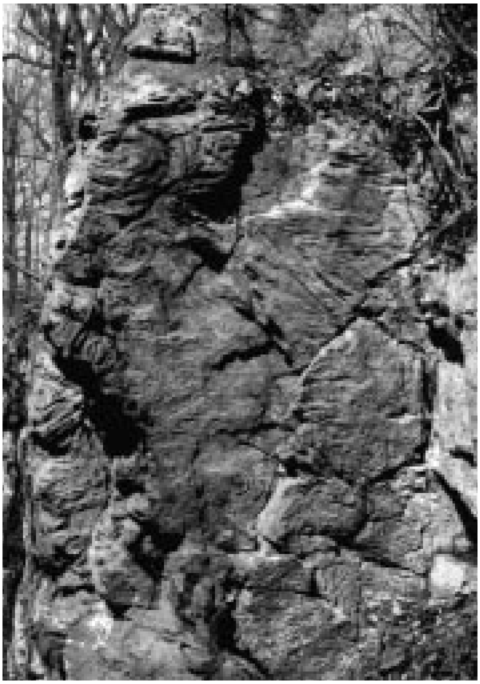
South of the quarries (see **K**–Mount Cuba Picnic Grove) is an unusually large vein of coarse-grained granitic pegmatite that is composed of pink and white feldspar, quartz, and black mica. It most likely crystallized from a water-rich magma that formed by partial melting of either local rock or rock at depth. Some of the rarer elements such as lithium, beryllium, uranium, and lead will preferentially concentrate in these partial melts, and as the melts crystallize, these elements may combine with other common elements to form rare, gem-quality minerals that are coveted by rock-hounds and serious mineral collectors. Black tourmaline, light green beryl, and large almandine garnets are the interesting minerals that have been collected from this pegmatite.

Folding vs. Rock Type

The rocks in this railroad cut (see **L**–Rock Cut at Mount Cuba) illustrate how rocks of different strength can be compressed into folds of very different styles. Experiments to study the effects of compression on rocks of varying strengths show that the strongest, hardest rocks respond to compression by thickening and gentle folding, whereas the weakest, softest rocks respond by thinning and crinkle folding. The weak layers give the impression that they have been subjected to more compression than the stronger rocks, but in reality they have all been subjected to the same stresses. In the Wissahickon, the strongest rocks are the amphibolites. They will compress to form large rounded folds. The weakest rocks are mica-rich gneisses that when squeezed will crinkle into small folds. Intermediate in strength are quartz-rich gneisses that will compress into folds with rounded crests and sharp troughs.

M ➧ *Steep Valley North of Rock Cut*

North of the Mt. Cuba Railroad cut the terrain becomes even more rugged. The track crosses a deep narrow valley with ridges of gneiss on both sides. The trend of this valley parallels that of the Appalachians, locally 45° to the northeast, and crosses the Red Clay Creek undisturbed. Here it seems reasonable to assume that the shape of the valley is controlled by the shape of the folds in the bedrock.



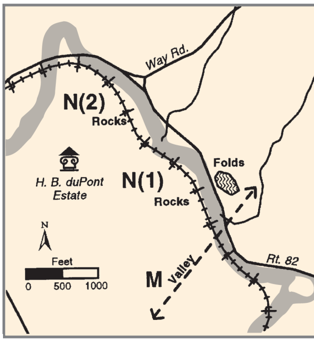
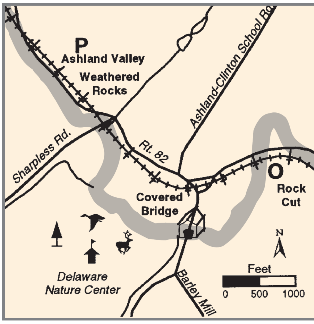


Figure 31. Recumbent folds in Wissahickon gneiss, Route 82.

N ➧ *Henry B. du Pont Estate*

(1) The small weathered outcrops on the west side of the track show an unusual variation in folding style. These folds have the familiar sharp crests and rounded troughs, but they are overturned rather than upright. For students interested in this folding style, it is beautifully displayed across the creek in a layered rock on Route 82 (Figure 31).

(2) A short distance down the track from these folded rocks is an enormous pile of boulders. These boulders are not "in place;" that is to say none of them formed in their present location. At one time these boulders probably supported a high ridge, but during construction of the track, rock was needed to shore-up the railroad bed, so the entire hillside was blasted to provide ballast for the railroad. The boulders in the pile are all folded gneisses.



O ➧ *Small Rock Cut at Ashland*

The creek bends sharply before it enters the valley at Ashland. At the bend there was not enough room between the creek and the hill for both a road and a railroad track, so again the builders of the railroad blasted the hillside, thereby exposing another "window" into some typical quartz gneisses. Many school children from the Delaware Nature Center have been introduced to metamorphic rocks in this railroad cut. The white marks on the rock face are caused by energetic students wielding rock hammers in order to experience first hand the strength of the gneisses, and to obtain fresh samples to use in identifying the minerals that make up the gneisses; black mica, glassy quartz, dull white feldspar, wispy sillimanite, and tiny red garnets.

P ➧ *Ashland Valley*

The topography changes as the train crosses a long trestle and enters a broad valley at Ashland. This valley is a flood plain that formed many years ago as a much larger Red Clay Creek meandered back and forth eroding a thick layer of mica-rich gneiss. Today's Red Clay Creek is an underfit stream; one that is too small to produce a valley of this size.

The gneiss is exposed along the track about midway though the valley in a highly weathered, decaying outcrop that is covered with gray-green fungus. Bits and pieces of rock, most of them so soft they will crumble in your fingers, lie all around the track. When freshly exposed, the gneiss is dark gray and glitters in the sunlight, but here where it is weathered, it is discolored to a dull rusty orange.

Q ➧ *Sharpless Road and Route 82*

The Ashland valley narrows abruptly at Sharpless Road as the bedrock changes from soft mica-rich gneiss to quartz-rich gneiss and amphibolite. Good outcrops along this narrow corridor display rocks that are prominently layered and tipped to the southeast at an angle of approximately 60° (Figure 32).

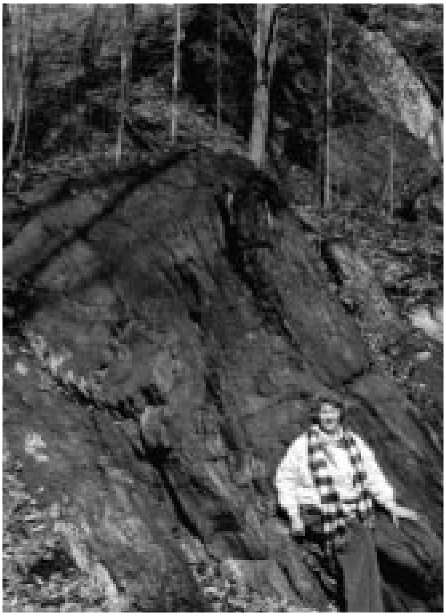
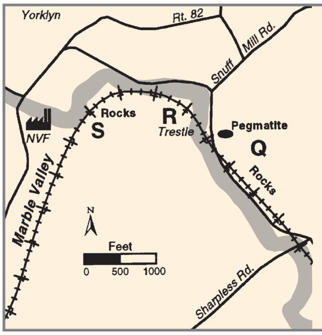


Figure 32. Outcrop along track and Route 82 north of Sharpless Road. Layers are tilted at 60° to the southeast.

Next to the intersection of the track and Route 82, there is a large outcrop partially covered with cool green moss. The moss grows where a fresh water spring flows out of the rock along a contact between a gneiss and a pegmatite. Such springs release ground water stored in the fractures to provide flow to the creek between periods of rain.



R ➧ *Wooden Trestle at Yorklyn*

The old trestle at Yorklyn is the longest wooden trestle remaining on the Wilmington and Western Railroad. From the trestle, you can look down and see the Red Clay Creek. We would like to tell you that you will see a clear stream bubbling over pristine rocks of the Wissahickon Formation, but instead you will see a murky stream flowing over rocks covered with brown sediment and algae. Unfortunately the Red Clay Creek has long been a polluted stream; however, spirited efforts in the last few years by industry and the community have vastly improved the quality of the water.

S ➧ *NVF Co., Yorklyn*

North of the trestle are several exposures of Wissahickon gneisses and amphibolites. The exposure near the NVF plant is unusual because the layering is accentuated by the presence of fault gouge between the layers (Figure 33). Fault gouge forms as movement along a fault in hard brittle rocks crushes and grinds the rocks into a powder. Gouge was a term used by miners because they could easily "gouge" it out of the rock. Here the gouge "weathered out" leaving deep indentations that emphasize the layer-

Figure 33. Rocks along the track at NVF Co., Yorklyn. Layers in gneiss and amphibolite dip 45° to the southeast.

ing and the tilt, which is to the southeast at an angle of about 45°. This angle is remarkably different from the upright layering seen in the rocks at Wooddale and Mount Cuba.

T ➧ *Cockeysville Marble*

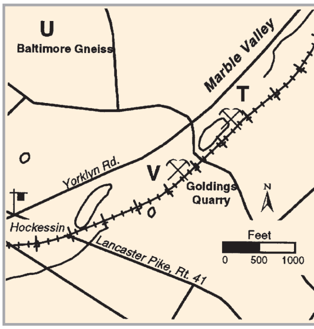
North of the track is a long, flat valley that begins at Yorklyn, extends through Hockessin, and ends abruptly along Limestone Road. This valley is underlain by the bright, blue-white marble of the Cockeysville Marble. Because the marble is easily eroded and dissolved by acidic water, it is rarely seen at the surface. Indeed, the lack of outcrop and float (loose rock) in low flat valleys is usually taken as evidence for underlying marble. Marble is dissolved by ground-water to form what hydrologists call solution channels, but what the rest of us call caves. These solution channels act as reservoirs for ground water, and, indeed, in the Hockessin area commercial wells drilled into the Cockeysville pump 1.5 to 2 million gallons of water per day. The marble aquifer is an important source of water for the residents of northern New Castle County.

Recharge of ground water to the marble is primarily from rainwater and by leakage from the steams that flow over the marble. Developers, attracted to the broad flat valleys underlain by the marble, have recently built a series of office complexes, shopping centers and high-density communities in the Yorklyn-Hockessin valley. These buildings with their asphalt driveways and parking lots restrict recharge and change the pattern of ground water flow. Alarmed by the loss of ground water, New Castle County has

Cockeysville Marble

Our knowledge of the marble comes from samples recovered while drilling wells and from the rocks exposed in abandoned quarries. The most common rock types are blue-white, coarsely crystalline, dolomitic marbles, and calc schists. The calc schists are common in the upper 250 feet of the formation, but because they are micaceous and dark gray, they are often mistaken for the mica-rich Wissahickon gneisses. The calc shists are composed of calcite and more than fifty percent silicate minerals such as quartz, feldspar, mica, and pyroxene. The thickness of the Cockeysville in Delaware has been estimated by various geologists to be between 400 and 800 feet.

recently declared the marble a resource protection area and applied land use restrictions. In some places the loss of ground water in the solution channels has caused the ground overlying the channels to collapse and form sinkholes.



Years ago the Hockessin-Yorklyn Valley and the Pleasant Hill valley were active mining districts. The marble was mined, heated in kilns, and sold to farmers for use as a soil conditioner.

U ➧ *Baltimore Gneiss*

The marble valleys occur in a northeast trending belt between Baltimore and Philadelphia. Within this belt and lying underneath the marble, are rocks identified as Baltimore Gneiss. These rocks are the oldest in the Piedmont and are the remains of the ancient North American continent. In Delaware, these ancient rocks lie immediately northwest of the Yorklyn-Hockessin Valley. Only the hills supported by these rocks can be seen north of the valley, but good exposures occur north of Yorklyn along the banks of the Red Clay Creek.

These billion-year-old rocks are a mixture of gneisses, amphibolites, pegmatites, and migmatites that have been intensely deformed and metamorphosed at least twice (Figure 34). The first metamorphism occurred approximately one billion years ago during the formation of the an ancient mountain range called the

Photo credit: Frank McRight

Figure 34. Boulder of Baltimore Gneiss unearthed during construction of Knoxland Farms, north of Yorklyn.

Grenville. The second occurred 440 million years ago during the formation of the Appalachians.

V ➧ Golding's Quarry

Between Yorklyn and Hockessin along the marble valley are several water-filled pits. At the turn of the century, kaolin was quarried from these pits. Kaolin is a fine white clay that occurs in thick seams within the Cockeysville Marble. Most of the clay was transported to Philadelphia where it was used to make fine china and porcelain; however, it has been reported that a candy shop located west of Hockessin in Southwood found the kaolin pure enough to use as a filler in their taffy.

Kaolin

Kaolin is an exceedingly common clay mineral that is formed principally by the alteration of feldspars by acidic ground water. Because feldspar is not a constituent of marble but of pegmatites, the kaolin must have formed by the alteration of pegmatites that intruded the marble.

If you have taken the Wilmington and Western train to view the geology of the Red Clay Valley, the train will stop at Hockessin and then return to Greenbank. On the return trip this guide may be followed backwards, giving passengers an opportunity to see anything they may have missed.

Glossary

Aquifer. A porous body of rock that can yield economically significant quantities of ground water.

Amphibole. A large group of dark colored, iron- and magnesium-bearing silicate minerals. Black hornblende is the most common amphibole in the Delaware Piedmont.

Amphibolite. A dark metamorphic rock composed chiefly of amphibole and feldspar.

Arc. A bow-like curve. Island arc refers to a chain of volcanic islands in an arc shape.

Ash fall. Fine particles formed as a result of an explosive volcanic eruption.

Asthenosphere. A weak layer in the mantle that occurs just below the lithosphere. The tectonic plates move on the asthenosphere.

Atlantic Coastal Plain. The lowland area that borders the Atlantic Ocean. It slopes very gently seaward.

Baltimore Gneiss. A rock unit metamorphosed one billion years ago, and again 470 to 440 million years ago. It is thought to represent the ancient North American continent (basement). Its type locality is in Baltimore, Maryland.

Basalt. A dark, fine-grained mafic, igneous rock composed chiefly of calcic feldspar and pyroxene.

Basement. The crystalline crust of the earth below sedimentary deposits.

Bedrock. The solid rock that underlies unconsolidated soils and sediments.

Brandywine Blue Granite. The name given to a metamorphic gneiss unit in the Wilmington Complex by the men who quarried it years ago.

Calcite. A common rock-forming mineral composed of calcium carbonate.

Calc-schist. A metamorphosed clay-rich limestone (dirty limestone) with schistose structure produced by the alignment of mica.

Carbonate bank. A rock mass made from minerals precipitated from sea water plus shells and skeletons of marine organisms. It probably stood above the surrounding sea floor during some of its depositional history.

Carbonate precipitate. Separated from a solution. Used here to describe the precipitation of carbonate minerals, usually calcite and dolomite, from sea water.

Chlorite. A group of platy greenish minerals. Chlorites are usually associated with and resemble micas. They usually occur in low grade metamorphic rocks.

Cockeysville Marble. A rock unit of the central Piedmont composed primarily of marble and calc schist. Its type locality is in Cockeysville, Maryland.

Compression. Stresses that act to shorten an object by squeezing it.

Convergent plate boundary. A boundary between two plates that are moving toward each other, i. e., a subduction zone.

Convection current. Circulating currents in a fluid or plastic body in which one area is uprising and another down flowing due to heat variations.

Continental margin. The region between the shoreline of a continent and the deep ocean basins. Includes the continental shelf, slope and rise.

Cretaceous Period. The final period in the Mesozoic Era, thought to cover the time span between 144 and 65 million years. The Mesozoic Era is named from the Greek word meaning middle life.

Crust. The rigid outer part of the Earth extending to a depth of 4 miles beneath the ocean and over 40 miles beneath the continents.

Deformation. Folding, faulting, and other changes in the shape of rocks in response to mechanical forces.

Diorite. An intrusive igneous rock composed of feldspar with lesser amounts of amphibole. It is sometimes described as intermediate in composition between granite and gabbro.

Dolomite. A common rock forming mineral composed of calcium and magnesium carbonate. Also the rock formed from this mineral.

Echo sounder. An instrument that determines water depth by measuring the time it takes a sonic sound signal to travel to and return from the sea floor.

Erosion. The sum of all the geologic processes that wear down the land and move it from one place to another.

Extrusive rocks. An igneous rock formed from material that has erupted onto the surface of the Earth; i. e., a lava flow.

Fall Line. The boundary between the Atlantic Coastal Plain Province and the Appalachian Piedmont Province. Marked in streams by waterfalls and rapids.

Fault. A fracture in the earth's crust in which the opposite sides have shifted past each other.

Feldspar. A large family of aluminum silicate minerals that constitute 60% of the earth's crust. They are usually white, pink, or green. Feldspars decompose to yield clays.

Float. Loose rock. Rock that is not "in place."

Fold. Rock deformed by bending or crumpling rock layers.

Formation. A mappable rock unit that is more or less homogeneous.

Fluid. Capable of flowing, either as a liquid or a gas.

Gabbro. A dark, coarsely crystalline rock composed of greenish feldspar and black pyroxene. It forms when basaltic magma cools slowly underground.

Garnet. A silicate mineral that forms distinct twelve-sided crystals. The dark red iron-rich variety is common in Wissahickon gneisses.

Glacier. A massive, long-lasting accumulation of snow and ice that forms on land.

Gouge. A thin layer of soft, rock material, called gouge because miners could "gouge" it out with a stick.

Grenville Orogeny. A major volcanic, metamorphic, and deformational event that occurred in eastern North America between 880 and 1200 million years ago.

Granite. A light coarsely crystalline rock composed of two varieties of feldspar and quartz with minor mica or amphibole. It forms when magma cools slowly underground.

Gneiss. A coarse-grained, high-grade metamorphic rock, in which there is prominent compositional banding. Gneiss is usually rich in feldspar and quartz; however, mineral composition is not an essential factor in its definition.

Ice Age. A time of extensive glacial activity when glaciers spread over the northern continents.

Igneous rock. A rock formed by crystallization from molten material either on the surface after it has erupted or at depth within the crust of the Earth.

Intrusive rock. An igneous rock formed when magma solidifies underground.

Joint. A simple fracture in the Earth's crust.

Jurassic Period. A period in the Mesozoic Era. The span of time between 201 and 144 million years ago.

Kaolin. A common clay mineral.

Lava. Magma that has erupted onto the earth's surface through a volcano or vent.

Limestone. A sedimentary rock composed chiefly of the mineral calcite (calcium carbonate).

Lithosphere. Solid outer portion of the Earth. It includes the crust and part of the upper mantle.

Magma. The natural molten liquid from which igneous rocks crystallize.

Magnetite. A black, strongly magnetic, iron oxide mineral. It is an important ore of iron.

Mantle. The zone of the Earth that occurs between the crust and the core.

Marble. Metamorphosed limestone or dolomite.

Massive. Adjective used to describe igneous or metamorphic rocks with a homogeneous texture. Massive rocks have no layering or other similar structures.

Metamorphism. The mineralogical, chemical, and structural adjustment of solid rocks to physical and chemical changes.

Metamorphic rocks. Rocks that have recrystallized under conditions of elevated temperature and/or pressure. Most of the rocks in Delaware's Piedmont are metamorphic.

Metasedimentary rocks. Rocks that were originally deposited as sedimentary rocks that have been metamorphosed.

Mica. A family of minerals with a pronounced basal cleavage. Micas may be transparent or occur in a variety of colors such as black, green, lavender, or gold. Black mica is the most abundant mica in the schists and gneisses of Delaware's Piedmont.

Migmatite. A rock composed of both igneous and metamorphic materials. Commonly it forms at very high metamorphic temperatures when the rock partially melts.

Monomineralic. A adjective used to describe a rock made up essentially of one mineral.

Orogeny. The process of mountain building.

Outcrop. A surface exposure of bedrock.

Overburden. The loose soil, silt, sand, or gravel overlying bedrock.

Paleozoic. A geologic era that lasted from the end of the Precambrian to the beginning of the Mesozoic or from 543 to about 245 million years ago. It was during this period that the Appalachian Mountains formed.

Pegmatite. A coarse-grained igneous rock, generally of granitic composition that has crystallized from a watery magma.

Piedmont. The foothills of a mountain range. The Delaware Piedmont is a part of a plateau that extends from New Jersey to Alabama and lies east of the Appalachian Mountains.

Plate tectonics. A theory that the entire crust of the Earth is broken into a small number of rigid (lithospheric) plates that constantly move on a zone of weakness within the upper mantle (asthenosphere).

Pyroxene. A large group of dark-colored silicate minerals that occur commonly in igneous and high-grade metamorphic rocks.

Quartz. A very common mineral in the Earth's crust. It comes in a variety of colors and forms but usually occurs as clear, glassy grains. Quartz is the mineral form of silica.

Quartz diorite. An intermediate intrusive igneous rock, usually containing a dark-colored amphibole, feldspar, and quartz with or without mica or pyroxene.

Radiometric age. An age expressed in years and determined by measuring radioactive isotopes and their decay products.

Rift. A deep penetrating tensional crack in the Earth's crust.

Schist. A coarse-grained metamorphic rock with strong layering due to the parallel orientation of platy minerals, such as mica or chlorite.

Sedimentary rock. Rock formed from sediment by cementation or by other processes that act at ordinary temperatures at or near the Earth's surface.

Seismic technology. Techniques used to study vibrations in the Earth, especially earthquake waves.

Serpentinite. A rock consisting almost wholly of minerals formed by the alteration of the iron- and magnesium-rich minerals, olivine and pyroxene. The rocks have a greasy feel and are usually greenish yellow.

Setters Formation. A rock unit of the central Appalachian Piedmont composed primarily of feldspar-rich quartzite. Its type section is Setters Ridge, Maryland.

Shear. Deformation in soft rock that causes one part of a rock to slide past another part.

Silica. The oxide of silicon, SiO_2.

Sillimanite. The Delaware state mineral. It occurs in wispy fibrous clumps and prisms in the metamorphic gneisses. This mineral forms only at the highest temperatures and pressures of metamorphism.

Sinkhole. A pit in the ground formed by solution and collapse of an underground cave.

Slickenside. A polished, smooth surface that results from friction along a fault plane.

Sonar. An acronym of sound navigation and ranging. A method used to study the ocean floor.

Subduction. A plate tectonic process in which one lithospheric plate descends beneath another at a converging plate boundary.

Subducting plate. A lithospheric plate that descends beneath another at a converging plate boundary.

Taconic Orogeny. One of the early mountain-building events in the series of events that built the Appalachian Mountains. It occurred in the early Paleozoic, between 470 and 440 million years ago.

Tectonic. Large scale deformation of the Earth's crust.

Tension. Stress that tends to pull a rock body apart.

Tertiary Period. A period in the Cenozoic Era. The span of time between 65 and about 2 million years ago.

Trench. A long narrow depression of the sea floor formed where a subducting plate sinks into the mantle.

Uncomformity. A gap in the geological record, usually of long duration.

Underfit stream. A stream too small to have carved the large features of the valley it occupies.

Vermiculite. A group of micaceous clay minerals derived generally from the alteration of micas in a zone of weathering.

Weathering. The physical disintegration and chemical decomposition of rock.

Wilmington Complex. A rock unit of the Delaware Piedmont composed of high-grade gneisses and igneous intrusives.

Wissahickon Formation. A rock unit of the Delaware Piedmont composed of metasedimentary gneisses, amphibolites, pegmatites, and minor serpentinites. Its type locality is along Wissahickon Creek in Philadelphia.

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Delaware Geological Survey, University of Delaware campus. Displays of local rocks,minerals, and fossils; maps and publications available on request; guided tours. The Survey is open to the public weekdays between 8:00 and 4:30.

Delaware Mineralogical Society. Meets the third Monday of each month at the Delaware Museum of Natural History, Kennett Pike, Greenville. Guests are welcome.

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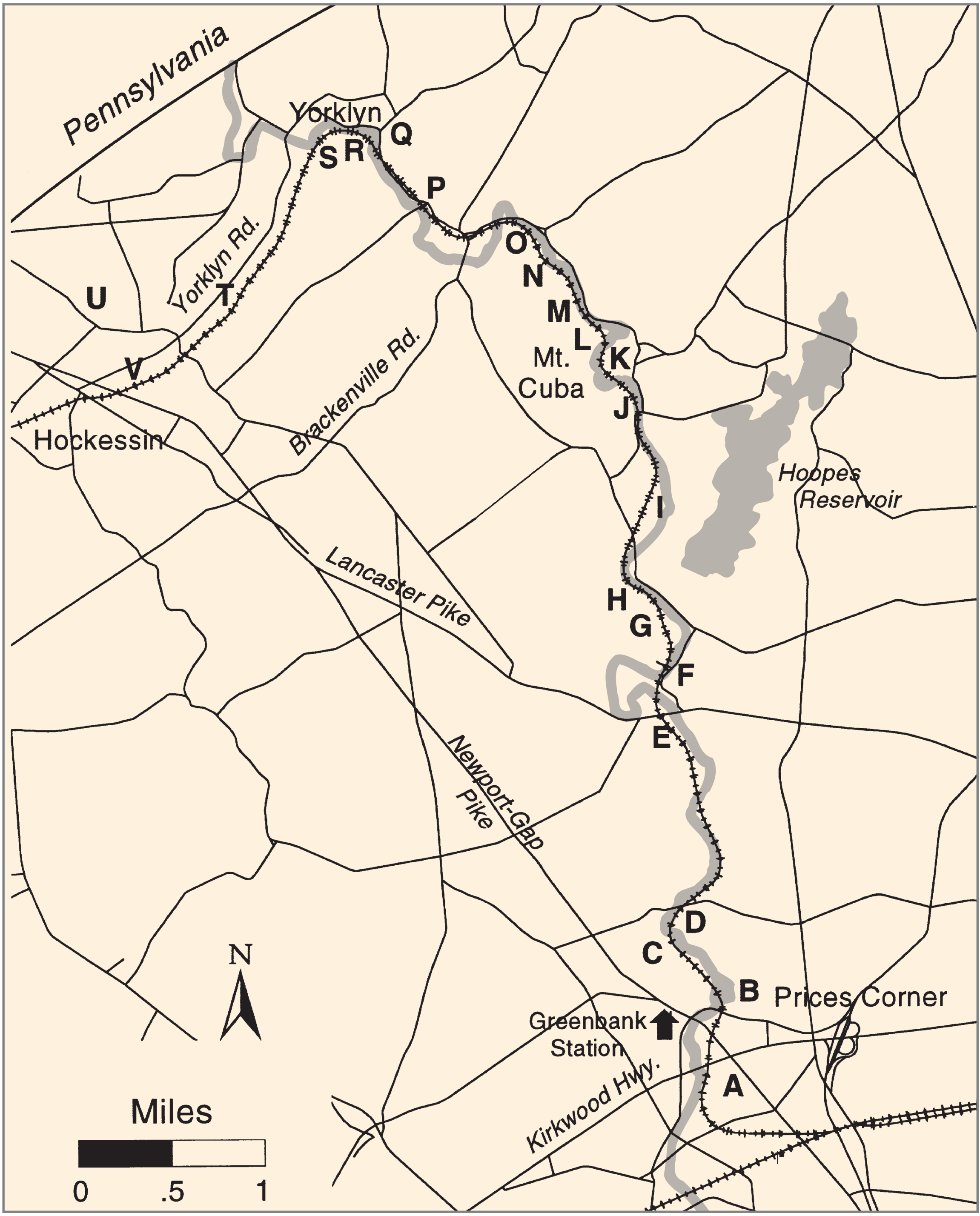
Notes

Figure 17.
Index map denoting the small maps used to show the locations of the described geologic features.

See pages 34–54 for details.

Caution: *With the exception of the Brandywine Spring Park and the Ashland Nature Center, all of the outcrops described in the rail log are on private property. Please do not trespass on the track, the right of way, or the adjoining privately-owned property without permission. Trespassing on any railroad is a federal offense and is prosectued by the Federal Railroad Administration.*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