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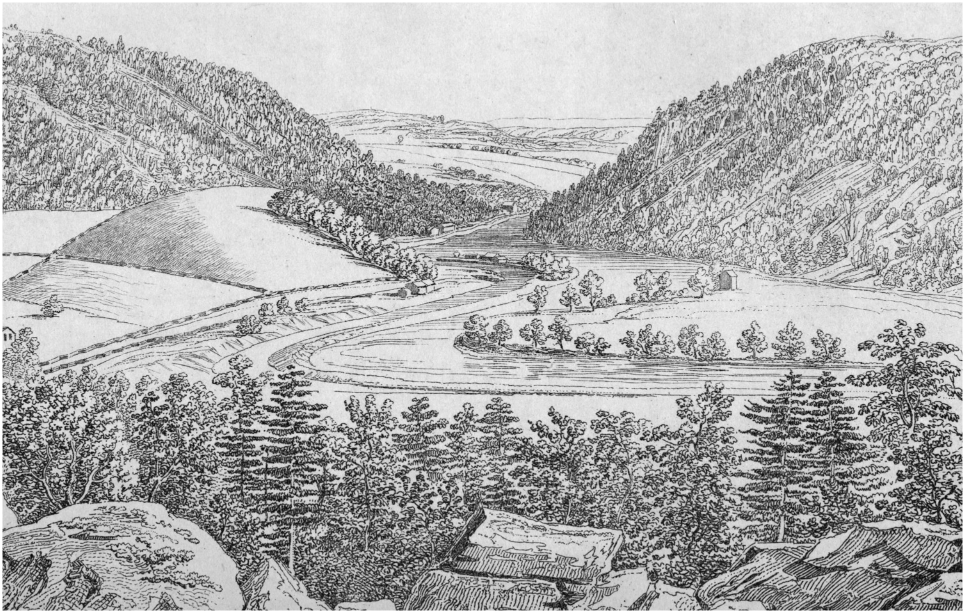

# THE GEOLOGICAL STORY OF PENNSYLVANIA

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF
CONSERVATION AND NATURAL RESOURCES
BUREAU OF GEOLOGICAL SURVEY

**COMMONWEALTH OF PENNSYLVANIA**
Josh Shapiro, Governor

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**CONSERVATION AND NATURAL RESOURCES**
Cindy Adams Dunn, Secretary

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**FRONT COVER:** Lehigh Water Gap from Stone Ridge. Illustration from Rogers, H. D., 1858, The geology of Pennsylvania—A government survey: Pennsylvania Geological Survey, 1st ser., v. 1, opposite p. 489 [Printed by William Blackwood and Sons, Edinburgh].

Educational Series 4

# The Geological Story of Pennsylvania

by John H. Barnes
and W. D. Sevon

PENNSYLVANIA GEOLOGICAL SURVEY
FOURTH SERIES
HARRISBURG

2014

When reproducing material from this publication, please cite the source as follows:

> Barnes, J. H., and Sevon, W. D., 2014, The geological story of Pennsylvania (4th ed.): Pennsylvania Geological Survey, 4th ser., Educational Series 4, 44 p.



Pennsylvania
Department of Conservation and Natural Resources
dcnr.pa.gov/about/Pages/default.aspx

Bureau of Geological Survey
dcnr.pa.gov/about/Pages/Geological-Survey.aspx

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*James H. Dolimpio, and Caron E. O'Neil*

First Edition, September 1962
Second Edition, January 1996
Third Edition, May 2002
Fourth Edition, October 2014
Second Printing, Slightly Revised, April 2016
Fourth Printing, December 2023

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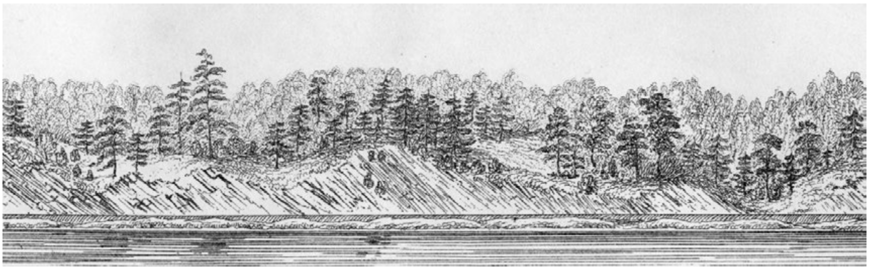
# THE GEOLOGICAL STORY OF PENNSYLVANIA

by John H. Barnes and W. D. Sevon[1]



Pennsylvania. The word can bring to mind visions of cities, mountains, and forests; lakes and rivers; fertile farmlands and rugged back country. Perhaps, too, thoughts of the coal mines and steel mills that helped forge the state's role as a leader in building America's industrial might. All of these things help define Pennsylvania and make it unique among the fifty states, and all are related to geology.

The dictionary lists two definitions of "geology." Geology is a science that deals with the study of the earth and its history. Geology is also a name given to the natural features of our planet. In this booklet, we will use the word in both senses. We will describe the natural features that are found in Pennsylvania, and we will see how the science of geology helps us to understand how those features came to be.

Just as you might use a dictionary for reference to check the spelling and definitions of words, there are tools that geologists use for reference. One of these tools, a geologic time chart, is shown on the back cover of this booklet. All scientific evidence indicates that the earth is about 4.6 billion years old. Geologists separate this time into the divisions shown on the chart and conveniently refer to the time intervals by name (for example, "Devonian Period") rather than by the range of years represented. This is similar to the way in which we group days into months and years rather than counting each day from the beginning of our lives.

[1]Retired.

Another tool is a special type of map called a geologic map. Most areas of Pennsylvania are covered by a few inches to many feet of soil. Solid rock that is found below the soil and in exposures where soil has been removed is called bedrock. Bedrock varies in composition and age, both geographically and with depth. A bedrock geologic map shows the age and type of bedrock that is closest to the surface. In the center of this booklet is a simplified geologic map of Pennsylvania. It distinguishes the main rock types found in each geologic period and where they occur in the state. It also shows the state's physiographic provinces, which are areas within which landscapes and rocks are somewhat similar.

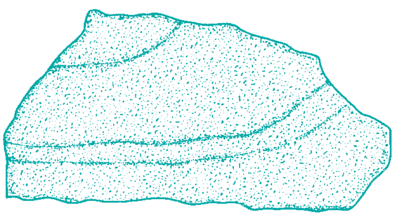
## KEEPERS OF THE GEOLOGIC RECORD

Imagine a winter's morning. The ground has a fresh white coating. No one has to tell you that snow fell overnight. You see tracks in the snow. Paw prints. A cat must have walked past after the snow stopped falling. Nearby are a person's footprints. An early riser, no doubt, but not as early as the cat. You know this because where the paths of the person and the cat crossed the cat's paw prints were destroyed by the person's footsteps.

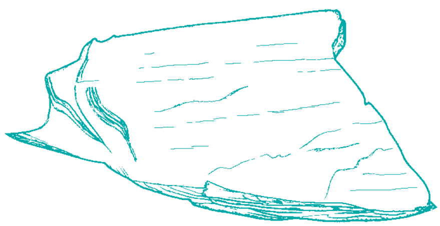
You dig through the snow and find a layer of old, dirty snow. You remember the snowfall of last week. You keep digging until you find some matted stems and leaves. This is the spot where, last spring, you planted a garden. The stems and leaves remind you of the flowers that bloomed on this spot.

The work of a geologist is much like this experience. Nature records many things in a language that we can read with a little practice. This record of events is called the geologic record. Each layer of rock is a keeper of the geologic record and has its own story to tell about how it formed and what plants and animals were present when it was forming. Structures in a layer can even tell us what geologic forces existed in the area while the rock was forming and after it was formed.

There are three major types of rocks, which are defined by the way in which they formed. In Pennsylvania, the type that we find most commonly is sedimentary rock. This includes rocks that have formed from gravel, sand, silt, or clay that has become naturally cemented together. The composition of the rocks can reveal something about how they formed. Sandstone consists of hardened layers of sand. Shale forms from layers of clay or mud. Rocks such as sandstone and shale are called clastic rocks. Other sedimentary rocks include carbonate rocks, such as limestone and dolomite, which are formed of calcium and magnesium carbonates produced by organisms in the sea. Some carbonates form huge mounds called reefs. Reefs that are hundreds of millions of years old can be found in the geologic record. There are also reefs forming today, the prime example being the Great Barrier Reef of Australia.

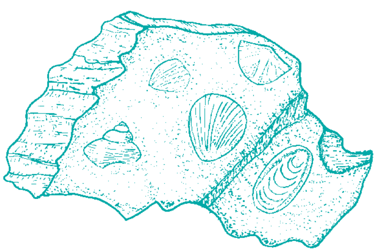


***Sandstone***



***Shale***

The accumulation of sediments is similar to a snowfall. The tracks in the snow and the remains of last summer's garden can be compared to the signs of past life that are sometimes found in rocks. Some are indirect signs, such as the footprints of animals that walked by when the sediments were accumulating. Others are more direct, such as the remains of the animals or plants themselves. Any sign of past life is called a fossil.



***Fossils in sedimentary rock***

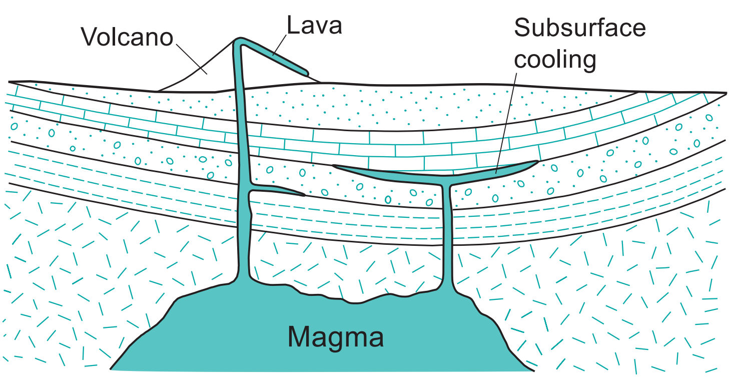
Plant and animal species very slowly evolve, or change, through time as they adapt to changes in their environment. The ones that are better able to adapt are more likely to survive and reproduce. If we compare fossils to each other and to living plants and animals, we can usually determine the relative ages of the rocks in which they are found and the conditions under which they formed.

Finding the dead plants beneath the snow told us that at some time in the past, conditions were suitable for them to grow. The fact that the plants died suggests that conditions changed rapidly as winter approached. The absence of living plants suggests, but does not prove, that those species of plants cannot live in the cold, snowy environment. But we do have proof that cats and humans can live under such conditions. We know this because we found their footprints in the snow.

**Gneiss**

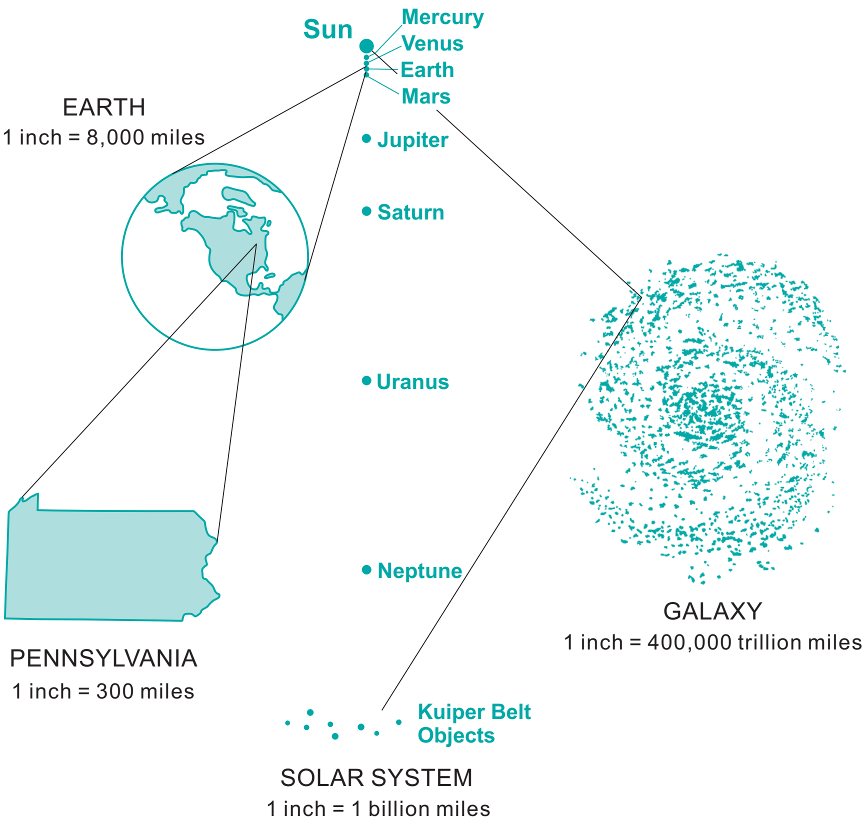
Metamorphic rocks, another of the major rock types, include the very old rocks in Pennsylvania—the ones that have seen the most history and that have the most to tell us. They can be found near the surface in the southeastern part of the state and at great depth anywhere in Pennsylvania. They are rocks that have been changed from their original forms, usually as a result of intense heat, pressure, or both. Gneiss, schist, and slate are examples of metamorphic rocks.

Igneous rocks, the third major type of rock, include rocks formed from red-hot material, called lava, that erupted from volcanoes, sometimes with explosive force. Many other igneous rocks formed quietly from magma (molten rock) that intruded existing bedrock and cooled slowly underground without ever reaching the surface. Examples include granite and diabase. Igneous rocks are found mainly in southeastern Pennsylvania, and many of the metamorphic rocks in that region of the state started out as igneous rocks.



## A DIM, DISTANT PAST

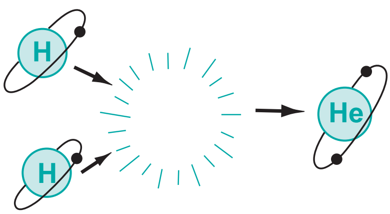
Before exploring the geologic record, let us travel back in time to a dim, distant past that even the geologic record does not reveal. The origin of Pennsylvania is tied, as it must be, to the origins of much larger things. Pennsylvania is a part of the North American continent on our planet Earth, which together with the sun, other planets, and




smaller celestial bodies make up the solar system. The sun, which dominates the solar system because of its great size, is a star. It appears so different from the stars of the night sky because it is very close to us—*only* 93 million miles away. The next nearest star, Proxima Centauri, is approximately 24.8 *trillion* miles away! Light from Proxima Centauri, traveling at 186,000 miles per second, takes 4.24 years to reach us. Light from the sun reaches us in about 8 minutes. The sun and Proxima Centauri are two of the 100 billion or more stars that form a huge spiral called the Milky Way galaxy. Our galaxy is so unimaginably enormous that a beam of light takes 100,000 years to travel across it. The universe is believed to contain a billion or more galaxies like the Milky Way!

Observations indicate that the universe is expanding. This, combined with other data, suggests that the universe came into existence about 14 billion years ago in an event called the Big Bang. In that instant, all the matter and energy that now exists in the universe began expanding outward from a single point, an expansion that continues today.

As matter spread out and cooled, hydrogen (the most abundant and simplest of the chemical elements) and minor amounts of helium and lithium formed and collected to create great rotating clouds. Within these clouds, which were to become the galaxies, smaller swirling clouds formed. Gravity caused the centers of these smaller clouds to become so dense that a reaction called nuclear fusion began to take place. Fusion converts hydrogen into the heavier element helium, giving off heat and light. These smaller clouds became the stars.



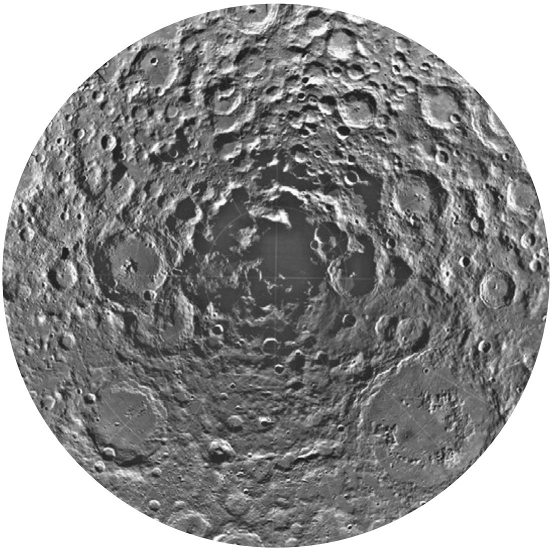

Billions of years passed between the Big Bang and the birth of our sun 4.6 billion years ago. During that time, many other stars were born and died. In many aging stars, some helium is converted into still heavier elements. Such common elements as oxygen, carbon, nitrogen, silicon, iron, calcium, and potassium were manufactured in stars in this way. At the end of their lives, some of the stars exploded, sending their elements hurtling through space. Because our sun formed after so many other stars had gone through this process, heavy elements were present in the cloud from which it formed. As the sun was forming, smaller condensations of matter formed around it. These smaller condensations became the planets, and the third one out from the sun became Earth.

When we study the geologic record to learn about the history of Earth, we find that the farther back we look, the more difficult it is to interpret the clues. This is because our planet is dynamic, having a surface that is always changing. These changes record events, but they also destroy evidence of earlier events, just as the person walking in the snow left footprints but destroyed some of the cat's paw prints. If enough people had walked by, their footprints might have destroyed all evidence that the cat had ever been there. If the day had become warm enough, the snow would have melted, and there would have been no evidence that anything had happened.

Probably the best record of what planet Earth might have been like in its earliest days can be found by studying less-active bodies in the solar system, where a record of events that took place long ago would more likely be preserved. Our moon is such a place. It is now geologically inactive. Its oldest surface areas are dominated by craters of all sizes, suggesting that it was once heavily bombarded by comets and asteroids. Relatively newer surfaces are covered by large lava flows and show much less cratering.

It is probable that Earth, too, was bombarded by comets and asteroids in its earliest days and later underwent a period of intense volcanic activity. Comets, asteroids, and volcanoes can release gases and water vapor. On the moon, the gases and vapor would have escaped the weak gravity field and drifted into space. On Earth, they remained to form the atmosphere and oceans.

The moon is now quiet, but Earth continues to change. Even the continents move! The great fun of geology is discovering the history of our planet by looking at the rocks that are all around us. They hold the clues to understanding the changes that have formed Earth as we know it today and to understanding the changes that are still taking place.



***Heavily cratered surface of the south polar region of the moon***

## THE HADEAN, ARCHEAN, AND PROTEROZOIC

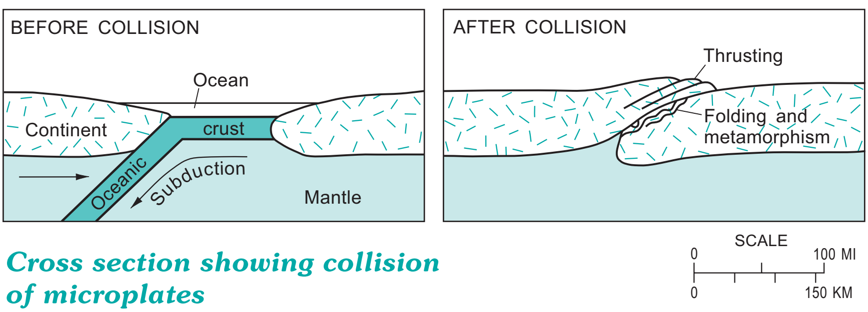
During Hadean time, which is thought to have extended from 4.6 to 4 billion years ago, the earth became zoned into contrasting concentric layers. A thin, silica-rich outer layer, the crust, floats on a thick, dense, silica-deficient partly molten layer called the mantle. Beneath that is a heavy-metal core. The outer part of the core is a very hot liquid. The inner part, at the center of the earth, is at least as hot but is a solid because of the tremendous pressure bearing down on it from the layers above.

Geologists believe that this time was marked by a heavy bombardment of the earth by comets and asteroids, known as the late heavy bombardment (LHB). This bombardment may have led to the development of continents and ocean basins. If the comets and asteroids were water-rich, as some believe, the water may have helped to later fill the ocean basins. The impacts created craters; they also increased the internal temperature of the earth because of the energy that was released upon impact. The increased temperature caused partial melting of the mantle and the generation of magma, which is molten rock. Because rocks become less dense when heated, the magma rose to the surface, and cooler, denser substances sank lower in the mantle to replace it. This exchange of hot and cold materials is a process called convection.

The magma created by the impacts eventually cooled to form small areas of igneous rock, which were probably more or less uniformly distributed around the earth. These areas of igneous rock were part of the earth's lithosphere, which includes the entire crust and the uppermost, coolest part of the mantle. The convection in the mantle caused the lithosphere to break apart into large and small segments, called plates. The plate segments moved away from areas where convection currents were rising and toward areas where the currents were descending. This plate movement continues to this day and is explained by the theory of plate tectonics. Because of plate tectonics, the positions of continents and ocean basins have been changing through time.

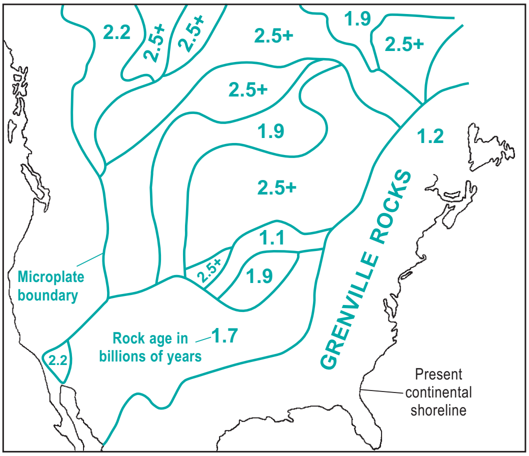
The LHB is thought to have continued at a less intense rate well into Archean time, but by the beginning of the Proterozoic, about 2.5 billion years ago, the steady bombardment had ceased. As previously stated, however, the dragging action of convection continued to move the plates, causing them to collide. The behavior of the plates when they collide is largely controlled by the type of crust on the plate. There are two main types of crust: continental crust, which is mostly composed of high-silica, low-density granitic rock, and oceanic crust, which is mostly composed of low-silica, higher density basaltic rock. The less-dense continental crust rides higher on the mantle, forming the landmasses. When two plates collide, they may be accreted, or combined, to make a larger plate, or the denser plate may be subducted, or pulled down, under the lighter plate.

The main masses, or cratons, of the continents were formed by the accretion of microplates. Even as the cratons formed, erosion began wearing away the surfaces of the land areas. The eroded sediments were transported by running water and deposited both within the land areas and at their margins. When a collision occurred, rocks and sediments at the margin of each microplate were deformed. The heat and pressure generated by such a collision was enough to alter the mineralogy of the marginal rocks and sediments to form new, metamorphic rocks.




***Cross section showing collision of microplates***

The Laurentian continental crustal block, which forms the craton of North America, is made up of many microplates that were accreted during the early Proterozic, about 2.5 to 1.0 billion years ago. By the time its formation was complete, Laurentia was part of a larger supercontinent known as Rodinia, which included all or most of the then-existing landmasses. Pennsylvania is believed to be underlain everywhere by metamorphic rocks known as Grenville rocks. These rocks represent one of the last accretions to the Laurentian block. Grenville rocks are mainly gneiss, a rock that has distinctive layering and min-




***Microplates of the Laurentian block***

eralogy. Some of these rocks can be seen at the surface in southeastern Pennsylvania, but in most of the state, they are deeply buried under younger rocks and commonly referred to as basement rocks. Note that bedrock units are usually named for places where they have been identified and described in detail. The Grenville rocks are named for a township in Ontario, Canada.

About 725 million years ago, convection in the mantle placed stress upon various parts of Rodinia and caused it to break up into several pieces, including the Laurentian block. This process, called rifting, created elongate basins parallel to the present eastern margin of North America. Sediments eroded from land to the west were carried by rivers and deposited in these basins. In addition to the eroded sediments, much of the material that filled these basins came from volcanoes and intrusions of magma. A second episode of rifting began about 570 million years ago, creating an ocean known as Iapetus to the east of North America.

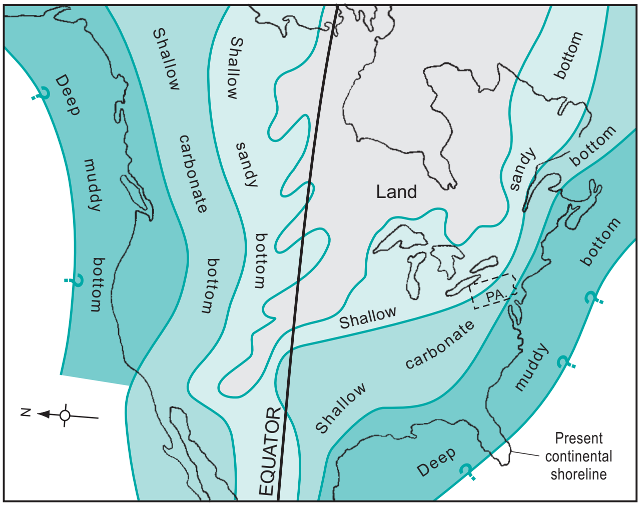
Geologic evidence shows that life first appeared during these early years of Earth's history in the Archean, approximately 3.9 billion years ago. The initial life-forms, such as bacteria, were simple, but there is uncertainty about how they originated. Studies have shown that comets and some asteroids contain complex organic molecules that, under the right conditions, could be the building blocks of primitive organisms. Life, therefore, may have been carried to our planet during the LHB. More complex forms of life, such as blue-green algae, single-celled animals, and eventually multicelled organisms, arose during the Proterozoic. The early algae were critical to the further evolution of life because they were able to take carbon dioxide out of the atmosphere and release oxygen into the atmosphere. Earth's atmosphere during the Proterozoic contained much more carbon dioxide than it does now, making it very suitable for the algae but inhospitable to other forms of life. As the amount of oxygen increased, new forms of life evolved, and by the end of the Proterozoic, about 541 million years ago, multicellular life was widespread and included such forms as mounds of algae (called stromatolites), jellyfish, and worms that lived in the sea.

## THE CAMBRIAN AND ORDOVICIAN PERIODS

At the start of the Cambrian Period, water from the Iapetus Ocean transgressed, or spread inland, across North America, covering the Proterozoic rocks of Pennsylvania with relatively shallow water and creating unique environments for the deposition of sediments and the development of life.

Much of North America remained above the sea and was eroded by running water. Clastic sediments were carried by rivers to the ocean. Sand accumulated near the shore while mud was deposited farther offshore. Carbonates were produced and deposited offshore in warm water that received little or no clastic sediments. As the shoreline moved west, the carbonate shelf moved with it, remaining under shallow water much of the time.

*Modified from Dott, R. H., Jr., and Batten, R. L., Evolution of the earth (4th ed.), ©1988, McGraw-Hill, Inc. Reproduced with permission of McGraw-Hill, Inc.*

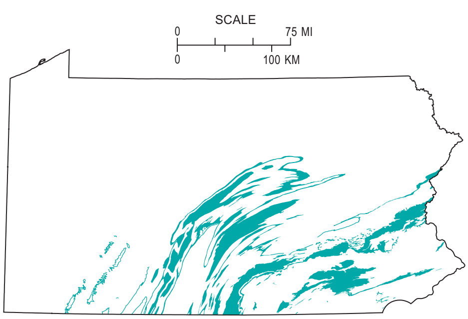



***Land and sea in the Late Cambrian. Different kinds of sediments were deposited in different areas.***

The position and orientation of the North American landmass have changed throughout its history because of the action of the convection currents in the mantle. During the Cambrian Period, North America was on the equator, so the climate was warm. The continent was oriented so that the present east coast faced south. For simplicity, geographic directions in this book are relative to North America's present orientation.

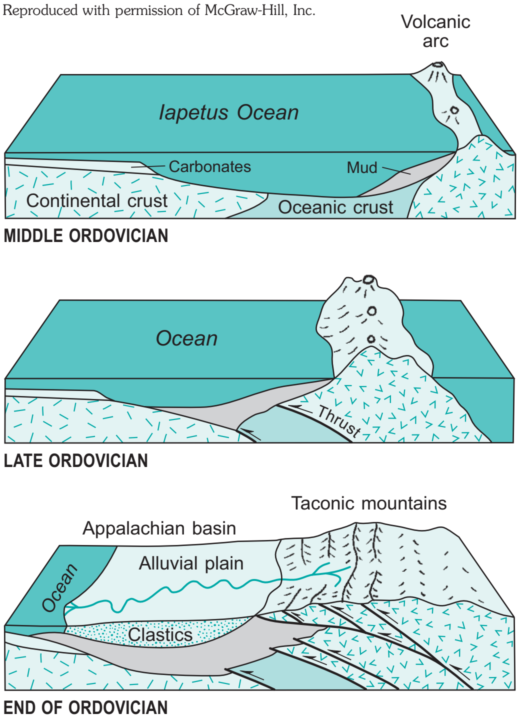
About 485 million years ago, the Cambrian Period ended and the Ordovician Period, which lasted approximately 42 million years, began. In Pennsylvania, the transition was peaceful with the continued deposition of sediments. However, the Ordovician became a time of dramatic changes.

In the Early Ordovician, east of North America and across an unknown distance of ocean, subduction began and new land in the form of a magmatic or volcanic arc was created. During subduction, part of the crust is pulled down toward the mantle and heated. The heating causes a buildup of pressure, which can lead to explosive volcanic activity. As a present-day example, the volcanic Aleutian Islands of Alaska exist because of subduction of the Pacific plate under the North American plate. Ash spewed by the volcanoes of the Ordovician magmatic arc east of North America fell into the water covering North America. Some of that ash was preserved and can be seen today in carbonate rocks that are exposed in central and eastern Pennsylvania.




***Location of carbonate rocks at the surface in Pennsylvania***

During the Middle Ordovician, the volcanic arc moved toward North America. By the Late Ordovician, material from both the arc and the floor of the Iapetus Ocean was thrusted onto the North American plate margin in an event called the Taconic orogeny. Mountains formed where material was thrust onto the continental plate. At the same time, the weight of the material thrust onto the plate margin caused it to subside. An elongate basin, called the Appalachian




***Ordovician tectonic events***

basin, formed west of the mountains. The basin, which extended from Newfoundland to Alabama, filled with marine water and existed for the next 200 million years. This example of plate tectonics is comparable to a present-day situation in the South Pacific Ocean, where the volcanic islands of Indonesia are moving toward Australia.

The mountains formed by the Taconic orogeny lay to the east of Pennsylvania. Sediments eroded from these mountains were carried westward by rivers and deposited in the water-filled Appalachian basin. Initially the sediments were mainly silt and clay, but by the end of the Ordovician, sand and gravel were being carried to the Appalachian basin. These clastic sediments brought an end to the long, uninterrupted time of carbonate deposition.

By the beginning of the Cambrian Period, the amount of oxygen in the atmosphere and shallow seas had accumulated to a high enough level that animal life was abundant. Some of the animals had hard shells that offered protection from predators. The animals, which were generally small, flourished, evolved, and became widespread during the Cambrian and Ordovician Periods. Trilobites, multilegged animals that crawled about scavenging for food at the bottom of the sea, were abundant, as were brachiopods, shelled bottom dwellers. They were joined in the Ordovician seas by mollusks, bryozoans, corals, and graptolites. Graptolites are thought to have been floating animals that lived attached to each other in colonies.

The change from deposition of carbonates to deposition of clastic sediments caused by the Taconic orogeny brought death to many animals because it destroyed their dwelling places. Tragedy for some was opportunity for others, however, as newly created environments were occupied by newly evolved animals. Most of the marine ecosystems that exist today were established during the Ordovician Period.

## THE SILURIAN PERIOD

During the Silurian Period, which began approximately 443 million years ago and lasted about 24 million years, the position of North America relative to the equator remained nearly the same. The continent, however, began a very gradual rotation that would eventually bring it to its present orientation.

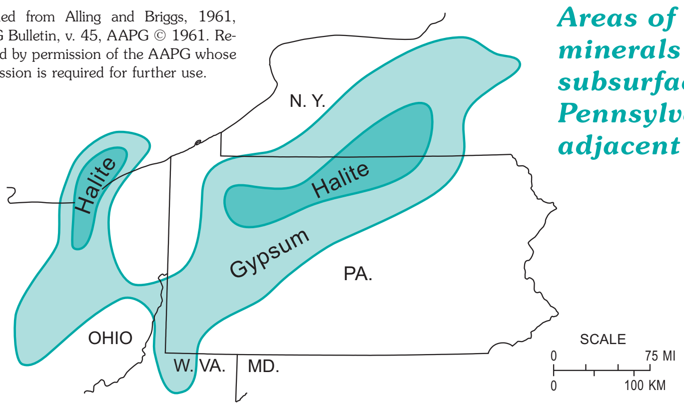
The Taconic mountains formed during the Ordovician Period continued to be a source of large quantities of sediments during the first half of the Silurian Period in Pennsylvania. Sand and gravel composed mainly of quartz were carried away from the mountains by streams and deposited on a flat, slightly inclined surface called an alluvial plain in the eastern part of the state. Additional quartz sand was carried farther west into the marine basin, where it was deposited on beaches or just offshore. Today, millions of years later, rock created by the cementation of this sand forms the crests of some of the long, linear ridges in the Ridge and Valley province (see centerfold map). This sandstone, called the Tuscarora Formation, is very hard and resistant to erosion. Because it is more resistant to erosion than rocks immediately adjacent to it, the Tuscarora forms the highest parts of some mountains, including Blue Mountain and Tuscarora Mountain.

Mud was deposited farther west in deeper marine waters. Carbonate deposition, similar to that of the Ordovician Period, occurred even farther west, beyond the boundaries of Pennsylvania. Very intense chemical weathering of the rocks in the mountains released large amounts of iron. This iron was carried in solution into the marine basin and precipitated there. Many of the resulting iron deposits were mined in Pennsylvania throughout most of the 1800s. They provided America with a valuable resource that greatly aided the development of our nation.

Erosion gradually lowered the height of the mountains formed by the Taconic orogeny, and eventually, the remnants of the mountains ceased to be a significant source of clastic sediments. Carbonate deposition dominated the second half of the Silurian Period, and limestone and dolomite formed in much of the Appalachian basin. At the same time, a shallow basin having very limited circulation of water with the open sea formed in what is now the northwestern part of Pennsylvania and in adjacent New York and Ohio. The warm temperatures associated with the basin's proximity to the equator caused the water to evaporate quickly. As evaporation took place, the remaining water became supersaturated, meaning it contained more material than could remain in solution. As a result, minerals such as halite (common table salt) and gypsum (the mineral used to make drywall) crystallized out of the water in large quantities. Today, these evaporite deposits are buried beneath younger rocks and are extensively mined in New York and Ohio. In Pennsylvania, however, most are buried too deeply to be mined profitably.

Life during the Silurian Period flourished, and many new species appeared. Corals became very abundant and began to form reefs in the carbonate areas. Corals deposit a very thin layer of lime (calcium carbonate) on their skeletons every day. The width of these layers, called growth rings, changes annually. Some geologists have used coral growth rings to estimate the lengths of years and days. They found that during the Late Silurian, a year consisted of approximately 407 21.5-hour days. If we compare that with today's 24-hour day, we can conclude that the rate of the earth's rotation on its axis is






***Areas of evaporite minerals in the subsurface of Pennsylvania and adjacent states***

slowing. This slowing is caused by friction generated by the continual movement of water across the seafloor in response to the gravitational pull of the moon and sun. We can observe this movement as the twice-daily rise and fall of ocean tides.

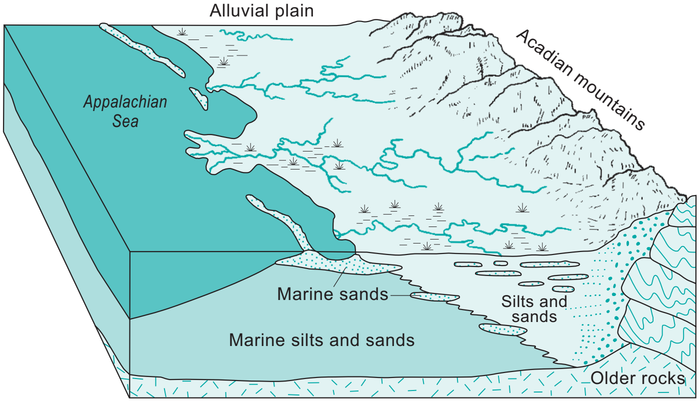
Two aspects of life in the Silurian Period are of particular importance to us today. The first is the evolution of fish. The earliest fish had bony plates and no jaws, only an open mouth. In the Silurian Period, fish developed jaws, their bony plates became smaller scales, and the strength of their fins increased. Their continuing evolution allowed fish to move into new environments, such as tidal and freshwater ponds. The second important aspect of Silurian life is the development of plants on the land. Plants having roots to obtain water and nourishment from the soil first appeared during the Silurian. Once plant life was established on the land, new environments and a food supply were available for evolving animal life.

## THE DEVONIAN PERIOD

The transition into the Devonian Period about 419 million years ago was quiet in Pennsylvania, and carbonate deposition continued for a few million years. However, by the end of the Devonian, about 60 million years later, dramatic changes had occurred.

Two landmasses, one called Avalonia and the other Europe, moved toward and eventually collided with North America in an event known as the Acadian orogeny. This collision affected the whole length of the Appalachian basin, but not all at the same time. The collision occurred first near Newfoundland and much later in the area that is now Pennsylvania. The orogeny created a new mountain range, the Acadian mountains, just east of Pennsylvania.

As the collision occurred and the Acadian mountains rose above sea level, sediments eroded from the mountains were transported by rivers to the Appalachian basin. The first sediments to be deposited can be seen today as black and gray shales and siltstones that extend from eastern Pennsylvania to western Ohio. (These rocks include shales, most notably the Marcellus shale, that are presently being developed for oil and gas in Pennsylvania.) Erosion of the mountains continued and coarse-grained clastic sediments were carried into the Appalachian basin.

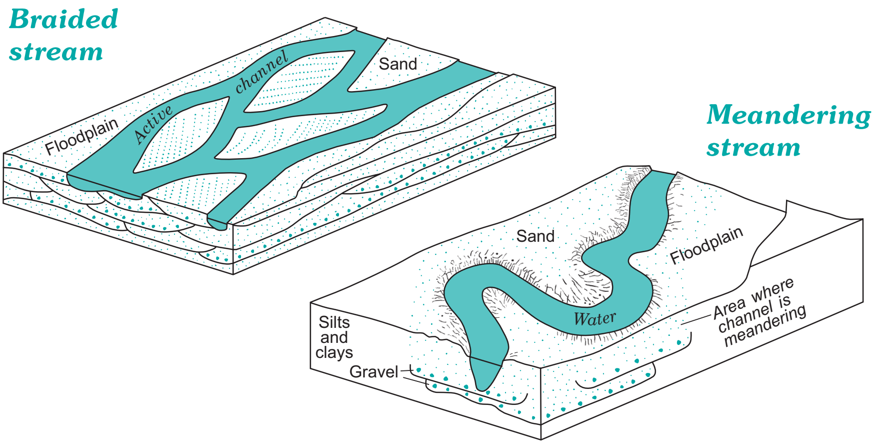



***Vertically stacked sediments resulting from migrating environments of deposition in the Late Devonian***

As more and more sediments poured into the basin, the part of the basin nearest the mountains was filled to sea level, and deposition in Pennsylvania and New York began to occur above sea level on an alluvial plain called the Catskill delta. The whole process of basin filling involved deposition of coarse-grained sediments on the alluvial plain, movement and deposition of fine-grained sediments by marine currents near the shore, and deposition from suspension of very fine grained sediments in deeper water farther west. The weight of the sediments being continually deposited in the basin depressed the crust into the underlying denser mantle. This caused the basin to subside, thus making room for the deposition of still more sediments.

As the shoreline was pushed westward by the growth of the alluvial plain, sediments previously deposited in marine environments were overlain by sediments deposited in nonmarine environments. This vertical stacking of sediments that were deposited in different and formerly adjacent environments is common in rock sequences, and its recognition in clastic, layered rocks is important in understanding the sequence of events recorded in the geologic record. It is also important in the exploration for mineral deposits and gas and oil accumulations.

The Devonian streams in Pennsylvania were of two different types, braided and meandering. Each type deposited distinctive and different sediments. The braided streams had many interconnected channels. These streams deposited mainly sand and some gravel.




The meandering streams had a single channel that wandered in a curved path. They deposited sand and gravel within the channel and sand, silt, and clay on the adjacent floodplain during periods of flood. As basin subsidence occurred and meandering continued, the channel moved across areas that were formerly floodplains, and new floodplains formed above former channels. The repetition of this process resulted in stacked cycles of deposition that can be seen in the sedimentary rocks today.

Continued erosion of the Acadian mountains produced abundant sediments throughout the remainder of the Devonian Period, and the eastern shoreline of the Appalachian basin was pushed almost to the Ohio border. Many of the sediments that were deposited on the alluvial plain are seen today as red clastic rock. The red color is derived from iron oxide, which forms part of the cement in the rock. This redness indicates that deposition occurred above sea level and that the climate was seasonally dry, thus allowing oxidation of iron in the sediments.

The alluvial plain was also seasonally wet. From the presence of fossils, we know that, at times, the surface was covered by abundant vegetation. Animal life was plentiful, not only in the seas but also on the land. During the Late Devonian, some fish evolved into amphibians, animals that live in water and breathe through gills in infancy and use lungs to breathe air in adulthood, thus allowing them to inhabit the land. Many insects and other arthropods were abundant in the forested areas. In a real sense, the land had become alive.

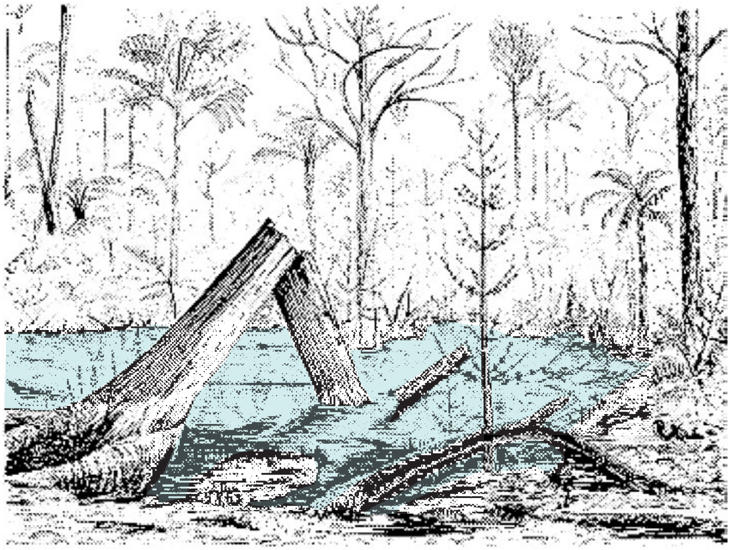
## THE MISSISSIPPIAN AND PENNSYLVANIAN PERIODS: CARBONIFEROUS TIME

The 60 million years of Carboniferous time, which started about 359 million years ago, is significant for two reasons. First, it was during this time that Pennsylvania's coal resources were formed. Second, it was the last time that marine waters of the Appalachian basin covered any part of Pennsylvania. The name "Carboniferous" is used to refer to two periods, the Mississippian (older) and the Pennsylvanian (younger).

Deposition on the previously formed alluvial plain continued as the Mississippian Period began, but the color of the resulting sediments was gray in contrast to the underlying red Devonian rocks. This could be because the climate had more rainfall and the seasons were less distinct. The amount of sediments being carried to the basin declined, and the eastern shoreline of the basin moved eastward across part of Pennsylvania. The fine-grained sediments that were deposited during the latter part of the Mississippian Period were turned red by oxidation of iron, perhaps because of a return to a seasonal climate. Also during this time, carbonates were deposited in the marine waters of western Pennsylvania, which was probably located about 10 degrees south of the equator.

By the end of the Mississippian Period, marine waters had advanced across the southwestern part of the state toward the northeast and into the Williamsport area. The northwestern part of the state was above sea level and was being eroded. Renewed uplift in the Acadian mountains east of Pennsylvania, possibly caused by a minor collision with an unknown landmass, resulted in coarser grained sediments being brought into the Appalachian basin during the Pennsylvanian Period. The sediments were deposited by rivers that meandered across a flat alluvial plain.

In the western part of the state during the Pennsylvanian Period, the area of the alluvial plain near the shoreline was covered by large swamps and lush fern and tree forests. The vegetation was abundant because Pennsylvania was only 5 to 10 degrees south of the equator and had a warm, moist tropical climate. The plants, which primarily included a large, scaly-barked tree called lycopsid, as well as ferns and tree ferns, produced large quantities of leaves, twigs,



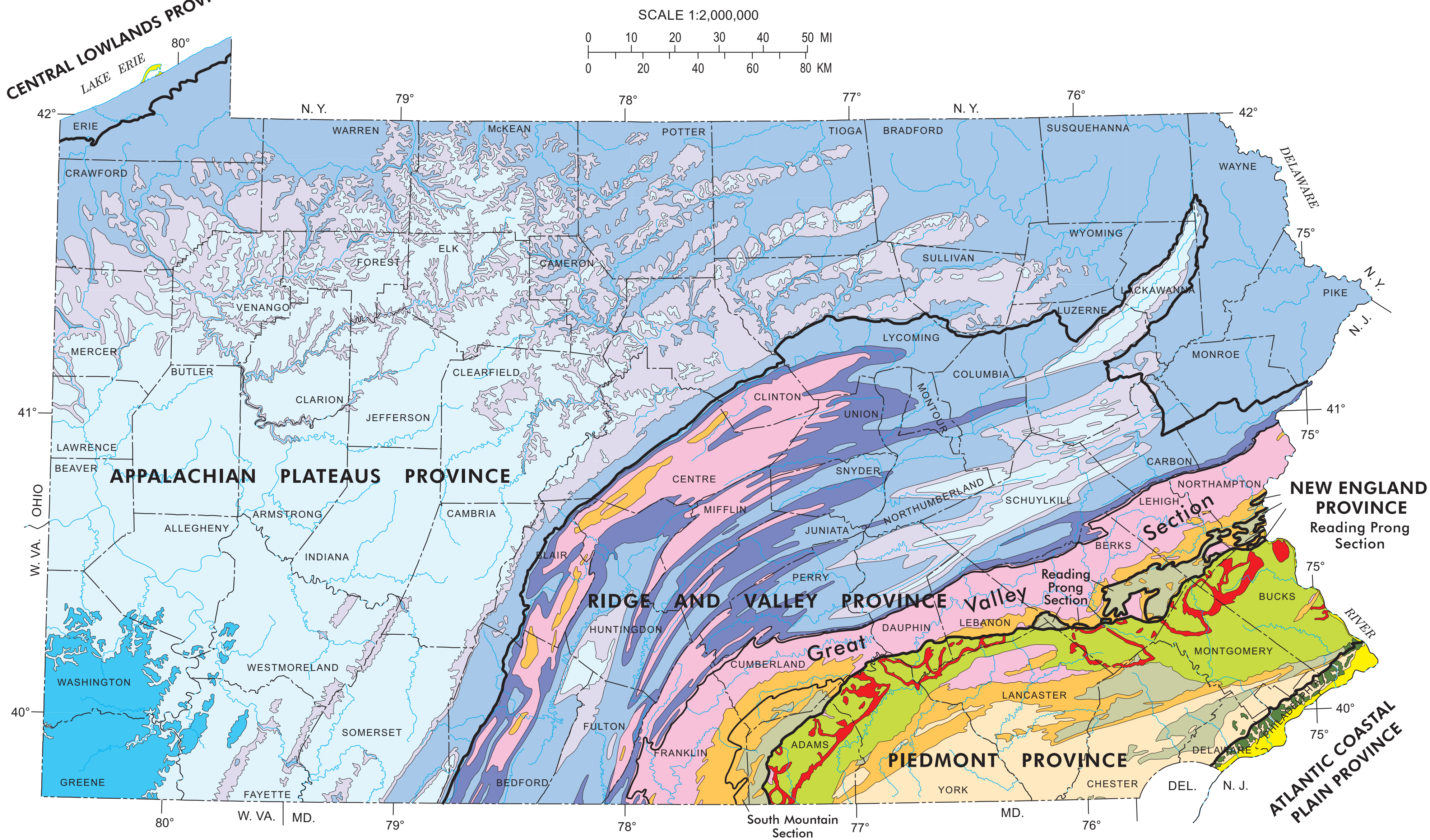
*Pennsylvanian-age swamp*

branches, and trunks that fell into the swamps. The fallen parts were protected from oxidation by the water and thus did not rot. This continuous supply of vegetation gradually accumulated as thick masses of wood debris called peat.

These swampy areas often received little or no sediments from the sluggish rivers. Basin subsidence, however, is a regional phenomenon and continued because of sedimentation elsewhere. The swampy areas that did not receive sediments were thus periodically drowned as subsidence continued, sea level rose, and the shoreline moved gradually eastward.

The process of subsidence and shoreline migration was very slow, and new swamps formed continuously adjacent to the sea. Once an area was covered by water, a nearby river would supply sediments that would bury it. The shoreline thus moved westward as the alluvial plain extended itself over the area. The heat and pressure caused by the weight of the overlying sediments compacted the peat and forced out some of the more easily vaporized compounds. This process concentrated the carbon and eventually turned the peat into coal. The greater the pressure, the greater the amount of volatile compounds that were forced out, making the coal richer in carbon, the chief element in coal that burns.

# GEOLOGIC MAP OF PENNSYLVANIA




EXPLANATION

| QUATERNARY | TERTIARY | * JURASSIC AND TRIASSIC | PERMIAN | PENNSYLVANIAN | MISSISSIPPIAN | DEVONIAN | SILURIAN | ORDOVICIAN | CAMBRIAN | LOWER PALEOZOIC | PRECAMBRIAN |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (0–2.6 mil. yrs.) | (2.6–66 mil. yrs.) | (145–252 mil. yrs.) | (252–299 mil. yrs.) | (299–323 mil. yrs.) | (323–359 mil. yrs.) | (359–419 mil. yrs.) | (419–443 mil. yrs.) | (443–485 mil. yrs.) | (485–541 mil. yrs.) | (443–541 mil. yrs.) | (older than 541 mil. yrs.) |
| Sand, gravel, and silt. | Sand, gravel, silt, and clay. | Red sandstone, shale, and conglomerate (green), intruded by diabase (red). | Cyclic sequences of shale, sandstone, limestone, and coal. | Cyclic sequences of sandstone, red and gray shale, conglomerate, clay, coal, and limestone. | Red and gray sandstone, shale, and limestone. | Red sandstone, gray shale, black shale, limestone, and chert. | Red and gray sandstone, conglomerate, shale, and limestone. | Shale, limestone, dolomite, and sandstone. | Limestone, dolomite, sandstone, shale, quartzite, and phyllite. | Schist, gneiss, quartzite, serpentinite, slate, and marble. | Gneiss, granite, anorthosite, metadiabase, metabasalt, metarhyolite, and marble. |
| *Sand and gravel.* | *Sand and gravel.* | *Building stone, iron.* | *Lime, clay.* | *Coal, clay, lime, building stone.* | *Flagstone, limestone, clay.* | *Flagstone, silica sand, clay, lime.* | *Lime, building stone.* | *Slate, limestone, zinc, clay.* | *Lime, building stone.* | *Building stone, talc.* | *Building stone, graphite, sericite.* |

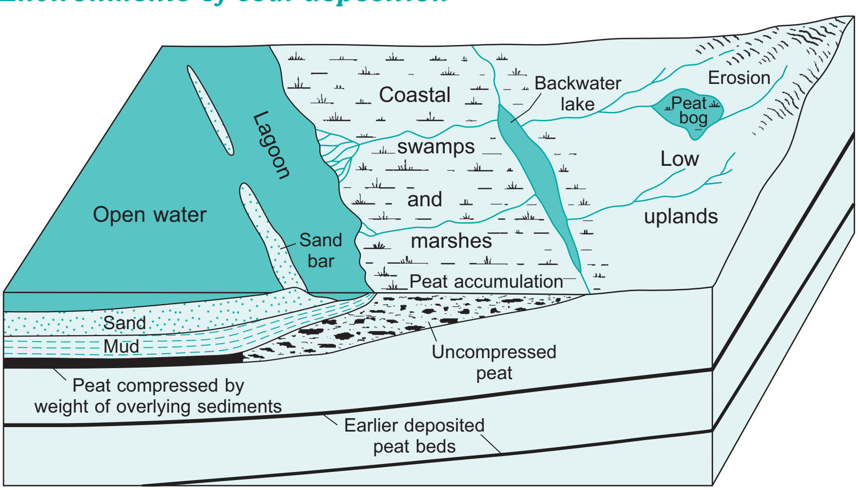
*Cretaceous rocks, which are present in small areas of southern Montgomery County, cannot be shown at the scale of this map.

The shoreline moved back and forth across the low, flat alluvial plain several times during the Pennsylvanian Period. It advanced as far eastward as Wilkes-Barre about 310 million years ago. By the end of the Pennsylvanian Period, the Appalachian Sea was completely gone from the state. Sediment deposition on the alluvial plain and the accumulation of wood in the swamps continued into the Permian Period.

Eastern Pennsylvania was far removed from the sea most of the time, but swamps were equally as common in areas adjacent to the rivers, and vast quantities of peat accumulated there, also. Periodic increases in the amount of sediments being brought to an area by a river caused the swamps to be buried. When the sediment supply decreased or the river shifted its channel, the swamps readily reestablished themselves, and more peat was formed. This cycle of peat formation and burial is responsible for the multiple seams of coal. The production of a 1-foot-thick seam of coal requires a 10-foot-thick deposit of peat; so the amount of wood in the Carboniferous forests must have been immense in order to produce the gross thickness of hundreds of feet of coal present in Pennsylvania.

In addition to trees and ferns, an increasingly diverse population of animals developed during Carboniferous time. Amphibians, primitive reptiles, air-breathing mollusks, and insects began to live in the many new habitats created by the diverse land plants.

***Environments of coal deposition***

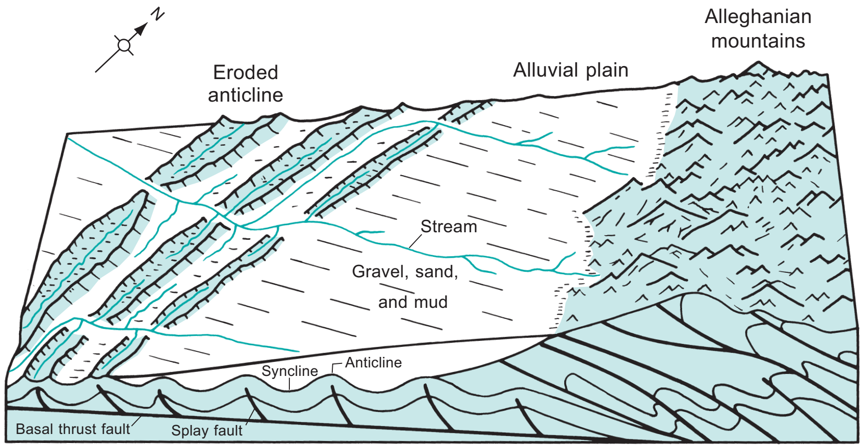


## THE PERMIAN PERIOD

The Permian Period, which started about 299 million years ago, was a time of dramatic change caused by the collision of North America with Africa. The collision resulted in a mountain-building episode called the Alleghanian orogeny, which was of much greater magnitude in Pennsylvania than both the earlier Taconic and Acadian orogenies. This collision caused deformation within the Appalachian basin. The stacking of thrust sheets in eastern North America raised a mountain range 150 miles wide, 750 miles long, and at least 2.5 miles high. The western margin of these Alleghanian mountains, which should not be confused with the present-day Allegheny Mountains, was located in the eastern part of Pennsylvania. The pressure and heat associated with the weight of this thick stack of rocks caused the underlying coal beds in eastern Pennsylvania to be altered to anthracite, which has relatively few volatile elements and a high carbon content. Erosion of this mountain range yielded vast quantities of sediments that were carried westward to the Appalachian basin.

The Piedmont province in southeastern Pennsylvania contains the eroded remnants of some of the large sheets of rock that were thrust onto the continent during the Alleghanian orogeny. Such thrust faulting also occurred in the subsurface rocks as far west as the Appalachian Plateaus province. Within the Ridge and Valley province, these nearly horizontal basal thrust faults commonly developed secondary splay faults that angled up toward the surface and caused upward bending of overlying rocks into folds called anticlines. The downward bends between the anticlines are called synclines. The orientation of the originally horizontal rocks was changed by various angles up to 90 degrees, and in some places, the rocks were even overturned. The folding also squeezed the existing rocks in eastern Pennsylvania so that they covered a smaller area than before. For example, the rocks presently forming the crest of Blue Mountain between Harrisburg and Chambersburg were situated about 50 miles farther east prior to folding.

Fractures that formed during the collision became avenues for water infiltration. This promoted weathering and disintegration of the rock. The large quantity of sediments eroded from the Alleghanian mountains was deposited on an alluvial plain that covered much of Pennsylvania as well as areas farther west. Little is known about the character of the sediments because they have all been eroded except for a small amount in southwestern Pennsylvania and adjacent states. By the end of the Permian Period, erosion had reduced the height of the mountain range in eastern Pennsylvania, and the remainder of Pennsylvania was mainly a westward-sloping alluvial plain across which streams flowed. The eroded tops of some anticlines probably protruded above the alluvial plain. This episode of deposition was the final one for the Appalachian basin. The Appalachian basin subsequently ceased to exist as an area of deposition.

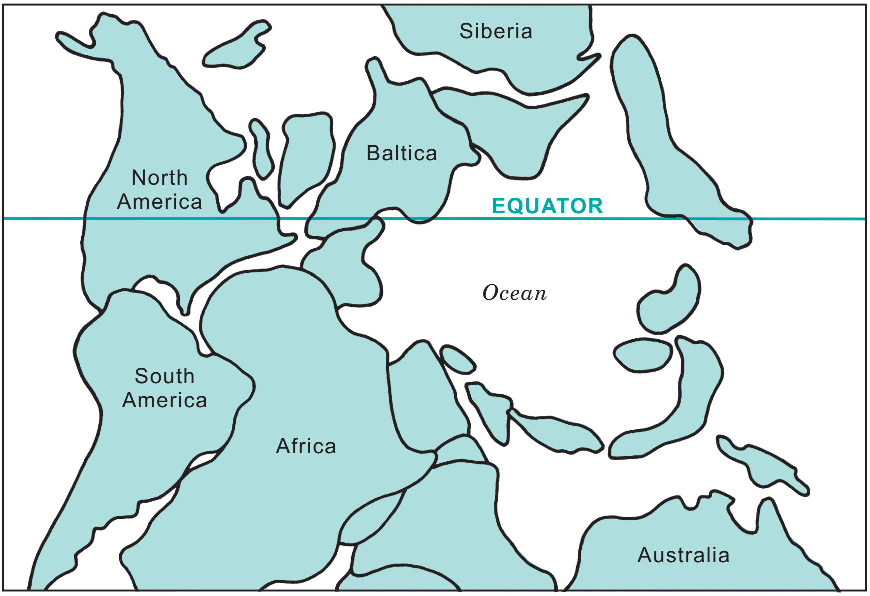



***Cross section and surface view of Pennsylvania at the end of the Permian***

During the Permian Period, Pennsylvania remained near the equator, but the climate became much drier. This happened because the plate movements that caused the Alleghanian orogeny involved all of the continents, which joined together to form a supercontinent called Pangea. There was limited rainfall in Pennsylvania because the state was near the middle of Pangea and no oceans were nearby. Thus, the swamps dried up, and the vegetation became less abundant and of a different type.

The formation of the supercontinent Pangea caused not only worldwide climate changes, but also worldwide changes in the ocean basins. In particular, the amount of shallow ocean water was greatly reduced, because joining the continents together greatly reduced the continental-margin area. As a result, the end of the Permian is marked by the extinction of a large number of marine organisms who lived in the shallow-water environments that were being destroyed. Included among these organisms was the trilobite, whose numbers had been declining since the Devonian Period.

Modified from Bally (1989). Reprinted with permission.




***Supercontinent Pangea at the end of the Permian***

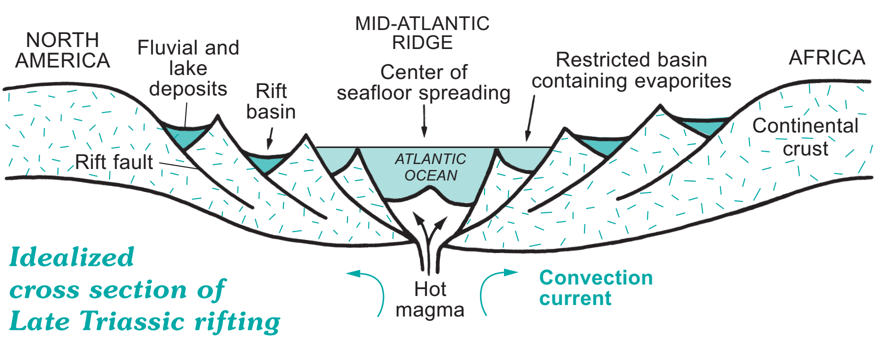
While some marine environments were being destroyed, new land environments were being created, and animal life flourished there. Insects were prolific. The amphibians evolved, but were restricted in where they could live. They needed to remain close to water because it was the initial habitat for their eggs. During the Permian Period, evolution solved the egg problem with the rise of the reptiles, cold-blooded animals that lay eggs with a hard shell. Having a hard shell meant the eggs could be laid on dry land. This allowed the reptiles to roam wherever they wanted, and soon they would dominate the animal world.

## THE MESOZOIC ERA

The Alleghanian orogeny changed Pennsylvania completely. It changed from a depositional basin receiving sediment to an area above sea level that has been eroded continuously ever since and is still supplying sediments to places outside the state. This long period of erosion, which started at least 250 million years ago, has produced the landscape that we see today. Most of the erosion was accomplished during the Mesozoic Era.

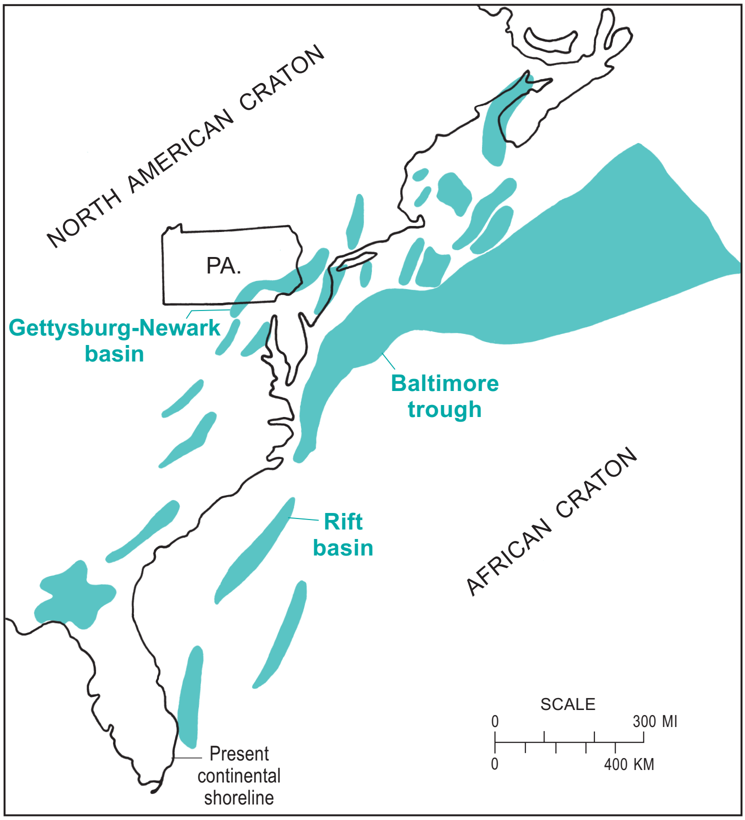
The three periods of the Mesozoic Era—the Triassic, Jurassic, and Cretaceous Periods—were approximately 51, 56, and 79 million years long, respectively. During the Triassic Period, the gradual northward movement of North America carried Pennsylvania across the equator into the northern hemisphere. The climate was subtropical to tropical. Rainfall was seasonal, and much of the year was very dry. In addition to annual wet and dry cycles, long-term wet and dry cycles occurred over tens of thousands of years. The long-term cycles are believed to be related to fluctuations in the amount of solar energy received. Erosion was probably intense at times, and much sediment was carried west or northwest away from Pennsylvania.

Sometime in the Late Triassic, possibly about 220 million years ago, the area where Africa and North America were joined together gradually began to separate. Convection currents in the mantle forced the continents apart and created new rock on the ocean floor that developed between them. This process is called seafloor spreading. As the separation of the continents took place, long, fault-bounded troughs, called rift basins, formed parallel to the margins of the con-




***Idealized cross section of Late Triassic rifting***

tinents. One of these rift basins is in southeastern Pennsylvania. All of the basins became sites for the deposition of sediments eroded from adjacent areas. During the wet part of the long climatic cycles, these basins were the sites of large lakes in which sediments were deposited. During the dry part of the cycles, the lakes dried up.




***Location of Late Triassic rift basins***

Modified from Manspeizer and others (1989). Reprinted with permission.

The process of seafloor spreading also caused deep-seated magma to approach the surface very early in the Jurassic Period. The magma cooled near the surface as diabase, a dark, hard igneous rock. In Pennsylvania, the Mesozoic sediments and diabase (shown in bright green and red on the centerfold map) are preserved in the Gettysburg-Newark basin of the Piedmont province.

While all of this was happening, the area between North America and Africa widened to create the Atlantic Ocean. The Atlantic is still widening today by about 1 inch per year. Near its center, at the Mid-Atlantic Ridge, magma continues to be brought to the surface, filling the available space between the separating plates with new rock.

Little is known about the Jurassic and Cretaceous Periods in Pennsylvania except that erosion occurred. Sometime, possibly during the Cretaceous but maybe earlier, rivers eroding the eastern part of the state began to flow eastward into the newly formed Atlantic Ocean, and the early stage of modern drainage was established. These rivers were very short initially, but gradually became longer through a process of headward erosion, which continues today. In this process, the length of a stream is extended by erosion at its source, or head, area. Often during this process, the head of one stream will intersect another stream and capture a part of that stream by a process called stream piracy.

As the Atlantic Ocean became larger and ocean currents were established, the ocean provided a nearby source of water. This caused the climate to become wetter, and the amount of vegetation increased. During the Late Cretaceous, vegetation was sufficiently abundant to cause the accumulation of some peat in the southeastern part of the state. Physical weathering (the mechanical breakup of rock) and erosion of clastic sediments slowed down considerably during the latter part of the Cretaceous Period. By the end of the Mesozoic Era, chemical weathering (the alteration of the chemical composition of minerals at the earth's surface) was dominant in Pennsylvania.

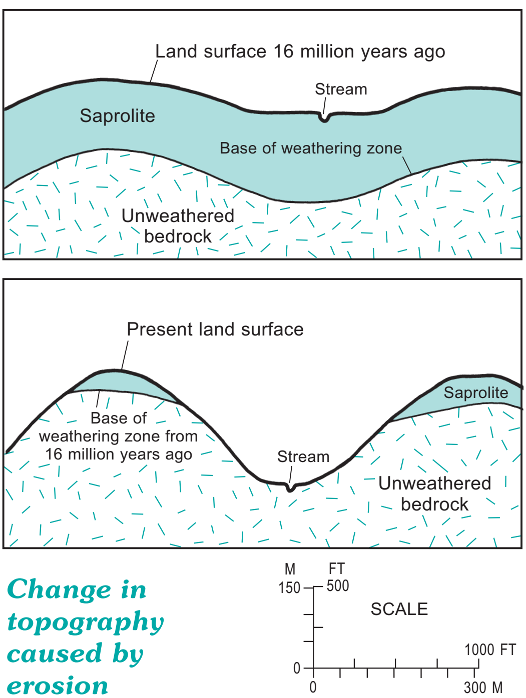
During the Mesozoic Era, the land was ruled by the dinosaurs, which flourished and evolved into many different types. Dinosaur footprints have been found in Triassic sedimentary rocks in Pennsylvania. Many other animals also existed. These included mammals and the first birds, both of which first appeared in the Late Triassic. Many of these land dwellers, as well as a variety of ocean dwellers, became extinct within a period of about a million years at the end of the Mesozoic Era. One hypothesis to explain this mass extinction involves the impact of a large asteroid. Such an impact would have created a huge cloud of dust around the world that blocked sunlight and severely affected life. The presence of a large impact site at Chicxulub, Mexico, and debris from this impact at the boundary between Cretaceous and Tertiary sediments at many places around the world provide support for such an idea, but the hypothesis is still debated today.

## THE CENOZOIC ERA

The Cenozoic Era, which started approximately 66 million years ago, is divided into the Tertiary Period (about 66 to 2.6 million years ago) and the Quaternary Period (about 2.6 million years ago to the present). The Cenozoic Era is commonly discussed in terms of shorter subdivisions of time called epochs. During the Cenozoic Era, North America continued its northward motion to its present position relative to the equator.

The warm and moist climate of the Cretaceous Period continued into the early part of the Cenozoic Era and apparently intensified. This resulted in much chemical weathering, by which solid rock was converted to materials such as clays. This process led to the development of thick zones of very weathered clay-rich rock called saprolite. The actual appearance of Pennsylvania probably changed very little during this period of many million years, but solid rock was nowhere close to the surface by the time the process ended.

During the Miocene Epoch, which started about 23 million years ago, the climate began to change slowly to somewhat cooler and drier conditions. This caused an increase in physical weathering and erosion of clastic sediments and a decrease in chemical weathering. A time of severe erosion started about 16 million years ago during the Miocene and has continued to the present. It was during this time that the landscape that we see today was sculpted. Parts, if not all, of the land surface in eastern Pennsylvania may have been lowered by several hundred feet. At the same



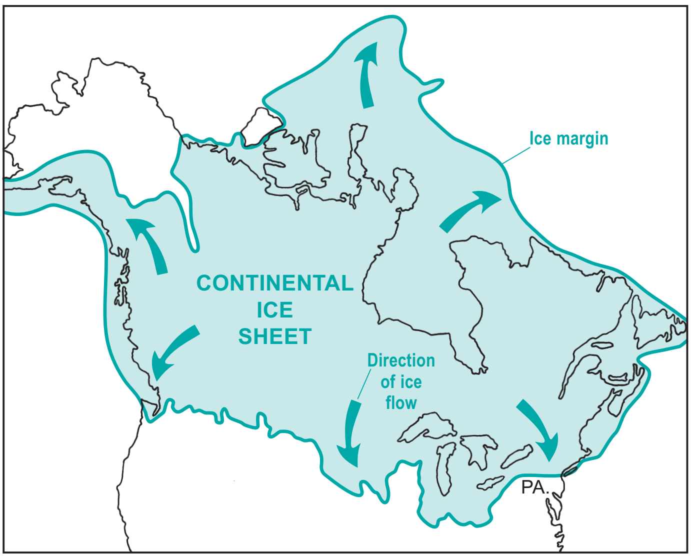

***Change in topography caused by erosion***

time, the difference in elevation between the highest and lowest points was increased considerably. The system of rivers, creeks, and rivulets that drain water from Pennsylvania today was established during this time of erosion, which was also a time of continued cooling.

During the Pleistocene Epoch, which started at the beginning of the Quaternary and lasted through most of that geologic period, large quantities of ice accumulated in Canada to form a continental glacier. This glacier flowed outward and at its furthest extent had advanced into the northeastern and northwestern parts of Pennsylvania, mainly in the Appalachian Plateaus province.

***Glaciation in North America***

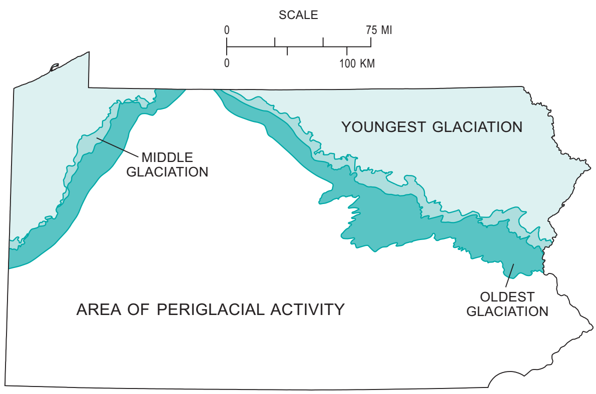
Modified from Prest and others (1968). Reproduced with the permission of the Minister of Public Works and Government Services Canada, 2002, and courtesy of Natural Resources Canada.




In the glaciated areas, the advancing ice eroded and significantly deepened valleys that were parallel to the direction of ice flow. The ice also scraped and lowered the tops of hills, particularly in places where the underlying rock was a soft shale or siltstone. When the ice finally started to melt, it left behind deposits such as till (a mixture of clay, silt, sand, and gravel) scattered randomly across the land surface and outwash (stream-deposited sand and gravel) that filled the bottoms of valleys leading away from the glacier.

The cold climate caused the ground in most of Pennsylvania to be frozen to depths of several feet. In the area beyond the limits of continental ice cover, numerous cycles of freezing and thawing occurred in the near-glacier, or periglacial, climate. The repeated freezing and thawing at the surface caused the breakup of large quantities of rock at the crests of ridges in the Ridge and Valley province. As a result, the crests of these ridges were lowered by several tens of feet. Loose rock, called talus, accumulated on the slopes of most ridges of central Pennsylvania and can be seen today in many places, such as the Juniata Narrows south of Lewistown.

There were four major glaciations during the Pleistocene Epoch. At least three of the glaciers entered Pennsylvania. Each successive glacier eroded deposits left by the earlier glaciers. Deposits of the earlier glaciers generally survived only where the earlier glaciers traveled farther south than their successors. The first of the glaciers arrived in Pennsylvania more than 800,000 years ago. The most recent arrived about 24,000 years ago. Between each glaciation, the climate became similar to that of today, or even warmer and wetter. It is possible that we are living in an interglacial period and that sometime in the future glaciers will again grow in Canada and move south into Pennsylvania.




***Glaciation in Pennsylvania***

Life on the land underwent many changes during the approximately 66 million years of the Cenozoic Era. Of particular significance was the appearance of grasses. The development of grass created a new food supply that was rapidly utilized by mammals, such as horses. The mammal population expanded and diversified to become the dominant class of animals on earth. Among these mammals were humans, who appeared very late in the Cenozoic.

## PENNSYLVANIA'S PHYSIOGRAPHIC PROVINCES

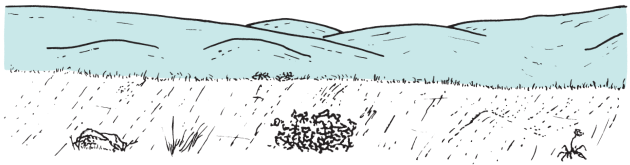
The present-day landscape of Pennsylvania reflects the billions of years of events that have been described in this booklet. The events that took place in various parts of the state were different, and the landscape reflects those differences. Because of this, the state is divided into six areas called physiographic provinces, each of which has a particular type of landscape and geology. The physiographic provinces are labeled on the map in the center of this booklet.

The state's southeasternmost physiographic province, the Atlantic Coastal Plain, includes all except the northwestern part of Philadelphia. It also includes the southeastern parts of Bucks and Delaware Counties. Beyond Pennsylvania, this province encompasses areas near the Atlantic Ocean from Massachusetts to Florida, including all of southern New Jersey and most of Delaware. It is marked by rather flat land and sandy soil. It contains sediments of Cenozoic age that are the result of erosion and deposition by rivers.

Moving inland, the first province that covers a large area within Pennsylvania is the Piedmont. From northwest Philadelphia, it extends north past Quakertown and west past Gettysburg. West Chester, Quarryville, Lancaster, and York are in this province. Metamorphic rocks that are at least 443 million years old underlie much of the Piedmont and have been greatly distorted by the forces of plate collisions. Following the Alleghanian orogeny, this was an area of grand mountain ranges. After millions of years of erosion, rolling hills are the only remnants of that early grandeur.

The part of the Piedmont that is shown in bright green and red on the map contains rocks that were formed during the beginning of the separation of North America and Africa. These rocks formed from sometime in the Late Triassic through the earliest Jurassic, about 220 to 200 million years ago. The landscape is one of rolling lowlands composed mainly of red sedimentary rock punctuated by hills of diabase, a hard igneous rock. Quakertown, Elizabethtown, and Gettysburg are in this part of the Piedmont province.

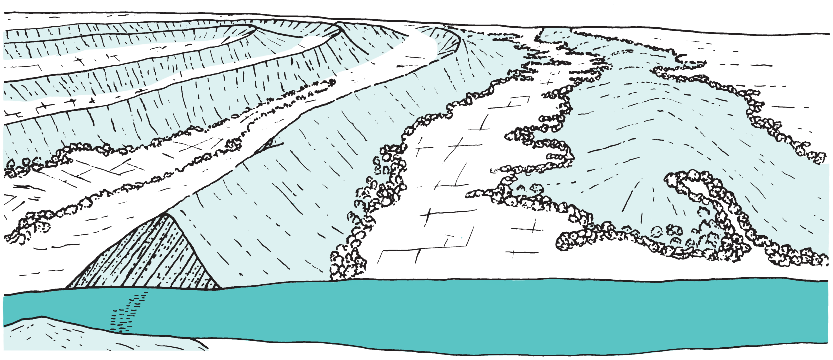
North of the Piedmont province in eastern Pennsylvania is a western extension of the New England province that is known as the Reading Prong. This area contains some metamorphic rocks that are about 500 million years old and many others that are more than a



*New England province*

billion years old. These rocks are resistant to erosion and form a highland characterized by rounded hills. From Reading's Mount Penn, the Reading Prong extends northeastward to Connecticut. It forms hills to the south of Allentown and Bethlehem. A small, isolated segment lies to the west of Reading.

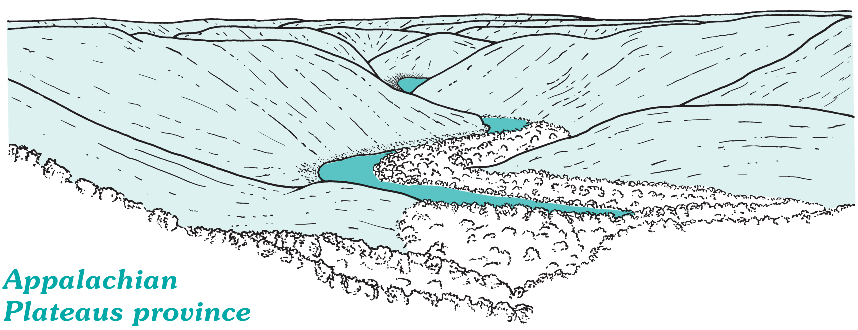
The next province moving inland, the Ridge and Valley, contains one of Pennsylvania's most distinctive landscapes. Geology students all over the nation study its unusual long, narrow, nearly parallel ridges and valleys, and they puzzle over the formation of water gaps that allow rivers to pass through the ridges. The province makes a broad sweep through the center of the state, extending northeastward into New Jersey and southwestward into Maryland and beyond. Most of the ridges and valleys consist of Paleozoic sedimentary rock. Some metamorphosed Proterozoic volcanic rock that is about 575 million years old forms minor ridges in the South Mountain section of the province, which extends approximately 30 miles into Pennsylvania from Maryland. The tremendous pressures that operated on the rocks of the Ridge and Valley province during the Alleghanian orogeny have left them folded and standing at angles far from the horizontal



*Ridge and Valley province*

position in which the sediments were originally deposited. Erosion since that time has formed valleys in areas of soft rock, such as shale and limestone, that alternate with ridges of harder rock, such as sandstone. Along the length of the southeastern side of the Ridge and Valley province is a broad, low valley called the Great Valley. Altoona, Williamsport, Scranton, Allentown, Harrisburg, and Chambersburg are in this province, the latter three being in the Great Valley.

The province that covers the largest area of Pennsylvania is the Appalachian Plateaus province. It extends from Greene, Fayette, and Somerset Counties in the southwest part of the state to Erie County in the northwest and Wayne and Pike Counties in the northeast. Pittsburgh, Johnstown, Bradford, and Towanda are in this province. As in the Ridge and Valley province, the rocks are of Paleozoic age, but they were not affected as much by mountain-building processes. This province is a highland that has been eroded by streams, creating deep valleys and hilly topography. Northern sections that were overridden by the glaciers of the Pleistocene Epoch also have lakes, swamps, peat bogs, and extensive deposits of loose sediments.

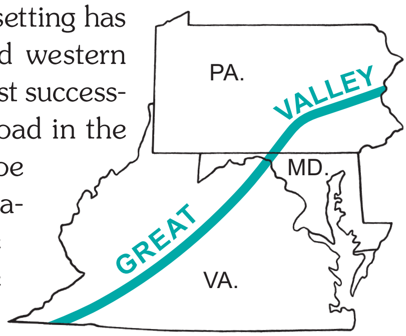


***Appalachian Plateaus province***

The northwesternmost province in Pennsylvania is the Central Lowlands province along the shore of Lake Erie in Erie County. Like the Atlantic Coastal Plain, only a small part of this large province is found in our state. From northwestern Pennsylvania and western New York, the province extends northwestward to Minnesota and southwestward to central Texas. The portion in Pennsylvania, which includes Erie, North East, and Girard, consists of gently rolling land. It contains low ridges of sand and gravel, old beaches that were formed by Lake Erie at the end of the Pleistocene glaciation. At that time, the water level in the lake was much higher than it is now because the lake's outlet, the Niagara River, was blocked by receding glaciers.

## GEOLOGY'S PRACTICAL SIDE

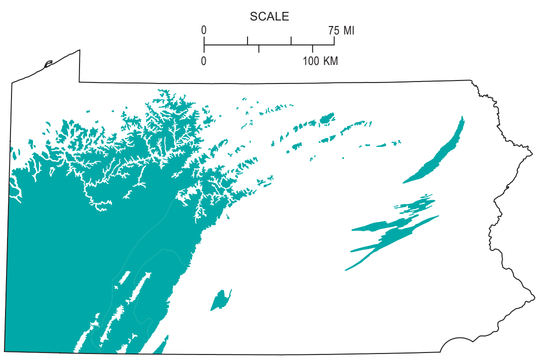
The settlement of Pennsylvania was affected by geology. The high, wall-like, parallel ridges of the Ridge and Valley province, sometimes called the Endless Mountains, presented a barrier that limited most British colonial settlement in Pennsylvania to areas east of the mountains. The French had easier access to western Pennsylvania from Québec via the natural transportation routes of the Great Lakes and the Allegheny River. Later, people in eastern Pennsylvania who were attracted to the frontier chose to follow the easy transportation route that the wide, relatively flat Great Valley section provided southwestward into Virginia, where it is known as the Shenandoah Valley. Many settlers who finally did reach western Pennsylvania came from western Virginia (now West Virginia) by following the rivers northward. Pennsylvania's geological setting has made the linking of the eastern and western parts of the state a challenge. The most successful links were the Pennsylvania Railroad in the 1850s, including the famous Horseshoe Curve near Altoona, and the Pennsylvania Turnpike in 1940. Both overcame the problem by tunneling through the mountains.




The effects of geology on settlement and transportation show us one aspect of geology's practical side. Its effects are not limited to transportation, and many are to our benefit. It is easy to forget that, one way or another, water, food, and the raw materials to make everything we use come from the ground.

Long ago, deposits of raw materials were found by chance. Today, we cannot depend on chance to feed our tremendous appetite for these materials. By studying Earth's history, we can rule out the least likely places to find what we need and concentrate on the places where we are more likely to have success. One important tool that helps us do this is the principle called "uniformitarianism," which states that the geological processes that we see operating today are the same as those that took place in the past. Using that principle and combining it with their knowledge of stratigraphy, or the order and distribution of rock units, that has been gained through generations of study, geologists can predict where resources might be found.

Pennsylvania's geologic history has left a legacy of many important resources. Coal formed from buried Pennsylvanian-age swamp vegetation is burned to generate electricity and to make iron and steel. Deposits of oil and natural gas, which are formed mainly from decayed organisms, are common in Pennsylvania's Silurian and Devonian rocks. Oil and gas are used in the manufacture of fuels and lubricants. Coal, oil, and natural gas are also important raw materials in the manufacture of plastics, glass, synthetic fabrics, fertilizers, pesticides, pharmaceuticals, and asphalt.

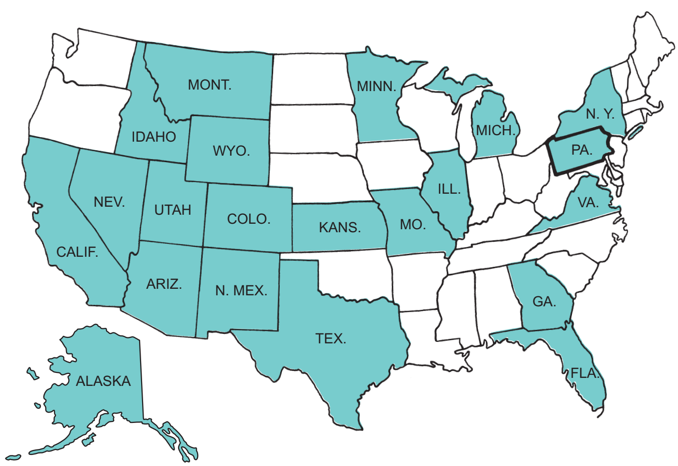



***Coal fields of Pennsylvania***

Pennsylvania is also an important producer of many nonfuel mineral resources. Sand and gravel, crushed sandstone, and crushed limestone are common construction aggregrates, materials used to pave roads. Limestone, which has many other uses, is quarried in large quantities in Pennsylvania. It is used in construction as the cement required to make concrete, in agriculture to improve the soil chemistry for better plant growth, and in scrubbers that reduce air pollution from burning coal. Sandstone, slate, limestone, diabase, and other rocks are used as dimension stone, which is stone that is cut and sometimes polished for use in buildings and monuments. Clay is another important product of Pennsylvania's mineral industry. It is used in the manufacture of bricks and ceramics, and as a sealer to protect water supplies from pollution caused by the disposal of hazardous waste. Clay and limestone are also used as fillers in the manufacture of foods, medicines, paper, and plastics.

The production of mineral resources in Pennsylvania can be traced to colonial times. Right from the start, to minimize the risk of fires that were known to destroy whole cities in those days, many buildings in Philadelphia were built of bricks made from locally derived clay. Pennsylvania was also an important producer of metallic mineral resources. Iron, zinc, lead, chromium, and nickel from Pennsylvania helped fuel America's development into an industrial nation. Because of depletion and the discovery of deposits elsewhere that can be mined more economically, metallic resources are not presently mined in Pennsylvania. An iron mine at Cornwall in Lebanon County that helped supply the Continental Army during the Revolutionary War closed in the 1970s after more than 230 years of operation. The last metallic mine, a large zinc mine in Lehigh County, closed in 1983.

Mineral resources continue to play an important role in Pennsylvania's economy and in providing what is needed to maintain our way of life. Pennsylvania is among the larger producers of geologic resources in the nation. The combined value of all of the geologic resources, other than oil and natural gas, produced here in 2011 was approximately $5.5 billion. The production of natural gas from shale gas reservoirs in Pennsylvania has been growing rapidly in recent




***States having nonfuel mineral production greater than 1 billion dollars in 2011***

years because of advances in horizontal drilling techniques combined with hydraulic fracturing and would add considerably to this total.

Tourism has become one of Pennsylvania's largest industries. Geology is an important aspect of many of the state's tourist attractions. Outdoor enthusiasts are drawn to places such as the Grand Canyon of Pennsylvania, Presque Isle, and Hickory Run Boulder Field. History buffs are attracted to sites such as the Gettysburg Battlefield, where the outcome of battle was largely shaped by the terrain and associated geologic features such as Devils Den and Little Round Top. The Pennsylvania Anthracite Heritage Museum, the Cornwall Iron Furnace, and the Drake Well Museum are examples of tourist attractions that are directly related to Pennsylvania's mineral resources. Even the difficulties posed in connecting the eastern and western parts of the state are recognized at tourist attractions that honor the ingenuity that was employed in getting people and goods across the mountains. Examples include the Horseshoe Curve and the Allegheny Portage Railroad.

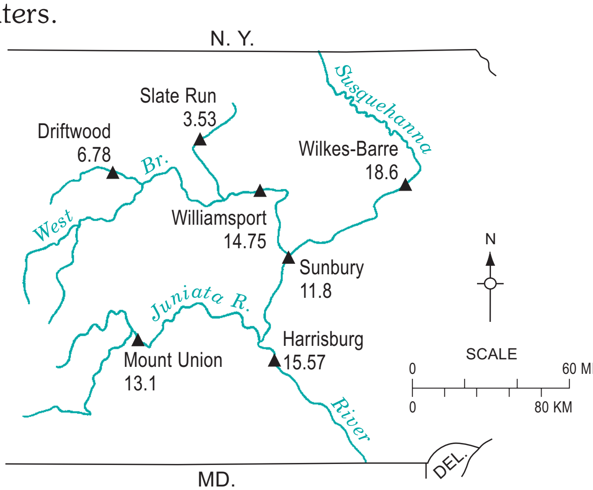
## SOMETIMES THINGS SEEM TO GO WRONG

Because our planet seems to be a pleasant place to live and provides all that we need to survive, it is easy to think of Earth as well adapted to our needs. This is especially true if we compare it to the other planets in the solar system. Mercury is airless. Venus is a cloud-shrouded oven that is hot enough to melt lead. The thin atmosphere of Mars and its frigid temperatures, lack of water, and raging dust storms make it less than ideal. The outer planets are balls of ice and poisonous gases. We have to be careful about how we think of Earth, though. Earth has not adapted itself to suit our needs. It is we, as a result of millions of years of evolution, who have adapted ourselves to live in the conditions that exist on Earth.

As pleasant as Earth may be, sometimes things seem to go wrong. Floods, earthquakes, landslides, and sinkholes seem to come randomly from nowhere and disrupt our lives. People wonder how such apparently bad things could happen. They happen because the geologic processes that change and renew the surface of the earth have not stopped. These processes are neither good nor bad. They happen naturally and often predictably. If we understand the processes, we can sometimes avoid their bad effects.

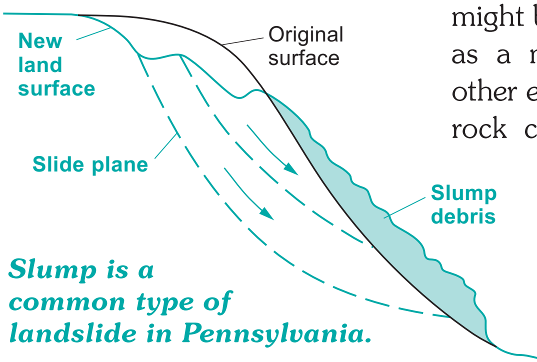
By studying geology, we can learn which processes are likely to present hazards in a particular area and how we can sometimes prevent damage before it occurs. In Pennsylvania, with its extensive river systems, floods cause great damage. Maps that show the elevation of the ground can be combined with accounts of past floods to provide an indication of where floods will occur in the future. In those areas, precautions can be taken to reduce flood damage. The most obvious precaution is to avoid building in those areas. Zoning laws that regulate development on flood plains can prevent much damage. In areas that are built up, the preservation of wetlands, which absorb floodwaters, can minimize the impact of flooding. Another precaution is to construct buildings in such a way that a flood would cause as little damage as possible, for example, placing the things that would suffer the greatest damage on upper floors. Some communities attempt to reduce flood damage by building dikes or levees that redirect floodwaters.

***Number of feet beyond which flood stage was exceeded in the Susquehanna River basin as a result of tropical storm Agnes, June 1972.***




Great earthquakes occur most often at plate boundaries in the Mediterranean region, southern Asia, and lands bordering the Pacific Ocean. Pennsylvania, which is far from a plate boundary, so far has had only small earthquakes over the 300 years since the first European settlers began to keep records. These earthquakes have caused little damage. Damage by major earthquakes can be reduced by use of construction techniques that isolate buildings from the violent motions of the ground, similar to the way shock absorbers allow cars to ride smoothly on bumpy roads.

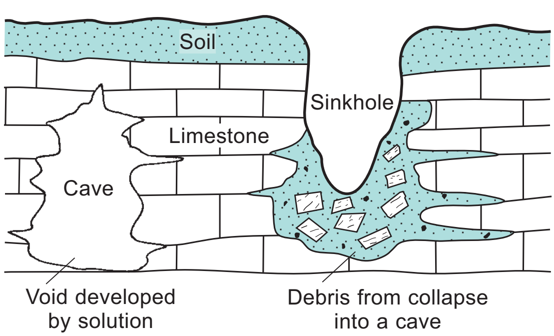
Landslides have caused much more damage in Pennsylvania than earthquakes. There are several kinds of landslides. Some act very slowly over a period of years. The only evidence of movement might be something subtle, such as a misaligned fence. At the other extreme, a mass of soil and rock can suddenly and rapidly careen down a hillside, knocking down trees as it goes. In a third type of landslide, called a slump, a block of soil or weathered rock on a hillside slowly slides down and rotates outward as the weight of the material at the top of the block pushes down on the material at the bottom.




***Slump is a common type of landslide in Pennsylvania.***

Much of the damage caused by landslides can be prevented by carefully studying the soil type, the slope, the presence and angle of fractures in the bedrock, and other factors before beginning a construction project. Sometimes, inappropriate construction can actually increase the risk of landslides. The danger can be reduced by taking precautions when preparing the site for construction.

Subsidence also causes problems in Pennsylvania. The usual cause of the ground caving in is the removal of bedrock. Bedrock can be removed by mining or, as unlikely as it might seem, by being dissolved. Groundwater that is slightly acidic slowly dissolves limestone, leaving an open space. Almost all well-known caverns formed in this way. If the rock remaining above the space is too weak to support the load above it, the ground collapses and a sinkhole forms. Careful study before construction is begun, especially in areas of limestone bedrock and old mine workings, can help prevent damage.



## A CHANGING ENVIRONMENT

Environmental change is as old as Earth itself. Since life arose, many things have changed, including the composition of the atmosphere, the amount of sunlight that reaches the ground, even the length of a day. Some of these changes were caused by the emergence of life. For example, when green plants first appeared in the Proterozoic Eon, they gradually removed some of the carbon dioxide from the atmosphere and replaced it with oxygen. Life has adapted to such changes slowly by evolution. In each generation, every individual is slightly different from all others. The individuals that are best suited to their surrounding conditions survive to reproduce and carry on their line. As conditions slowly change, individuals having slightly different characteristics become the ones that are best suited to the new conditions and are the ones that reproduce. It is through this process of natural selection that one species gradually evolves into another.

Regardless of our level of technology, we change the earth by our presence, just as the Proterozoic plants changed the composition of the atmosphere by their presence. To some extent, probably every plant and animal has done this. There is evidence that changes taking place now may be occurring more rapidly than many of the changes that have taken place in the past. Conditions that developed over thousands or millions of years may be changing in decades. For example, a relatively rapid retreat of glaciers in North America, Europe, the Antarctic, and other places is causing a slight increase in sea level. The decade from 2001 to 2010 was declared by the World Meteorological Organization to be the warmest since modern record keeping began in 1850. Natural selection cannot cope with rapid changes. We face a challenge in determining whether the changes that have been observed represent a long-term trend of rapid change. If so, we face the additional challenge of trying to slow that change or adjust to it.

In addition to the effects of possible climate change, there are other ways in which we might be modifying our environment too rapidly. One is by changing the quality of the world's water. For many years, people have dumped their refuse into bodies of water without considering the consequences. Today, we know that components of trash and sewage that are not disposed of properly can find their way into groundwater and streams and contaminate water supplies hundreds of miles away.

Most of Pennsylvania is an upland from which water flows via four major drainage systems through or past 15 other states, the District of Columbia, and two provinces of Canada before reaching the Atlantic Ocean and the Gulf of Mexico. Water from much of the interior of Pennsylvania flows down the Susquehanna River into Chesapeake Bay, which also receives water from a small area of south-central Pennsylvania through tributaries of the Potomac River. Delaware Bay receives water from many industrial areas of eastern Pennsylvania that line the Delaware, Lehigh, and Schuylkill Rivers. Most water from western Pennsylvania flows into the Allegheny and Monongahela Rivers, which meet at Pittsburgh to form the Ohio River. At Cairo, Ill., the Ohio River discharges into the Mississippi River, which carries Pennsylvania's water to Louisiana and the Gulf

of Mexico. Water from the lakeshore region of Erie County and from part of Potter County drains into the Great Lakes, then follows the St. Lawrence River through eastern Canada. Rivers also bring water into Pennsylvania from adjacent states. Lake Erie brings water to our shore from streams as far away as Minnesota.

It is now common to carefully plan trash-disposal sites and line them using clays and other materials as barriers to water movement. The barriers can help prevent pollution from entering water supplies. We no longer think of Earth's resources as infinite. The ocean once seemed so huge that nothing could possibly pollute it. Today, we know that some pollutants stay around for a long time and build up until their effects can no longer be overlooked, even in the ocean. Awareness of this, and of the natural systems that govern everything on Earth, is making us think more about what we are doing and how we might do it better.

In these pages, we have journeyed through time from the Big Bang and the origins of the universe to the present. We have seen a dramatic sequence of events that has led to the development of modern-day Pennsylvania. We have also seen the importance of understanding this geologic history so that we can locate raw materials. Understanding the geologic framework allows us to reduce damage to property by predicting where geologic hazards might occur, and it allows us to avoid the mistakes of the past and to better protect the environment.

There are few aspects of life that are not dependent on geology. Nearly every object, every building, every vehicle, every appliance, is made from raw materials that come from the ground. Even food and raw materials such as cotton, wool, and wood are affected by geology because of the dependence of plants and animals on nutrients from the soil. Energy is stored in the ground in the form of oil, gas, uranium, and coal. The use of geothermal energy, using the heat of the earth's interior, is becoming more common. Without water, our most precious resource, life itself would not be possible.

Today, we are faced with possibly our greatest environmental challenge, climate change. Whether the warming that has been observed is a result of natural processes, man-made carbon dioxide emissions, or a combination of the two, the result may be a significant sea-level rise, shifting climate zones, storms, or the migration of plant and animal species. There is evidence that we are already starting to see some of these effects.

Despite our best efforts, we cannot live on earth and use its resources without changing it. Our challenge is to keep the changes as small as possible. Adopting alternative energy sources combined with other measures may help us to meet that important challenge.

## ACKNOWLEDGMENTS

The fourth edition of *The Geological Story of Pennsylvania* uses much of the material that was in the third edition, and the authors are grateful to the reviewers listed in that volume. In addition, they acknowledge the thorough review of this publication by Kristin M. Carter, Economic Geology Division Manager and Assistant State Geologist, Pennsylvania Geological Survey, and Jeb Baxter, professor of physical science and geology, Harrisburg Area Community College. Mark A. Brown, staff geologist (and astronomer), Pennsylvania Geological Survey, lent his expertise to the section "A Dim, Distant Past," and fellow Survey geologist Caron E. O'Neil provided helpful changes to the section "The Hadean, Archean, and Proterozoic." The authors also thank Caron for her editorial improvements and technical support in the preparation of this booklet.

## CREDITS FOR ILLUSTRATIONS

**River scene (p. 1).** From Rogers, H. D., 1858, The geology of Pennsylvania—A government survey: Pennsylvania Geological Survey, 1st ser., v. 1, opposite p. 211 [Printed by William Blackwood and Sons, Edinburgh].

**Gneiss (p. 4).** From Lapham, D. M., and Geyer, A. R., 1962, Common rocks and minerals of Pennsylvania: Pennsylvania Geological Survey, 4th ser., Educational Series 1, p. 17.

**South polar region of the moon (p. 7).** An uncontrolled image mosaic provided by the U.S. Geological Survey. Images from the Clementine mission.

**Microplates of the Laurentian block (p. 10).** Modified from Hoffman, P. F., 1988, United plates of America, the birth of a craton—early Proterozoic assembly and growth of Laurentia: Annual Review of Earth and Planetary Sciences, v. 16, Fig. 1, p. 544.

**Land and sea in the Late Cambrian (p. 11).** Modified from Dott, R. H., Jr., and Batten, R. L., 1988, Evolution of the earth (4th ed.): New York, McGraw-Hill, Fig. 11.8, p. 279.

**Location of carbonate rocks (p. 12).** Modified from Pennsylvania Geological Survey, 1990, Limestone and dolomite distribution in Pennsylvania (4th ed.): Pennsylvania Geological Survey, 4th ser., Map 15, scale 1:2,000,000.

**Ordovician tectonic events (p. 13).** Modified from Dott, R. H., Jr., and Batten, R. L., 1988, Evolution of the earth (4th ed.): New York, McGraw-Hill, Fig. 12.33, p. 331.

**Areas of evaporite minerals (p. 15).** Modified from Alling, H. L., and Briggs, L. I., 1961, Stratigraphy of Upper Silurian Cayugan evaporites: AAPG Bulletin, v. 45, Fig. 8, p. 541.

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**Geologic map of Pennsylvania (centerfold).** Modified from Pennsylvania Geological Survey, 2007, Geologic map of Pennsylvania (3rd ed., 4th printing, slightly revised): Pennsylvania Geological Survey, 4th ser., Map 7, scale 1:2,000,000, and Sevon, W. D., compiler, 2000, Physiographic provinces of Pennsylvania (4th ed.): Pennsylvania Geological Survey, 4th ser., Map 13, scale 1:2,000,000.

**Environments of coal deposition (p. 21).** Modified from Edmunds, W. E., and Koppe, E. F., 1968, Coal in Pennsylvania: Pennsylvania Geological Survey, 4th ser., Educational Series 7, p. 6.

**Supercontinent Pangea (p. 24).** Modified from Bally, A. W., 1989, North America; plate-tectonic setting and tectonic elements, chap. 1 *of* Bally, A. W., and Palmer, A. R., eds., The geology of North America—An overview: Boulder, Colo., Geological Society of America, Decade of North American Geology, v. A, Fig. 9, p. 9.

**Location of rift basins (p. 26).** Modified from Manspeizer, Warren, DeBoer, Jelle, Costain, J. K., and others, 1989, Post-Paleozoic activity, chap. 6 *of* Hatcher, R. D., Jr., and others, eds., The geology of North America—The Appalachian-Ouachita orogen in the United States: Boulder, Colo., Geological Society of America, Decade of North American Geology, v. F–2, Fig. 3, p. 323.

**Glaciation in North America (p. 29).** Modified from Prest, V. K., Grant, D. R., and Rampton, V. N., compilers, 1968, Glacial map of Canada: Geological Survey of Canada, Map 1253A, scale 1:5,000,000.

**Glaciation in Pennsylvania (p. 30).** Modified from Sevon, W. D., and Braun, D. D., 1997, Glacial deposits of Pennsylvania (2nd ed.): Pennsylvania Geological Survey, 4th ser., Map 59, scale 1:2,000,000.

**Coal fields of Pennsylvania (p. 35).** Modified from Pennsylvania Geological Survey, 2000, Distribution of Pennsylvania coals (3rd ed., revised): Pennsylvania Geological Survey, 4th ser., Map 11, scale 1:2,000,000.

**Number of feet beyond flood stage (p. 38).** Modified from Sevon, W. D., 1972, The flood and the Survey: Pennsylvania Geology, v. 3, no. 4, Fig. 1, p. 22.

**Geologic time scale (back cover).** Ages from International Commission on Stratigraphy, 2013, International Chronostratigraphc Chart, v. 2013/01, http://www.stratigraphy.org/index.php/ics-chart-timescale (accessed on November 6, 2013).

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# GEOLOGIC TIME SCALE

| AGE (millions of years) | ERA OR EON | PERIOD | ACTIVITY AFFECTING PENNSYLVANIA | MAIN ROCK TYPES OR DEPOSITS IN PENNSYLVANIA | SOME DOMINANT LIFE-FORMS IN PENNSYLVANIA |
|---|---|---|---|---|---|
| 0-2.6 | CENOZOIC ERA | QUATERNARY | Glaciation; periglacial erosion and deposition; formation of Lake Erie | Sand, silt, clay, gravel | Hominids (esp. man) and other mammals, grasses, flowering plants |
| 2.6-66 | | TERTIARY | Weathering and erosion; creation of landscape south of glaciated areas | Sand, silt, gravel | Primates (first hominids) and grazing mammals, birds, flowering plants, grasses |
| 66-145 | MESOZOIC ERA | CRETACEOUS | Erosion and weathering | Clay, sand | Dinosaurs, reptiles, mammals, birds, rays, sharks, ammonites |
| 145-201 | | JURASSIC | Diabase intrusions; opening of Atlantic Ocean | Diabase | Dinosaurs, reptiles, mammals, birds, ammonites, rudistid bivalves, conifers, cycads |
| 201-252 | | TRIASSIC | Separation of Africa from North America; sedimentation in rift valley | Shale, sandstone, conglomerate, siltstone | Early dinosaurs, reptiles, early mammals and birds, conifers, cycads, seed plants |
| 252-299 | PALEOZOIC ERA | PERMIAN | **Alleghanian Orogeny:** Collision of Africa and North America creates Appalachian Mtns; thrust faulting, folding; erosion | Sandstone, shale | Conifers, fungi, insects and other arthropods, amphibians, reptiles |
| 299-359 | | PENNSYLVANIAN AND MISSISSIPPIAN (Carboniferous) | Erosion of southeast highland; deltaic transitioning to alluvial deposition; development of alluvial plain | Sandstone, siltstone, shale, conglomerate, coal, limestone | Land plants, crinoids, foraminiferans, insects, bryozoans, brachiopods, amphibians, air-breathing snails, early reptiles |
| 359-419 | | DEVONIAN | **Acadian Orogeny:** Collision of Avalonia, Europe, North America; formation of Catskill Delta | Sandstone, siltstone, shale, conglomerate, limestone | Armored and lobe-finned fish, tetrapods, brachiopods, reef corals, ammonoid cephalopods, insects, land plants |
| 419-443 | | SILURIAN | Erosion of mountains; deposition of sand and mud | Sandstone, shale, quartzite, siltstone, limestone | Crinoids, brachiopods, corals, reef-building stromatoporoids, jawed and jawless fish |
| 443-485 | | ORDOVICIAN | **Taconic Orogeny:** Thrusting of volcanic arc; development of Appalachian basin | Limestone, dolomite, shale, sandstone, siltstone, chert, schist, gneiss, phyllite | Trilobites, graptolites, mollusks, bryozoans, conodonts, echinoderms, jawless fish |
| 485-541 | | CAMBRIAN | Transgression of the sea; carbonate deposition | Limestone, dolomite, quartzite, sandstone, shale, schist, gneiss | Trilobites, brachiopods, hyoliths, bizarre "Burgess Shale"-type life-forms |
| 541-2,500 | PROTEROZOIC EON | Geologic time older than Cambrian is commonly referred to as Precambrian | Accretion of microplates to form Laurentia | Gneiss, serpentinite, metabasalt | Blue-green algae, Ediacaran life-forms, jellyfish, worms |
| 2,500-4,000 | ARCHEAN EON | | Bombardment by comets and asteroids; creation of continental crust | None identified in Pennsylvania | Bacteria |
| 4,000-4,600 | HADEAN EON | | Formation of Earth and solar system | None identified in Pennsylvania | None identified |