GEOLOGY OF NEW YORK

A Simplified Account

Educational Leaflet No. 28

The University of the State of New York
The State Education Department
Albany, New York 12230

Geology of New York

A Simplified Account

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PREFACE

The New York State Geological Survey was founded in 1836 and is the longest continuously operating geological survey in the world after the national surveys of France and Great Britain. In 1986, our sesquicentennial year, this book and the accompanying *New York State Geological Highway Map* were conceived as especially worthy projects to celebrate our 150th birthday.

The first *Geology of New York* was published by the Survey in 1966. At the end of the Foreword, we stated that the publication was only a progress report and that "at any time, a new breakthrough in knowledge could necessitate a different translation of the record written in the rocks." The revolutionary new concept of plate tectonics (summarized in Chapter 3) came shortly afterward, and in succeeding years we have gained an understanding of the geological history of the State and surrounding areas in terms of plate tectonic theory.

Thanks to this theory, we can now speak of past continents colliding to form supercontinents; of suture zones along the lines of collision, some with fragments of oceanic crust that testify to closed ocean basins; pieces of proto-Africa stuck to North America; and rift zones where supercontinents broke apart. New York State has been the site of mountains as high as the Himalayas, wide seas, rifts as spectacular as the East African Rift system, seas as warm as the Caribbean, and climates as cold as Greenland. Evidence for these dramatic events is recorded in the rocks of New York and can be observed by an interested student.

The geological history of New York State is long and complex. In the text of this publication, we have attempted either to minimize the use of scientific terms or to define them where they are introduced. To further help comprehension, a glossary has been included. We have made an effort to keep the language clear and readable, although many of the ideas presented are both unfamiliar and complex. We suggest that teachers review the sections that are relevant to their classes and decide which parts to assign or interpret for their students.

As a natural laboratory that is easily accessible to a large population, the diverse geology in New York is perhaps without peer in North America. The State contains parts of several major geologic provinces: the Canadian Shield, the Taconic thrust belt, the Alleghanian fold and thrust belt, the Allegheny Plateau, a Mesozoic rift basin, the marine coastal plain, and the modern continental shelf, continental slope, and continental rise. The varieties of rocks and structural style in each of these provinces provides a wealth of instructive material, and comparisons among the various provinces challenge scientific thought at all levels.

We view these publications as part of the renewed national effort to improve scientific literacy in America. We hope that they will pique students' curiosity about natural phenomena, help earth science teachers prepare a more interesting course by giving them insights into the local geology, provide accurate and appropriate material for training earth science teachers, and give the public a window into the geology that begins in their backyards.

Welcome, then, to the geology of New York. The Niagara River cascading over a thick ledge of Silurian dolostone at the American Falls; the Adirondacks' High Peaks cut out of feldspar-rich "moon-like rock"; the Palisades of the Hudson—a rampart of Mesozoic basalt pillars; and Long Island—a giant "sand pile" dumped at the front of a melting Pleistocene continental glacier. Each of New York's magnificent scenic features, indeed our entire landscape, derives its shape from the composition and structure of the geologic materials beneath it and from the geologic processes that have acted upon it. The history of human settlement in New York from the earliest Indians to present-day Empire Staters has been greatly influenced by the geology of the State.

More than a billion years of geologic history are recorded in the rocks of New York State. This record tells of repeated submergences beneath shallow seas, of mountain-building, of volcanoes, dinosaurs, and wooly mammoths, of lush tropical forests and frigid continental glaciers. As geologists continue to study exposures of rock and sediment in New York, that history becomes refined—new chapters are added and details revealed—yet the basic saga remains relatively intact. We must understand the geologic record if we expect to understand our planet, protect ourselves from geologic hazards such as earthquakes and floods, and find and develop our mineral resources.

Robert H. Fakundiny
State Geologist

ACKNOWLEDGMENTS

The scientific publications of a great number of geologists provided the basis for this book.

The editors also wish to acknowledge the efforts of a number of colleagues. Timothy Mock and Richard Nyahay provided geologic assistance. Barbara Tewksbury helped to edit Chapters 4 and 7 and created the 61 diagrams in Figure A.4. Craig Chumbley provided technical review for Chapter 11. Robert Allers helped with the chapters on glaciation. Eva Gemmill provided editorial assistance. Robert H. Fakundiny offered many helpful suggestions on improving the manuscript and figures. Donna Jornov and Patricia Thela provided splendid clerical support. John B. Skiba provided us with his expert advice and assistance with graphic presentation. Rachel Garrison, Roberta Wilson, and Mike Storey drafted many of the figures.

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PART I

Background

CHAPTER 1
FIRST THINGS FIRST
Introduction[1]

The surface of the earth is a sculpture that is never finished. Year after year, century after century, the rind of rocks enveloping the globe continues to change. Even the "everlasting hills" are temporary; wind, water, and ice will, in time, erode the very highest mountains down to sea level.

Some of the forces that shift and rearrange the earth's crust are swift and dramatic. Rocks on the side of a mountain break free and cascade to the valley floor. Without warning, a volcano erupts along the west coast of North America or in the South Pacific; farms and villages nestled at the foot of the mountain are left buried beneath a blanket of lava. Off Iceland, a new volcanic island rises from the ocean floor. All of Alaska shudders in earthquake shock as the rocks yield at last to stresses that built up for centuries.

Modern examples of geologic change are all around the edge of the Pacific Ocean—the northward shift of western California along the San Andreas fault; the Aleutian Island volcanoes of Alaska; the rise of coastal mountain ranges in North, Central, and South America; earthquakes of the Pacific coast of Asia; the volcanic islands of Japan, the Philippines, the East Indies, New Guinea, and New Zealand. In all these places, we find one or more of the geologic processes that happen during mountain-building: periodic earthquakes, erupting volcanoes, and deformation of rocks deep underground.

Less dramatic changes occur in the earth's crust as well. In the 10,000 years since the ice sheets of the Pleistocene Epoch melted, the crust of northern North America, relieved of that enormous weight, has risen steadily. In Montreal, Canada, the ocean deposited beach sands with marine shells and whale bones immediately after the ice sheets' retreat. Those beaches are now 165 m above sea level on Mount Royal in the heart of Montreal. Thus, the "solid" rock of the earth's crust can be squashed down and later spring back, like bread dough.

Today the crust is relatively stable in New York State. It has not always been that way! Rocks that were formed as flat layers in shallow seas now lie well above sea level and are tipped, folded, and contorted. Even the highest mountains in New York State contain rocks that were deposited in a quiet sea. The rocks of New York contain evidence that our State has had a long and complex geologic history. There have been repeated floodings by the sea, at least four major cycles of mountain-building, and multiple advances of thick glacial ice. In some areas, the rocks even tell us of nearby ancient volcanoes, long since eroded away.

This book comes with a companion publication, *New York State Geological Highway Map*, which supplements it. The map sheet is printed on plastic instead of paper for durability. Together, these two publications are for people who are interested in the ground they stand on—both in their own backyards and throughout the State. What is the land made of? Where did it come from? How did it get the way it is today? What lies beneath? How old is it? What is its geologic future? What explains the diversity of landforms in the State?

The outline of the text can be seen in the table of contents. By using it, you can jump directly to any area of particular interest. However, we advise at least a preliminary glance at Plates 1 and 4 of the *Geological Highway Map* and Chapter 3 of this book, to provide a regional background.

If you would like to find out about the geology of a particular area, the map in Figure 1.1, which shows regions of the State, will be useful. Chapters 4 through 10 cover bedrock geology by region. Glacial features are covered by region in Chapter 13.

[1]By Y.W. Isachsen

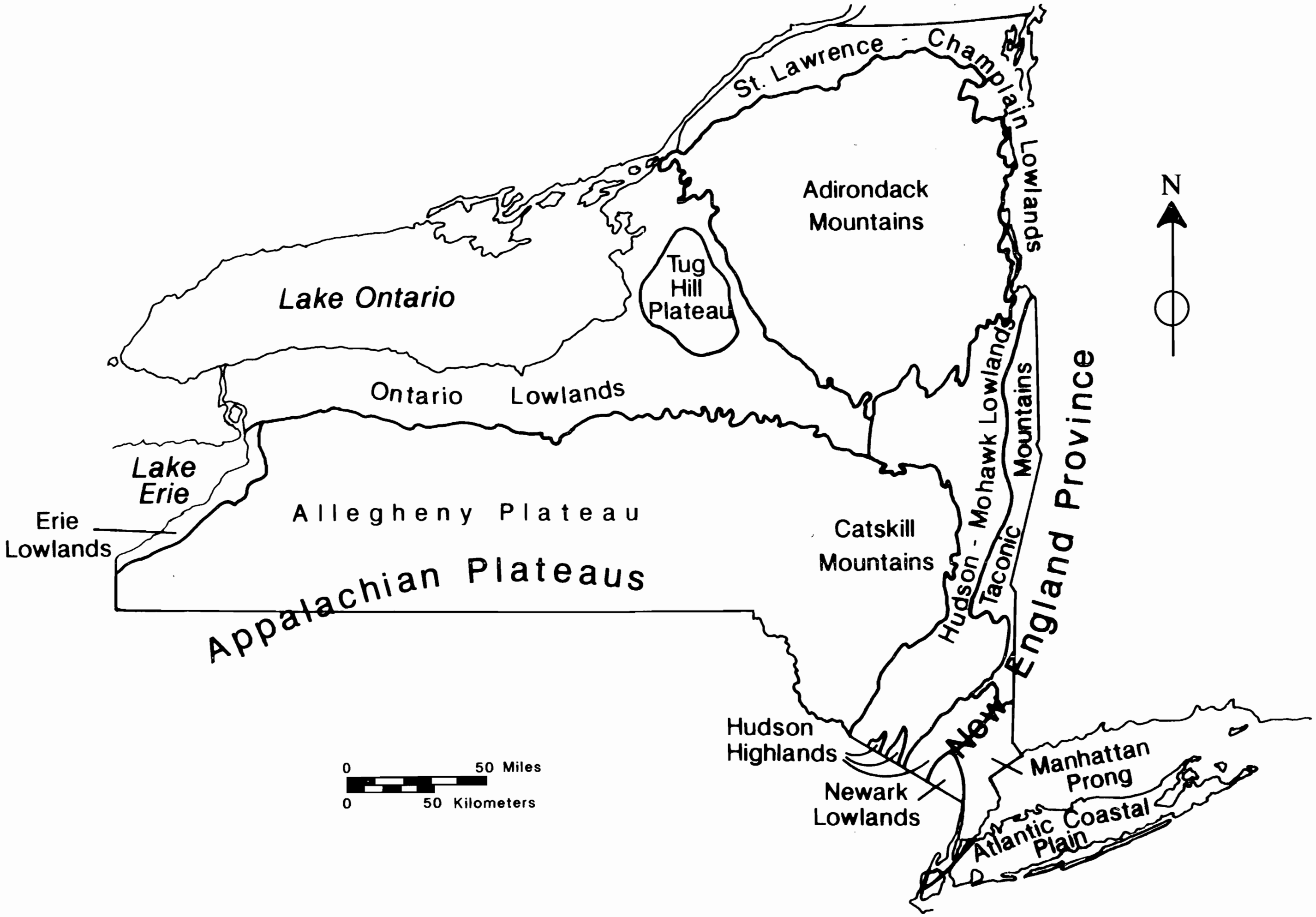


Figure 1.1. Regions of New York State used in discussing bedrock geology (in Chapters 4 through 10) and glacial features (in Chapter 13).

CHAPTER 2
CLOCKS IN THE ROCKS
Measuring Geologic Time[1]

SUMMARY

Geologic history takes in a vast amount of time, close to 4.6 billion years. The relative time scale, which is based mainly on observations about rocks and the fossils they contain, puts geologic events in historical order. The discovery of radioactivity and the development of radiometric dating gave us the first reliable way to create a quantitative time scale. This scale assigns ages, in years before the present, to the events in the relative time scale.

INTRODUCTION

In order to understand geology, we have to understand the vast scale of geologic time. The earth as we know it is the product of 4.6 billion years of changes. These changes are usually very slow, but occasionally they may be rapid or even catastrophic, like an earthquake, volcanic eruption, or landslide.

Through geologic time, continent-size pieces of the earth's crust collide, break apart, and grind sideways past each other. Mountains are built and eroded. Sediments are deposited, compacted, and turned into rock. That rock may in turn be deformed by stress or metamorphosed by heat and pressure. Molten rock rises from the earth's interior, cools, and forms igneous rock. Most of these processes are so slow that the changes they produce during one human lifetime can scarcely be noticed. In fact, the amount of time involved is so immense that it's extremely difficult to imagine. Here's one way to think about it.

Suppose the entire history of the earth were compressed into one year. Most of the year would be taken up by the Precambrian, that long age that started 4.6 billion years ago with the origin of the earth. Life began in the Precambrian; the oldest known fossil-bearing rocks were formed about 3.5 billion years ago (about March 28 of our imaginary geologic year). We still know relatively little about the earliest life-forms, because most of them were very small or soft-bodied and were seldom preserved as fossils. In addition, most of the very old rocks have either been eroded away or deformed and metamorphosed enough to destroy any fossils that might once have been present.

The Cambrian Period, when marine animals with easily fossilized hard parts (such as shells or bones) first became abundant, would start late on November 18. The dinosaurs would appear on December 13 and would survive for 13 days, to disappear late on December 26. The first humans wouldn't show up until shortly after 8PM on December 31. All of written human history would fit in the last 42 seconds of New Year's Eve. The average lifetime of a late 20th century American would occupy the last half second before midnight.

Yet despite humanity's late appearance on the scene, we have been able to piece together a picture of the earth's history. That history is summarized in the geologic time scale (Figure 2.1). This time scale was constructed in two stages. First came our study of rocks and the sequence of fossils and deductions about what changes had happened and in what order. The resulting list of events is a *relative time scale.* Then, early in this century, radioactive "clocks" were recognized that could be used to calculate the number of years between events. This process made it possible to create a quantitative time scale.

THE RELATIVE TIME SCALE

Relative geologic time refers to the order in which things happened—which events are older and which are younger. Much of the evidence for relative geologic time is based on simple, commonsense observations. For example, in undisturbed sedimentary layers or lava

[1] Adapted from a manuscript by P.R. Whitney.

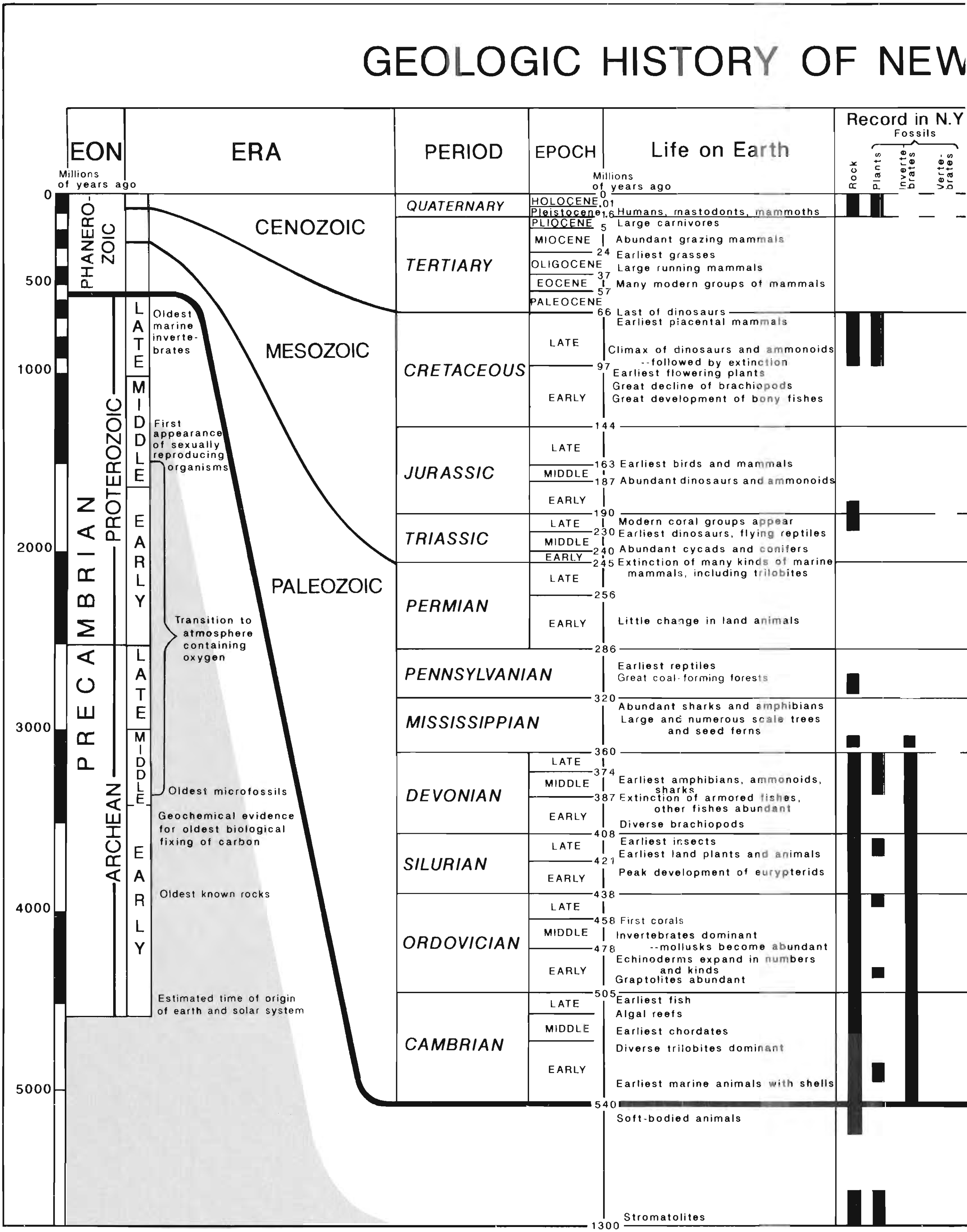
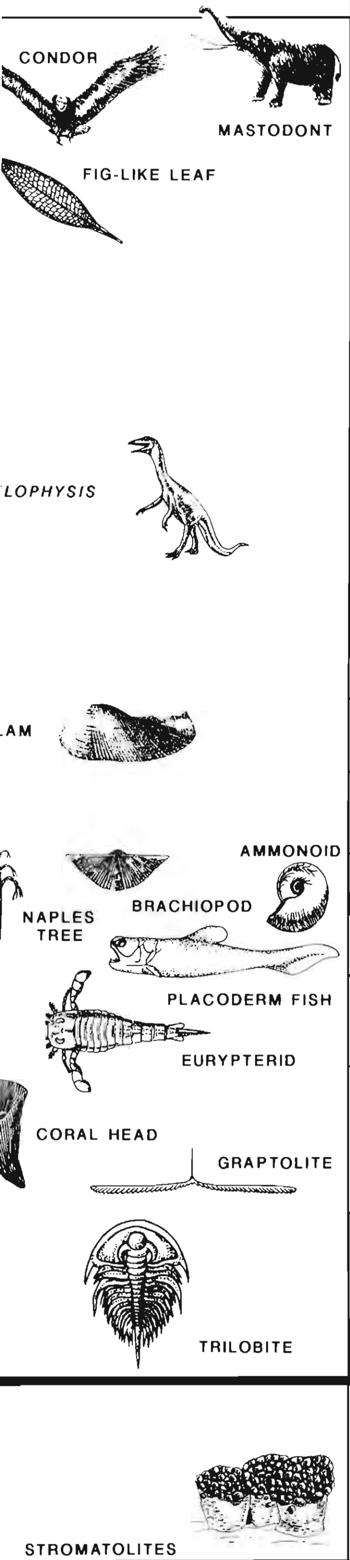


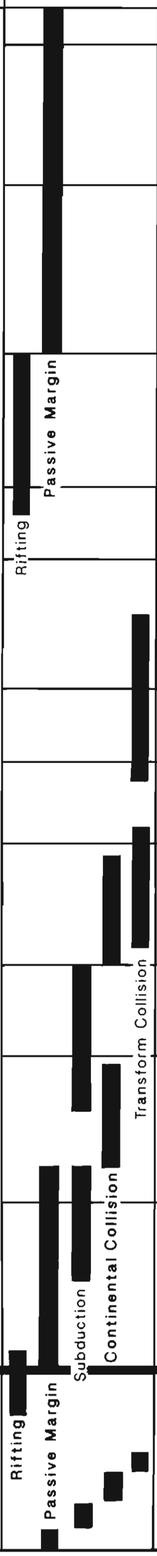
Figure 2.1. This figure includes the geologic time scale. In the left-hand part of the chart, the columns headed "EON," "ERA," "PERIOD," and "EPOCH" make up the relative time scale. The two columns headed "Millions of years ago" convert it to the quantitative time scale. The rest of the figure summarizes important events in the geo-

YORK STATE AT A GLANCE

Important Fossils of New York

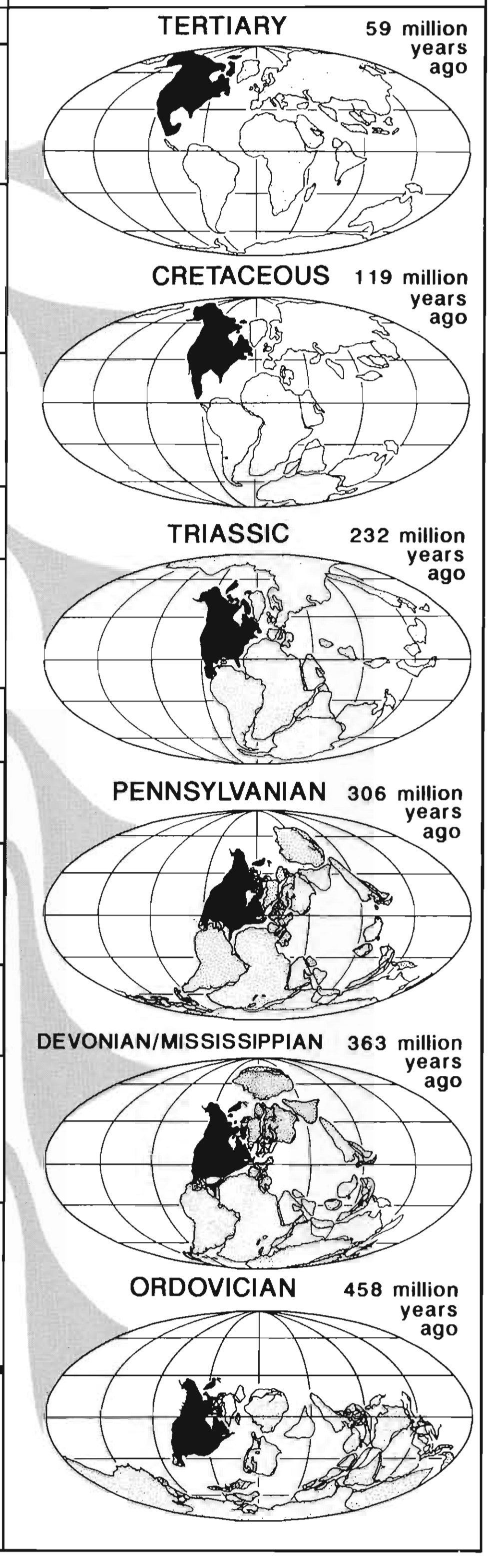


Tectonic Events Affecting Northeast North America



Important Geologic Events in New York
Advance and retreat of last continental ice
Uplift of Adirondack region
Sandstones and shales underlying Long Island and Staten Island deposited on margin of Atlantic Ocean Development of passive continental margin Kimberlite and lamprophere dikes
Atlantic Ocean continues to widen Initial opening of Atlantic Ocean
Intrusion of Palisades Sill Rifting
Massive erosion of Paleozoic rocks Alleghanian Orogeny caused by collision of North America and Africa along transform margin
Catskill Delta forms Erosion of Acadian Mountains Acadian Orogeny caused by collision of North America and Avalon and closing of remaining part of Iapetus Ocean
Evaporite basins; salt and gypsum deposited
Erosion of Taconic Mountains; Queenston Delta forms Taconian Orogeny caused by closing of western part of Iapetus Ocean and collision between North America and volcanic island arc
Iapetus passive margin forms
Rifting and initial opening of Iapetus Ocean Erosion of Grenville Mountains Grenville Orogeny: granite and anorthosite intrusions Subduction and volcanism Sedimentation, volcanism

Inferred Position of Earth's Landmasses



logic history of the world and of New York State. (The words used in the column "Tectonic Events Affecting Northeast North America" are explained in Chapter 3. The term *transform collision* refers to a collision that takes place along a transform margin.)

flows, the rocks at the bottom of the stack were obviously deposited before the younger rocks above. This principle is known as *superposition*. Similarly, where layered rocks have been partly worn away by erosion and new ones deposited on the eroded surface, the worn layers are older. Where molten rock has risen from below and cut across layers in the rocks already there, we easily see that the once-molten rock is younger. By combining such observations we can construct a relative time scale for any given area.

But how do we determine the relative ages of events in one area compared with those in another? Fossils in sedimentary rocks give us valuable clues!

Geologists in the late 18th and early 19th centuries studied sedimentary rocks whose relative ages were known from simple observations like superposition. They observed that many fossils in older rocks were never found in younger rocks; such species had become extinct with the passage of time. These geologists also found that new fossil species appeared in younger rocks. They noticed that fossils in the older rocks were very unlike modern, living organisms; fossils in younger rocks became progressively more like living plants and animals. They observed that these changes were in the same order in rocks all over the world. This fact led to the conclusion that fossils provided *time markers*. In other words, by observing what fossils are present, geologists were able to *correlate*, or match up, sedimentary rocks of the same age, even when those rocks were far apart.

These methods tell us which rocks are the same age, which are older, and which are younger. When we know the ages of rocks relative to each other, we can construct a relative time scale. But these methods don't tell us how long ago the rocks were formed. To find this information, we need a method for measuring geologic time in years or millions of years. This method will be discussed in the next section.

The relative time scale we use today is the result of information that has been collected for two centuries throughout the world. It is a result of direct observations on fossils and rocks and is continually being tested and refined. The Phanerozoic Eon (Figure 2.1) is that part of earth's history that began with the Cambrian Period, when animals with shells, bones, or other hard parts first appeared. Animals without hard parts are very rarely preserved as fossils. Because we have more fossils from the Phanerozoic Eon than from earlier (Precambrian) time, we understand its history in far greater detail. It has been subdivided into eras, periods, epochs, and smaller time divisions on the basis of fossils (Figure 2.1). This detailed time scale, however, covers only the last one-eighth of the history of the earth.

It has been more difficult to subdivide the earlier seven-eighths of geologic time, in part because of the scarcity of fossils. *Radiometric dating*, a method developed during the 1930s and widely used since about 1950, has proved to be very useful in studies of these older Precambrian rocks. It has also helped refine the Phanerozoic time scale and determine just how long ago the events in that relative time scale took place. This method provides the basis for a *quantitative time scale*.

Developing a Quantitative Time Scale

It has long been clear that the processes that shaped the earth must have taken an immense amount of time. It has been more difficult, though, to figure out just how much time and to express it in years.

Early geologists tried to figure out how fast erosion happened, sediments were deposited, and dissolved salts accumulated in the oceans. They compared those estimates with the results we see today to figure out how long it would take to produce such results. However, the rates of most geologic processes are both variable and very difficult to measure. Therefore, the answers that geologists got with these methods usually did not agree with each other. Obviously, another approach was needed in order to figure out the ages of rocks and to date the events in geologic history.

Radiometric Dating

The discovery of radioactivity led to an accurate method for determining ages. All atoms have a nucleus that contains *protons*—positively charged particles. Each atom of a specific chemical element has a fixed number of protons. (For example, atoms of carbon always have 6 protons, and atoms of oxygen always have 8 protons.)

The nucleus of an atom also usually contains *neutrons*—uncharged particles. Each chemical element consists of one or more *isotopes*. All atoms of a specific isotope have both a fixed number of protons and a fixed number of neutrons. (For example, the isotope carbon-12 contains 6 protons and 6 neutrons. The isotope carbon-14 contains 6 protons and 8 neutrons. Both isotopes are the element carbon.)

Some chemical elements have naturally occurring isotopes that are *radioactive*. (For example, potassium and uranium both have radioactive isotopes.) Radioactive isotopes are unstable: that is, atoms of a radioactive isotope (the *parent*) change into atoms of another isotope (the *daughter*) by giving off particles, energy, or both. This change, called *radioactive decay*, occurs at a constant rate that we can accurately measure in the laboratory.

Small amounts of several different radioactive parent isotopes exist in all rocks, along with the daughter isotopes produced by their decay. Modern laboratories can measure accurately the amounts of both parent and daughter isotopes in a rock or mineral sample. Since we know the rate of radioactive decay and can measure the amounts of parent and daughter in a rock, we can calculate how long ago that rock was formed—how long ago the radioactive "clock" started ticking.

This method is called *radiometric dating*. It can give us very accurate ages for some rocks and minerals. In general, it works best with igneous rocks and minerals that have not been metamorphosed. The heat and pressure required for metamorphism can "reset" the radiometric clock in a rock. Therefore, radiometric dating of a metamorphic rock may give the time when metamorphism occurred, not the time when the rock first formed. Sedimentary rocks can only rarely be dated by radiometric methods.

Radiometric dating has given us ages for the eras, periods, and epochs of the Phanerozoic relative time scale. It is also providing us with the information that is needed to construct a detailed time scale for the Precambrian. Both are summarized in Figure 2.1. The left-hand part of the figure, without the columns of numbers giving ages, is a relative time scale. Adding the numbers converts it to a quantitative time scale.

Review Questions and Exercises

Define the following terms as they are used in this chapter:

- relative time scale
- quantitative time scale
- superposition
- correlate
- time marker
- isotope
- radioactivity
- parent
- daughter
- radiometric dating

What methods were used to put together the relative time scale? The quantitative time scale?

Because geologic time is so long, the geologic time line in Figure 2.1 is not drawn to scale. On a long strip of paper, redraw the time line to scale.

CHAPTER 3
CONTINENTS ADRIFT
The Plate Tectonic History of New York State[1]

SUMMARY

The movement of tectonic plates on the earth controls the distribution of rocks and life on the planet. By applying the theory of plate tectonics to ancient rocks, geologists have deciphered much of New York's geologic history. The State's oldest rocks were deposited about 1.3 billion years ago in shallow seas. They were deformed and metamorphosed in the Grenville Orogeny, a continent-continent collision that occurred 1.1 to 1.0 billion years ago and produced a high mountain range and plateau. Over the next 400 million years, erosion reduced the mountains and plateau to flat lands. During this time, all the earth's continents became joined into one supercontinent. Then, about 660 million years ago, the supercontinent began to break apart and split along the east coast of proto-North America. New oceanic crust formed in the widening rift about 600 to 560 million years ago. The rift grew into the Iapetus Ocean. A very long volcanic island arc formed in the ocean about 550 million years ago, and volcanic activity lasted until about 450 million years ago. At this time, the island arc collided with proto-North America. The collision—the Taconian Orogeny—built a mountain range that extended from Newfoundland to Alabama. The mountains eroded as they rose, and rivers flowing down the western slopes carried the sediments into a shallow inland sea. Then, the remaining part of the Iapetus Ocean closed; the ensuing collision was the Acadian Orogeny. This orogeny built high mountains and a large plateau along the eastern part of the continent, but it had few direct effects in New York State. However, sediments eroded from the mountains formed the huge "Catskill Delta," which partially filled in the shallow sea. About 330 to 250 million years ago, proto-Africa slid past proto-North America along a transform margin. This collision, the Alleghanian Orogeny, built the Appalachian Mountains. As the mountains began to erode, sediments were dumped into the shallow sea and eventually forced it far to the south and west. As a result of these and many other orogenies, all the earth's continental crust was again joined in a supercontinent called Pangea. Pangea has been breaking apart in a worldwide rifting event that began 220 million years ago. After Africa separated from North America, the rift widened into the Atlantic Ocean. Today, the east coast of North America is tectonically quiet.

INTRODUCTION

The theory of *plate tectonics* has been called the "glue" that holds geology together because it relates all subdisciplines of geology to each other. Plate tectonic theory explains the mechanisms that move and deform the earth's crust. This movement and the interaction of the plates control the type and distribution of sedimentary deposits, the type and distribution of volcanic and other igneous activity, the location and intensity of earthquakes, and indeed the very evolution of life on this planet.

The outermost shell of the earth, called the *lithosphere*, is composed of rigid crust with an underlying layer of rigid mantle. The lithosphere floats on a soft, flowing shell of the mantle called the *asthenosphere* (Figure 3.1). The lithosphere is broken at present into about eight large and several smaller fragments, or *plates* (Figure 3.2),

[1]By A.E. Gates.

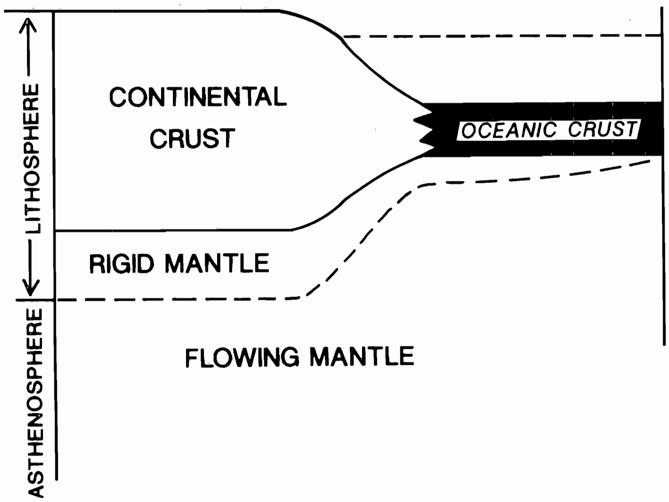


Figure 3.1. This diagram shows the general structure of the outer part of the earth. The outermost shell, the lithosphere, is made up of crust and rigid mantle. The asthenosphere below it is made up of flowing mantle. Notice that the light continental crust is much thicker and floats higher than the dense oceanic crust. Continental crust is normally about 35 km thick, whereas oceanic crust is normally about 10 km thick.

which resemble broken shell fragments on a hard-boiled egg. A plate may contain continental crust, which is thick (normally about 35 km) and of relatively low density; oceanic crust, which is thin (about 10 km) and of relatively high density; or pieces of both. Because of its high density, oceanic crust floats low on the asthenosphere and forms ocean basins. Continental crust floats high and commonly forms land. The North American plate, which includes continental as well as oceanic crust, extends to the middle of the Atlantic Ocean.

Convection currents, which are similar to the motion in a slowly boiling pot of oatmeal, occur in the asthenosphere. The plates move around the earth by riding the flow of these convection currents. The currents affect the plates in three ways.

1. They can stretch the crust and pull plates apart to form a *divergent margin* (Figure 3.3A).
2. They can push plates together to form a *convergent margin* (Figure 3.3B).
3. They can cause plates to grind sideways past each other to form a *transform margin* (Figure 3.3C).

A divergent margin usually begins as a splitting or *rifting* of continental crust. Molten rock from the mantle and lower crust seeps up to fill the gaps and forms volcanoes. It hardens there to form dense new rock called *basalt.* If rifting continues, the basalt will become new oceanic crust (Figure 3.4). Most divergent margins are under the oceans and are marked by a *mid-oceanic ridge.*

There are three types of convergent margins, depending upon the type of crust involved (Figure 3.5):

1. *ocean-ocean collisions,*
2. *ocean-continent collisions,* and
3. *continent-continent collisions.*

In an ocean-ocean collision, oceanic crust on one plate is driven beneath oceanic crust on another plate (Figure 3.5A). The down-going plate sinks into the asthenosphere and is consumed. This sinking process, called *subduction,* creates a volcanic *island arc,* which appears as a chain of volcanic islands on the overriding plate. Two modern examples are the Caribbean Islands and the Philippines.

In an ocean-continent collision, continental crust overrides oceanic crust (Figure 3.5B). The subduction process forms a *magmatic arc,* which appears as a mountain chain on the edge of the continent. Two modern examples are the Cascade Mountains along the west coast of North America and the Andes Mountains in South America.

Continent-continent collision events build mountains and are called *orogenies.* In a continent-continent collision, one continent may override another (Figure 3.5C). However, continental crust is very light and buoyant; it does not sink easily. Instead, the crust commonly piles up—something like an auto collision. The result is a wide area of uplift, highly deformed rocks, and greatly thickened crust. A modern example is the Himalayan Mountains and Tibetan Plateau.

Most transform margins occur on oceanic crust. At transform margins, rocks move sideways past each other. When a transform margin occurs on continental crust, the movement is accompanied by uplift of the earth's surface along some segments and downwarping on others. One modern example of a transform margin is the San Andreas fault in California. There, the Pacific plate on the southwest is slipping to the north past the North American plate.

Formation of New York's Oldest Rocks

The rocks in the northeastern United States record a long and complex plate tectonic history. The oldest rocks in New York State are part of the Grenville Province (see Figure 4.2). About 1.3 billion years ago, the continent that would become North America looked very different from today. This continent, called *proto-North America,* was largely covered by shallow seas. Sand, mud, and lime-rich muds accumulated in the seas. The underlying rock, which was eroded to make the sand, is unknown. We do know that it was much older. Grains of the mineral zircon in the sandstones formed from this sand have ages of 2.7 billion years. This age is the same as that for the Superior Province to the west.

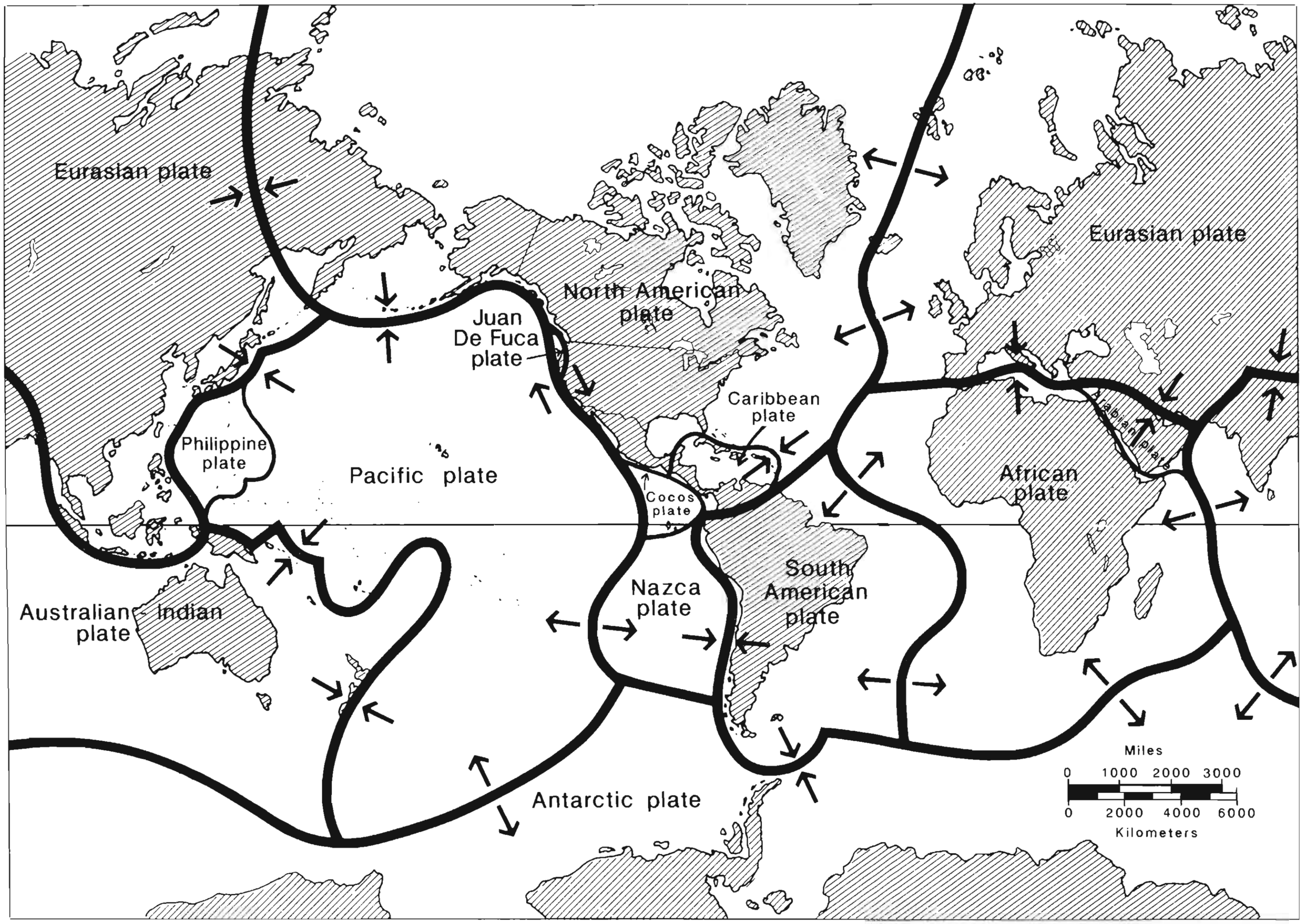


Figure 3.2. A simplified map showing how the lithosphere is broken into plates. The arrows indicate the relative movements between plates. The Juan De Fuca plate is moving toward North America.

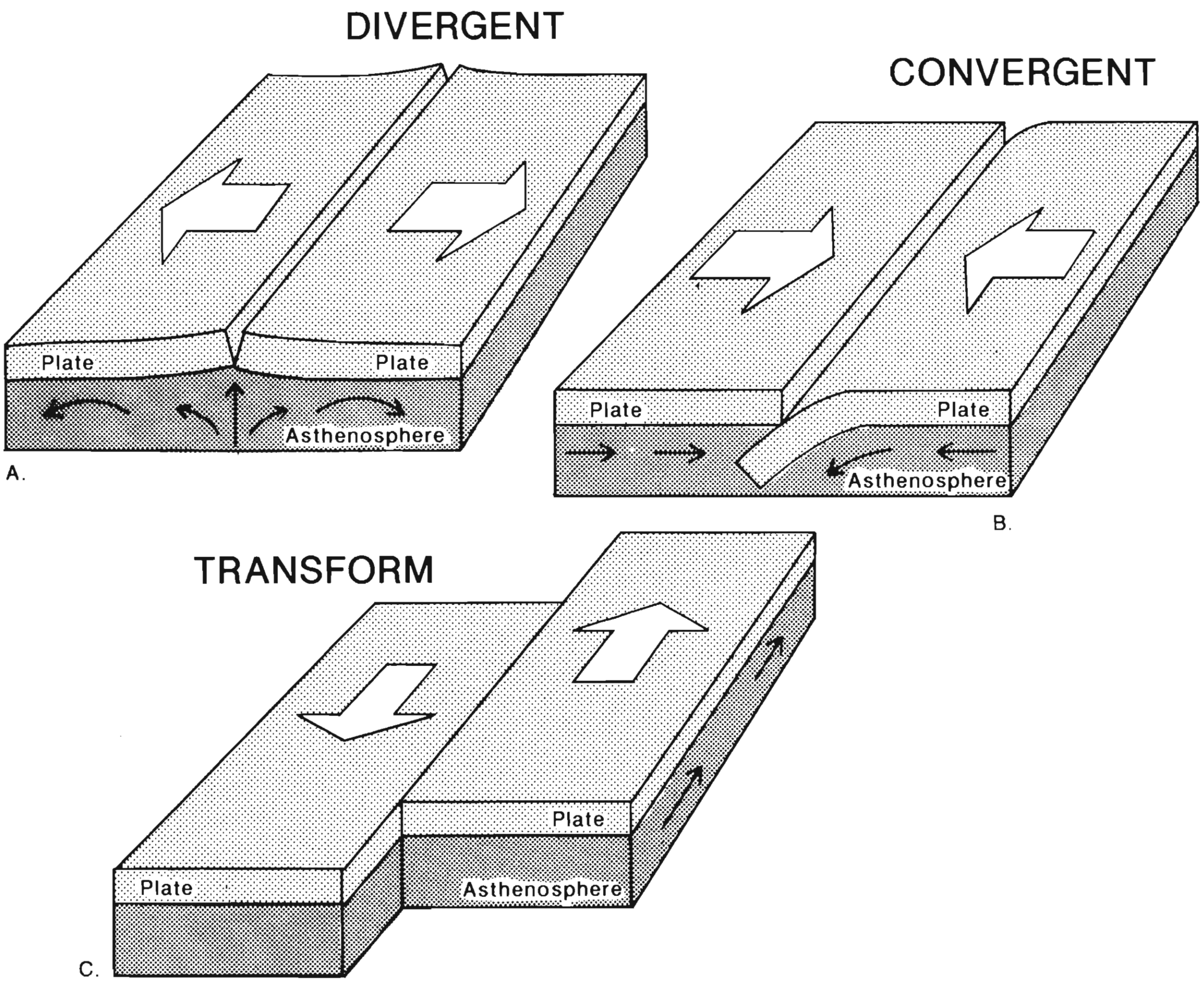


Figure 3.3. The three types of plate margins: (A) divergent; (B) convergent; (C) transform. The black arrows show the motion of convection currents in the asthenosphere.

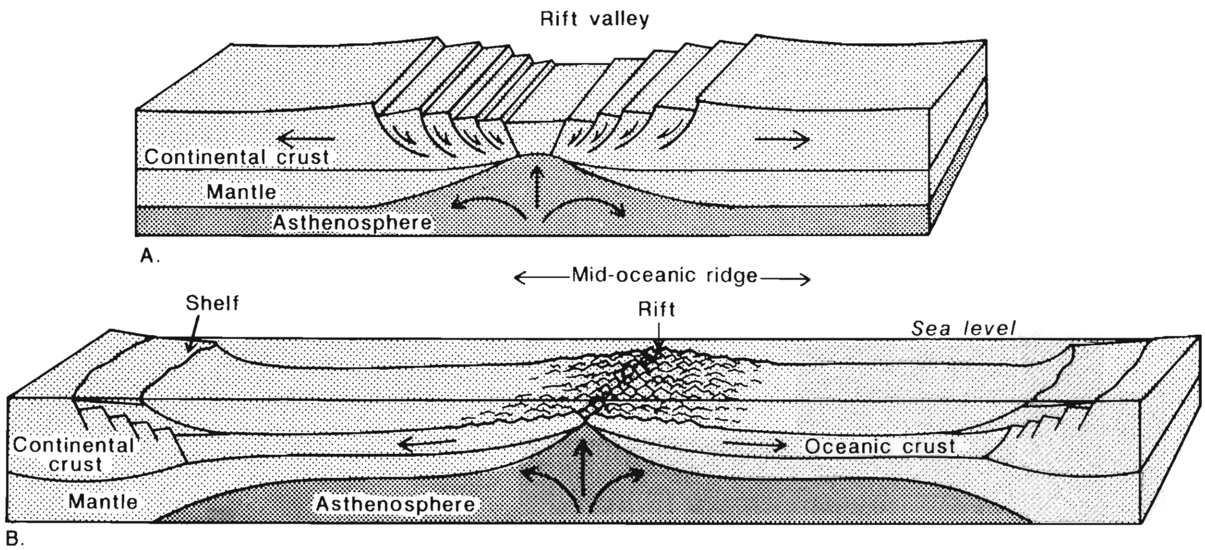


Figure 3.4. Two stages of rifting. In (A), the plate has begun to separate and a rift valley has formed. In (B), the rift has widened and become a new ocean basin between two new continents. Notice the mid-oceanic ridge in the basin.

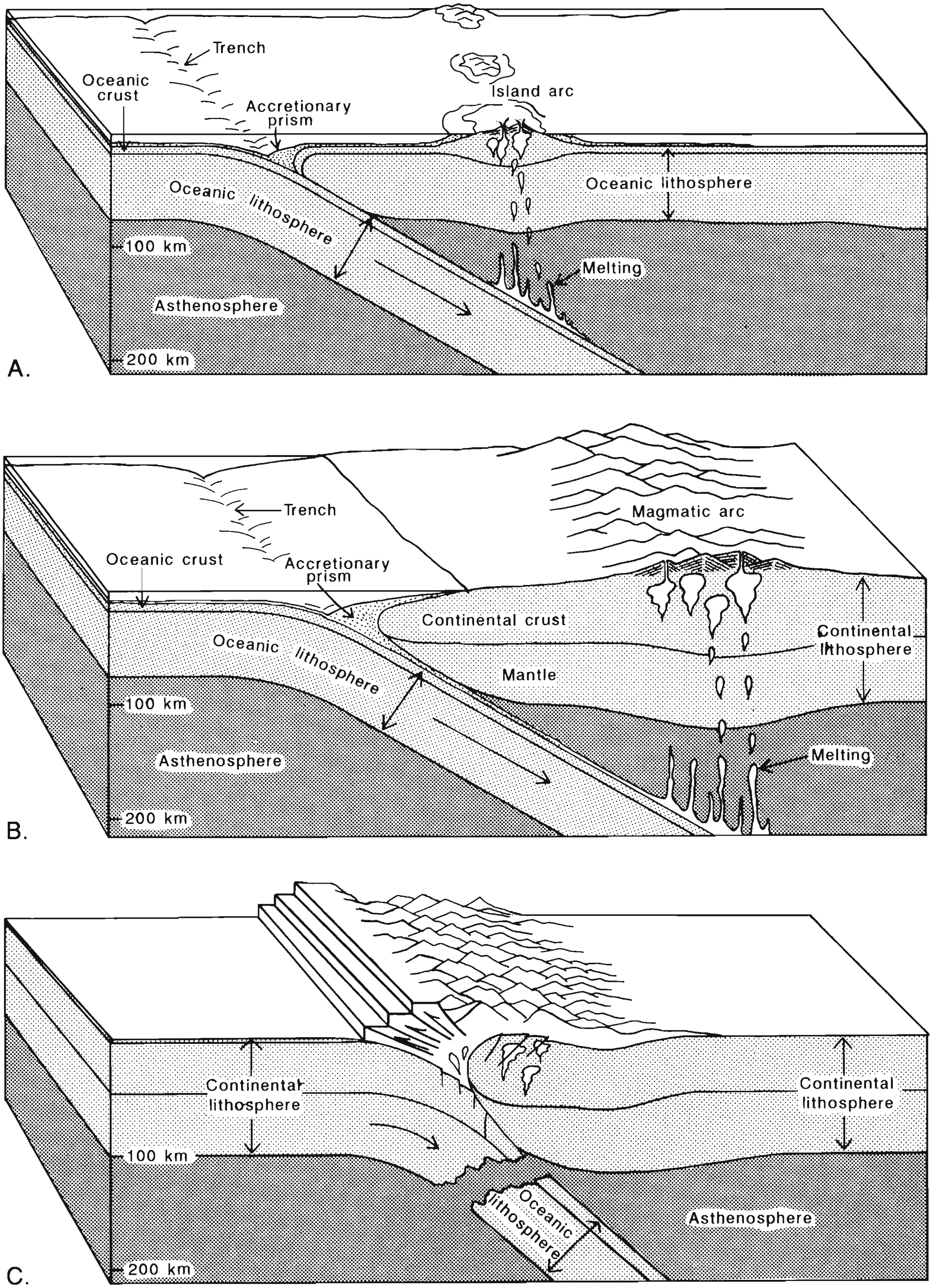
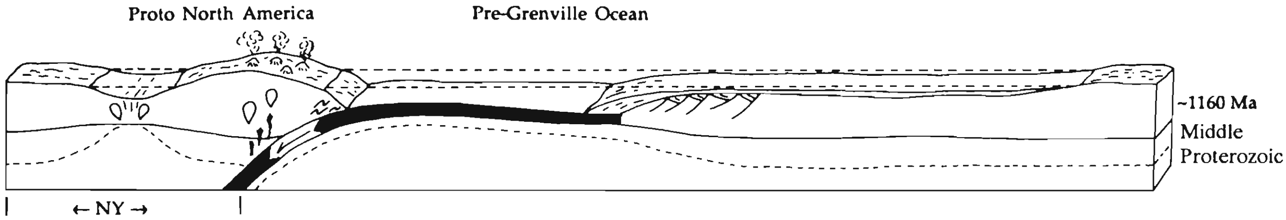
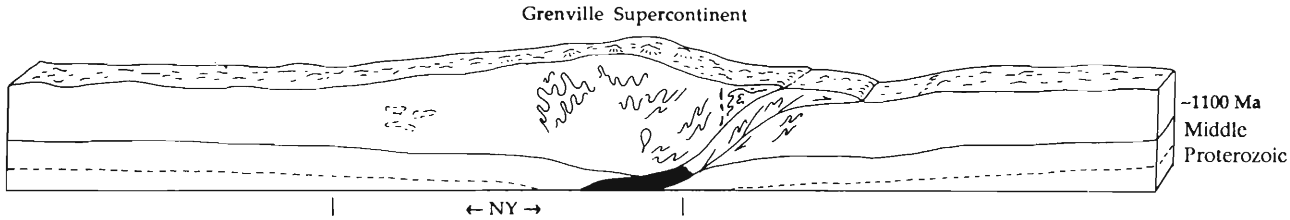


Figure 3.5. The three types of convergent margins: (A) ocean-ocean collision; (B) ocean-continent collision; (C) continent-continent collision. Notice that as the plates converge, the oceanic lithosphere is bent downward and is consumed in the asthenosphere.



Development of Magmatic Arc and Back Arc Rift

Figure 3.6. Block diagram showing subduction beneath proto-North America between 1.2 and 1.1 billion years ago. Notice the volcanoes in the magmatic arc and the rift beginning behind it. (Compare with Figure 3.1 to recognize continental and oceanic crust and the boundaries of the crust, lithosphere, and asthenosphere.)



Continued Grenville Orogeny

Figure 3.7. Block diagram section showing the results of the Grenville Orogeny. Notice the double-thick continental crust where the continent-continent collision built mountains and a high plateau.

Approximately 1.1 to 1.2 billion years ago, oceanic crust to the east of proto-North America began to subduct beneath it in an ocean-continent collision (Figure 3.6). A magmatic arc formed on the edge of the continent. Proto-North America began to rift behind the magmatic arc, but little or no oceanic crust was produced. The east coast of proto-North America at that time probably looked much like the mountainous west coast of South America today. As the ocean-continent collision went on, the oceanic crust continued subducting beneath proto-North America and a separate continent attached to the oceanic crust slowly drifted closer.

About 1.1 billion years ago, all the of the oceanic crust was subducted. The approaching continent collided with proto-North America in a continent-continent collision (Figure 3.7). This collision is called the *Grenville Orogeny*. It produced a large mountain range, similar to the Himalayan Mountains, along the collision zone (called a *suture zone*). The two continents continued to push against each other, and a broad area became uplifted on proto-North America behind the mountain range. We think that it was similar to the modern Tibetan Plateau in China north of the Himalayan Mountains. (In the Tibetan Plateau, the crust is 70-80 km thick—double the normal thickness—and the surface is 5 km above sea level.) This "Grenville Plateau" may have extended from Labrador, Canada, south through Georgia and Texas into Mexico.

The Grenville Orogeny ended about 1.0 billion years ago. After the orogeny ceased, the "Grenville Plateau" began to collapse and spread sideways. This spreading thinned the double-thickened crust. Over the next 400 million years, erosion removed about 25 km of rock. Eventually, the mountain range and plateau were reduced to flat lands at sea level. As rock was removed, the mountains and plateau remained relatively high because the buoyant continental crust rebounded during erosion.

The rocks of the Grenville Province form the *basement* for all of New York State (see Figure 4.2). This basement is buried by younger rocks over most of the State. However, it has been re-exposed at the surface in the Adirondack Mountains and the Hudson Highlands (see Chapters 4 and 5).

Rifting and Opening of the Iapetus Ocean

During the 400 million years of erosion in proto-North America, numerous orogenies occurred throughout the rest of the world. Each orogeny added another continent to a growing Grenville supercontinent. At the end of this time, all land was joined into one huge continent. When all the continental crust is on one side of the earth, however, the situation is unstable. The Grenville superconti-

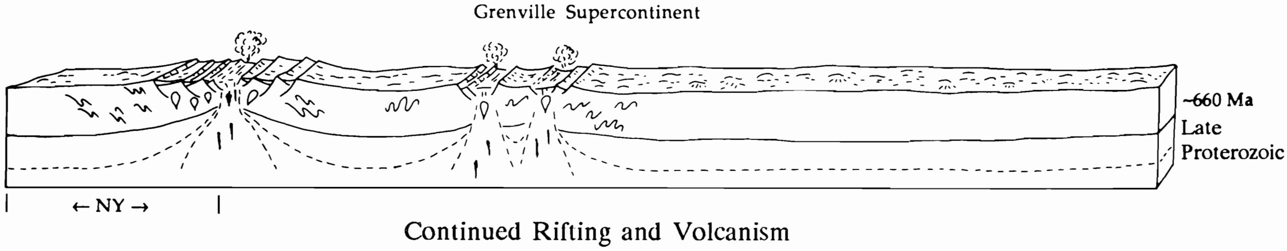


Figure 3.8. Block diagram showing the rifting of the Grenville supercontinent along the east coast of proto-North America.

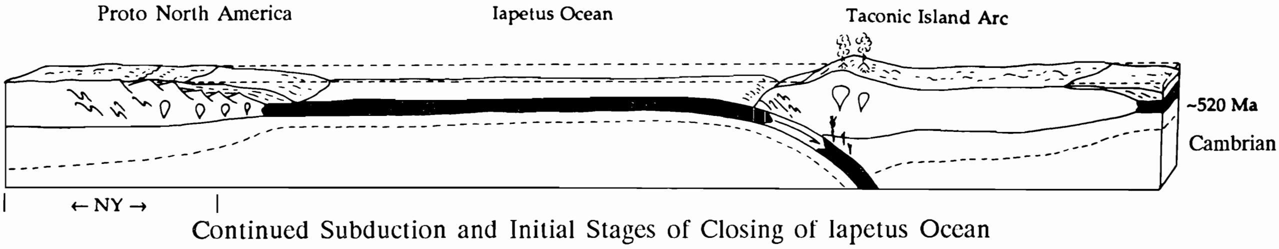


Figure 3.9. Block diagram showing the Taconic island arc approaching proto-North America as the western part of the Iapetus Ocean closes.

nent therefore began to split apart in a worldwide rifting event. About 660 million years ago, a large divergent margin developed along the east coast of proto-North America, approximately along the earlier Grenville suture zone (Figure 3.8). Rift basins began to open, and very coarse sediments were deposited in huge alluvial fans along their steep walls. Approximately 600 to 560 million years ago, during the Late Proterozoic, large amounts of dense volcanic rock seeped up into the rift. This basaltic rock eventually became new oceanic crust between proto-North America and the rest of the Grenville supercontinent to the east. As the basin continued to widen, a new ocean called *Iapetus* with a mid-oceanic ridge was formed.

The eastern edge of the proto-North American continent was no longer the edge of a plate. Rather, it had become a *passive margin* within a plate, similar to the Atlantic coast of North America today. Although tectonic activity continued at the divergent margin in the middle of the Iapetus Ocean, the margin of the continent was tectonically quiet; it had no earthquakes or volcanoes. Beach sands and shelly material were deposited during the Cambrian and most of the Ordovician Periods, until about 460 million years ago. A wide continental shelf covered with these sedimentary deposits formed along the east coast. Marine life flourished in the sea and is recorded in the many fossils in the rocks of that age in New York. These sedimentary rocks originally covered most of the State.

The Taconian Orogeny: Island Arc Collision

Starting about 550 million years ago, a large volcanic island arc developed within the Iapetus Ocean (Figure 3.9). The island arc was the result of an ocean-ocean collision; oceanic crust of the proto-North American plate was subducted beneath a plate to the east. The arc was very long and extended from Newfoundland to Alabama. The volcanic activity lasted from 550 to 450 million years ago, but it occurred at different times at different places along the arc.

The island arc eventually collided with the proto-North American continent. This collision is called the *Taconian Orogeny* (Figure 3.10). At the beginning of the collision, the eastern edge of proto-North America was bent upward in the west and downward in the east. The uplift on the west arched and fractured the edge of the continent, raising the carbonate rocks of the continental shelf above sea level and exposing them to erosion. East of the uplift, the edge of the continental crust was bent downward. As that edge approached the subduction zone, it sank beneath the sea. A deep marine trough formed as the shelf approached the subduction zone. Silty mud and impure sand of late Middle Ordovician age were deposited on top of the continental shelf carbonate rocks in the trough.

As the collision proceeded, the rocks in the trough were pushed westward over the rocks of the shelf. This

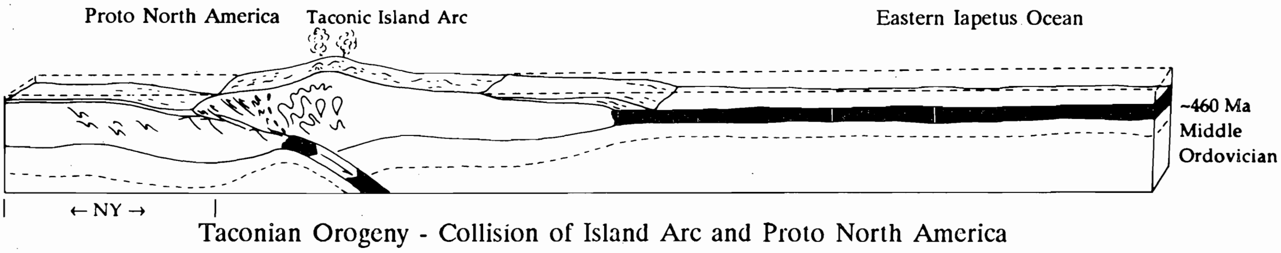


Figure 3.10. Block diagram showing the collision between the island arc and proto-North America. This collision is the Taconian Orogeny. Sediments eroded from the mountains built the Queenston Delta in western New York.

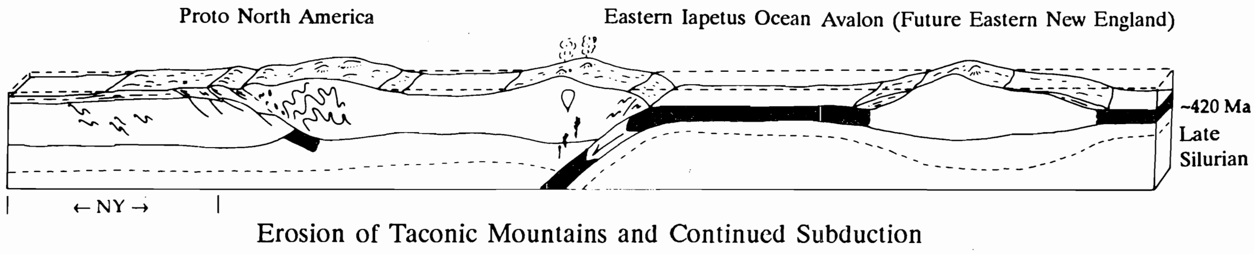


Figure 3.11. Block diagram showing the small continent of Avalon approaching proto-North America as the eastern half of the Iapetus Ocean closes.

stack of rock was, in turn, pushed westward over other shelf rocks on huge thrust faults. These rocks now make up the Taconic Mountains in eastern New York State and western New England. At the suture between the island arc and proto-North America, pieces of Iapetus Ocean crust are preserved. The best example in New York is the Staten Island serpentinite (see Plate 2 of the *Geological Highway Map*).

The mountains formed 450 million years ago by the Taconian Orogeny extended from Newfoundland to Alabama. These mountains—as high as the Himalayas—were rapidly eroded during the orogeny and especially after it. Huge rivers flowed down the western slopes of the ancestral Taconic Mountains, depositing coarse sand and gravel in a shallow sea that covered the middle of proto-North America. The river deposits formed the enormous Queenston Delta.

The Acadian Orogeny: Indirect Effects

After the western part of the Iapetus Ocean closed, the crust of the eastern Iapetus Ocean began subducting beneath the proto-North American continent in an ocean-continent collision (Figure 3.11). We think that subduction was most intense under present-day Greenland, southeastern Canada, and northernmost New England. The east coast of proto-North America looked similar to the Andes Mountains today, with elevations becoming gradually lower to the south.

When subduction had consumed all the Iapetus Ocean crust, an intense continent-continent collision ensued (Figure 3.12). The most intense part of the collision was between proto-Scandinavia and northeastern proto-North America (eastern Greenland); it lasted from

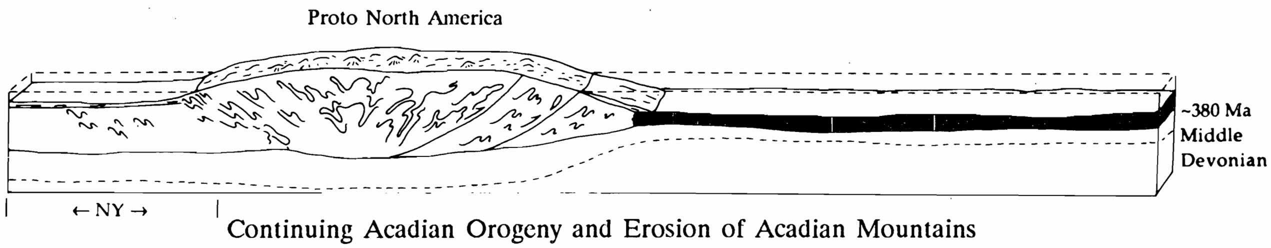


Figure 3.12. Block diagram showing the mountains built by the Acadian Orogeny—the collision between Avalon and proto-North America. Sediments eroded from the mountains built the "Catskill Delta" to the west of the mountains.

approximately 410 to 380 million years ago. Another part of the collision is recorded in Great Britain and Ireland and involved southeastern Canada and parts of New England. The southernmost part of the collision is called the *Acadian Orogeny*; it resulted when a small continent called *Avalon* was attached to proto-North America. Part of this continent can be found today in easternmost New England.

The collision built high mountains along the eastern part of the continent. It also greatly thickened the crust of proto-North America and formed a large plateau. This "Acadian Plateau" was similar to today's Tibetan Plateau in China. It extended to the Green Mountains of Vermont and possibly as far south as Connecticut. There was little uplift in New York. The only direct effects of the initial collision are some small igneous rock bodies in the southeastern part of the State.

Although the Acadian Orogeny had few direct effects on New York, the erosion of the Acadian Mountains and plateau was very important. The shallow Devonian sea on the interior of the proto-North American continent teemed with life. Much shelly debris accumulated, and limestones were deposited before the orogeny. As the Acadian Mountains rose, large rivers coursed down their western slopes, spreading sand and gravel across the region where the limestones had accumulated. The rivers deposited the huge "Catskill Delta," which partially filled the shallow sea. These deposits now make up the Catskill Mountains in southeastern New York.

The Alleghanian Orogeny: The Final Collision

The last orogeny recorded in the Appalachians, the *Alleghanian Orogeny*, lasted from about 330 to 250 million years ago. In the Alleghanian Orogeny, proto-Africa was attached to eastern proto-North America. The orogeny produced the Appalachian Mountains we still see today. The mountain chain extends from Alabama to Newfoundland.

Once, geologists thought that proto-Africa collided head-on with proto-North America in a huge continent-continent collision. They thought that this collision followed the subduction of an Atlantic-sized ocean basin under proto-North America. After careful study of the Alleghanian faults along eastern North America, however, we now think that proto-Africa probably slid southward past proto-North America along a transform margin. There was little, if any, subduction involved (Figure 3.13). As proto-Africa slid southward, it rotated clockwise, pushing westward into the southern part of proto-North America. This westward push produced large faults. There was more movement along the faults towards the south. Therefore, the Appalachian Mountains were uplifted higher in the south than in the north. Only portions of New York State were deformed.

A shallow sea extended across the central part of proto-North America after the end of the Acadian Orogeny. This shallow sea had huge swamps around its edges just before the Alleghanian Orogeny. The uplift of the Alleghanian Mountains again resulted in extensive erosion. Huge rivers flowed down their western slopes and dumped large amounts of sand and gravel into the shallow sea. The swamps were filled in, and the shallow sea was forced to the far south and west of the United States. The eastern part of the proto-North American continent was once again nearly all dry land.

Rifting and the Opening of the Atlantic Ocean

The Taconian, Acadian, and Alleghanian Orogenies were three of many orogenies that took place around the earth during the Paleozoic. Each of these orogenies sutured continents to each other. As each collision took place, there were fewer remaining separate continents around the earth. Finally, one supercontinent, called *Pangea*, formed (just as the Grenville supercontinent had formed 650 million years earlier). Having all the continental mass concentrated in one supercontinent again

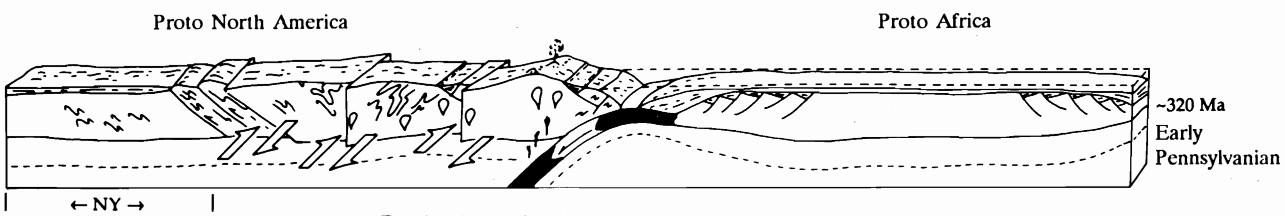


Figure 3.13. Block diagram showing proto-North America and proto-Africa colliding along a transform margin. This collision, the Alleghanian Orogeny, built the Appalachian Mountains.

caused instability in the asthenosphere. Pangea broke apart in a worldwide rifting event that began 220 million years ago. Continents moved apart very quickly (up to 18 cm/year). Some of the largest volcanic eruptions in the earth's history covered large areas of the crust with lava.

A divergent margin developed along the Appalachian Mountains, and Africa began to rift from North America (Figure 3.14). The rift first developed on continental crust. The rifting created long, steep-sided valleys. Rivers deposited huge alluvial fans of coarse sand and gravel on the margins of these rift valleys; lakes filled the central parts of valleys. Eastern North America looked very much like the Basin and Ridge Province of the western United States today. As rifting continued, volcanoes erupted and covered the sediments with lava. Finally, in the central portion of the rift, new oceanic crust began to form. This event was the birth of the Atlantic Ocean. The Atlantic continued to open over the next 160 million years and became a full-sized ocean basin. The east coast of North America developed into a passive margin with a wide continental shelf—the situation we have today. Sediments eroded from the continent over millions of years built the shelf.

Some of the sediments deposited during the early part of the rifting filled the Newark Basin, which underlies most of Rockland County, New York, and extends into New Jersey. The volcanic rocks, such as the lava flow near Ladentown, formed during the rifting. The Palisades Sill, which forms cliffs on the west side of the Hudson River near New York City, was a large mass of molten rock that cooled and hardened underground. The sediments deposited since the passive margin formed are found in the Atlantic Coastal Plain. They include today's beaches.

The east coast of North America is tectonically quiet today. However, judging by past experience, it is only a matter of time before active tectonism begins again.

Review Questions and Exercises

Why is the theory of plate tectonics important in geology?

What are the two kinds of crust? How are they different?

Why do plates move? Describe the different ways in which they interact?

How old are the oldest rocks in New York State? Where are they found?

Put the following events in chronological order, and describe what happened in each:
Acadian Orogeny
Alleghanian Orogeny
erosion of Grenville Plateau
formation of "Catskill Delta"
formation of Grenville supercontinent
formation of Pangea
formation of Queenston Delta
formation of volcanic island arc in Iapetus Ocean
Grenville Orogeny
opening of Atlantic Ocean
opening of Iapetus Ocean
shallow inland sea forced far to south and west of proto-North American continent
Taconian Orogeny

Identify the following. Explain when and how they were formed:
basement rocks of New York State
the rocks of the modern Taconic Mountains
the Staten Island serpentinite
the rocks of the Catskill Mountains
the Appalachian Mountains
the rocks of the Newark Basin
the Palisades Sill
the sediments of the Atlantic Coastal Plain

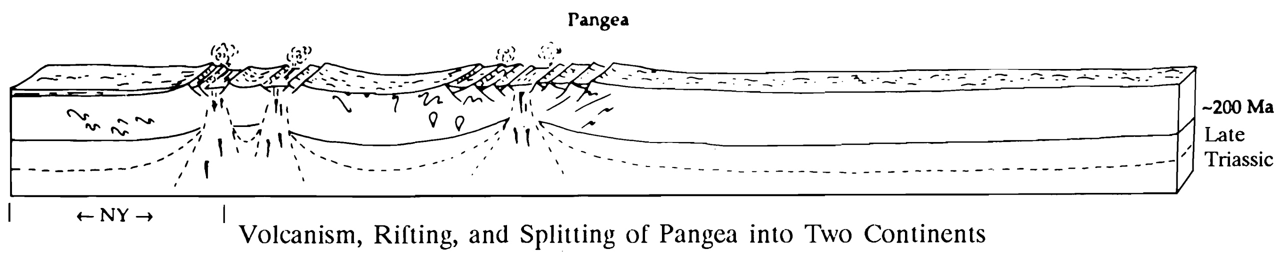
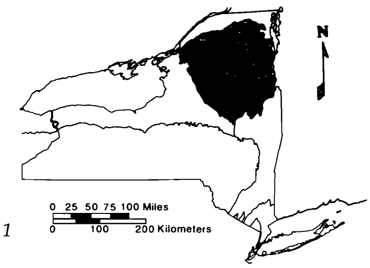


Figure 3.14. Block diagram showing the rifting of the supercontinent of Pangea. The Newark Basin is a rift formed at this time.

PART II
Bedrock Geology

Chapter 4
New Mountains From Old Rocks
Adirondack Mountains[1]



Summary

The Adirondack Mountains make up a circular region that is part of the Grenville Province, a large belt of basement rock. The region is divided into the Central Highlands and the Northwest Lowlands, which are separated by the Carthage-Colton Mylonite Zone. It was once covered by the same layers of sedimentary rock that now surround it, but recent uplift and erosion have exposed the basement. Seen from space, the region has several prominent features: long, straight valleys; gently curved ridges and valleys; and a radial drainage pattern.

The rocks of the Adirondacks, almost without exception, are metamorphic. They have been subjected to high temperatures and pressures at depths of up to 30 km in the earth's crust. Most of the rocks in the Northwest Lowlands are metasedimentary or metavolcanic and have a complex history. Most of the rocks in the Central Highlands are metaplutonic; granitic gneiss is the most common. Metanorthosite forms several large bodies in the Central Highlands; the largest makes up the High Peaks area. Olivine metagabbro bodies are scattered throughout the eastern and southeastern Adirondacks.

The Adirondack rocks have been both severely folded and sheared by ductile deformation and shattered by brittle deformation. Ductile deformation has produced very complicated folds of all sizes throughout the region. Ductile shearing created intensely deformed mylonites, which are found throughout the region but are most abundant in the southeastern Adirondacks and in the Carthage-Colton Mylonite Zone. Long, straight valleys that run north-northeast mark the most prominent examples of brittle deformation. These valleys are the results of accelerated erosion along major faults and fracture zones. In addition, most Adirondack rocks have an abundance of joints. The Adirondack deformation happened when the crust of the region was severely compressed during the Grenville Orogeny.

Almost all Adirondack rocks are Middle Proterozoic in age. The oldest metasedimentary rocks were deposited in shallow seas beginning about 1.3 billion years ago. Metavolcanic rocks of the same age show that volcanoes were active at that time. Some Adirondack metasedimentary rocks contain grains eroded from a much older landmass. Most of the metaplutonic rocks, including the metanorthosite, granitic gneiss, and olivine metagabbro bodies in the Central Highlands, were formed from magmas that were intruded about 1.15 to 1.1 billion years ago.

All these rocks were then buried as much as 30 km below the surface during the Grenville Orogeny. The crust was severely deformed and thickened, and the rocks at depth were intensely metamorphosed. Deformation and metamorphism peaked between 1.1 and 1.05 billion years ago. Over the next several hundred million years, erosion stripped away more than 25 km of rock, and major faults were formed. The region was then covered by shallow seas, in which sediments accumulated through the Cambrian and Ordovician Periods. Sediment accumulation probably continued into the Pennsylvanian Period. Most of these sedimentary rocks have been removed by erosion, but traces can be found in grabens. From the Middle Ordovician into the Tertiary Period, there was no significant tectonic activity in the Adirondack region. Sometime in the Tertiary, the Adirondack dome began to rise, possibly because of a hot spot near the base of the crust. Erosion then carved the region into the separate mountain ranges we see today.

[1]Adapted from a manuscript by P.R. Whitney.

INTRODUCTION

The Adirondack Mountains are young, but these young mountains are made from old rocks. How do we explain this seeming contradiction? First, we try to answer many other questions. What kinds of rocks do we find in the Adirondacks? Under what conditions were they formed? How old are they? How have they been deformed? The answers to these questions give us clues to the geologic history of the Adirondacks.

THE BIG PICTURE

The Adirondack Mountains make up a roughly circular region about 200 km in diameter in northern New York State (see Figure 1.1). The region is divided into two subregions, the Central Highlands and the Northwest Lowlands. They are separated by the *Carthage-Colton Mylonite Zone*, a narrow belt of intensely deformed rocks (Figure 4.1; see also Plate 2 of the *Geological Highway Map*, on which the Carthage-Colton Mylonite Zone is labeled *CCMZ*).

The metamorphic bedrock in the Highlands resists erosion well. It was left towering over the rest of the countryside when the sedimentary rocks that once covered it were worn away. The highest elevations are found in the High Peaks area of the Central Highlands; there, numerous summits rise above 1200 m. The highest peak, Mount Marcy, is more than 1600 m high. Elevations fall off rapidly north and east of the High Peaks and more gradually to the south and west.

The Adirondack region is part of a much larger area called the *Grenville Province* (Figure 4.2). The Grenville Province is a broad belt of mostly metamorphic rock of Middle Proterozoic age; it extends along the western side of the Appalachian Mountains from Labrador to Mexico. Around the Adirondacks and south of the region, this belt is almost entirely covered by younger sedimentary rocks.

The Adirondack region was once flat and was covered by the same sedimentary layers that now surround it (see Plate 2). However, in relatively recent geologic time, the Adirondack region was uplifted, forming a dome. During uplift, erosion removed the sedimentary layers from the region. This erosion eventually created a "window" through the sedimentary rocks that permits us to see the much older basement rocks[2] beneath. The Adirondack basement extends into Canada at the surface along a narrow zone called the *Frontenac Arch* (Figure 4.2). The Frontenac Arch crosses the St. Lawrence River at the Thousand Islands.

Seen from space, the Adirondack Highlands look cracked and wrinkled (Figure 4.3). We can see three prominent types of features on the satellite image:

1. Long, straight valleys that run north-northeast are the most prominent. Throughout the Adirondacks, these valleys contain streams and lakes (Figure 4.1). Many of the larger Adirondack lakes, such as Lake George, Schroon Lake, Indian Lake, and Long Lake, follow this north-northeast trend. Figure 4.4 A shows one example. In the High Peaks region, these valleys divide the area into a number of long, straight mountain ranges (Figure 4.4 B). These long, straight valleys have formed along faults and fracture zones where the broken rocks are less resistant to erosion.
2. Gently curved ridges and valleys. These ridges and valleys are usually more subtle than the deep, fault-related ones. They are most prominent in the central and southern Adirondacks, where they make an east-west arc. They follow the layering in folded rocks. Harder, more erosion-resistant rocks (such as granitic gneiss) form the ridges, while softer layers (like marble) form the valleys.
3. Radial drainage pattern[3]. Streams and rivers in general flow out from the central and northeastern parts of the Adirondack dome toward its edge. We can see this pattern most clearly in the outer parts of the dome; elsewhere, the rivers tend to follow the dominant north-northeast valleys. Figure 4.5 shows this radial drainage pattern in some detail and compares it to structures in the underlying bedrock.

ADIRONDACK ROCKS AND THEIR METAMORPHISM

Almost all of the rocks in the Adirondack region are metamorphic rocks. Three general types are present. *Metasedimentary* rocks, as the name suggests, were formed by metamorphism of sedimentary rocks. *Metavolcanic* rocks are metamorphosed lavas and volcanic ash. *Metaplutonic* rocks were formed by metamorphism of igneous rocks that cooled and crystallized from *magma* (molten rock) deep in the earth's crust. The more important kinds are shown on Plate 3. Each kind of rock is made up of a specific collection of minerals, called a *mineral assemblage*. Before describing the main rock types that make up the Adirondacks, it will be useful to discuss the conditions under which they were metamorphosed.

[2]*Basement rock* refers to the deeply eroded metamorphic bedrock that is usually covered by younger sedimentary rocks.
[3]The *drainage pattern* of a region is the pattern made by streams and rivers. By looking at this pattern on a map, we can tell a great deal about the shape of the landscape. For example, the radial drainage pattern in the Adirondacks is the one we would expect to develop on a newly formed dome.

Figure 4.1. This physiographic diagram shows the circular shape of the Adirondack region. The heavy lines outline the the Northwest Lowlands, the Central Highlands, and the Carthage-Colton Mylonite Zone that separates them. Bodies of water are shown in black. This figure shows the same area as the satellite photo (Figure 4.3).

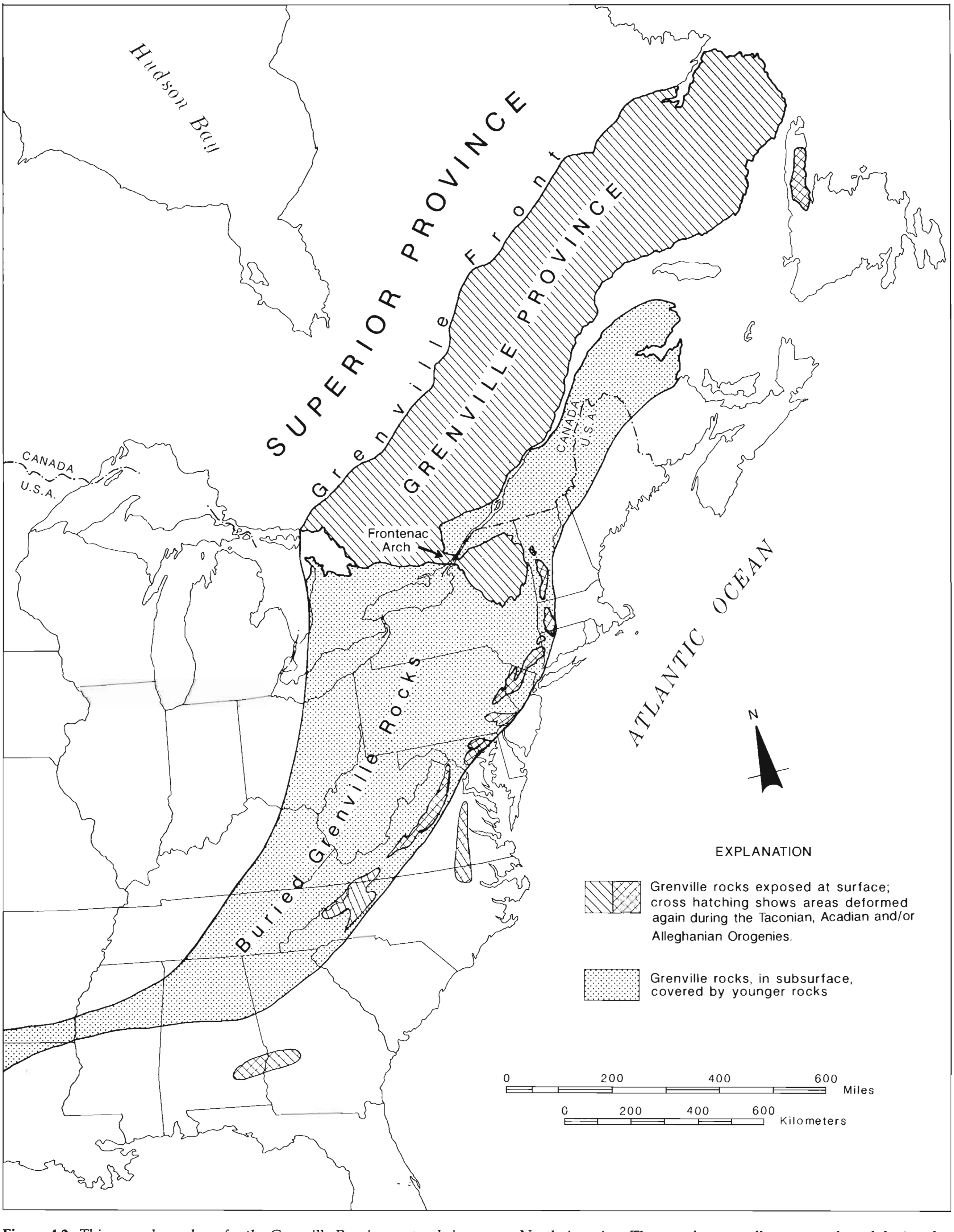


Figure 4.2. This map shows how far the Grenville Province extends in eastern North America. These rocks were all metamorphosed during the Grenville Orogeny approximately 1.1 billion years ago. Slanted lines show where Grenville rocks appear at the surface. The cross-hatch pattern shows locations of Grenville rocks that were deformed again during the Taconian, Acadian, and/or Alleghanian Orogenies. The dot pattern indicates where Grenville rocks are buried beneath younger rocks.

Figure 4.3. This satellite photo shows how the Adirondack region looks from space. The circular dome shape is easy to see. In the central and southern Adirondacks, you can see east-west valleys that arc to the north. Compare this image with Plate 2 to see how these valleys reflect the patterns of the underlying rock types. Notice how the eastern half of the Adirondacks is cut by straight valleys that run roughly north-northeast. These valleys lie along faults and fracture zones (Figures 4.18 and 4.19), where the broken rock erodes easily. Major streams, rivers, and lakes follow this north-northeast trend.

Figure 4.4. (A) This photo looks south-southwest along a long, straight valley in the Adirondacks. The entire valley is 115 km long. You can see about 30 km of that length in this picture. The lake in the valley is the longest lake in the central Adirondacks, appropriately named Long Lake. (B) This aerial view of Mt. Colden in the High Peaks, looking southwest, shows how the area is divided into long, narrow mountain ranges by valleys that run north-northeast. The bedrock here is metanorthosite. The valleys are formed by erosion along faults and fracture zones.

Rock becomes metamorphosed when it is subjected to elevated pressures and temperatures. In a continent-continent collision, mountain-building forces bury rock many kilometers beneath the earth's surface. The weight of the overlying rock subjects the buried rock to enormous pressures. The internal heat of the earth gradually heats the buried rock to extremely high temperatures. Under these conditions, the minerals in the buried rock react chemically with each other to form new mineral assemblages.

The original composition of the rock, together with the temperature and pressure to which it is subjected, determines what kind of metamorphic rock will form. It is difficult to reconstruct what conditions were like during metamorphism in the Adirondacks because metamorphism takes place deep below the surface of the earth. However, we can use laboratory experiments to estimate the pressures and temperatures that produced the rocks we see at the surface today.

One laboratory approach is to determine both the mineral assemblage found in a rock, and the chemical composition of that rock and its minerals. Artificial "rocks" of the same composition are then exposed to various temperatures and pressures in laboratory apparatus. If the mineral assemblage produced by the experiment at a certain temperature and pressure matches that in the natural rock, we conclude that the rock formed under roughly the same conditions. Another approach is to study the way in which the properties of minerals change with temperature and pressure, and then use this information to calculate the conditions under which a rock with a certain mineral assemblage was formed. Such experiments (the actual procedures are much more complicated!) allow us to determine approximately what the temperatures and pressures were during the metamorphism.

When we compare Adirondack rocks with experimental results, we conclude that rocks in the Central Highlands were formed under rather extreme conditions—at temperatures of 750-800°C and at pressures 7000 to 8000 times the pressure of air at sea level. These pressures are equivalent to those at depths of 25 to 30 km below the earth's surface.[4] Conditions affecting the rocks of the Northwest Lowlands were a little less extreme. Temperatures were about 600-750°C, and burial depths were about 20-25 km. When we learn how deeply they were buried, we realize that the rocks we now walk on in the Adirondacks once lay beneath nearly a full thickness of continental crust.

To reconstruct the geologic history of the Adirondack region, we need to figure out what the rocks were like before they were metamorphosed. The first question is: Were they sedimentary or igneous? For some rocks we need only look at the mineral makeup. For example, we know that the metamorphic rock quartzite (Figure 4.7) must have originally been a quartz sandstone, because both rock types are made almost entirely of the mineral quartz and there are no igneous rocks of that composition. Similarly, metanorthosite has the same mineral composition (chiefly plagioclase feldspar) as the igneous rock anorthosite, which is unlike any known sedimentary rocks. Certain sedimentary or igneous features in the original rock may have survived metamorphism. These features are also clues to what the rock was before meta-

[4]At these temperatures, the mineral assemblages within a rock may partially melt. Rock pressures may then force the newly melted material to concentrate into layers. Rocks formed in this way, called *migmatites*, have a layered appearance (Figure 4.6). They are part igneous and part metamorphic. Today, we find migmatites in the Adirondacks. Many of them contain white or pink layers of quartz and feldspar that formed during this partial melting process.

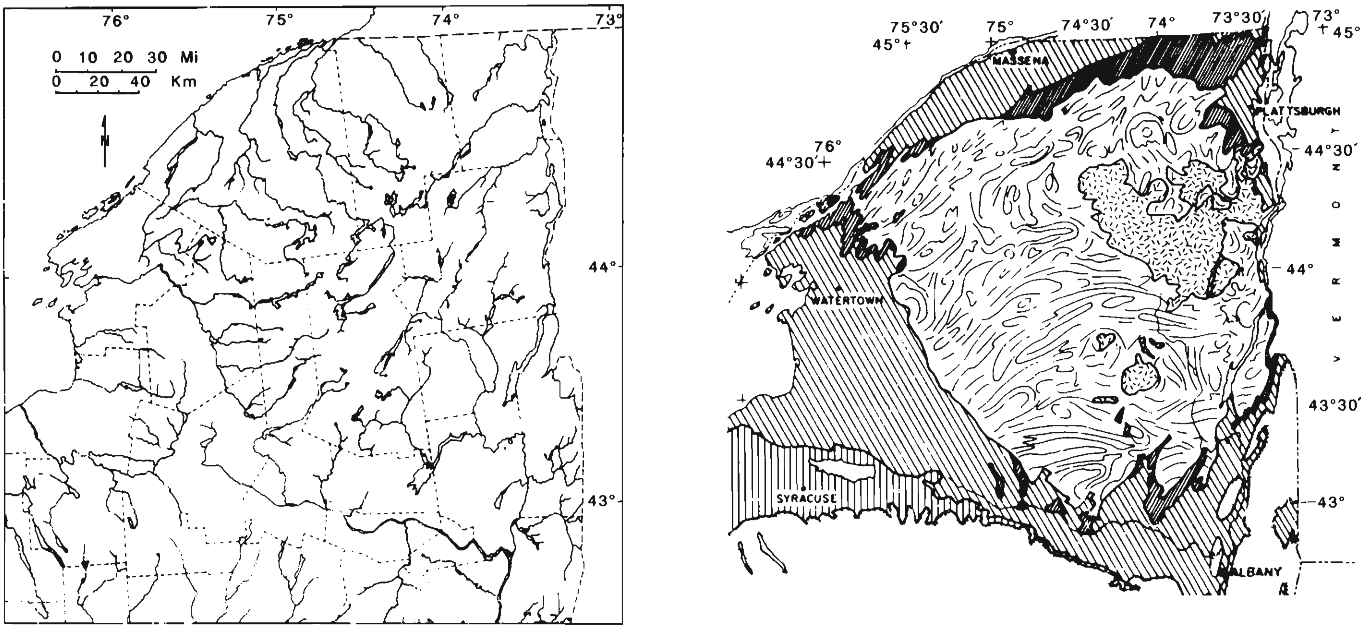


Figure 4.5. (A) Map showing the radial drainage pattern within the Adirondack dome. B) Simplified map of Adirondack bedrock. (See Plate 2 for detailed bedrock map.) The curved lines represent boundaries between strong rocks that resist erosion well and weaker rocks. Notice that the stream pattern ignores the bedrock pattern. This fact suggests that the metamorphic rock of the Adirondacks was uncovered relatively recently. The streams have not yet had time to find the weaker rock and carve valleys there. Areas marked with straight lines represent different types of Paleozoic rock. These younger rocks once covered the entire region but were removed from the Adirondack dome by erosion. This erosion exposed the older metamorphic rock beneath.

morphism; some examples are shapes of mineral grains or the presence of sedimentary bedding. Some metanorthosites (Figure 4.8A) and metagabbros have mineral grain shapes that show the original rock crystallized from magma. For other Adirondack rocks, the nature of the original rock is much less clear. We do not yet know, for instance, whether some granitic gneisses are metaplutonic, metavolcanic, or metasedimentary.

Metasedimentary and Metavolcanic Rocks

Metasedimentary and metavolcanic rocks make up well over 80 percent of the exposed bedrock in the Northwest Lowlands. They are less abundant in the Central Highlands, where most of the rocks exposed at the surface are metaplutonic. They include both marbles (metamorphosed limestones) and quartzite, as well as various kinds of gneisses that are the end products of metamorphism of shales and sandstones.

What was the environment like when the original sedimentary and volcanic rocks were formed? An exciting discovery in recent years gives us some help in finding an answer. In the early 1980s, fossils of dome-like, laminated structures called *stromatolites* were discovered in the Adirondacks. They were found in marbles near Balmat (Figure 4.9). This find was very surprising, because the rock containing the stromatolites had been metamor-

Figure 4.6. This migmatite is a mixed rock—part igneous and part metamorphic. The light layers are composed largely of quartz and alkali feldspar. The dark layers are composed of plagioclase feldspar, biotite, and quartz. The migmatite may have been formed when the rock was metamorphosed at such high temperature and pressure that it began to melt and the melted portion separated into layers.

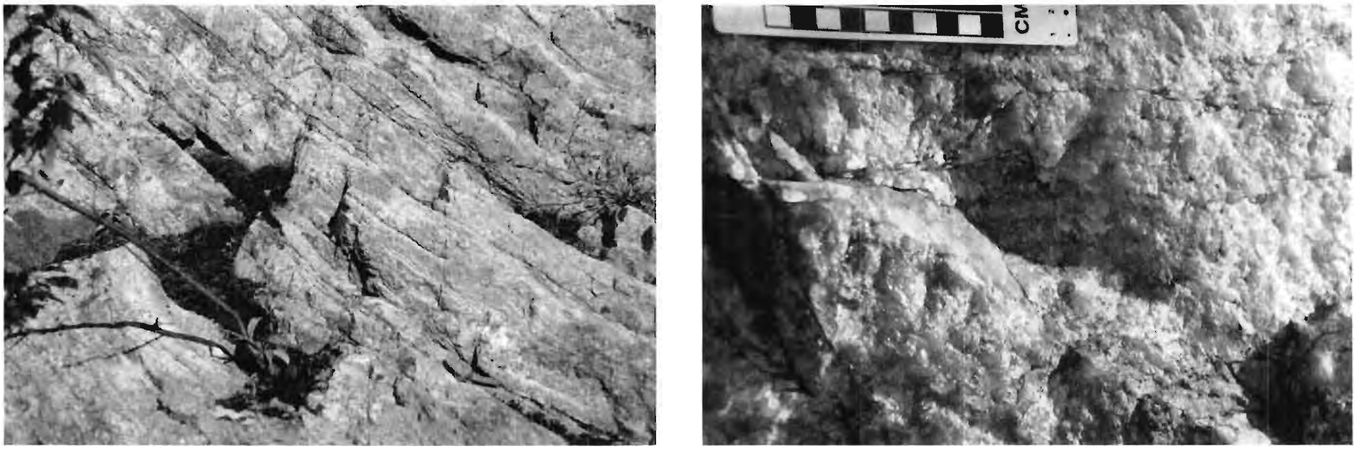


Figure 4.7. (A) is metamorphic quartzite formed from quartz sandstone. Notice that you can still see the original bedding, even though the rock has been metamorphosed. In a close-up view in (B), however, you can see how the rock has been changed. The original sandstone was made of individual round sand grains. During metamorphism, the grains have completely recrystallized. The final product—a glassy quartz rock.

phosed and deformed. Usually, intense deformation and recrystallization destroy any fossils that are present. In fact, stromatolites are the only fossils ever found in the metamorphic rocks of the Adirondacks. Both ancient and modern stromatolites are formed by *cyanobacteria* (blue-green algae) that live in shallow, well-lit water. We conclude from the presence of stromatolites in Adirondack marbles that these rocks were originally deposited in shallow marine waters.[5]

The metasedimentary and metavolcanic rocks of the Adirondacks record a complex geologic history. These rocks were originally horizontal layers. Now, the layering has been complexly folded and faulted, and in places disrupted by magma.

Metaplutonic Rocks

Three major types of metaplutonic rocks are found in the Adirondacks: granitic gneiss, metanorthosite, and olivine metagabbro.

Granitic gneiss.—The most common metaplutonic rock in the Adirondacks is granitic gneiss (see Plate 2). Geologists are still arguing about the origin of these rocks. However, much of the granitic gneiss in the Central Highlands appears to be metamorphosed plutonic rock, so we have put it in the metaplutonic category. This rock is composed largely of alkali feldspar and quartz, with lesser amounts of other minerals.

Metanorthosite.—Metanorthosite (Figure 4.8) forms several large bodies in the Central Highlands. It is an unusual rock, composed chiefly of a single mineral type, plagioclase feldspar. It is similar to the rock that makes up the highlands (bright areas) of the Moon. The largest metanorthosite mass in the Adirondacks, called the *Marcy Massif*, underlies roughly 1500 km^2, including most of the High Peaks area. Near its southern border, we find ore deposits composed of heavy, black iron and titanium oxides. One such deposit, at Tahawus, has been mined for both titanium and iron. There are also several smaller, dome-shaped masses of metanorthosite in the northeastern and south-central Adirondacks. A number of even smaller bodies are scattered throughout the region.

The metanorthosite originated as anorthosite magma in the earth's mantle and lower crust. The magma rose into shallower levels of the crust, where it cooled and hardened. Later metamorphism converted the anorthosite to metanorthosite.

How do we know that the metanorthosite of the Adirondacks was originally igneous anorthosite? In the less deformed parts of the metanorthosite bodies, we find textures typical of igneous rocks (Figure 4.8A). These textures survived metamorphism. In addition, we find blocks of older rocks in the metanorthosite. These blocks were broken off the surrounding rock and mixed in with the magma as it forced its way up through the crust.

Olivine metagabbro.—Olivine metagabbro is less abundant than granitic gneiss and metanorthosite, but numerous masses of this rock are scattered throughout the eastern and southeastern Adirondacks (see Plate 2). Like metanorthosite, olivine metagabbro commonly has textures that show its igneous origin. It also contains features called *coronas* (Figure 4.10), which show incomplete

[5]The shape of the stromatolites is also very useful in our study of the rocks of the Adirondacks. Their shape tells us whether they are right side up or upside down where we find them in the folded rocks. We can see that the stromatolites in Figure 4.9A are upside down—so we know that the marble that contains them has been folded enough to overturn one limb of the fold. These fossils gave us the first reliable way to tell which way is up in the folded and refolded metasedimentary rocks of the Adirondacks.

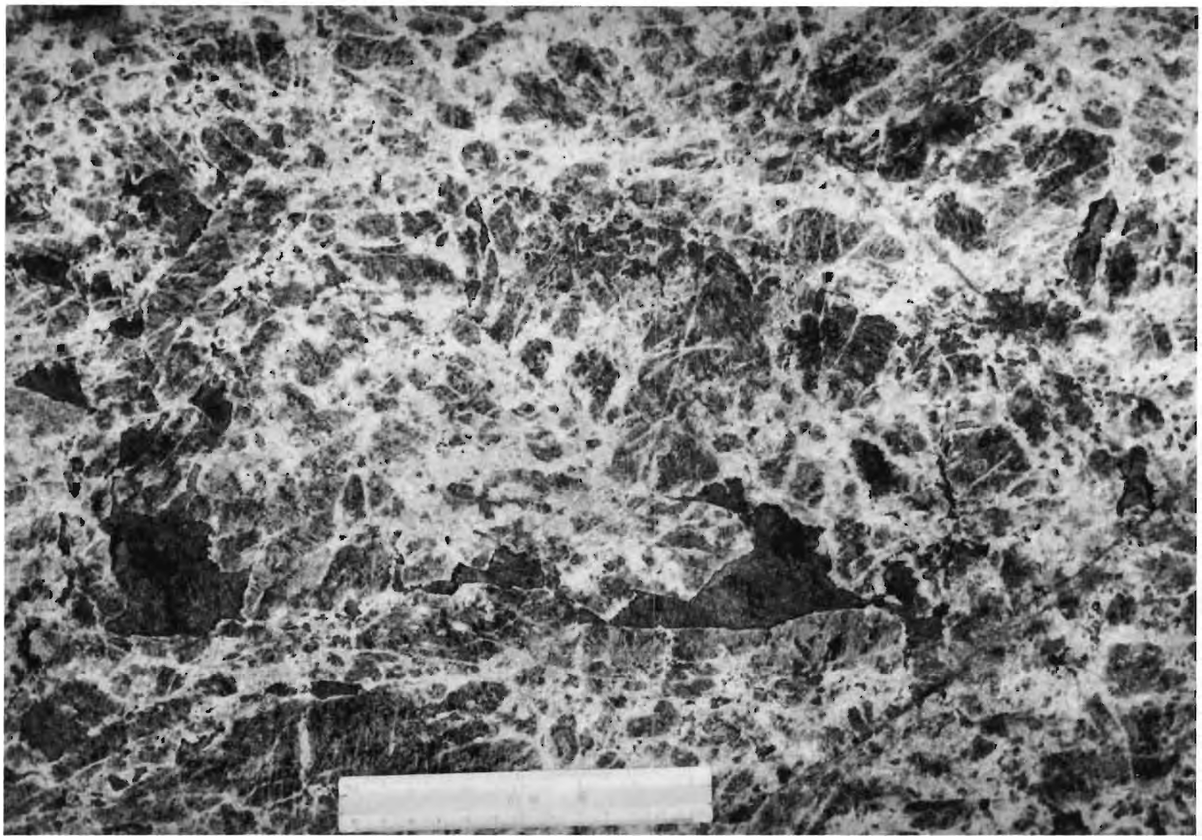
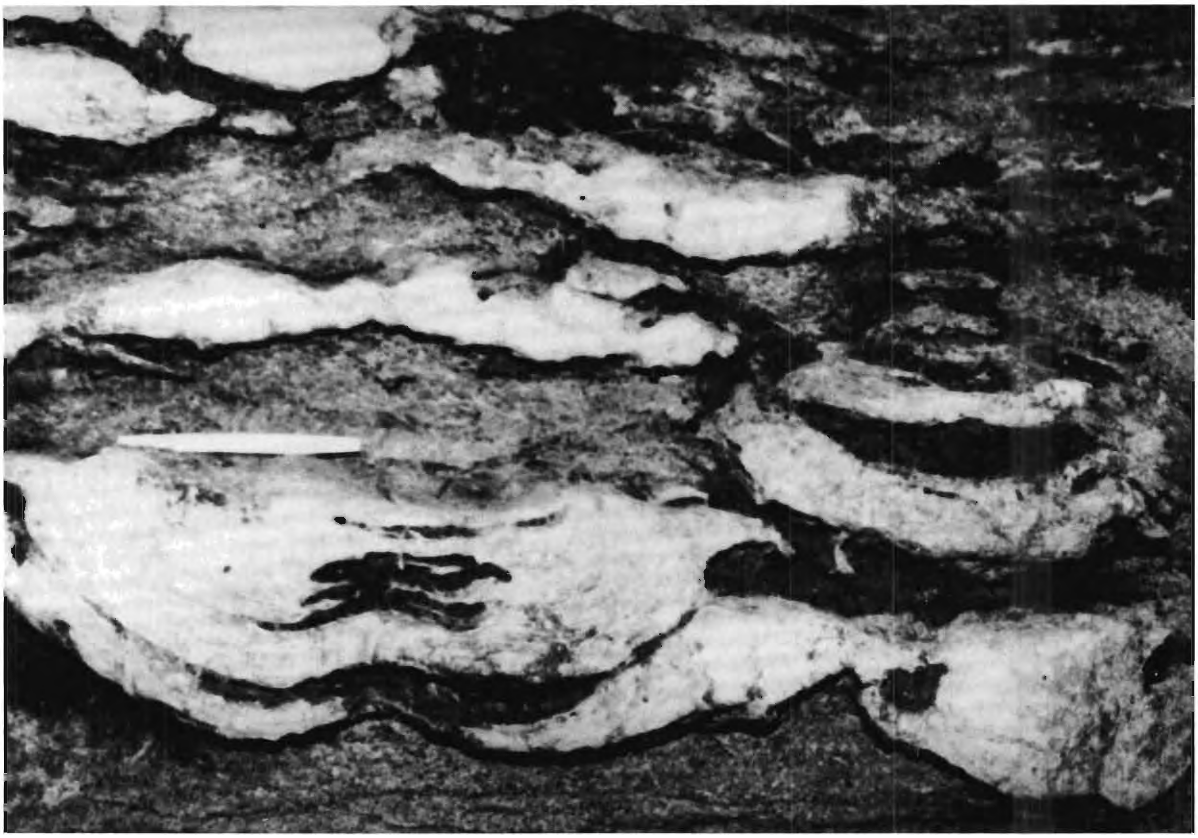


Figure 4.8. These two photos show Adirondack metanorthosite. The metanorthosite in (A) contains large crystals of plagioclase (medium gray), fine-grained plagioclase (white), and green pyroxene (dark gray). (The ruler is 15 cm long.) (B) shows strongly deformed metanorthosite. The layering is called *foliation* (Figure 4.15). The large crystal in the left part of the photo is a garnet.

A.



B.

C.

Figure 4.9. These photos show a side view (A) and an eroded bottom view (B) of fossil stromatolites found in marble in the Northwest Adirondacks. (C) shows modern stromatolites at Shark Bay, Australia. This picture was taken at low tide. When we compare the fossils in (A) with the modern stromatolites in (C), we can see that the fossils are upside down. This fact is evidence that the rock in layer (A) has been overturned by folding.

chemical reactions between minerals. These reactions happened during metamorphism, but so slowly that even in the millions of years before the rock cooled the original minerals were not wholly consumed. Near the edges of some olivine metagabbro bodies, we find spectacular large red garnets that also formed during metamorphism (Figure 4.11). At the Barton Mine on Gore Mountain near North Creek, garnets up to one meter in diameter have been found.

Deformation of Adirondack Rocks

The rocks of the Adirondack region have been complexly deformed. *Deformation* refers to folding, faulting, and other processes that change the shape of rock bodies.

We find two main kinds of deformation in the Adirondack rocks: *ductile deformation* and *brittle deformation*. Brittle deformation occurs in rocks that are at shallow depths or at the surface, where they are cold; here they deform by breaking. Ductile deformation can occur in rocks that are deeply buried and hot enough to bend or flow without breaking.

Ductile Deformation

One of the most obvious kinds of ductile deformation in the Adirondacks is folding. We find folds of all sizes in the rocks of the region. The complex patterns on the geologic map (Plate 2) result in part from large, irregular folds. Some of these folds in the southern Adirondacks are tens of kilometers across. Major folds in the northwest Adirondacks generally run northeast. Those in the southern half of the Adirondacks make an east-west arc.

We also see folds in individual rock exposures (Figures 4.12, 4.13, and 4.14). We find folded rocks throughout the Adirondacks; some of them appear to have been folded several times. Clearly, great geologic forces were needed to make such folds. In the folded rocks, we often find a layer-like arrangement of minerals called *foliation* (Figure 4.15) and parallel streaks of minerals called *lineation* (Figure 4.16). Foliation and lineation give us clues about the directions in which the folding forces acted.

Rocks at high temperatures deep within the crust may also deform by *ductile shear*. Ductile shear happens when one block of rock slides past another; the rock between the blocks deforms and stretches like chewing gum or hot plastic, rather than breaking to form a fault as it would at lower temperatures. This movement creates a

A.

B.

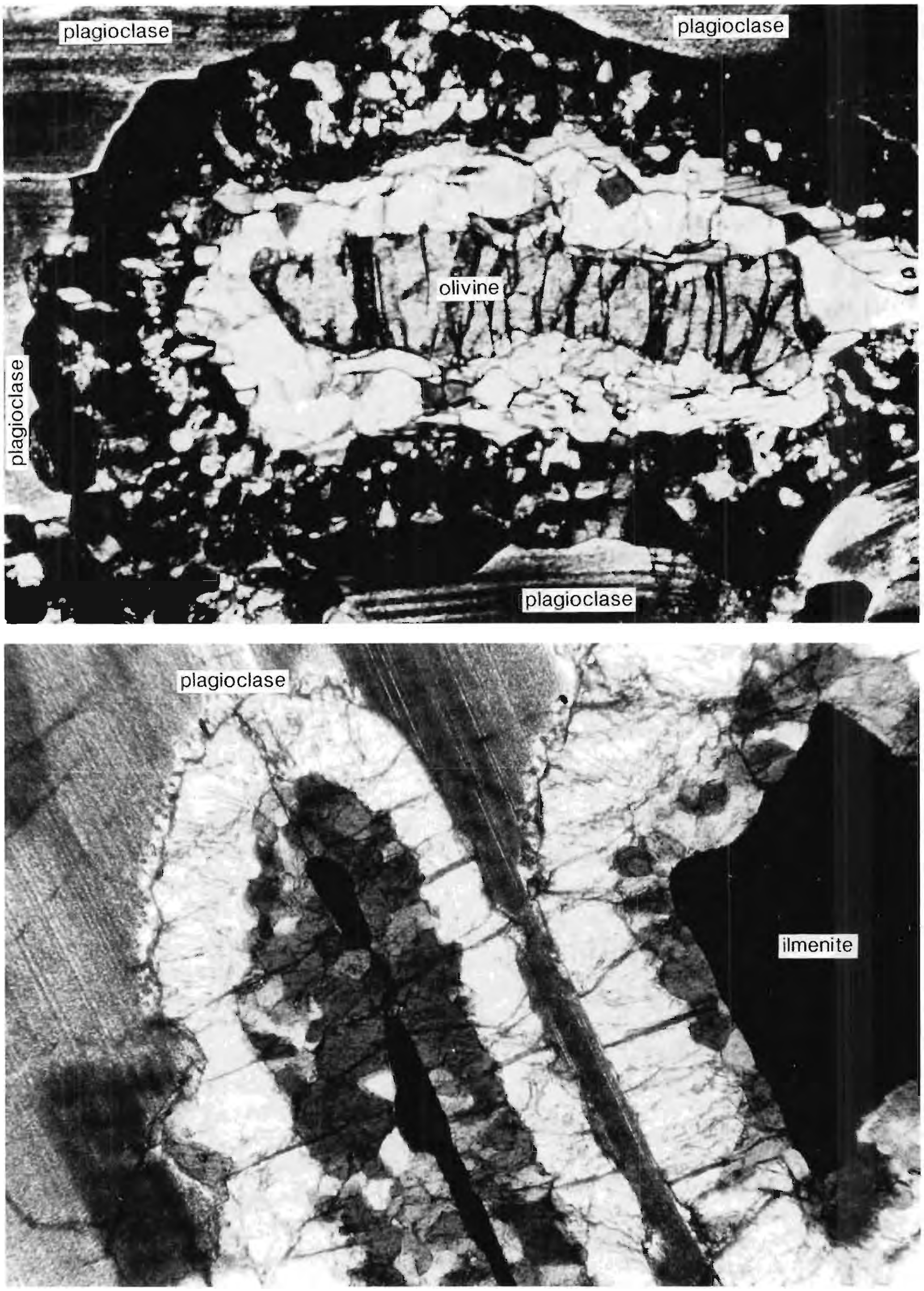


Figure 4.10. These two photographs are of paper-thin rock slices as seen under a special microscope used by geologists. The photos show rings of minerals (called *coronas*) that formed when the rocks were metamorphosed at very high temperatures and pressures. In (A), the original minerals in the rocks were olivine and plagioclase feldspar. These minerals reacted to form the new metamorphic minerals that make up the coronas: pyroxene, pale plagioclase, and red garnet (black in photo). Plagioclase outside the corona looks dark because it is full of tiny grains of the mineral spinel. These same reactions can be reproduced in the laboratory, but it requires a temperature of up to 800°C and pressures equivalent to 25-30 km of overlying crust. Coronas like these can be seen with the unaided eye in most exposures of olivine metagabbro. (See Plate 2 for places where olivine metagabbro appears at the surface.) (B) shows another type of corona that forms in olivine metagabbros. Here, the two core crystals of ilmenite (black) reacted with plagioclase feldspar to form coronas of hornblende, biotite (black mica), and red garnet (white in photo).

A.

ductile shear zone—a relatively narrow, intensely deformed area between the two blocks. The rock in such ductile shear zones is greatly stretched and flattened and commonly shows strong foliation and lineation.

As movement occurs in a ductile shear zone, the minerals in the rock recrystallize. This process reduces the size of the mineral grains, sometimes drastically. The result is a fine-grained rock called a *mylonite* with strong foliation and lineation (Figure 4.17). From the shapes of the mineral grains in a mylonite, we can sometimes tell which way the blocks of rock moved along the shear zone.

Mylonites are common throughout the Adirondacks, but are most abundant in the southeastern Adirondacks and along the Carthage-Colton Mylonite Zone, which separates the Central Highlands and the Northwest Lowlands (Figure 4.1). They range in width from a few centimeters to several kilometers. In the mylonites of the Carthage-Colton Mylonite Zone the shapes of the mineral grains tell us that the Lowlands probably slid along this zone northwestward and down relative to the Central Highlands. We can't tell how far the Lowlands moved, but it may have been a considerable distance. In other parts of the world, blocks of crust have moved tens or even hundreds of kilometers along similar ductile shear zones.

B.

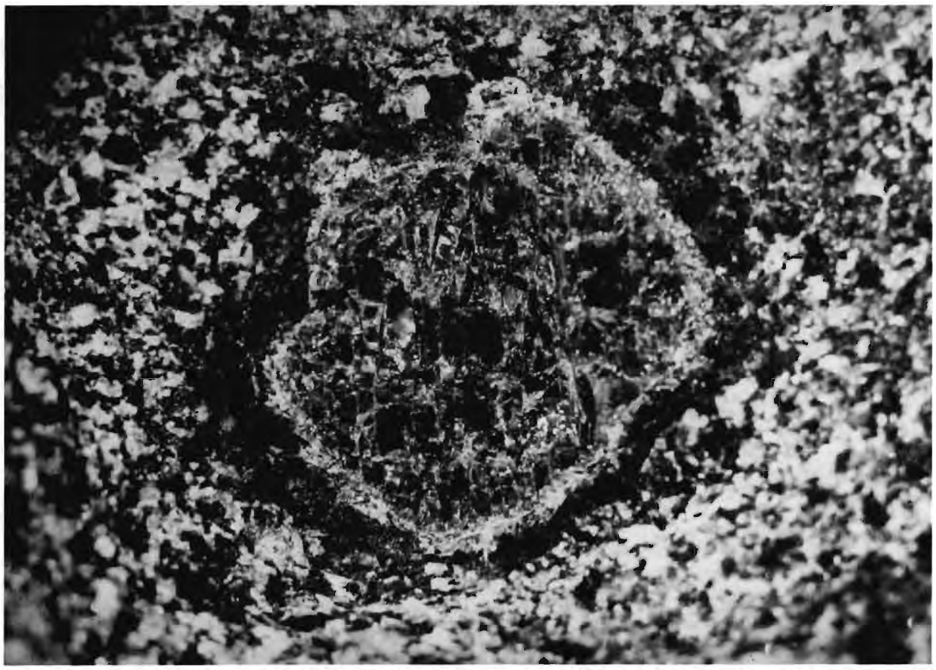


Figure 4.11. These photos are two views of unusually large Adirondack garnets. (A) shows garnets surrounded by rims of the mineral hornblende. The rock is olivine metagabbro. These garnets are found along Wall Street, near I-87, east of Chestertown, Warren County. (B) is a closeup of a single garnet from the Barton Mine at Gore Mountain, Warren County. New York State's garnet mines are world famous, and garnet is the official State mineral.

Brittle Deformation

Brittle deformation refers to the breaking of rock, in contrast to the flowing of rock that accompanies ductile deformation. In the Adirondacks, we find the most prominent examples of brittle deformation in the long, straight valleys that run north-northeast across the eastern half of the region.

Some of these valleys, such as those occupied by Lake George and Schroon Lake, have steep faults on either side. The central block has moved down at least 400 m along these faults. Such down-dropped blocks of crust are called *grabens*. In the southern Adirondacks, we find several grabens that contain flat-lying sedimentary rocks of Cambrian and Ordovician age. The most recent fault movement must have happened after deposition of the Cambrian and Ordovician rocks cut by the faults—that is, sometime after Middle Ordovician time. We think that some of these faults originally formed in the Late Proterozoic and were reactivated in Middle Ordovician time. We can see small faults in many outcrops in the Adirondacks (Figure 4.18A). Some faults contain shattered rocks known as *fault breccias* (Figure 4.18B).

Other straight valleys are the result of erosion along zones of intensely broken rock called *fracture zones* (Figure 4.19). Valleys form along such zones because the broken rock erodes more rapidly than the surrounding rock. Fracture zones differ from faults: the blocks on opposite sides of the zone have not moved relative to each other, but the rock has simply shattered in place. In addition to the faults and fracture zones that run north-northeast, we find many others that run east-northeast, east, and southeast.

Joints, another type of brittle deformation, are found in every Adirondack rock exposure (Figure 4.20). These breaks look like neat slices through the rock. A joint is different from a fault because there has not been any movement along a joint.

How Adirondack Deformation Happened

What caused the deformation of the Adirondack rocks? Immense tectonic forces compressed the entire region now known as the Grenville Province (Figure 4.2). This compression, or squeezing, of the crust was accompanied by folding of the rock layers. As the crust was squeezed, it thickened and shortened in the same way that a cube of soft caramel candy shortens and thickens when you push on its sides. In addition to the folding, large blocks of crust moved along ductile shear zones and were stacked one on top of the other. As the crust thickened, the lower parts were buried deeper beneath the surface. There, they were subjected to high pressures created by the weight of the overlying rock. These pressures, along with heat rising from the mantle and additional heat from intrusions of magma, thoroughly metamorphosed the rocks.

Where did these forces come from? Our best guess is that they resulted from a collision between two continents. This collision began the complicated sequence of events we call the *Grenville Orogeny* (see Chapter 3).

Figure 4.12. These two photos illustrate the kinds of dramatic effects of deformation and metamorphism that occurred during the Grenville Orogeny. The contorted layers in (B), found in the Adirondacks, once looked like the flat layers shown in (A), younger limestone beds of Ordovician age. The limestone beds are found near the edge of the Adirondack region. Their gentle tilt was caused by the rising of the Adirondack dome (Figure 4.23). The white rock in (B) is coarse-grained marble; it was once fine-grained limestone and dolostone. The contorted dark layers are calcsilicate rock; they were once unbroken, parallel layers of impure dolostone.

Figure 4.13. This photo shows complexly folded rock layers in the northwest Adirondacks. The thin layers are impure quartzite and calc-silicate rock. These layers were originally flat-lying.

Summary of the Geologic History

We know enough about the geology of the Adirondack region to begin to piece together a history of the Middle and Late Proterozoic there. But there are many things we still don't know. We have to make some educated guesses at nearly every stage of our reconstruction.

We find the age of igneous rocks by radiometric dating (see Chapter 2). However, this task is not simple. Sometimes intense metamorphism, like that which occurred in the Adirondacks, can "reset" some or all of the radioactive "clocks" in the rock. If this resetting happens, radiometric dating will tell us when the rock was metamorphosed. It will not give us the age of the original igneous rock. Radiometric dating has been done on many Adirondack rocks, but we have to be very careful in interpreting the results.

We have found that almost all rocks in the Adirondacks are of Middle Proterozoic age. Radiometric dating of the metavolcanic rocks suggests that the oldest ones may be as much as 1.3 billion years old. We think the metasedimentary rocks were deposited as sedimentary rocks beginning at about the same time.[6]

The original sedimentary rocks of the Adirondack basement—sandstone, limestone, dolostone, and shale—were probably deposited in a shallow inland sea. Although they were deposited most likely no more than 1.3 billion years ago, some contain grains of the mineral zircon that are about 2.7 billion years old. This fact tells us that the sediments that formed these rocks were eroded from a much older landmass. This landmass was probably the Superior Province, located to the west and north of the Grenville Province (see Physiographic and Tectonic Maps on Plate 4). Metavolcanic rocks that occur with the metasedimentary rocks indicate that volcanoes were present in the region at that time.

Most of the metaplutonic rocks of the Adirondack Highlands are probably between 1.15 and 1.1 billion years old. Shortly before the Grenville Orogeny, large volumes of magma may have risen from the mantle into the crust. Heat from the magma partially melted the surrounding crust, producing molten rock of different compositions. The various kinds of molten rock, such as anorthosite and granite, tended to rise through the crust because they were less dense than the surrounding rocks. Some continued to rise even after they partly cooled and solidified, eventually forming balloon-like domes or spreading out as thick sheets within the crust.

At some point during the Middle Proterozoic, the rocks we now find at the surface in the Adirondack region were as much as 30 km below the surface. Remember that some of these rocks began their existence as sedimentary rocks at the surface, which means that they must have been pushed down that far. For them to be buried so deeply, the continental crust in the region had to be nearly twice as thick as normal continental crust (see Chapter 3). A modern example of double-thick crust is the Tibetan Plateau just north of the Himalayan Mountains. As India continues to collide with Asia, the collision is creating the Himalayas—the world's highest mountains—along the collision zone, and a double thickness of continental crust under them and to the north. This double-thick crust makes Tibet the world's highest plateau region, with an average elevation of 5 km above sea level. Far below the surface, the rocks are subjected to very high temperatures and pressures.

The Grenville Orogeny, which may have been caused by a similar collision, buried the Adirondack rocks. It is diffi-

[6]Metasedimentary rocks cannot be dated directly. However, we think that the metasedimentary rocks are the same age as the metavolcanic rocks because they are often found together.

cult to say when the orogeny began. It was under way at least 1.1 billion years ago. The deformation and metamorphism appear to have peaked between 1.1 and 1.05 billion years ago. Some additional plutonic rocks may have been formed at the time, either by partial melting of the crust or by injection of new magma from below. By about 900 million years ago, the rocks had cooled again. We still don't know the details of these complex events.

Like the collision of India and Asia, the Grenville Orogeny built huge mountain ranges along the collision zone and a high plateau behind it. Over the next several hundred million years, erosion coupled with uplift levelled the mountains and stripped more than 25 km of rock from the plateau. Between 650 and 600 million years ago, the crust of eastern proto-North America was stretched and was broken by major faults. These faults are the ones that run north-northeast throughout the eastern Adirondacks. There are also many smaller faults running east-northeast, east, and southeast. Igneous rocks called *diabase dikes* (Figure 4.21) show that molten rock was injected and hardened in narrow vertical zones, often along faults. Radiometric dating tells us that these dikes were formed about 600 million years ago.

Beginning in the Late Cambrian, the Adirondack region was gradually submerged beneath shallow seas. Sandstones with trilobite fossils (see Figure A.3) were deposited over much of the region. The contact between these younger rocks and the underlying basement is visible in several places near the outer edge of the present Adirondack dome (Figure 4.22). Sediments continued to accumulate across much of the eastern United States (with some interruptions) through the Pennsylvanian Period, but no rocks younger than Middle Ordovician remain in northeastern New York.

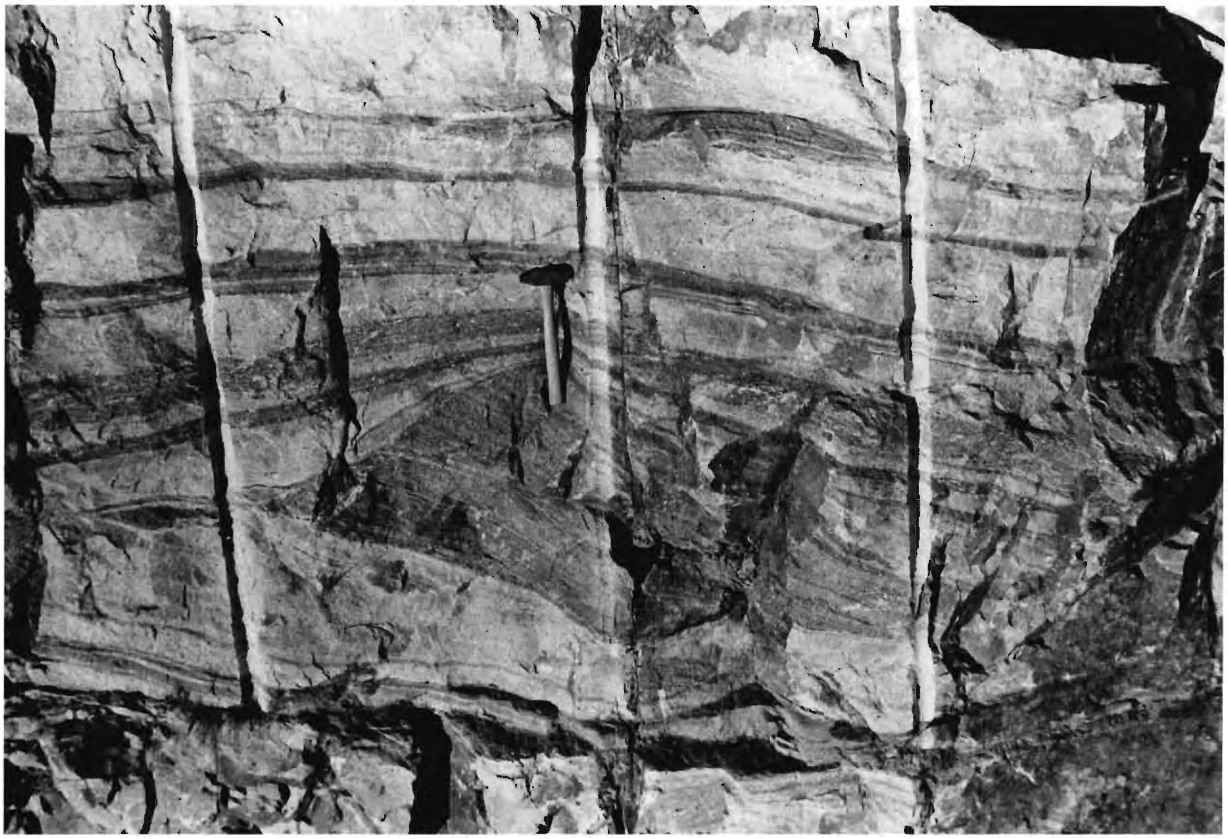
Later erosion in the Adirondack region stripped off nearly all of the Paleozoic sedimentary rocks. However, there are still traces of Cambrian and Ordovician rocks within the Adirondacks; this fact proves that they once

A.

B.

Figure 4.14. These photos show dramatic folding in Adirondack rocks. The severely crumpled rocks in (A) are alternating layers of marble (light) and calcsilicate rock (dark). The rock in (B) is granitic gneiss (light) with a layer of amphibolite (dark).

A.



B.

Figure 4.15. These two photos show *foliation* in Adirondack rocks. Foliation refers to layer-like structures that form when a rock is deformed. (A) is a garnet-bearing gneiss. (The vertical channels are drill holes that were used in blasting this road cut.) (B) is calcsilicate rock.

Figure 4.16. This photo shows *lineations*—streaks of minerals that form in rock when it is severely flattened and stretched. The lineations are ribbon-like bands of quartz; they show the stretching direction. The rock is granitic gneiss.

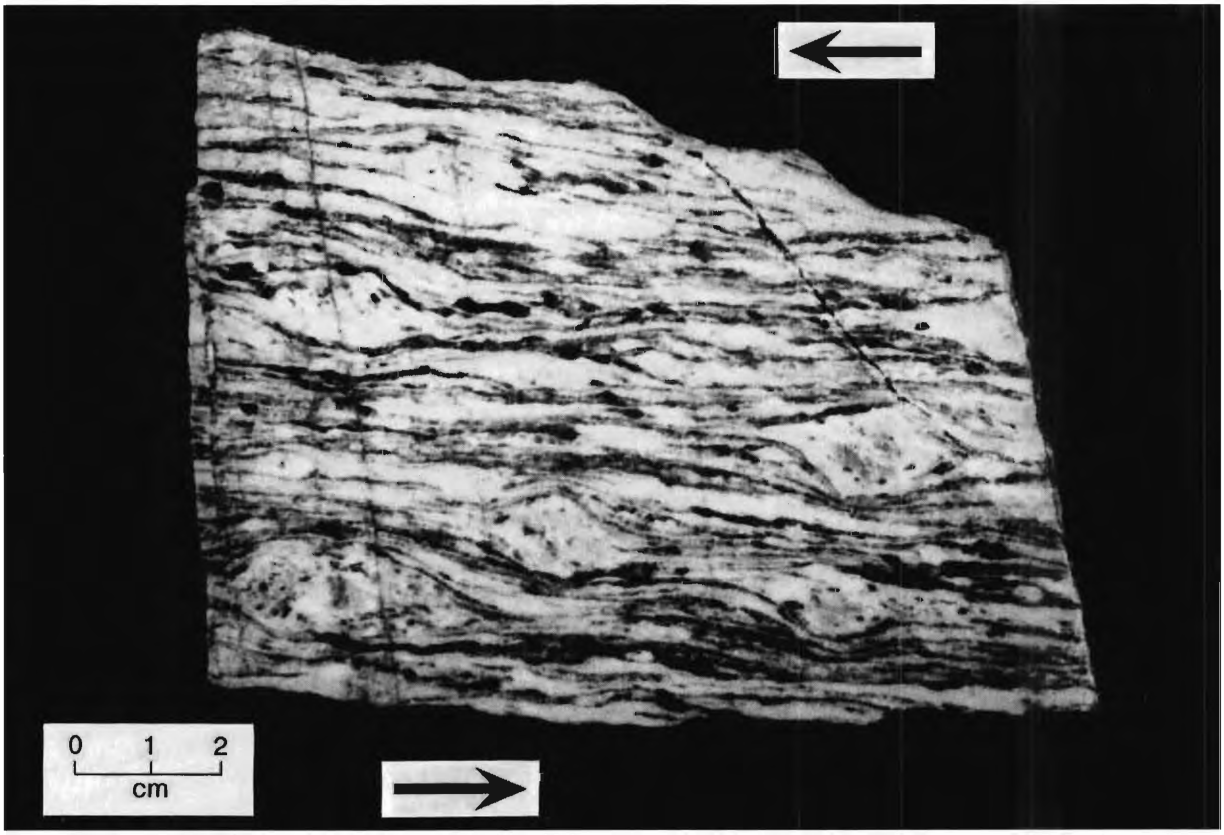


Figure 4.17. This photo shows an Adirondack mylonite. Mylonites are formed as minerals recrystallize in a ductile shear zone. This process makes the mineral grains in the rock much smaller. The large grains are made of the mineral feldspar. Their shapes tell us the directions of the deforming forces. The "tails" on the upper left and lower right of these grains point in the direction of movement (as shown by the arrows). The streaks in the rock are foliation (Figure 4.15).

Figure 4.18. (A) shows a small fault in the Adirondacks. (B) shows breccia in another fault in the Adirondacks. Large, angular fragments of gneiss are enclosed in finer grained, crushed and shattered rock of the fault zone.

covered the region. In the southern Adirondacks, we find grabens that contain Cambrian and Ordovician rocks formed in these seas. Because these blocks dropped down lower than the surrounding landscape, they were saved from erosion when the other Paleozoic layers were worn off during regional uplift. The Lower Paleozoic rocks that originally covered the region still encircle the Adirondack dome.

From the Middle Ordovician into the Tertiary Period, there is no evidence of any tectonic activity in the Adirondacks, despite three more mountain-building events that affected New England and southeastern New York (see Chapter 3). The region that is now the Adirondack Mountains was flat, just like the rest of the region west of the Appalachian Mountains. In Jurassic or Cretaceous time, some small dikes intruded in the eastern Adirondacks and Vermont.

Sometime in the Tertiary Period, the Adirondacks began to rise (Figure 4.23). Why? Our best guess is that a hot spot formed under the region near the base of the crust. This hot spot heated the surrounding material at depth, causing it to expand. This expansion raised the crust above, causing the present dome-shaped uplift (Figure 4.23). In the early 1980s, remeasurement of the elevations of old surveyors' bench marks showed that the Adirondacks may be rising at the astonishing (to a geologist!) rate of 2 to 3 mm per year. The mountains are growing about 30 times as fast as erosion is wearing them away. We suspect, however, that the present rapid uplift is a temporary spurt, and the average rate may be much less.

After the Adirondack dome began to rise, stream erosion (and much later glacial erosion) started wearing away the softer rocks and the fractured zones. Eventually, erosion carved the region into the separate mountain ranges we see today. Glacial ice entered the region about 1.6 million years ago; that episode is discussed in Chapter 12.

Figure 4.19. This photo shows a well exposed fracture zone at Split Rock Fall near Elizabethtown. Although the rock has shattered in place, it did not move along the zone. This fact makes a fracture zone different from a fault.

Figure 4.20. This cliff contains widely spaced joints. Joints are fractures that looks like neat slices through the rock. The rock has not moved along the joints as it does along faults. The joints in this outcrop are vertical. The horizontal lines are foliation (Figure 4.15).

A.

B.

C.

Figure 4.21. These three photos show *dikes* in the Adirondack region. These dikes formed when magma was pushed up from below and hardened. The dike in (A) is made of *pegmatite*, a very coarse-grained igneous rock, cutting across olivine metagabbro. The dike in (B) is the igneous rock *diabase* cutting across marble. The cracks in the dike formed when the magma hardened and shrank. The dike in (C) is diabase cutting across metanorthosite.

Review Questions and Exercises

Most of the bedrock in this region is of which type—igneous, sedimentary, or metamorphic?

Most of the Adirondack rocks date from what geological era? How do we know? Why do we find so few rocks younger than that in the Adirondack region?

How did the Adirondack region become mountainous? Why does it look so different from the areas around it?

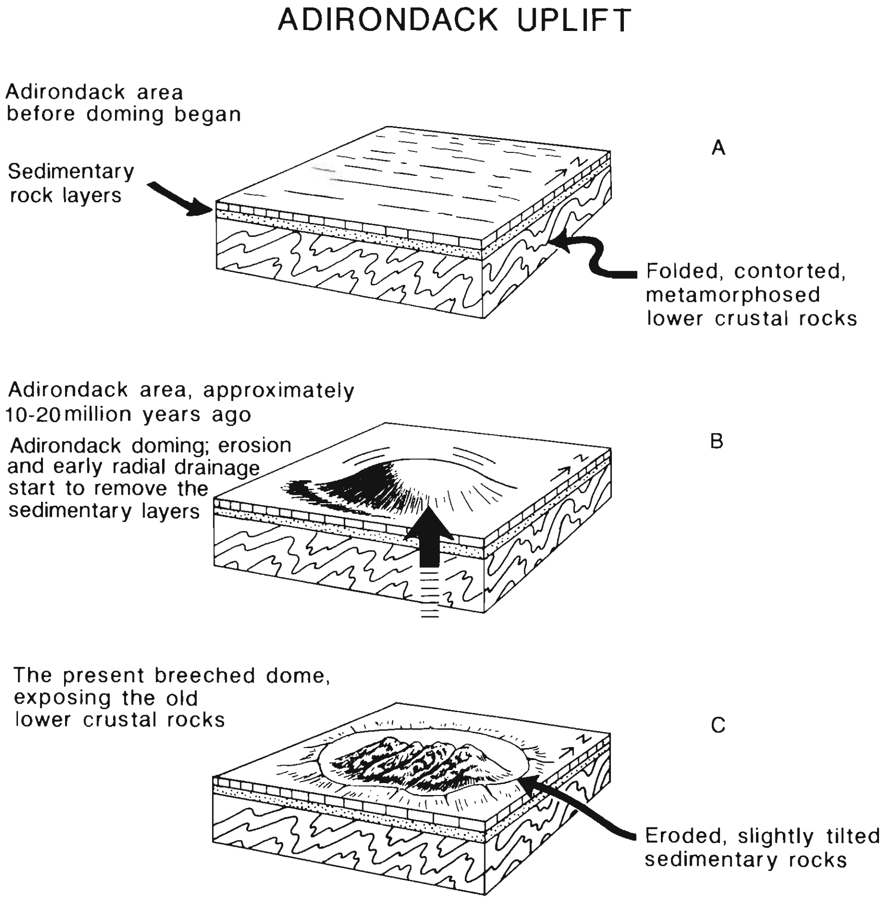
The media sometimes call the Adirondacks "the oldest mountains in the world." You sometimes hear that the mountains were "made by the glacier." Are these descriptions correct? Explain your answers.

Figure 4.22. The rock in the lower part of this picture is gneiss. The layers are vertical and the rock has foliation (Figure 4.15). The gneiss ends abruptly; on top of it is a horizontal layer of pebble conglomerate. As we continue to move upward, the conglomerate becomes finer grained until it eventually become quartz sandstone. (The vertical line in the sandstone is a drill hole that was used during the blasting of this road cut between Ticonderoga and Port Henry.)

This picture tells only part of the story. The gneiss is a folded metamorphic rock that formed deep within the crust. A long period of erosion uncovered the gneiss. Then the land was submerged beneath a shallow sea. The conglomerate and sandstone were deposited on top of the gneiss in that sea.

Rare fossils in the sandstone tell us that it is Cambrian—a little more than 500 million years old. Radiometric dating tells us that the gneiss is at least 1.1 billion years old. That means that almost 600 million years of geologic history are lost in the time gap between the two rock units. The surface that separates them and represents the time gap is called an *unconformity*.

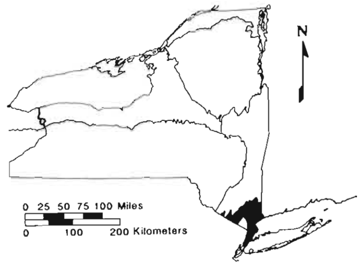
Figure 4.23. These drawings show three stages in the uplift of the Adirondack dome. (A) represents the situation 10-20 million years ago. The region is flat, with layers of sedimentary rock covering the contorted, metamorphosed basement rock. In (B), uplift has created a dome shape. Running water, in a radial pattern, begins to wear away the sedimentary layers. (C), representing the present, shows the basement rock exposed, surrounded by eroded sedimentary rock. The escarpment of sedimentary rocks is grossly exaggerated to illustrate the concept of upturned sedimentary rocks surrounding the dome.



CHAPTER 5

COLLISION!

Hudson Highlands and Manhattan Prong[1]



SUMMARY

The rocks of southeastern New York State have a complex 1.3 billion-year history. That part of the State is divided into four geologic regions: the Hudson Highlands, the Manhattan Prong, the Newark Basin, and the Coastal Plain. This chapter covers the first two regions.

The metamorphic rocks of the Hudson Highlands form the mountains of southeastern New York. The Hudson Highlands are divided into three major areas that are separated by ancient faults. The bedrock, which is the oldest in that part of the State, forms complex patterns. These rocks were deposited as sedimentary and volcanic rocks 1.3 billion years ago. During the Grenville Orogeny, the rocks in the eastern and central areas were metamorphosed into gneiss, and limestone in the western area became the Franklin Marble. The faults and folds in the Hudson Highlands determine the positions of ridges and valleys.

The Manhattan Prong has a less rugged landscape of rolling hills and valleys. Gneiss, schist, and quartzite form the hills, while marble makes up the valleys. The rocks of the Manhattan Prong were deformed and metamorphosed during the Taconian Orogeny.

The early geologic history of southeastern New York is probably similar to that of the Adirondack region. About 1.3 billion years ago, sediments and volcanic material were deposited in a shallow sea in eastern proto-North America. The Grenville Orogeny, caused by a continental collision about 1.1 billion years ago, greatly compressed and thickened the crust and metamorphosed the rocks there. It built a massive mountain range and a high plateau behind it. By 600 million years ago, the plateau had been eroded to a flat plain and its ancient roots—the rocks of the Hudson Highlands—exposed. Faults and volcanoes formed in the region when the Grenville supercontinent broke up. From the beginning of the Cambrian through the Middle Ordovician, sediments were deposited in a shallow sea that flooded the eastern half of proto-North America. In the Middle Ordovician, an island arc advanced toward the edge of the continent, and rocks of the accretionary prism and a few pieces of oceanic crust were trapped between the island arc and the continent. This collision, about 450 million years ago, caused the Taconian Orogeny, which built a mountain range and deformed and metamorphosed the rocks of southeastern New York. The Acadian Orogeny, about 380 million years ago, and the Alleghanian Orogeny, about 325-250 million years ago, again deformed and metamorphosed the rocks of the region. About 200 million years ago, the Atlantic Ocean began to open. At about the same time, movement on the Ramapo Fault caused formation of a basin, in which were deposited sediments eroded from the Hudson Highlands. Today, that area is the Newark Basin, New York's "dinosaur country." The same fault movement caused magma to squeeze up from below and form the Palisades Sill.

[1]By Y.W. Isachsen and A.E. Gates.

Introduction

The rocks in southeastern New York State formed through a series of complex geologic processes. These processes began about 1.3 billion years ago and continue today. Over this long period of time, southeastern New York has been the most geologically active part of the State

The rocks at the surface in southeastern New York are highly complex. In them we find evidence for at least three, and possibly four, major mountain chains over the 1.3 billion-year history. Major *orogenies*, caused by continent-continent collisions, formed these mountains. Erosion by water, wind, and ice eventually wore away each mountain chain to a low plain. At present, only the rocks that formed in the deep roots of the mountains remain. These rocks are the ones that we must study to unravel the geologic history of this complex area.

Southeastern New York contains four distinct geologic regions (Figure 5.1).

1. The Hudson Highlands. This area consists of low mountains (including the Ramapo Mountains). They are composed of metamorphic rocks of Middle Proterozoic age.
2. The Manhattan Prong (New York City-Westchester County area). This rolling lowland area is composed of metamorphic rocks of Early Paleozoic age.
3. The Newark Basin (Rockland County and part of Staten Island). The rocks here are Triassic-Jurassic sedimentary and igneous rocks.
4. The Coastal Plain and Long Island. Mesozoic and Cenozoic sedimentary rocks underlie this area.

We will be looking at the Hudson Highlands and the Manhattan Prong in this chapter (see Figure 1.1). The other two areas are discussed in Chapters 9 and 10.

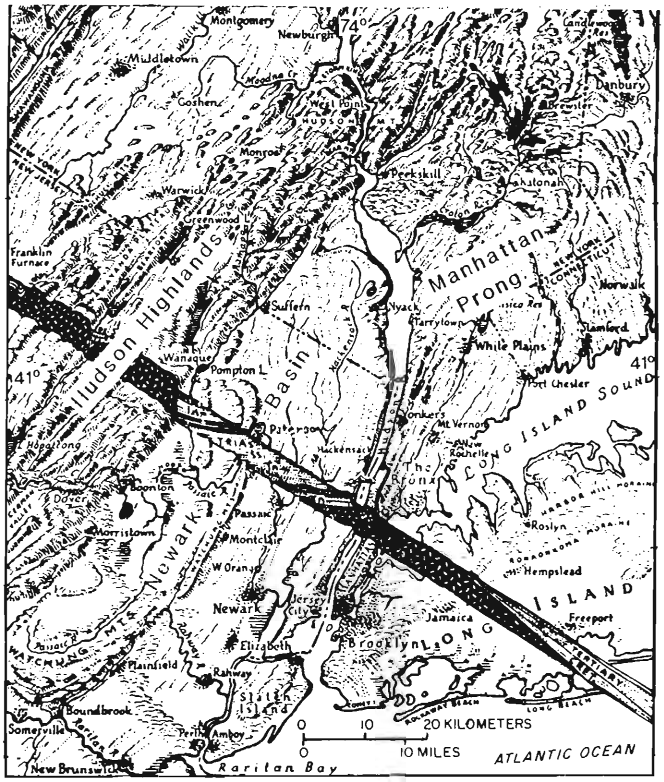


Figure 5.1. Block diagram of southeastern New York showing the four physiographic provinces and a simplified geologic cross section. (Figure taken from Erwin Raisz, XVI International Geological Congress, Guidebook, 9, 1936.)

Hudson Highlands

The Hudson Highlands region is narrow, elevated, and composed of metamorphic rocks. The area crosses the southeastern portion of the State in a northeast direction across Orange, Rockland, Putnam, Dutchess, and Westchester Counties (Figure 5.2; see also all Plates of the *Geological Highway Map*). The Hudson Highlands are part of the geologic province called the *Reading Prong*, which extends from Pennsylvania to Connecticut. The Reading Prong is composed of metamorphic rocks that were formed during the Proterozoic and deformed during the Grenville Orogeny. Many of these rocks are rich in uranium, and they therefore produce high levels of the radioactive gas radon. The presence of radon has attracted publicity to the province.

Elevations in the Hudson Highlands range from the bottom of the Hudson River (a surprising 240 m below sea level) to North Mount Beacon (405 m above sea level). In most places, the land is relatively high and rugged. North and south of the Hudson Highlands, however, the land is much lower, about 100 m above sea level. The Hudson Highlands, therefore, form the mountains in southeastern New York.

The Hudson Highlands are divided into three major areas. The central area, which is the largest, has a higher elevation than the western and eastern areas. The areas are separated by ancient faults. The western area is a short extension of the New Jersey Highlands. It is separated from the central area by a fault called the *Reservoir Fault* and a strip of Paleozoic sedimentary rocks called the *Green Pond Outlier*. The eastern area, which lies east of the Hudson River, is separated from the central area by a fault called the *Ramapo Fault* and related faults.

The pattern of the bedrock in the Hudson Highlands is so complicated that both the map in Figure 5.2 and the map on Plate 2 are too small to show all of the details. The rocks include a variety of layered and unlayered metamorphic units, most of which are highly resistant to erosion. They record the earliest geologic history of southeastern New York.

The rocks in the central and eastern areas were originally deposited in a shallow sea about 1.3 billion years ago. They started out as sandstones, shales, and shaly limestones, as well as volcanic rocks. During the Grenville Orogeny, these rocks were metamorphosed into gneiss. They contain large deposits of *magnetite*, a kind of iron ore. These deposits were mined for iron in the 18th and 19th centuries. Uranium was also mined from these rocks in several areas.

The rocks in the western area started out as thick limestones, sandstones, and volcanic rocks. During the Grenville Orogeny, the sedimentary rocks were metamorphosed. The limestone became the Franklin Marble. *Magma* (molten rock) was later intruded into the marble. The magma added heat and new chemical elements, allowing a wide variety of minerals to form in the marble. In northern New Jersey, this marble belt now contains more mineral varieties than almost any other area in the world.

The Hudson Highlands contains many faults. Faults also separate the Hudson Highlands from the other geologic provinces. In addition, some folds in the rock are large enough to show up on the geologic map (Plate 2). The faults and folds are generally parallel to each other. Compare the maps in Figures 5.1 and 5.2, which are at the same scale. Notice how the faults and folds have determined the positions of ridges and valleys.

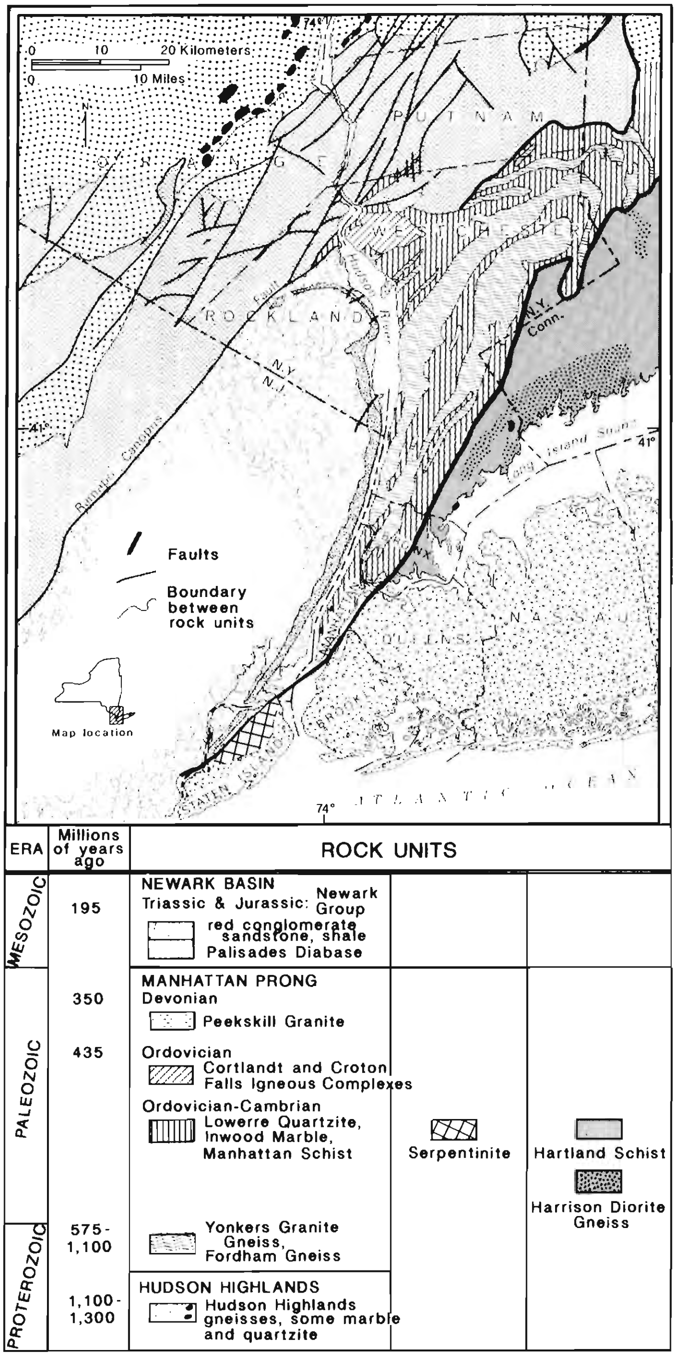


Figure 5.2. Geologic map of southeastern New York. It shows the same area at the same scale as Figure 5.1. Compare the two and note how the shape of the landscape corresponds to the underlying geology. The stippled patterns on Long Island and in western Orange County indicate rock units outside the region described in this chapter.

MANHATTAN PRONG

The Manhattan Prong has a landscape of rolling hills and valleys. The greatest elevation is about 100 m above sea level. The shape of the land's surface is closely controlled by the underlying bedrock (compare Figures 5.1 and 5.2). Much of the bedrock, however, is covered by Atlantic Coastal Plain deposits. Metamorphic rocks that are resistant to erosion make up the hills. They include the Fordham Gneiss, the Yonkers Gneiss, the Manhattan Schist, and locally, the Lowerre Quartzite. The Inwood Marble, which overlies the Lowerre Quartzite, makes up the valleys because it is easily erodible. The Hudson, Harlem, and East Rivers and the major north-south valleys in northern Westchester County are all underlain by Inwood Marble.

The rocks of the Manhattan Prong were tightly folded and metamorphosed primarily during the Taconian Orogeny (see Chapter 3 and the Tectonic Map on Plate 4). This orogeny occurred about 450 million years ago. The folds are oriented north-south and are long and narrow. Minor faults produced earthquakes in the area many times during geologic history. Some of these faults are still active today.

Geologic History of Southeastern New York

The earliest geologic history of southeastern New York is recorded by the rocks in the Hudson Highlands. It is very difficult to reconstruct this history because the rocks have been deformed and metamorphosed by at least three orogenies. Another major problem is that we can see only fragments of an ancient landmass that was once huge. The rest has been removed by erosion. However, the early history of the Hudson Highlands was probably similar to that of the Adirondack region (see Chapter 4). Both regions are made up of Middle Proterozoic-age rocks, and they are connected underground beneath a thick cover of younger, Paleozoic sedimentary rocks (see Figure 4.2). By combining the geologic evidence from both of these areas, we can better solve this complex puzzle.

About 1.3 billion years ago, much or all of the eastern edge of proto-North America[2] was a shallow sea. Sediments were carried into this sea from an older landmass, which was formed about 2.7 billion years ago. At the same time, volcanic material was also deposited, perhaps from a nearby volcanic island arc or magmatic arc (Figure 5.3). Over the years, the sediments piled up until they were thousands of meters thick. Then, a drifting continent collided with proto-North America. This collision squeezed the crust together, causing the mountain-building event called the Grenville Orogeny (Figure 5.4).

During the orogeny, the crust was compressed until it was double its normal thickness. Sediments in the lower part of the double-thick crust were buried 25-30 km beneath the surface, where pressures were very high and where temperatures reached 750-800°C. These conditions of high pressure and high temperature metamorphosed the original sedimentary rocks. Extensive chemical and physical changes created new metamorphic minerals and textures in the rocks. Several kinds of magma pushed up into the Hudson Highlands rocks from below. The magma slowly cooled and hardened underground.

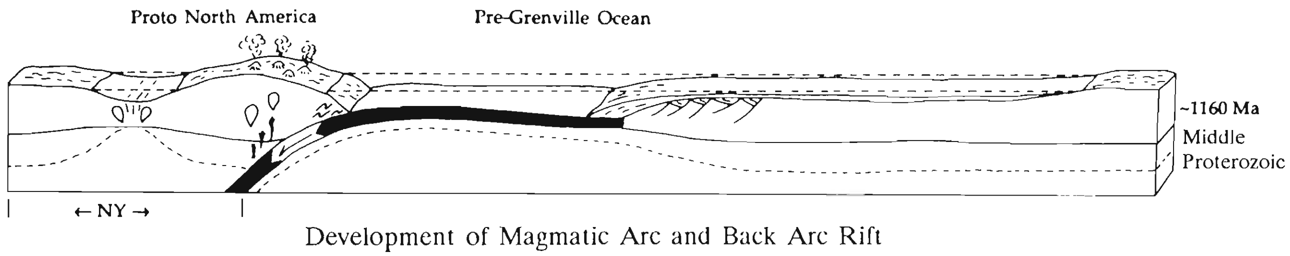


Figure 5.3. Block diagram showing the position of proto-North America and the approaching continent just prior to the Grenville Orogeny. (Compare with Figure 3.1 to recognize continental and oceanic crust and the boundaries of the crust, lithosphere, and asthenosphere.)

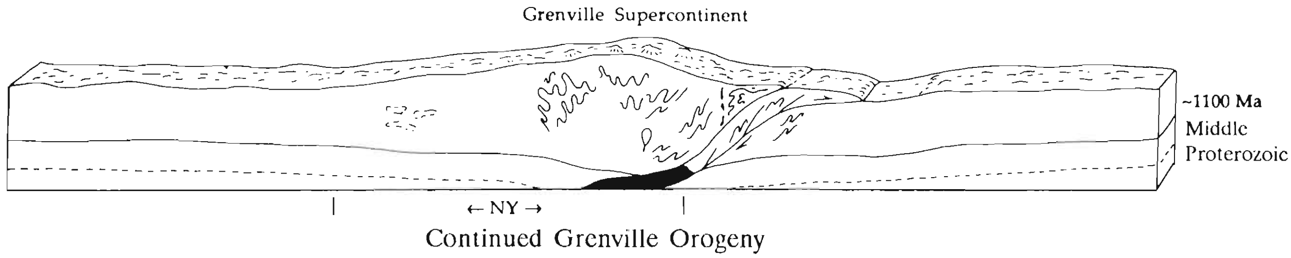


Figure 5.4. Block diagram showing a stage in the Grenville Orogeny. Notice the double-thickened crust.

[2]The term *proto-North America* refers to the continent that would later become modern North America. It has also been called Laurentia.

Radiometric dating tells us that this igneous activity and metamorphism happened about 1.1 billion years ago. At that time, the whole area from Labrador to Georgia (including all of New York State) was a very extensive high plateau. The plateau formed behind the massive mountain range built by the Grenville Orogeny. The whole region may have averaged about 5 km above sea level. It probably looked like the Tibetan Plateau north of the modern Himalayan Mountains. There, a double-thick crust has formed because India, originally a separate continent, is now being pushed into southern Asia. This collision began about 40 million years ago and continues today.

As this ancient "Grenville Plateau" formed, it began to erode. As the crust was "unloaded" by this erosion of rock material, the land rebounded. This process of erosion, rebound, erosion, etc., eventually resulted in the removal of some 25-30 km of rock. By 600 million years ago, the once-high mountains and plateau had been worn away to a low, flat plain. The original deep roots of the plateau were then exposed at the surface. These roots are the rocks we find today in the Hudson Highlands.

The oldest rock in the Manhattan Prong is the Fordham Gneiss, a rock of variable composition. The younger Yonkers Gneiss was originally an igneous rock that either hardened underground from magma or reached the surface as a volcanic ash or lava flow. The Hudson Highlands and Manhattan Prong underwent rifting during the latest Proterozoic with the breakup of the Grenville supercontinent (Figure 5.5). Basaltic volcanism and normal faulting occurred as a result of this rifting. The mountains were further reduced during this event.

Approximately at the beginning of the Cambrian Period, a shallow sea gradually flooded most of the eastern half of proto-North America. It advanced from east to west across the continent. In southeastern New York during the Early Cambrian, sand collected in low areas. This sand and the much older gneiss were covered by carbonate sediments during the Early Cambrian through Early Ordovician (Figure 5.6). These carbonate sediments were later metamorphosed and became the Inwood Marble. After an interval of erosion, a thin unit of limy mud and a much thicker unit of silty mud were laid down during the Middle Ordovician. The rocks formed from these muds were later metamorphosed into the Walloomsac Schist.

During the Middle Ordovician, a volcanic island arc moved toward the east coast of proto-North America (see Chapter 3). As it approached, it scraped up sedimentary rocks that had been deposited in the ocean off the proto-North American coast. These rocks piled up to the west, along the advancing edge of the island arc (Figure 5.7) (A pile that includes folded, faulted, and metamorphosed oceanic rocks formed in this way is called an *accretionary prism.*) When the island arc collided with proto-North America, the rocks of the accretionary prism were trapped between the two and pushed onto the edge of eastern proto-North America.

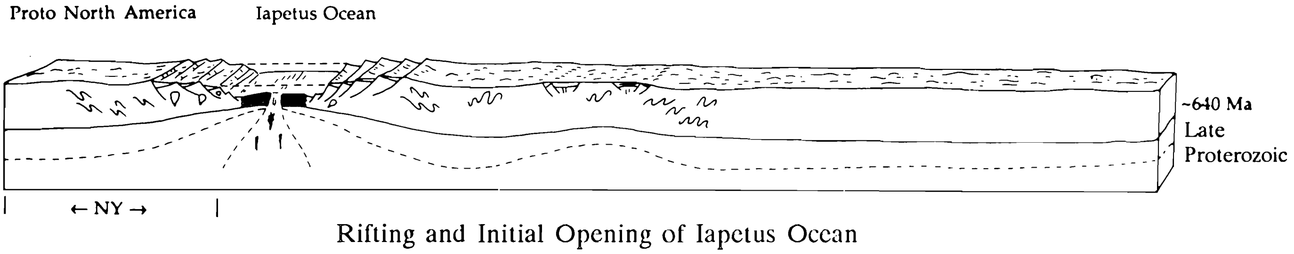


Figure 5.5. Block diagram showing Late Proterozoic rifting of proto-North America and the formation of the Iapetus Ocean. As a result of this stretching of the crust, normal faulting occurred and basaltic lava poured out onto the expanding ocean floor.

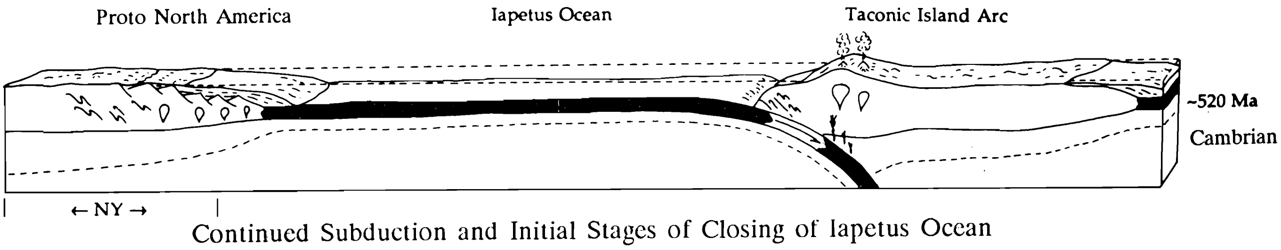


Figure 5.6. Block diagram showing Cambrian passive margin on proto-North America and Taconic island arc.

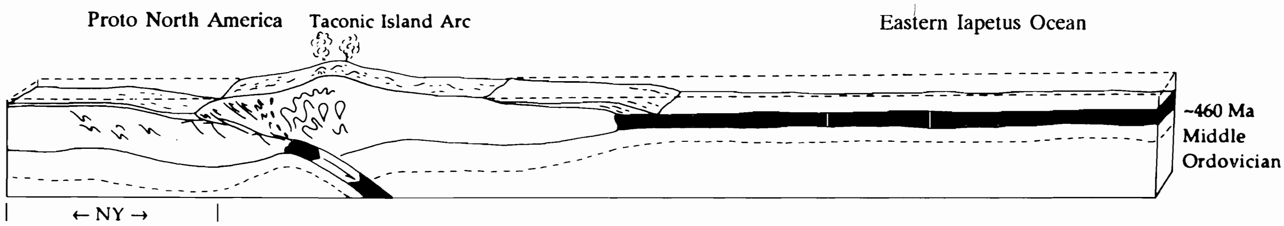


Figure 5.7. Block diagram showing the Middle Ordovician Taconian Orogeny. Notice the volcanic island arc pushing sedimentary rocks westward toward proto-North America.

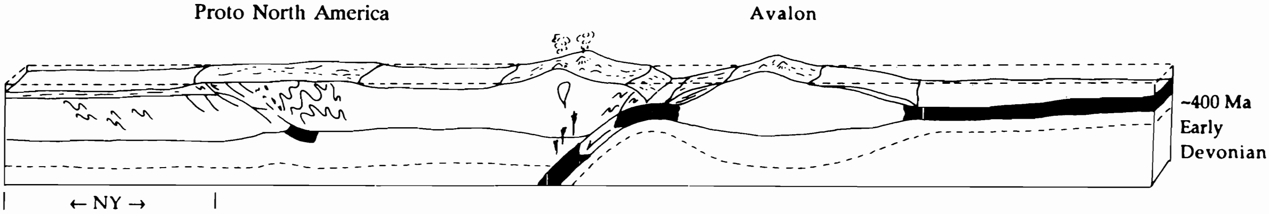


Figure 5.8. An offshore continent, Avalon, moves toward proto-North America; their collision caused the Early Devonian Acadian Orogeny.

Another sort of rock was caught in the collision as well. As the volcanic island arc moved toward proto-North America, most of the oceanic crust between them slid down under the arc. However, a few pods of oceanic crust were brought up along the collision zone. The largest of these masses forms the backbone of Staten Island, the highest point on the Atlantic coast south of Maine.

The collision of the island arc with proto-North America caused the Taconian Orogeny. This mountain-building event created the ancient Taconic Mountains and deformed and metamorphosed the rocks of southeastern New York. It occurred about 450 million years ago and added to the proto-North American continent (see the Tectonic Map on Plate 4).

At the end of the Taconian Orogeny, molten rock was pushed up from below along the southern border of the Hudson Highlands east of the Hudson River. The magma hardened to form dark gray to black igneous rocks. These rocks have unfamiliar names like pyroxenite, gabbro, diorite, and periodotite; they form the Cortland Complex. The heat from the molten rock metamorphosed parts of the surrounding Manhattan Schist into emery deposits.

Eventually, the ancient Taconic Mountains were worn down to a flat plain. This plain was gradually submerged by an advancing sea. Thick sequences of Silurian and early Devonian sedimentary rocks were deposited. Then, about 380 million years ago, the Acadian Orogeny occurred (Figure 5.8). This orogeny began when a continent called *Avalon* (which included eastern Canada and eastern New England) collided with proto-North America. Still later, near the end of the Paleozoic (325-250 million years ago), proto-Africa collided with proto-North America along a transform margin (Figure 5.9). This collision caused the Alleghanian Orogeny. Many other continental collisions took place around the world as well. Eventually, these continental collision assembled many small continents into a supercontinent called *Pangea*.

All of these events deformed and metamorphosed the rocks of southeastern New York. From looking at those rocks today, it is difficult to figure out exactly which faults, folds, and metamorphism were caused by which event.

The next major event in the geologic history of southeastern New York happened about 200 million years ago. After so many episodes of collision and compression, Pangea began to be stretched. This stretching caused it to break apart (Figure 5.10). This rifting event marked the birth of the Atlantic Ocean. After the break, part of proto-Africa, as well as the earlier Taconian island arc, remained attached to North America. They now form part of eastern New England. The Atlantic Ocean continues to widen today at this latitude at approximately 2.5 cm per year.

At about the same time, new movement occurred along the old Ramapo Fault. An area southeast of the fault was dropped down some 1500-2400 m to form a basin in Triassic-Jurassic time (about 200 million years ago). The Newark Basin is one of several basins along the east coast of North America (see Figure 9.6). As the basin formed, it became filled with lake and river sediments that were transported mainly from the adjacent Hudson Highlands. These sediments became the present red con-

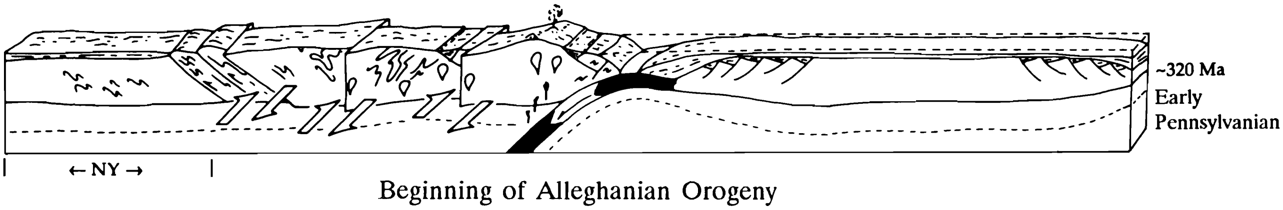


Figure 5.9. Block diagram for the Late Mississippian part of Alleghanian Orogeny. Notice the arrows that show horizontal, or *transform*, movement of blocks of crust. The Alleghanian Orogeny, which was the collision of proto-North America and proto-Africa along a transform margin, was one of many orogenies that occurred around the world. Together, these collisions formed the supercontinent Pangea.

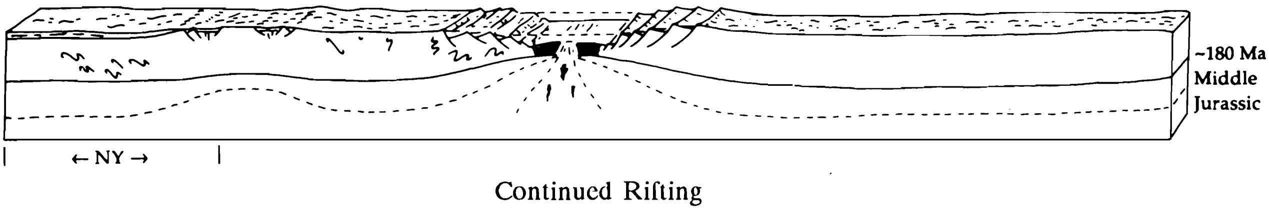


Figure 5.10. Block diagram showing the Jurassic rifting of Pangea to form the North American and African continents.

glomerates, sandstones, and shales of Rockland County. These rocks are the "dinosaur country" in New York and New Jersey. Thus far, the only dinosaur fossils discovered in New York are footprints of the meat-eating bipedal dinosaur *Coelophysis*.

The faulting that formed the Newark Basin also tapped magma at depth. The molten rock squeezed in between the sandstone layers and solidified as a sheet, or *sill*, of black diabase 120-300 m thick. The east-facing eroded edge of this slab creates the majestic cliffs of the Palisades (see Figure 9.4). This escarpment extends along the west shore of the Hudson River from New York Harbor to north of Nyack. From there, it curves westward toward the Hudson Highlands. As the magma cooled, it shrank and broke along vertical fractures to produce five- or six-sided columns. The columns look something like the vertical logs used to build a fort, so the escarpment was named "Palisades." (A *palisade* is a log fence built for defense.) In New Jersey, lava flows reached the surface during the Triassic Period. They now form the Watchung Mountains. Additional information on the Newark Basin appears in Chapter 9.

Review Questions and Exercises

Most of the bedrock in the Hudson Highlands is which type—igneous, sedimentary, or metamorphic? Which type is found in the Manhattan Prong? How old are these rocks?

How has the bedrock in this region affected the shape of the modern landscape? Give several examples.

Why is it hard to figure out the exact history of the rocks in this region? Give three reasons.

What is special about the rocks that form the backbone of Staten Island?

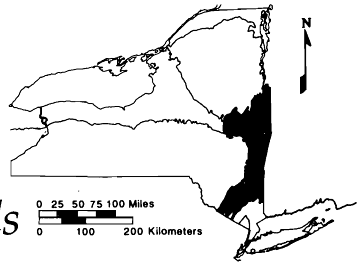
At what rate is the Atlantic Ocean opening today?

Extra credit question: If Columbus were to make his voyage from Spain to North America today, instead of in 1492, how much farther would he have to travel?

When and how was the Palisades Sill formed?

CHAPTER 6
A VIEW FROM THE HUDSON

Hudson-Mohawk Lowlands and Taconic Mountains[1]



SUMMARY

The region covered in this chapter includes the broad, gently rolling lowlands of the Hudson, Mohawk, and Wallkill River valleys and the highlands of the Taconic Mountains.

The Cambrian and Lower Ordovician rocks in this region formed in two environments: on the shallow continental shelf and in the deep waters of the continental slope and rise of proto-North America. The shelf deposits include quartz sandstone with a thick interval of carbonate rock on top of it. The older slope-rise deposits were formed chiefly from sediments eroded from proto-North America. The overlying deep water deposits reveal the approach of an island arc from the east during the Middle Ordovician. As it approached, it pushed the slope-rise deposits (called the Taconic Sequence) westward onto the shelf rocks. The Taconic Sequence includes fossils of Early and Middle Cambrian creatures that lived on the shelf edge and in slope-rise environments. These fossils are found commonly in chunks of rock that formed on the shelf and upper slope and tumbled down to the lower slope and continental rise; there, they became parts of limestone conglomerates.

The Upper Cambrian rocks record the advance of a sea that flooded large portions of New York State. They include the spectacular sandstones of Ausable Chasm and the fossil stromatolite reefs of the Petrified Gardens. One dolostone unit formed in a shallow, very salty sea contains the quartz crystals known as "Herkimer Diamonds."

The Lower Ordovician rocks are distinguished from those of the Cambrian by the fossils they contain. These thick carbonate deposits, formed in the shallow, warm water of the shelf, include many fossils of shelled animals. The slope-rise deposits of the Taconic Sequence contain different fossils: a few bottom-dwellers together with floaters and swimmers. At the end of the Early Ordovician, the sea became very shallow on the shelf and eventually retreated completely and exposed the rocks to erosion. The resulting gap in the geologic record is represented by the Knox Unconformity.

Later in the Middle Ordovician, the sea advanced again, flooding most of the eastern half of proto-North America. Sediments piled up in a trough in front of the advancing island arc; the island arc pushed the rocks of the Taconic Sequence into the younger trough deposits. The Middle Ordovician rocks on the shelf contain ash blown from the volcanoes of the island arc. Life flourished in the seas.

During the Late Ordovician, the collision between the island arc and the continent—the Taconian Orogeny—built a high mountain range along the eastern seaboard. Many large faults formed in this region, and rock layers of today's Taconic Mountains were folded and metamorphosed. The sea retreated again during the latest part of the Ordovician, possibly because an ice age in the southern hemisphere caused sea level to drop around the world.

The Shawangunk Conglomerate, which forms mountains in southeastern New York, was deposited during the Silurian. On top of the conglomerate are red and green shale and sandstone deposited by streams. Still younger deposits of a shallow, highly salty Late Silurian sea are largely concealed along the west face of the Shawangunk Mountains. The youngest Silurian rocks contain fossils and were probably deposited in a sea with more normal marine saltiness. On top of them is another unconformity.

[1]Adapted from a manuscript by E. Landing.

Description of Hudson-Mohawk Lowlands and Taconic Mountains

The lowlands of the Hudson, Mohawk, and Wallkill River valleys are broad and gently rolling. These broad valleys are surrounded by mountains (see the Physiographic Map on Plate 4 of the *Geological Highway Map*). The Adirondacks lie to the north, the Catskills and the Shawangunks to the west, the Taconic Mountains and the Hudson Highlands to the east. The Helderberg Escarpment is the south border of the Mohawk Valley.

The bedrock of the Hudson-Mohawk Lowlands is shale, siltstone, sandstone, and limestone and dolostone. Much of this rock was formed during the Middle and Late Ordovician Period.[2] Most of them are relatively soft sedimentary rocks and easily eroded. Thus, they are worn away to low plains while areas with harder rocks are left towering over them.

The highlands surrounding this region are all made of rocks that are much more resistant to erosion. The Adirondacks and the Hudson Highlands are mainly metamorphic rock. The Shawagunks are made of the hard sandstones and conglomerates of the Shawagunk Formation and the Helderberg Escarpment largely of carbonate rocks. The Taconic Mountains are largely metamorphosed shale and sandstone.

In this chapter, we treat the Taconic Mountains as part of the same region as the Hudson-Mohawk Lowlands. These hills run in a narrow strip along New York's border with Vermont, Massachusetts, and Connecticut (see Figure 1.1).

The ridges and valleys in the Taconic Mountains generally run north-south. This arrangement is the result of a collision between a volcanic island arc and the continent of proto-North America; this collision is called the *Taconian Orogeny* (see Chapter 3). The collision pushed rocks from western Massachusetts into New York about 450 million years ago. These rock layers, which had once lain flat, were bent up. Now, as you travel from west to east in the region, you move across the edges of layers of different kinds of rock. The softer rocks are worn away to form the valleys. The harder rocks form the hills.

Before the Taconian Orogeny: Cambrian and Lower Ordovician Rocks

Rocks found at many places in the Hudson-Mohawk Lowlands and the Taconic Mountains were formed between 540 and 478 million years ago during the Cambrian and Early Ordovician Periods. Their names and sequence are summarized in Figure 6.1. They were formed in two different kinds of ocean environments—the shallow water of the continental shelf and the deeper water of the continental slope and rise. These environments were located off the east coast of the proto-North American continent. (The Physiographic Map on Plate 4 shows the modern continental shelf, slope, and rise off New York State's shore.)

Continental Shelf Deposits

The first sediments deposited on the Early Cambrian continental shelf were quartz sand. On top of that was a thick interval of *carbonate sediments* (made from the shells and hard parts of living creatures). The quartz sand became a hard quartz sandstone, and the carbonate sediments became limestone or dolostone on top of the sandstone. There is very little shale.

Fossils are abundant in many of these deposits. Many sea animals lived on the shallow shelf. The rocks formed from these shelf deposits are up to 1200 m thick in easternmost New York. They are found along the northern border of the Hudson Highlands and along the eastern part of the Taconic Mountains, near the Green and Berkshire Mountains. Information on these rocks is summarized in Table 6.1.

Taconic Sequence

At the same time the shelf deposits were forming, other kinds of sediments were being deposited on the continental slope and rise. The rocks formed from these sediments are described in Table 6.2. The entire sequence of slope-rise rocks is at least 900 m thick. They are found in outcrops in the Taconic Mountains east of the Hudson River.

Most of the slope-rise rocks are formed from sediments that were eroded from the land. There are few carbonate rocks. Fossils, except for trilobites and graptolites (see Figure A.3), are rare.

When we examine the slope-rise rocks, we discover evidence that that another landmass was approaching proto-North America from the east at the time they were formed. How do we know that? There are two kinds of clues in the rocks.

[2]These rocks were originally covered by layers formed during the Silurian and Devonian Periods. Those younger layers have been eroded away to expose the Ordovician rocks beneath.

When sediments are eroded from the land and deposited in the ocean, the water carries large particles only a short distance. It carries smaller particles farther. The older slope-rise rocks are thicker and coarser in the west. Therefore, we deduce that these sediments were eroded from a landmass in the west—the continent of proto-North America.

Younger, Middle Ordovician sediments were deposited on top of these rocks. These younger rocks are thicker and coarser in the east. Thus, we know that they were eroded from a landmass approaching from the east at that time.

The kinds of sediments in these younger rocks give us more information. We find volcanic ash and small grains of metamorphic rock. We also find grains of an unusual mineral called *chromite*. We would expect such sediments to be made from volcanic rocks and sediments from the ocean floor. If a landmass were advancing toward proto-North America, it would scrape up a pile of contorted rocks and sediments, including volcanic rock and ocean floor sediments, in front of it. The more deeply buried rocks in this pile would be strongly deformed and subjected to relatively high temperature; as a result, they would be metamorphosed. Such a pile of contorted rocks is termed an *accretionary prism* (see Chapter 3). We deduce that the sediments in the younger slope-rise rocks were eroded from an accretionary prism. This clue also suggests that a landmass was advancing toward proto-North America from the east.

The sediments eroded from the eastern landmass and its accretionary prism gradually built up into a thick blanket of mud and sand. This blanket buried the older slope-rise sediments.

The approaching landmass was a volcanic island arc (see Chapter 3). The eventual collision between the island arc and proto-North America in the Middle Ordovician started the Taconian Orogeny. But before the collision, the island arc scraped up and stacked huge masses of the blanket of younger sediments. Some of the younger sediments were sandwiched along faults with the older slope-rise rocks. The entire pile is known as the *Taconic Sequence.*

The rocks of the Taconic Sequence were originally formed to the east of the carbonate shelf rocks. The rocks from the Taconic Sequence and from the shelf are of the same age. However, as the island arc continued to advance, it pushed the entire Taconic Sequence in front of it and up on to the shelf. Today, the Taconic Sequence lies on top of the carbonate shelf rocks.

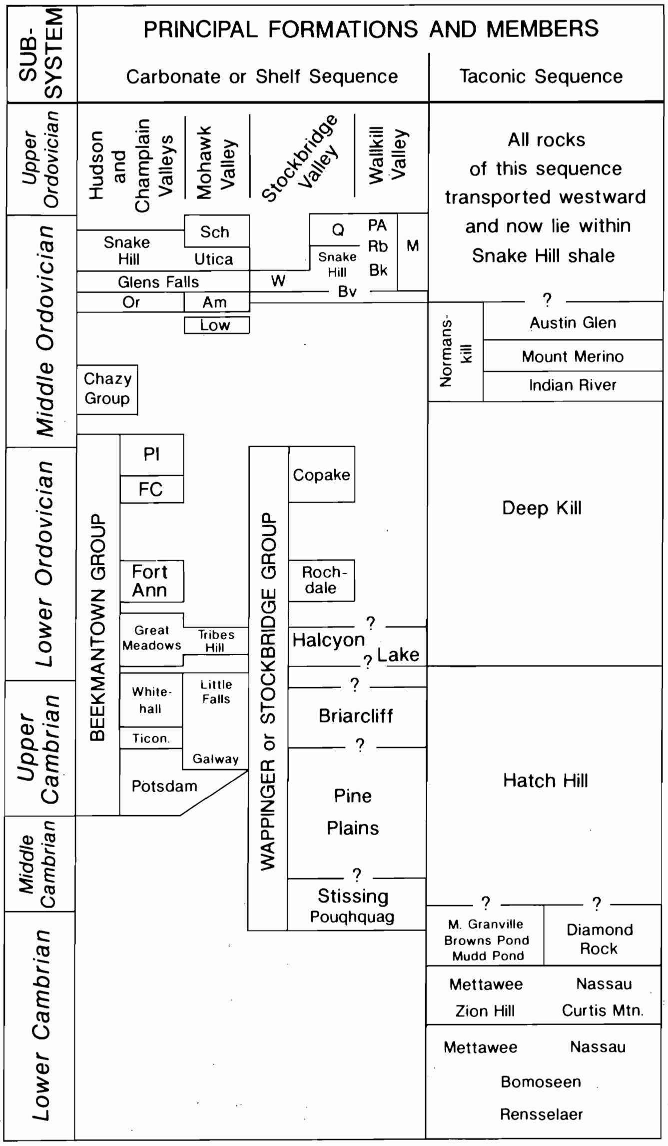


Figure 6.1. This chart summarizes the Cambrian and Ordovician rock formations found in the Hudson-Mohawk Lowlands and Taconic Mountains. Compare this figure with Plate 3 to see how these formations fit into the geology of the State as a whole. Abbreviations are translated as follows: Am=Amsterdam; Bk=Bushkill Shale; Bv=Balmville; FC=Fort Cassin; Low=Lowville; M=Martinsburg; Or=Orwell; PA=Pen Argyl; PI=Providence Island; Q=Quassaic; Rb=Ramseyburg Member; Sch=Schenectady; Ticon=Ticonderoga; W=Walloomsac.

Fossils in the Cambrian to Middle Ordovician Rocks

At some places in the world, we find evidence of *cyanobacteria* (blue-green algae) in rocks as old as 3.5 billion years. These traces are extremely rare, though. It was

Table 6.1
Lower Cambrian-Lower Ordovician Carbonate or Shelf Sequence

Formation and Description	Location	Thickness	Age	Fossils	Environment
Stissing through Copake Formations; Ticonderoga through Providence Island Formation: limestone & dolostone shale scarce or absent	along northern flank of Hudson Highlands; on western flank of Green & Berkshire Mountains	1200 m maximum	Early Cambrian to Early Ordovician	abundant in many places	shallow-water shelf
Poughquag & Potsdam Formations: quartzite or clean sandstone shale scarce or absent					

Table 6.2
Lower Cambrian-Middle Ordovician Taconic Sequence

Formation and Description	Location	Thickness	Age	Fossils	Environment
Mount Merino & Austin Glen Formations	Taconic Mountains east of Hudson River	thicker & coarser in east	Middle Ordovician	rare, except for graptolites and radiolarians	deep-water muds & sands
Indian River Slate includes volcanic ashes, metamorphic rock fragments, & exotic sand-sized fragments of chromite	locally west of Hudson River				deep water muds
Rensselaer?, Bomoseen through Deep Kill Formations graywacke; chloritic quartzite; silty micaceous shale; purple & green slate; black shale or green argillite interbedded with quartz arenite, limestone, & limestone conglomerate carbonate rocks sparse	Taconic Mountains east of Hudson River locally west of Hudson River	at least 600 m; older rock thicker and coarser in west	Early Cambrian to early Middle Ordovician	rare, except for trilobites, graptolites, conodonts, & burrows	deep-water slope-rise

about 540 million years ago, at the beginning of the Paleozoic Era, that animal fossils first became plentiful.

Why do these fossils suddenly become abundant in rocks 540 million years old? Recently, geologists have done a lot of work on that question. Looking at the evidence, scientists concluded that animals with hard parts (like shells) appeared relatively suddenly about 540 million years ago.[3] Almost all fossils are of bones, shells, or other durable structures. It's very unusual for soft-bodied creatures to be preserved. By studying rocks in Australia, Newfoundland, and other places, we know that there were relatively large sea creatures from about 650 to about 540 million years ago, but they had no hard parts. The only traces they left were impressions in a few sedimentary rocks.

Fossils help geologists set up a relative time scale (see Chapter 2). Plants and animals appear, evolve, and become extinct. By tracing the development of different species, we can put rocks in order from older to younger. Where major changes occur in the fossils, we break the time line into eons, eras, periods, and smaller subdivisions. For example, the appearance of animals with hard parts about 540 million years ago is the dividing line between the Proterozoic and Phanerozoic Eons. In the same way, the extinction of the dinosaurs and many other species 66 million years ago is the dividing line between the Mesozoic and the Cenozoic Eras.

Fossils have helped us reconstruct the geologic history of the Phanerozoic Eon in some detail. However, because older rocks have very few fossils in them, it is much more difficult to puzzle out the detailed history of the earth's development at that time.

New York in the Early and Middle Cambrian.—In New York, the best known fossils from the Early Cambrian are in the Taconic Sequence. Many of these fossils are strange creatures with no living descendants. Therefore, we can't always tell where they fit in relation to other animals. One such curious fossil is *Hyolithellus*. This extinct creature lived on the sea bottom in Early Cambrian seas around the world. There were different kinds of *Hyolithellus*. They may be related to modern-day tube-building worms.

The most numerous inhabitants of the Early Cambrian seas were trilobites (see Figure A.3). They were early arthropods.[4] Two important groups of trilobites were the *olenellids* and the *agnostids*. The olenellids were spike-tailed creatures with many body segments; some adults were relatively large (0.5 m). The agnostids were small trilobites with heads and tails that were almost alike; one group of agnostids lacked eyes. Olenellid trilobites lived on the sea bottom. Some scientists think that agnostids were swimmers.

Also present in the Early Cambrian seas were small sponges, sponge-like creatures called *archaeocyathans* that built reefs, brachiopods (see Figure A.3), and various kinds of worms.

Middle Cambrian rocks are not well known in ancient shelf deposits in New York. An earlier interpretation is that they were never deposited in this region, or they may have been eroded away. However, it is possible that there are Middle Cambrian rocks in this area of the State, but we haven't found fossils in these rocks that would allow us to determine their age. Many Middle Cambrian trilobites, brachiopods, and conodonts[5] have also been found in the Taconic Sequence in Columbia County.

These Early and Middle Cambrian animals became fossils in the sedimentary rocks at the margin of the continental shelf. These rocks were formed in the shallow water where the animals lived, died, and were buried. However, most of these fossils are not found in the undisturbed shelf rocks but are found in rocks that were deposted on the upper slope.

Many of these rocks from the upper continental slope broke off and tumbled farther down the slope into deeper water. There, pieces of limestone and quartz sandstone from the upper slope got mixed up with the sediments on the lower slope and rise. This mixture eventually became a conglomerate. *Limestone conglomerates* of this type are found in the Taconic Sequence (Figure 6.2). They contains many of the fossils of Cambrian animals found in the State.

In addition, ocean currents carried many shelf Cambrian animals into deeper water after they died. There, they were buried outside of their natural habitats.

These displaced Early and Middle Cambrian fossils are very important in the Taconic Sequence. The Taconic Sequence is the only place in New York State that we find abundant fossils of animals that lived on the continental shelf and upper slope at this time. Thus, they give us information about the Cambrian that we can't get anywhere else.

New York in the Late Cambrian.—Upper Cambrian rocks, on the other hand, are quite common in New York State. (They are described in Table 6.3.) During the Late Cambrian, the sea flooded extensive areas of proto-North America. Shelf deposits from this time overlie the Grenville *basement rock* that forms the Adirondacks (see Figure 4.2); they are exposed in a belt that surrounds the Adirondacks. They also lie under younger rocks in the Hudson and Wallkill Valleys. Slope-rise rocks are found

[3]It may have taken only a few million years for animals to evolve hard parts. That is very fast on the geologic time scale.

[4]Some modern-day examples of *arthropods* are insects, spiders, lobsters, crabs, and barnacles.

[5]*Conodonts* are an extinct group of animals that are known from small tooth-like fossils. They are very important in determing relative ages of Paleozoic through Triassic rocks. We don't know how conodonts are related to other animals, but it is possible that they were swimming animals related to early fish.

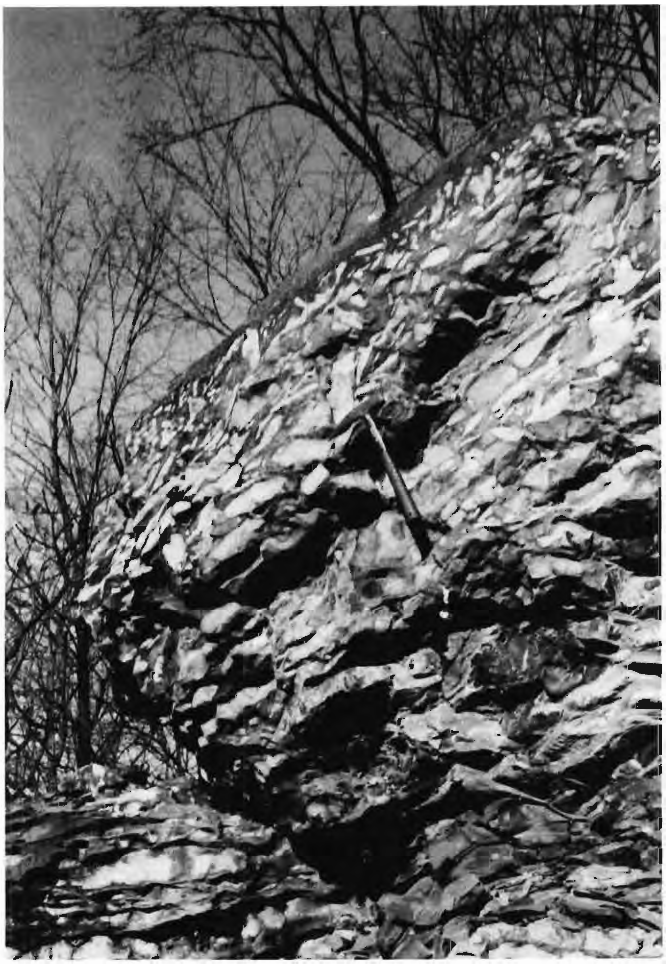


Figure 6.2. Limestone conglomerate in the Taconic Sequence, with broken pieces of limestone in a shale matrix in the Lower Cambrian Nassau Formation. (Found along the Conrail tracks, south of Schodack Landing, Columbia County.)

farther to the east, in the Taconic Mountains, where they are about 200 m thick. Rocks deposited on the continental slope and rise include shale, sandstone, and limestone conglomerate.

As the Cambrian sea advanced across New York State, it deposited ripple-marked, nearshore quartz sandstones. These deposits are younger and thinner in the west, older and thicker in the east. This arrangement shows us that the sea advanced from east to west.

Ultimately, the sandy deposits buried the ancient Adirondack region. (Since then, almost all the sandstone has been eroded away.) We can see this 140-meter-thick interval of sandstone best in Ausable Chasm. This spectacular site is in the Champlain Valley northeast of the Adirondacks (see Figure 7.2).

The layers of beach and nearshore sand alternated with layers of mud farther offshore. In other areas, colonies of algae called *stromatolites* grew in shallow waters (see Figure A.3). Limy sediments were deposited in these waters; these sediments later became limestone and dolostone.

We can see fossil stromatolite reefs at the Petrified Gardens, four miles west of Saratoga Springs (Figure 6.3). These dome-like fossils are made of wavy circular layers of calcium carbonate (Figure 6.4). From time to time their growth was slowed or stopped by sand that was washed into the water. Snails and a variety of trilobites lived between the stromatolites.

Where the water was not as clear, sandy or silty mud accumulated. This mud was rich in the mineral *dolomite*. In the same places, we find minerals like *halite* (common salt) and the sedimentary rock *chert*. The dolomite, halite, and chert are commonly found together in deposits from warm, shallow, very salty seas.

One dolostone unit deposited under these conditions is called the Little Falls Dolostone. Cavities in this unit contain exquisite quartz crystals called *"Herkimer Diamonds"* (Figure 6.5). These crystals formed from groundwater that was rich in silica. *Anthraxolite*, a black substance similar to hard asphalt, also is common in cavities in the Little Falls Dolostone; it is evidence that petroleum was present in these groundwaters.

New York in the Early Ordovician.—The environments of the Late Cambrian continued on into the Early Ordovician. How can we tell the difference between the Cambrian and Ordovician rocks, then? We recognize the younger Ordovician rocks because they contain fossils of different invertebrate animals. The animals known as *graptolites* (see Figure A.3) first became abundant as floating colonies at the beginning of the Ordovician, about 500 million years ago. We find Ordovician rock throughout the Hudson-Mohawk Lowlands and the Taconic Mountains. See Table 6.4 for a description.

The thickness of the Ordovician rocks varies greatly. The maximum thickness, in the eastern part of the State, is about 1500 m. However, if we added in the Upper Ordovician layers that have been eroded away, the grand total would be about 2300 m.

In the Early Ordovician, most of New York was flooded by a clear, shallow sea. Thick carbonate deposits (limestone and dolostone) accumulated in the sea. These deposits contain occasional lumps of chert that formed within the soft calcareous or dolomitic sediments.[6]

The environment of the Early Ordovician was hospitable to many forms of life. There were many shelled animals and marine algae. Their remains produced carbonate sediments. Stromatolite reefs in places protected the sediments from being washed away by waves. The sediments were rapidly cemented together on the sea floor, and the carbonate deposits built up very fast.

[6] *Calcareous* means containing calcium carbonate. *Dolomitic* means containing the mineral dolomite.

Table 6.3
Upper Cambrian-Lowest Ordovician Carbonate or Shelf Sequence

Formation and Description	Location	Thickness	Age	Fossils	Environment
.ittle Falls Dolostone sandy or silty dolostone with evaporite minerals and chert; "Herkimer Diamonds"; anthraxolite common	middle part of Mohawk Valley	unknown	Late Cambrian and earliest Ordovician	stromatolites, conodonts, very rare trilobites	very saline conditions
;alway & Ticonderoga Formations	Saratoga County & Champlain Valley	unknown	Late Cambrian	stromatolites in clear intertidal waters interreef fauna of snails & assortment of trilobites	nearshore sand interfingered with mud rich in calcium & magnesium carbonates
›otsdam Sandstone	Saratoga County, Champlain Valley, northern margin of Adirondacks	younger & thinner in west 140 m exposed in Ausable Chasm	Late Cambrian	rare trilobites, snails, brachiopods, burrows, and trails	ripple-marked beach and nearshore deposit of quartz sand

We find these shallow-water shelf carbonates from the Early Ordovician in the Hudson, Mohawk, and Wallkill Valleys and along the western border of the Green and Berkshire Mountains. They are more than 300 m thick.

We find many fossils in these deposits. They tell us that the dominant species at the time may have been snails and squid-like animals with shells called *nautiloid cephalopods* (see Figure A.3). In some places there were many trilobites, as well. However, there were not as many different kinds here as there were in other places in North America.

Figure 6.3. A slab of Upper Cambrian Hoyt Limestone with undulatory stromatolites. (Found at the Petrified Gardens, west of Saratoga Springs, Saratoga County.)

In such a gentle environment, we would have expected to find a greater variety of animals than has been found. It may be that the saltiness of the water was too high or too variable.

In the Taconic Sequence, we find very different animals. There are very few bottom-dwellers like snails and trilobites. There were soft-bodied worm-like animals. We find traces of their burrows in the rocks.

There were, however, more floating and swimming animals. Colonies of graptolites (see Figure A.3) built lightweight skeletons of organic materials. They probably floated near the surface in the deep water during the Early Ordovician. After they died, the colonies sank and accumulated in the muds of the Taconic Sequence. Their remains were carbonized later, when the rocks were buried deeply and heated. We find distinct black impressions of graptolites in shales of the Taconic Sequence.

The fossils of conodonts are also found in Lower Ordovician rocks. These fossils are phosphatic,[7] tooth-like structures found in shallow and deep seas from the Cambrian through the Triassic. Those from the Early

[7] *Phosphatic* means containing phosphate minerals.

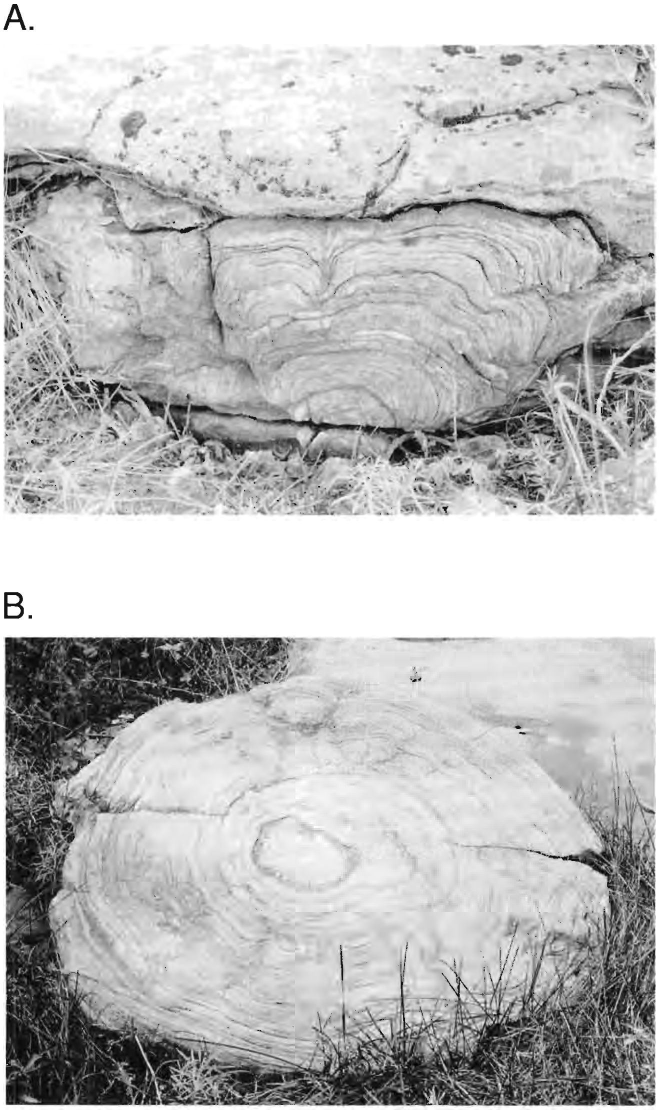


Figure 6.4. Side (A) and top (B) views of domal stromatolite in the Hoyt Limestone west of Saratoga Springs, Saratoga County.

Ordovician are up to several millimeters in size. Those in the shallow-water shelf carbonate rocks are completely different from those in the deep-water Taconic Sequence. This fact indicates that each kind of conodont animal was specialized and lived in only one kind of environment.

The seas of New York became very shallow at the end of the Early Ordovician. How do we know? We look at the fossils. Rocks from this time contain only a few fossils of animals. The animals whose fossils we do find—*ostracodes* (small bean-shaped crustaceans[8]), certain types of conodonts, and snails—can all survive in water where the saltiness is high and varies, as in shallow seas. We also find rocks called *evaporites* that form as shallow, salty water evaporates.

The Knox Unconformity.—It took approximately 30 million years to deposit the Lower Ordovician rocks in New York. They are separated from younger Middle Ordovician rocks by a widespread erosional surface. This surface was created when the carbonate shelf rocks were exposed to erosion. Because of this erosion, part of the geologic record is missing (Figure 6.6). This kind of erosional surface, which represents a gap in the geologic record, is called an *unconformity*. This one is known as the *Knox Unconformity*. It is one of the biggest unconformities found in rocks from the Early Paleozoic. The events that produced the Knox Unconformity took a long time in the early part of the Middle Ordovician.

The rocks from the last part of the Early Ordovician and the first part of the Middle Ordovician are missing at the Knox Unconformity. This fact tells us that the sea continued to get shallower until it disappeared completely from the region. The sediments were exposed to the air and eroded. No new sediments were deposited until the area was underwater again.

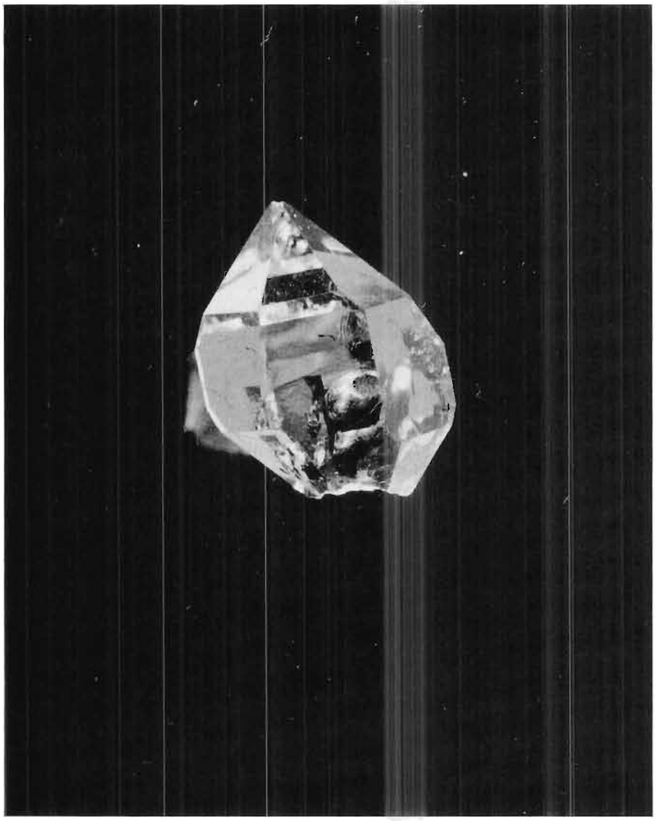


Figure 6.5. An example of a "Herkimer Diamond," a quartz crystal found in the Upper Cambrian Little Falls Dolostone, Herkimer County.

[8]A *crustacean* is a type of arthropod. Some modern examples are lobsters, shrimp, and barnacles.

Table 6.4
Lower-Middle Ordovician Carbonate or Shelf Sequence

Formation and Description	Location	Thickness	Age	Fossils	Environment
Trenton Group (and Balmville Formation	Black River, Mohawk, and Champlain Valleys	unknown	late Middle Ordovician	dominant species: snails (gastropods) & nautiloid cephalopods	deep to shallow, normal marine salinity
Black River Group		unknown	Middle Ordovician	trilobites abundant in places some conodonts	high to normal salinity; shallow to intertidal
Chazy Group lower calcareous sandstones, limestones with coral reefs	Champlain Valley	unknown	early Middle Ordovician	few fossils in Providence Island Dolostone--animals adapted for life in	normal marine salinity
upper part of Beekmantown Group (including Providence Island Dolostone) limestone & dolostone beds with chert in places	Hudson, Mohawk, & Wallkill Valleys & along west flank of Green & Berkshire Mountains	more than 300 m	Early Ordovician	high & fluctuating salinities--ostracodes, conodonts, snails	shallow clear sea--high or variable salinities

What caused the sea to retreat? We don't know for sure. But this unconformity is found in rocks around the world. Therefore, we know that whatever caused this event happened worldwide. For some reason, sea level dropped around the world.

Figure 6.6. The Knox Unconformity (at the lower end of the hammer) between the Lower Ordovician Chuctanunda Creek Dolostone Member of the Tribes Hill Formation and the overlying Middle Ordovician Glens Falls Limestone. (Found on the west side of Canajoharie Creek in the village of Canajoharie, Montgomery County.)

During the Taconian Orogeny: Middle and Upper Ordovician Rocks

After the Knox Unconformity was formed, sea level rose again. This rise happened 475 million years ago in the Middle Ordovician. At this time, seas covered all of New York and most of the eastern half of proto-North America.

The oldest rocks deposited in these seas were limestones. We find them today in the Champlain Valley and in the upper Mohawk and Black River valleys. (They are discussed in Chapter 7.) However, we don't find them in the Hudson, lower Mohawk, or Wallkill valleys. If they ever were deposited in this region, they were later worn away almost completely by erosion. In most places, the first Middle Ordovician deposit in this region is a thin blanket of younger limestone with many fossils (Table 6.4). At different places in the region, this limestone lies on top of different kinds of rock from the Early Cambrian through the Early Ordovician.

We find Middle and Upper Ordovician rock in the Hudson and Mohawk Valleys, the Wallkill Valley (including the Marlboro Mountains), and the Taconic Mountains. On top of the limestone is a thick deposit of black silty shale, siltstone, and impure sandstone (Table 6.5). This deposit originated in deep water. It contains

Table 6.5
Middle & Upper Ordovician Clastic Shelf to Deep Water Sequence

Formation and Description	Location	Thickness	Age	Fossils	Environment
thick deposit of black silty shale, siltstone, & impure sandstone Schenectady & Quassaic Formations: impure sandstones Snake Hill & Martinsburg Formations: silty muds	Hudson & Mohawk Valleys, Wallkill Valley (including Marlboro Mountains), & Taconic Mountains	varies greatly --1500 m maximum in east Projection of Upper Ordovician strata not present in eastern NY would increase total to 2300 m	Middle & Late Ordovician	clams and brachiopods in Snake Hill and Martinsburg	trough--deep water

few fossils. We don't know the total thickness of the Middle and Upper Ordovician rocks in this region. It may be as much as 1500 m.

You will recall that an island arc was moving toward proto-North America during the Middle Ordovician. It was pushing in front of it an accretionary prism—the pile of rocks and sediments it had scraped up. It pushed the accretionary prism westward across the edge of proto-North America. As the prism crossed the continent's edge, it was uplifted above sea level.

A trough formed in front of the advancing accretionary prism. The sea flowed into this trough, which made the waters there much deeper than they had been. Silty muds and sandstones accumulated in the trough.

As we mentioned above, the advancing island arc had stacked up the rocks of the Taconic Sequence. This stack of rocks was pushed across the younger Middle Ordovician silty muds and sandstones of the trough. Thus, today we find the Cambrian and early Middle Ordovician rocks of the Taconic Sequence in and above the trough sediments that were deposited during the late Middle Ordovician.

At the base and in front of the Taconic Sequence, we find slivers of carbonate rocks. As the rocks of the Taconic Sequence were pushed across the carbonate rocks of the shelf, pieces of the shelf rocks were torn away. These broken pieces got mixed with broken pieces from the Taconic Sequence rocks. This mixture formed conglomerate rocks with very large boulders in them. The size of these boulders allows us to call these rocks *megaconglomerates*. We know these megaconglomerates formed at the time of the Taconian Orogeny because graptolite fossils have been found in the muds that accumulated between the boulders. The age of the graptolites indicates the age of the megaconglomerates.

The Taconian Orogeny reached its climax during the Late Ordovician. The island arc finally collided with proto-North America, and the two were fused together. The collision built the ancestral Taconic Mountains—a high and rugged mountain range that extended along most of the eastern seaboard.

At this time, the trough in front of the accretionary prism stopped sinking and was gradually filled in by sediments. We know that deep-water sediments of the trough were covered by shallow-water sandstones as the trough was filled in. However, except for one formation near Poughkeepsie, we can't find any trace of these sandstones in the Hudson and Wallkill Valleys.

We find fossils in shallow-water sandstone beds from the Late Ordovician. They are, naturally, very different from the ones we find in the older sandstones formed in the deep water of the trough. Worm-like animals burrowed through the sand. We find the marks they left in the rocks. In addition, for the first time, we find an abundant variety of clams that lived on the sea bottom.

As we move west across New York State, we find that the silty mud of the eastern part of the trough gradually changed into black mud to the west during the late Middle Ordovician. That mud is now black shale that is 275 m

Figure 6.7. Pillow lava, which formed as a lava flow under the ocean. (Found at Stark's Knob north of Schuylerville, Saratoga County.)

thick. As we move even farther west, the black shale changes into about 135 m of limestone. This limestone was formed in shallower seas in central New York. Interspersed throughout all these late Middle Ordovician formations are thin clay layers. These clay layers are formed from volcanic ash.

Where did the volcanic ash come from? As we mentioned in Chapter 3, the island arc that forms along the edge of the overriding plate at a subduction zone includes volcanic islands. The volcanic ash blown from the volcanoes during eruptions was transported by the wind. These layers of clay show us how close this volcanic island arc was at that time.

We've discussed the sedimentary rocks formed in New York during the Taconian Orogeny. In addition, some igneous rocks were formed in this region at the same time. North of Schuylerville at Stark's Knob, we can see the remains of an underwater lava flow (Figure 6.7).

Life flourished in the late Middle Ordovician seas. It included bottom-dwellers, swimmers, and floaters. Brachiopods (see Figure A.3), for example, multiplied very rapidly. In fact, some rock layers are completely covered by just one species (Figure 6.8). The highly mobile trilobites also were abundant. Gardens of animals called *sea lilies* or *crinoids* (see Figure A.3) covered large areas of the sea bottom. The sea bottom was also the home of corals, bryozoans (see Figure A.3), and carnivorous gastropods.[9]

In very shallow waters, ostracodes became one of the most important animal groups (see Figure A.3). In addition, graptolites reached the peak of their abundance during the late Middle Ordovician. They are very common in the black shales from this time.

At the time of the Taconian Orogeny, the Adirondack region was apparently underwater. How do we know that? The orientation of fossils in some limestones and shales lets us deduce the direction that sea currents flowed. The direction of ripple marks also give us a clue. For the currents to be moving in this direction, the Adirondack region must have been almost completely underwater.

We also find local areas of sedimentary rocks from the Cambrian and Ordovician in the Adirondacks. Since these rocks must have been deposited in an ocean, they show that the region was underwater at that time.

Frequent earthquakes probably shook New York State during the Taconian Orogeny. In eastern New York, the crust was broken by long fractures. We find similar fractures today in unstable regions like California and Japan.

Faults are common in the northern Hudson and eastern Mohawk Valleys and in the eastern and southern Adirondacks. The largest faults tend to run north or slightly east of north. Smaller faults tend to run east.

In some places, the faults broke the earth's surface into raised and lowered blocks. The blocks were either dropped down (called *grabens*) or pushed up (called *horsts*). We find a horst and graben landscape in the Mohawk Valley. The Mohawk River flows east across these blocks. Where it moves from higher to lower blocks, the river has cut deep, narrow notches, called *water gaps*, in the raised block. Some examples are the water gaps at Little Falls, Hoffmans, and The Noses (between Canajoharie and Fonda). In other places, groundwater seeps up through these faults. One example is the mineral springs at Saratoga Springs.

The Taconic Mountains have many large faults formed during the Paleozoic Era. These faults run toward the north. Some run from Washington County all the way down to the Hudson Highlands and are over 160 km long.

[9]A *gastropod* is an animal that has a head with eyes and a broad foot. Most gastropods have a single shell. A snail is one example of a gastropod.

Figure 6.8. The brachiopod *Sowerbyella* in the Middle Ordovician Glens Falls Limestone. (From the north side of N.Y. Rte. 67, 0.6 km east of Manny Corners, Montgomery County.)

In the Taconic Mountains, the rock layers have been folded up like an accordion or a paper fan. These folds are packed so tightly together that the layers on either side of each fold are nearly parallel. The layers on the east side of the folds have been completely turned over. As we move east through the region, we find that the rocks have been more and more strongly metamorphosed. The shales have been turned into slates, phyllites, schists, and gneisses (Figure 6.9). The carbonate rocks have been turned into marble.

Metamorphism generally destroys most fossils. This fact makes it difficult for geologists to determine in what order the rocks of the Taconic Mountains developed. Therefore the ages of many rocks east of the Hudson River close to New York State's eastern border are not known precisely.

We don't find any rocks from the latest part of the Ordovician or the earliest part of the Silurian in the Hudson-Mohawk Lowlands and Taconic Mountains. The region was above sea level and being eroded from that time until it was flooded again during the Early Devonian. The eroded sediments formed sandstones and shales in western New York and southern Ontario during the Late Ordovician.

Why was this region above sea level after having been underwater for so long? There are two possible reasons. Something may have caused the ancestral Taconic Mountains to be uplifted again at this time. However, we know that at this time glaciers were advancing across the continent called *Gondwana.* (This continent, which was then at the south pole, included modern Africa, South America, India, Australia, and Antarctica.) These glaciers apparently contained so much water that sea level dropped around the world. If sea level dropped enough, it would have exposed the Taconic highlands to the open air again.

After the Taconian Orogeny: Silurian Rocks

We find rocks of Silurian age (408 to 438 million years old) near Catskill in the Hudson Valley (Table 6.6). As this belt of rock continues down the valley, it thickens to form the imposing Shawangunk Mountains. These mountains run along the west edge of the Wallkill Valley in southeastern New York and continue into New Jersey.

Most of the Silurian rocks in New York State lie almost flat. They dip toward the south at less than 1°. In southeastern New York, however, they dip much more steeply—up to 60°—to the northwest.

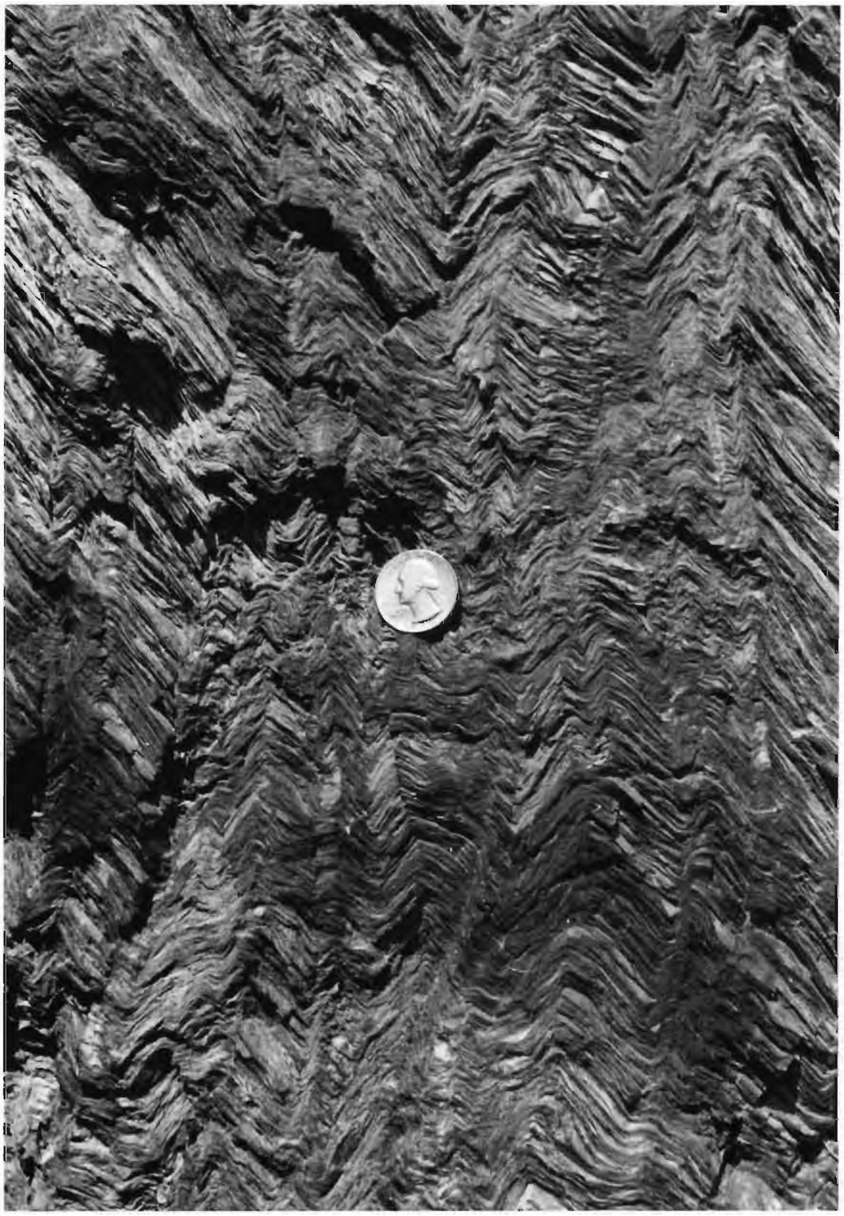


Figure 6.9. Chevron folds in the Lower Cambrian Everett Schist. (Found along N.Y. Rte. 55, east of the Taconic Parkway, eastern Dutchess County.)

During the Silurian, sediments eroded from land to the east piled up in southeastern New York. The final result was about 300 m of white sand and quartz pebbles. This deposit became the Shawangunk Formation. It is highly resistant to erosion and can be seen today on the east face of the Shawangunk Mountains. Excellent quartz crystals, zinc, and lead minerals have been collected from the Shawangunk Formation.

On top of the Shawangunk Formation is a layer of red and green shale and sandstone. These rocks were deposited in marine nearshore environments and on land by meandering streams.

During the Late Silurian, southeastern New York lay beneath a shallow, highly salty sea. Muddy carbonate sediments and mud rich in the mineral gypsum were deposited in this sea. These deposits are today largely concealed along the west face of the Shawangunk Mountains.

The youngest Silurian rocks in this area seem to have been formed in a sea with more normal saltiness. They are limestones and dolostones that contain fossils. These fossils show that the environment was hospitable to animals. Along the Helderberg Escarpment south of Albany, these rocks lie on top of folded and eroded Middle Ordovician layers (Figure 6.10). The surface between them is another unconformity, called the *Taconic Unconformity*. Rocks from the time between the Middle Ordovician and the Late Silurian are missing in this area.

Table 6.6
Silurian

Formation and Description	Location	Thickness	Age	Fossils	Environment
Bossardville, Decker, & Rondout Formations: limestone & dolostone	along Helderberg Escarpment south of Albany	unknown	?	contains fossils	
Poxono Island Formation: muddy carbonate & mud rich in gypsum	concealed along west face of Shawangunk Mountains	unknown	Late Silurian	?	shallow supersaline sea
Bloomsburg shale & siltstone: red & green					nonmarine; formed by meandering streams
Shawangunk Conglomerate white sand & quartz pebbles; contains quartz crystals, zinc & lead minerals	along east face of Shawangunk Mountains --west margin of Wallkill valley	300 m	?	?	braided streams

Figure 6.10. The Taconic Unconformity. Upper Silurian Rondout Dolostone lies on top of early Middle Ordovician Austin Glen Formation of the Normanskill Group. The layers of the Austin Glen Formation have been tipped until they are vertical. (Found along N.Y. Rte. 23, near Catskill, Greene County.)

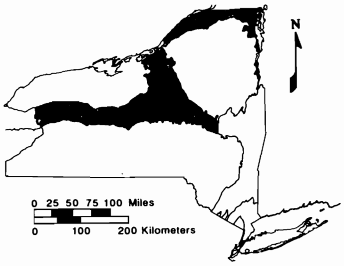
Review Questions and Exercises

Most of the bedrock in the Hudson-Mohawk Lowlands is which type—igneous, sedimentary, or metamorphic? How about the Taconic Mountains? How does the bedrock affect the landscape in this region?

How did the Taconic Sequence get where it is today? Are the rocks just under it older, the same age, or younger?

What were some of the effects as the volcanic island arc approached the coast of proto-North America? Discuss several.

Chapter 7
Sand, Salt, and "Scorpions"
Northern Lowlands and Tug Hill Plateau[1]



Summary

The rock of the northern lowlands can be divided into three packages separated by unconformities. Package One represents Cambrian through Early Ordovician time. Package Two was deposited during Middle and Late Ordovician time. Package Three consists of Silurian rock. In the Package One rocks, we read the history of the rifting of the Grenville supercontinent and the sinking and re-exposure of the east edge of proto-North America. Package Two reflects the advance of a volcanic island arc that eventually collided with proto-North America. The rocks of Package Three tell the story of shallow seas with a great variety of environments.

The rocks of Package One lie on top of an unconformity on the basement rock. The unconformity and sedimentary rocks dip away from the Adirondack dome and are buried more and more deeply. The oldest rocks in Package One, the lower and middle parts of the Potsdam Formation, were possibly deposited during Early and Middle Cambrian time; they occur in patches. Above them, the sandstone of the upper Potsdam Formation, deposited in Late Cambrian time, is much more widespread. The sequence above the Potsdam is dominated by dolostone and limestone and was deposited in a shallow sea during Late Cambrian and Early Ordovician time; some of the dolostones formed in a very salty sea. These rocks once covered the Adirondack region but were later removed by erosion. At the end of the Early Ordovician, much of New York State was above sea level. Erosion created the gap in the rock record represented by the Knox Unconformity.

The history we read in the rocks of Package One starts with the breakup of the Grenville supercontinent. Sediments were deposited in patches in rift valleys and low-lying areas. As the rift widened into the Iapetus Ocean, the shore advanced westward across the northern lowlands, leaving a deposit of beach sand. As the shoreline continued to move west, the continental shelf of proto-North America widened, and limestones and dolostones were deposited above the sand. At the end of the Early Ordovician, a worldwide drop in sea level exposed these rocks to erosion.

The rocks of Package Two record Middle and Late Ordovician time. The oldest rocks in this package are limestones of the Chazy Group, found only in limited areas. The Chazy limestones contain a host of new creatures, including bryozoans, stromatoporoids, and the first true corals. An unconformity separates the Chazy Group from the overlying Black River Group, which was deposited across much of New York State. The limestones of the Black River Group contain a record of abundant life and were deposited in a variety of tropical environments. This sequence also includes layers of bentonite formed from volcanic ash blown in from a landmass offshore. Above the bentonite layers is the Trenton Group, in which thick layers of limestone alternate with thin layers of shale; the sediments in the shale were eroded from a landmass to the east. The alternating limestone and shale may have originated when layers of fossil hash were colonized by organisms that were later smothered by a layer of mud. East of the Trenton Group, the Dolgeville Formation consists of alternating layers of shale and limestone of approximately equal thickness. The limestones were deposited on the slope by turbidity currents; mud piled up slowly on top of them to form shale. On top of and east of the Trenton Group lies hundreds of meters of black shale, formed from mud eroded from land to the east; this mud eventually blanketed the carbonate environments. The shale contains few fossils; it formed in a deep basin

[1]Adapted from a manuscript by L.V. Rickard.

where there was little oxygen. During part of the Middle Ordovician, the Trenton Group, the Dolgeville limestone, and the Utica Shale were all being deposited at the same time in different environments: the shelf, slope, and basin of the sea. Above the Utica Shale, rock units deposited during Late Ordovician time contain increasing amounts of coarser material deposited in shallower and shallower water; these deposits gradually spread from east to west as the deep Middle Ordovician basin was filled in. The youngest of New York's Ordovician rock is the Queenston Delta, part of an enormous apron of sediment that spread across a large portion of proto-North America. The sediment was eroded from highlands to the east when they were exposed to erosion, perhaps because a major glaciation on another continent caused sea level to drop.

The rocks in Package Two reflect the effects of the Taconian Orogeny to the east. As the Taconic island arc neared its collision with proto-North America, ash blew in from its volcanoes. Its approach bent the continental shelf down into a deep basin. Sediments eroded from the island arc and its accretionary prism, and later from the mountains built by the collision, poured into the basin. By the end of the Ordovician, the basin was filled in and the mountains eroded. A drop in sea level may have exposed the eastern highlands to more erosion, and sediments from the east built the Queenston Delta.

An unconformity, probably formed when the region was above sea level, lies below the Silurian rocks of Package Three. New York's Silurian rocks record of a varied geologic history. The oldest are the Medina Group. The lower part was deposited by a sea that advanced from west to east. On top of that are red and green sediments that may have been part of a delta, and above that a layer of white quartz sand. Above the Medina Group, the Clinton Group represents a wide variety of environments. The oldest Clinton unit is conglomerate that was deposited as a beach. Above some major unconformities are limestones that contain hematite. The environments represented by the lower part of the Clinton Group teemed with life. There are fewer fossils in the middle Clinton rocks. In the upper Clinton Group is a layer of black shale that formed in a lifeless deep-water environment with little oxygen. The limestone unit above the shale formed in shallow seas that were more hospitable to life. On top of that, the Rochester Shale contains more fossils than any other Silurian formation in New York. The animals found in the lower Clinton Group reach their peak of abundance and diversity here. East of the Rochester Shale is a sandstone unit formed in shallow water and on beaches. Above the Rochester Shale in western New York is a thin layer of limestone that was lifeless for unknown reasons. Above that, the limestones of the lower Lockport Group formed in warm, clear, shallow seas that sustained a variety of animals. Fossils are rare higher up in the Lockport. The rocks of the Lockport Group are seen at Niagara Falls and at the Niagara Gorge, where the rocks are the reference section for the Early Silurian in eastern North America. Above the Lockport Group, we find Silurian rocks that contain clay and silt, probably deposited by low-energy waves and currents during the Late Silurian. Above the Lockport Group is the Salina Group, most of which was deposited in the shallow waters of a very salty sea. It includes layers of shale and dolostone with very few fossils alternating with layers of rock salt. The highly salty Silurian seas had inhabitants that could tolerate the conditions, among them the scorpion-like eurypterids, but most Silurian fossils are found in rock units that formed in more normal sea water. Late in the Silurian, water circulation improved dramatically and animals thrived. At the very end of the Silurian, though, another inhospitable environment appeared; it is represented by dolostones deposited across much of the State.

Shallow seas covered the northern lowlands for much of Silurian time. Early in the period, a sea advanced eastward, then shrank westward. Several million years later the sea advanced again. Toward the end of the Silurian, poor circulation produced large, very salty pools and tidal flats. Throughout the Silurian, the region was geologically quiet; the advance and retreat of the sea may have been related to movements of tectonic plates.

Invertebrates dominate the fossil record of the early Paleozoic, although fish—the first vertebrates—had become relatively abundant by the end of the Silurian. Evolution took important steps during this time. A large variety of invertebrates competed for food and survival in the Silurian seas, and air-breathing arthropods colonized the land in the Late Silurian. Land plants had also appeared by the end of the Silurian.

INTRODUCTION

This chapter covers the bedrock of the St. Lawrence-Champlain Lowlands, the Ontario Lowlands, and the Tug Hill Plateau (see Figure 1.1). For convenience, we refer to the two lowlands regions together as the northern lowlands.

In this chapter, we are concerned with sedimentary rock units of Cambrian, Ordovician, and Silurian age. These units are shown on the geologic map (Plate 2 of the *Geological Highway Map*) by yellow, blues, brown to pale orange, and shades of reddish purple to pink. These colors also appear on the legend (Plate 3) in the lower parts of Columns 1, 2, 3, 7, and 8. Plate 2 shows the areas in the State where these rock units appear at the earth's surface; Plate 3 shows them in reference to geologic time, with the oldest at the bottom.

Plate 3 is drawn so that all rock of the same age is at one horizontal level. Notice the pale yellow areas of the legend between some of the rock units. This yellow represents periods of geologic time not recorded by rock in that region. For example, in the Finger Lakes region (Column 2 on Plate 3), the oldest sedimentary rock unit (shown in blue with blue stripes) includes a number of limestone units of the Black River and Trenton Groups. This sequence of rock was deposited during Middle Ordovician time. No rock is present in that area from the Cambrian and the Early Ordovician Periods. The limestone beds of the Black River Group here rest upon metamorphic *basement rock* of Middle Proterozoic age (represented on Plate 3 by pale orange with random red dashes). The rock record of many millions of years of geologic time is missing in this place. Later Proterozoic through Middle Cambrian rocks were never deposited in the region, and erosion removed Late Cambrian through Early Ordovician rocks. The erosional surface on the older rock, which represents this missing time and which is buried by the younger sedimentary rock, is called an *unconformity*.

In the Finger Lakes region there is another unconformity at the top of the Trenton Group, and yet another at the top of the Queenston shale (yellow-orange with red dashes). To the east, the upper unconformity cuts across older and older sedimentary units. This arrangement indicates that erosion removed more of the rock section in that direction. Further study of Plate 3 will show you the regions of the State where the sedimentary rock record is best preserved.

The Rock Packages

We can divide the sequence of sedimentary rock exposed in the northern lowlands into three packages separated by unconformities.[2] These packages can be seen on Plate 3. The oldest package rests on an unconformity on the Proterozoic basement rock. Bedrock in Package One crops out in the Mohawk Valley, the Champlain Valley, and the St. Lawrence Valley (Columns 3, 7, and 8 on Plate 3; these units are described in Tables 7.1 and 7.2). Rock units in this package are represented by yellow and blue on Plates 2 and 3. They were deposited during Late Cambrian through Early Ordovician time. An unconformity bounds the top of this package.

Package Two is represented by several colors on Plates

Table 7.1
Rocks of Package One
Ontario Lowlands & Tug Hill Plateau

Rock and Description	Age	Environment	Fossils	Thickness
ittle Falls Dolostone & Tribes Hill Formation* otsdam Sandstone & Theresa Formation**	Late Cambrian to Early Ordovician	shallow carbonate shelf of proto-North America	rare trilobites, conodonts, stromatolites in Little Falls; trilobites & mollusks in Tribes Hill; trilobites in Potsdam/Theresa	unknown

ound in Herkimer & western Montgomery Counties.
Found in northwestern Jefferson County.

[2]Unconformities are good ways to separate rock packages because they represent significant changes in geologic activity.

Table 7.2
Rocks of Package One
St. Lawrence & Champlain Lowlands

Rock and Description		Age	Environment	Fossils	Thickness
Beekmantown Group limestone & dolostone		Early Ordovician	carbonate shelf of proto-North America	moderate number of fossils	
Potsdam Sandstone	Keeseville Member	Late Cambrian	sandy shelf	trilobites, rare snails	
	Ausable, Allens Falls, & Nicholville Members sandstone rich in feldspar	Early (?) Cambrian	nearshore to subaerial	rare or absent	140 m

2 and 3: blue with blue stripes, light brown, pale orange, and yellow-orange with red dashes. Parts of this package occur in the Niagara, Finger Lakes, Finger Lakes-Catskill, and Champlain Valley regions (Columns 1, 2, 3, and 7 on Plate 3; these units are described in Tables 7.3 and 7.4). This rock was deposited during Middle and Late Ordovician time. As you can see from Plate 3, the top of this package is an unconformity throughout the State; in places, there are unconformities within the package as well.

Package Three consists of the sedimentary units that were deposited during the Silurian Period in the Niagara, Finger Lakes, and Mohawk Valley regions. These units are represented by reddish purple, pink with red stripes or blue stripes, and solid pink on Plates 2 and 3. (They are described in Tables 7.5, 7.6, and 7.7.) As you can see, some Silurian rock occurs in the southern Catskill Mountains and in small areas of southeastern New York. These rocks are discussed Chapters 6 and 8, but they will be mentioned here as well, because they relate to the story. The top of Package Three is bounded by an unconformity in the west, but we have a continuous record of the change into the overlying sequence of rock in the eastern part of the State.

The Story in the Rocks

We can decipher remarkable events in the geologic history from the sedimentary rock in these three packages. (See Chapter 3 for a summary of the geologic history of New York State.) Package One tells us that the supercontinent Grenville split up in Late Proterozoic time. An ancient ocean, the Iapetus, formed between the pieces. The ancient continent of proto-North America formed one shore of this ocean. The eastern edge of proto-North America gradually submerged into the sea during Cambrian and Early Ordovician time. It then emerged from the sea and was exposed to erosion.

The story of the Package Two rocks starts with our part of proto-North America as a shallow marine shelf. The western part of the Iapetus Ocean began to close as an offshore volcanic island arc moved toward a collision with proto-North America. As the island arc was pushed onto proto-North America, the eastern part of the shelf was depressed to form a deep basin where dark mud collected. This collision marked the beginning of the Taconian Orogeny, which formed a range of high mountains east of the basin. Debris eroded from these mountains eventually filled in the basin and extended westward over the entire shelf. This sandy debris eventually built above sea level in easternmost New York State.

After a period of erosion, the rock of Package Three records another advance of the sea. This time the shore zone moved from west to east. The sea remained shallow and even withdrew in the middle of the Silurian. Highlands existed to the east; debris eroded from these highlands was carried westward. The area was again submerged and remained so throughout the Late Silurian. Toward the end of this time, water circulation with open water to the south became restricted. Evaporation concentrated the sea water into a strong brine that precipitated the minerals *halite* (rock salt) and *gypsum* in widespread layers. The rock units in Package Three and their fossils record a great variety of environments within a shallow sea. These environments ranged from nearly

Table 7.3
Rocks of Package Two
Ontario Lowlands & Tug Hill Plateau

Rock and Description		Age	Environment	Fossils	Thickness
ueenston Shale* red shale, red siltstone, red sandstone		Late Ordovician	nonmarine to shallow marine --part of large delta	few	
orraine roup	Oswego Sandstone coarser grained sandstone	Late Ordovician	nearshore & beach	few trace fossils	
	Pulaski Formation fine-grained sandstone		shallow water	many fossils of bottom-dwelling clams & brachiopods	
	Whetstone Gulf Formation siltstone & shale		moderately deep water	graptolites & trilobites	
tica Shale black shale; thickest in east-central New York, thins to west		late Middle Ordovician to Late Ordovician	deep basin	graptolites & trilobites	275 m near Herkimer
renton Group thin black shale alternating with thicker layers (5-30 cm) of limestone		Middle Ordovician	several underwater environments, each with its own diverse community of sea creatures: lagoons, barrier shoals, shallow shelf, deep shelf, slope between shelf & basin	many fossils, including Prasopora & other bryozoans, corals, attached echinoderms, brachiopods, & trilobites	160 m near Watertown 130 m at Trenton Falls 4.5 m at Canajoharie Creek
lack iver roup	Watertown Limestone	Middle Ordovician	shallow marine carbonate mud on level sea floor	many fossils	90 m in places
	Lowville Formation mudcracked lime mudstone in thin to thick layers		variety of mud flats between low & high tide	many fossils	
	fossil hash limestone		underwater carbonate sand	abundance of coral Tetradium	
	Pamelia Formation dolostone & sandstone		mud & sand flats just above high tide		

ound on south shore of Lake Ontario.

perfect for shallow marine animals to completely inhospitable. You can guess that fossil collecting in these rocks goes from good to bad, depending on the rock type.

How can we construct the history outlined above? We must seek out clues in the rock with a practiced eye and determination. The geologic map (Plate 2), the legend (Plate 3), and Tables 7.1 through 7.7 summarize facts many generations of geologists have learned from studying the rock in the field and the laboratory. We'll use these facts as the basis for our story.

Rocks of Package One: Late Proterozoic through Early Ordovician Time

The end of the Proterozoic Era through the Early Ordovician Period represents 95 million years. As you can see on the geologic map (Plate 2), sedimentary rock formed during that time *crops out* (appears at the earth's surface) around the Adirondacks—in the St. Lawrence

Table 7.4
Rocks of Package Two
St. Lawrence & Champlain Lowlands

Rock and Description	Age	Environment	Fossils	Thickness
Iberville Shale dark gray shale rich in carbonate sediments Stony Point Shale dark gray shale	Middle Ordovician	basin	graptolites	300 m
Cumberland Head Argillite banded mudstone	Middle Ordovician	basin	uncommon, broken, usually small: brachiopods, pelecypods, nautiloids, trilobites	unknown
Trenton Group Glens Falls Formation limestone	Middle Ordovician	shelf to slope	many fossils	unknown
Black River Group Isle La Motte & Lowville Formations limestone	Middle Ordovician	shallow shelf	many fossils	unknown
Chazy Group* Valcour, Crown Point, & Day Point Formations limestone	early Middle Ordovician	shallow shelf	host of new creatures: ornamented brachiopods, specialized nautiloids, "wart-skinned" trilobites, clams, snails (especially Maclurites), bryozoans, stromatoporoids (such as Cystostyoma), corals, echinoderms	up to 245 m

*Found only in New York's Champlain Valley & Canada's northern St. Lawrence Valley.

and Champlain Valleys and in parts of the Mohawk Valley. The legend (Plate 3) shows you that sedimentary rock at the bottom of the pile lies on top of the Proterozoic metamorphic rocks of the basement. An unconformity lies between the sedimentary rocks and the basement. We know the ages of both the sedimentary and the metamorphic rocks. There is a great difference in their ages. This difference tells us that there is a great gap in the rock record. Erosion removed much of this record, and no sediment was deposited here between the Middle Proterozoic and the Cambrian.

Both the unconformity and the overlying sedimentary rocks dip gently away from the Adirondack dome on all sides. We know that the rocks extend into the subsurface. As we move away from the Adirondacks, we would expect that these sedimentary layers become buried more deeply. How can we test this idea?

Road cuts and quarries expose rock layers that have been buried by younger ones. Such exposures give us valuable geologic clues, but they don't extend far below the surface. Deep holes drilled in the search for oil and natural gas give us more information. Samples of rock taken from these holes tell us the depth to basement rock and the kind of sedimentary rocks that lie above it. By matching this information to the rock exposed in outcrops, we have developed a three-dimensional picture of the geology. The cross sections below the geologic map (Plate 2) show this kind of subsurface information. From drill holes, for example, we know that the unconformity on top of the basement rock dips gradually downward to

Table 7.5
Rocks of Package Three
Medina Group

	Rock and Description	Age	Environment	Fossils	Thickness
›dina ›oup	Thorold & Kodak Formations* sandstone; white quartz sand reworked from upper Grimsby Formation	Early Silurian	nearshore marine		
	Grimsby Formation red, green, & mottled sandstone, siltstone, & shale		often interpreted as a delta--random arrangement of beach-dwelling animals, ripples, mud cracks, cross-beds, & presence of conglomerate indicate deposition in shallow, turbulent water	few fossils--most common are <u>Arthrophycus</u> (burrow of worm-like animal), the brachiopod <u>Lingula</u>, clams, snails, ostracodes, & an occasional nautiloid	
	Power Glen Formation mudstone		muddy offshore		
	Whirlpool Sandstone white clean sandstone cross-bedded & ripple marked		braided streams, sand flats, nearshore marine, shore zone, fluvial		

›is sandstone merges with the Oneida Conglomerate in Oneida County.

the southwest from the Adirondacks. At the Pennsylvania border in south central New York, this unconformity is nearly 3.6 km below sea level.

The Sedimentary Record

The legend (Plate 3) indicates that the oldest sedimentary rocks in the northern lowlands are in the St. Lawrence Valley area; they were deposited during the Early Cambrian (lowest part of the yellow in Column 8; they are described in Table 7.2). We are not certain this age is accurate, because no fossils are found in these beds. These deposits form the lowest part of the Potsdam Formation; they consist of poorly sorted conglomerate and sandstone. The conglomerate contains boulders and cobbles of metamorphic rock; these pieces are fragments of the Proterozoic basement. Deposits of this sort occur as scattered patches that lie between the Proterozoic basement and overlying widespread layers of well sorted sandstone. One of these patches of material lies against a vertical surface of basement rock; this arrangement suggests that the material formed at the base of an old sea cliff.

The legend (Plate 3) shows the middle part of the Potsdam Formation to be a deposit of Middle Cambrian time. This age is also uncertain because of the lack of fossils. This unit is more widespread, is better sorted, and has more distinct layering than the one at the base of the Potsdam. It contains some pebble conglomerate and abundant feldspar grains and displays large-scale *cross-bedding*—inclined layers within a sedimentary layer (Figure 7.1). The arrangement of its bedding suggests that it was deposited by *braided streams*—streams that divide into a number of smaller channels that later reunite. In places, some of this rock may contain windblown sand as well.

The upper part of the Potsdam Formation (described in Tables 7.1 and 7.2) was deposited during Late Cambrian time. We know this age from the fossil trilobites in the rock. These fossils and others tell us the rock is a marine deposit—deposited on the sea floor in sea water. This part of the Potsdam Formation is much more widespread

Table 7.6
Rocks of Package Three
Clinton Group

Rock and Description		Age	Environment	Fossils	Thickness
Clinton Group	DeCew Dolostone* limestone rich in dolomite & clay	Early Silurian	shallow, highly salty water	no fossils, but some strange contorted sedimentary structures of unknown origin	up to 75 m in the east
	Herkimer Sandstone**		beach & shallow water deposit with ripple marks & mud cracks	clams, brachiopods, worm borings, trilobite trails	
	Rochester Shale calcareous shale alternating with limestone		open marine shelf	more fossils than any other Silurian formation; over 200 species, including 84 bryozoans, ostracodes (some elaborately ornamented), stalked echinoderms (cystoids, blastoids, & crinoids), brachiopods, trilobites, tentaculitids, corals, snails, clams, nautiloids	
	Irondequoit Limestone		warm, clear, shallow shelf	reefs built by algae & bryozoans, brachiopods, trilobites, broken crinoids between reefs	
	Williamson Shale black shale		poor circulation; little oxygen; deep water poisoned with hydrogen sulfide; few animals able to survive	mainly floating animals, including the graptolite Monograptus clintonensis	
	Middle part of Clinton Group*** marine green & gray sandstone & siltstone alternating with shale (Sauquoit Formation); going east, changes to nonmarine red sandstone & siltstone containing quartz pebbles, alternating with green shale (Otsquago Formation)		shallow shelf nonmarine fluvial	ostracodes, clams, brachiopods green shale in Otsquago Formation contains no fossils	
	Wolcott Limestone		subtidal, nearshore to shallow shelf	abundant brachiopod Pentamerus oblongus	
	Sodus Shale Wallington Limestone		nearshore, subtidal quiet water to shallow shelf	some "pearly layers" densely crowded with shelf of brachiopod Eocoelia hemispherica	
	Hickory Corners Limestone		shallow shelf	mats of bryozoans cover some layers	
	Furnaceville hematitic limestone thin, widespread layers of limestone very rich in hematite		shallow water in depressions between nearshore ridges of sand		
	Oneida Conglomerate quartz pebbles cemented together with silica		beach		

*Lies on top of the Rochester Shale in western New York.
**To the east, the Rochester Shale changes to the Herkimer Sandstone.
***These rocks crop out only between Herkimer & Oswego Counties.

Table 7.7
Rocks of Package Three
Upper Silurian

Rock and Description		Age	Environment	Fossils	Thickness
ondout Formation dolostone rich in clay		Late Silurian	shallow, highly salty water	stromatolites, rare ostracodes	
obleskill & Glasco Limestones		Late Silurian	seas of normal salinity	brachiopods, ornamented ostracodes, corals, bryozoans	
alina roup	Camillus & Bertie Formations shale rich in anhydrite; dolostone rich in clay	Late Silurian	shallow shelf, very salty water	sparse life including eurypterids, scorpions, ostracodes, brachiopods, a few snails, & worms	300 m some salt layers in Syracuse thicker than 30 m salt layers in Vernon 3-4 m
	Syracuse Formation green or gray shale rich in anhydrite; dolostone; numerous salt layers			fossils rare	
	Vernon Formation red & green silty shale that changes to gray shale, dolostone, & evaporites (including several salt layers) in the west		red Vernon: coastal plain gray Vernon: shallow shelf During deposition of middle part of Vernon, seas evaporated nearly to dryness from time to time		
ockport roup	Illion Formation* dark gray shale	Late Silurian	shallow shelf		60 m
	several formations mostly dolostone with some chert; contain a variety of minerals		probably very shallow shelf to carbonate flats	fossils rare; mostly mollusks, especially snails, nautiloids, & clams	
	Gasport Formation limestone & dolostone; contains reefs built by corals		shallow shelf, warm, clear water	honeycomb corals (Favosites) chain corals (Halysites), tube corals (Syringopora), solitary horn corals (Cystiphyllum), bryozoans, broken crinoids	

n central New York, the Lockport carbonate layers pass eastward into the Illion Formation.

than the older parts beneath; therefore, much of it lies directly on the basement rock. Pebbly conglomerate layers are common near the unconformity. Bedding in this upper Potsdam is uniform and well defined, although cross-bedding is common within individual beds. The sand grains are nearly all quartz, in contrast to the feldspar-rich sandstone below. We can see spectacular exposures of the upper Potsdam Formation in Ausable Chasm (Figure 7.2) and at the falls of the Chateaugay River in Franklin County.

The Potsdam Sandstone becomes thicker from west to east in the St. Lawrence Valley. This trend continues farther east into the Champlain Valley. What do you suppose this arrangement might tell us about the geography when the Potsdam Sandstone was deposited?

Above the Potsdam, the rock sequence includes dolostone, limestone, sandstone, and shale (described in Tables 7.1 and 7.2). We will refer to this rock as a *carbonate sequence* because it is dominated by carbonate rocks—dolostone and limestone. Chemically, these carbonate

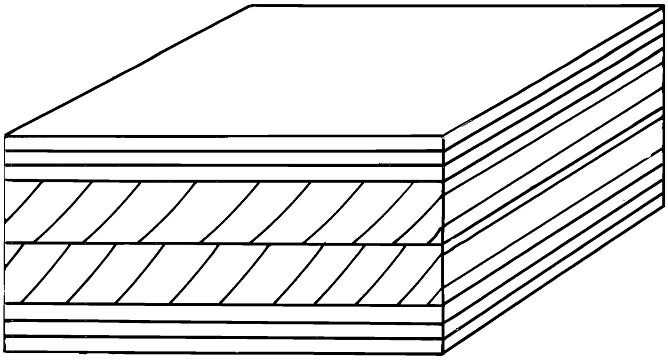


Figure 7.1. This simplified diagram shows two layers with cross-bedding sandwiched between horizontally layered units of sedimentary rock.

rocks are magnesium calcium carbonate (the mineral *dolomite*—chemical composition $(Ca,Mg)(CO_3)_2$) and calcium carbonate (the mineral *calcite*—chemical composition $CaCO_3$). The fossils and sedimentary structures[3] in these layers indicate that they were deposited in a shallow sea during Late Cambrian and Early Ordovician time. As you can see on the geologic map (Plate 2) and legend (Plate 3), this sequence (shown in blue) crops out in the same general area as the Potsdam, but it is more extensive, especially south and east of the Adirondacks. Information from drill holes tells us that layers of this carbonate sequence extend in the subsurface beneath the Ontario Lowlands and continue beneath the Appalachian Plateaus (see Figure 1.1). Indeed, rock of this type and age occur over much of eastern North America. Like the Potsdam Formation, this carbonate sequence becomes thicker from west to east along the St. Lawrence Valley. This thickening trend continues across eastern New York into western New England and gives us more clues to the geography of the time.

Some of the dolostones appear to have formed in a sea that was very salty. One such formation, the Little Falls Dolostone, contains exquisite quartz crystals. These crystals are called "Herkimer Diamonds" (see Figure 6.5). They formed in holes that developed in the dolostone long after the sediments became rock.

The carbonate sequence does not cover the Adirondack region now. However, from the thickness of this sequence around the edge of the Adirondacks, we deduce that it once covered most of that region. We do find scattered outcrops of these carbonate rocks in down-dropped fault blocks within the Adirondacks. These outcrops supply strong evidence to support the conclusion that they once covered the Adirondack region.

By combining many careful studies, we have learned that the New York region was above sea level and exposed to erosion at the end of the Early Ordovician. The legend (Plate 3) shows this conclusion in the several regions where rock of this age crops out. (The Taconic Region is an exception. How are we going to explain this difference? See Chapter 6 for some help.) By examining Plate 3, we can speculate about some local details of the history of this erosion. For example, the carbonate sequence is missing in the western part of the Mohawk Valley region but is present in the east. Maybe this sequence was never deposited in the west, or maybe it was thinner there and so eroded completely away, or maybe the western area was exposed to erosion for a longer time. Erosion was widespread in eastern proto-North America at the end of the Early Ordovician and created a gap in the rock record. We call the unconformity that resulted the *Knox Unconformity*. As you can see on the legend (Plate 3), the time gap represented by this unconformity varies considerably from place to place.

Interpretations

What history can we write about Late Proterozoic, Cambrian, and Early Ordovician time from the record in the rocks of Package One?

The poorly sorted conglomerate in the lowest part of the Potsdam Formation occurs in patches; in places, it was deposited against a steep rock face. These characteristics could mean that it was deposited at the foot of a cliff. This arrangement fits with the interpretation that the crust in this region was stretched and broken in the Late Proterozoic. Rift valleys developed in it. They must have looked much like today's East African and Rio Grande Rifts. Sediments piled up at the base of steep slopes in those early rift basins, just as they do in modern ones.

This rifting was part of the breakup of the Grenville supercontinent. As the rift widened, it was flooded with sea water to become the Iapetus Ocean. Proto-North America lay on the west side of the Iapetus Ocean. The rock of the northern lowlands was generally exposed and eroded. Streams deposited sand and gravel in low-lying areas. Remnants of these deposits remain as the Ausable Member of the Potsdam Sandstone. Figure 7.3 summarizes these events.

The fossils and bedding of the upper part of the Potsdam sandstone indicate that the shore zone of the Iapetus Ocean had advanced across the edge of proto-North America to the northern lowlands during the Late Cambrian. The advance of the shore zone deposited a blanket

[3]*Sedimentary structures* are features like cross-bedding, ripple marks, and mud cracks formed as sediment is deposited.

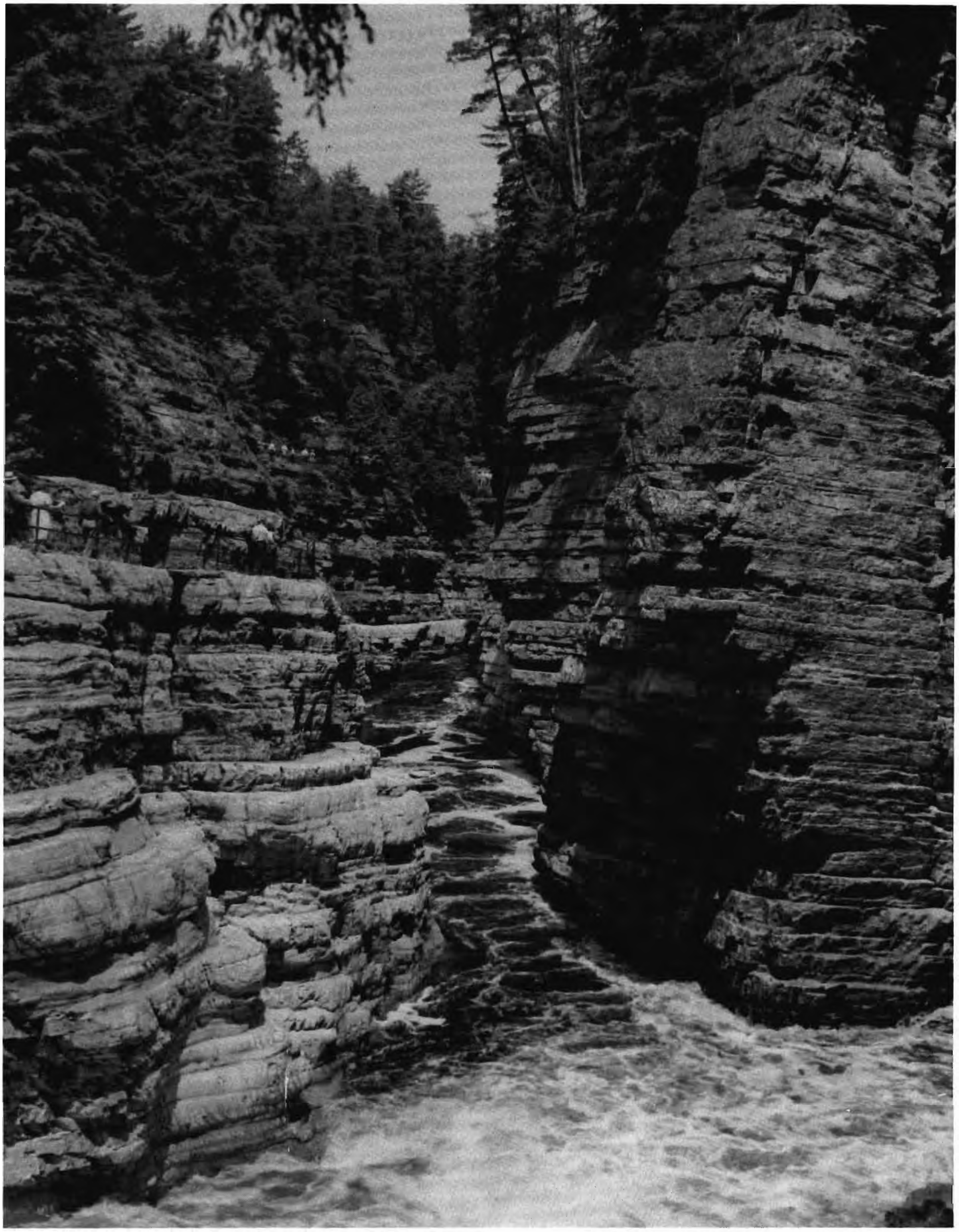
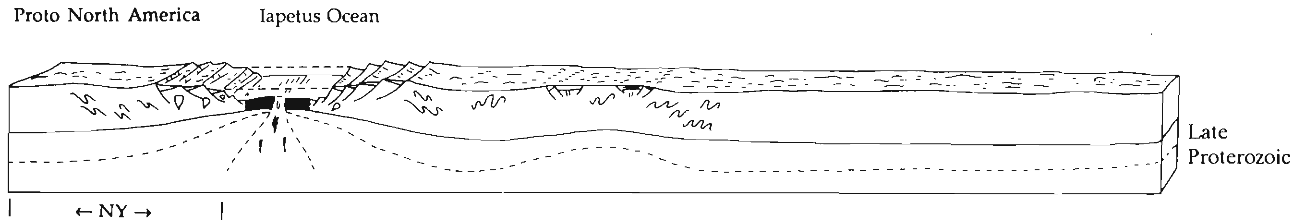
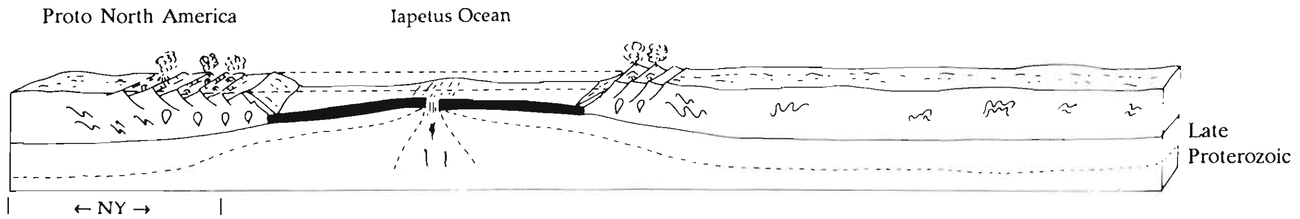


Figure 7.2. The Potsdam Formation exposed in Ausable Chasm, Clinton and Essex Counties.



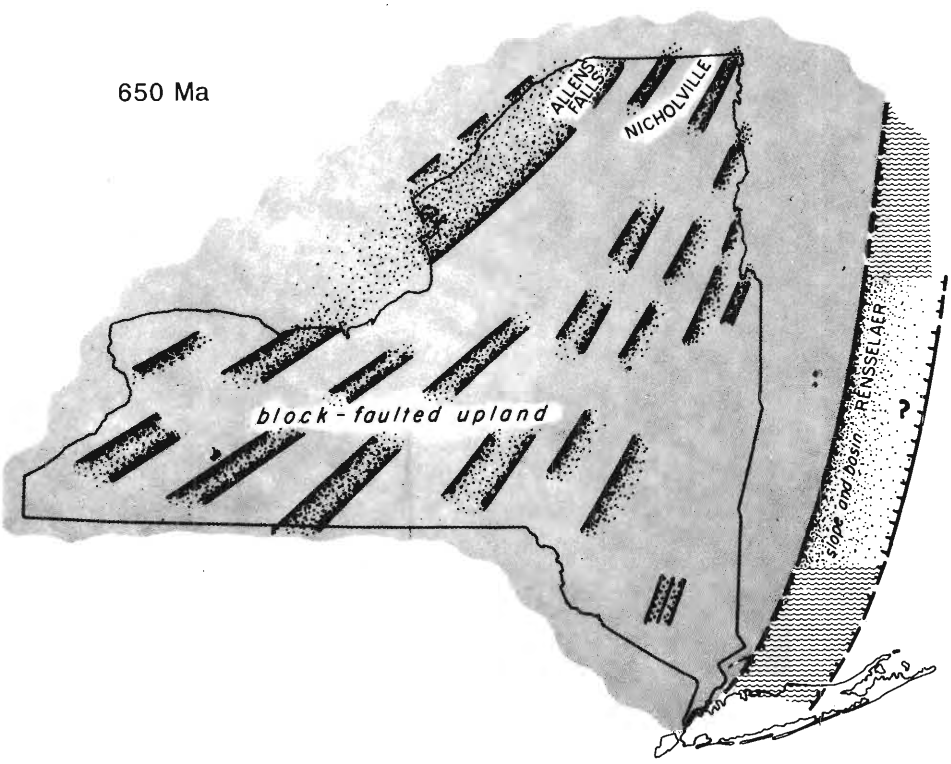
Rifting and Initial Opening of Iapetus Ocean

Figure 7.3. Rifting of the Grenville supercontinent. (A) A stretching event thins and splits the Grenville crust. Rift basins develop in the stretched crust. A main rift widens and floods with sea water to form the Iapetus Ocean. Some rift basins remain above sea level; some near the edges of the main rift become submerged. Debris eroded from the rift margins is deposited in the basins. (Compare with Figure 3.1 to recognize continental and oceanic crust and the boundaries of the crust, lithosphere, and asthenosphere.)



Continued Rifting and Opening of Iapetus Ocean

(B) Rifting continues and the Iapetus Ocean widens. Volcanic activity occurs in the rift basins, and deposition continues in the basins.



(C) Probable appearance of the region in the late Proterozoic. Rift valleys are filled with sediment and the western edge of the main rift is buried by offshore sediment.

of beach sand in its wake. This sand lay on top of the eroded Proterozoic basement rock and the scattered remnants of sediments that filled rift basins.

As the sea crept west, the beaches moved westward too, and the continental shelf widened. Some of the sand eroded from the land is trapped and deposited at the beach and on the shoreward part of the shelf. However, much can be moved farther offshore. As we mentioned earlier, all of Package One is thicker to the east, in the offshore direction. This thickening is because the edge of proto-North America sank farther below sea level and made more room for sediment to accumulate. Sediment piled up as fast as the basement sank, so the water never got very deep on the shelf. That is why we have a thick shelf sequence all of which was deposited in shallow water. Eventually, toward the end of the Early Ordovician, eastern proto-North America was submerged as a great continental shelf dominated by carbonate sediment. The region may have resembled the modern Grand Bahamas Banks or the Florida Keys, except that there was no vegetation growing on land. The end of Early Ordovician time is marked in our rock record by the Knox Unconformity. Apparently sea level dropped worldwide at this time and left the broad continental shelves exposed. Erosion then did its work. Figure 7.4 summarizes this history graphically.

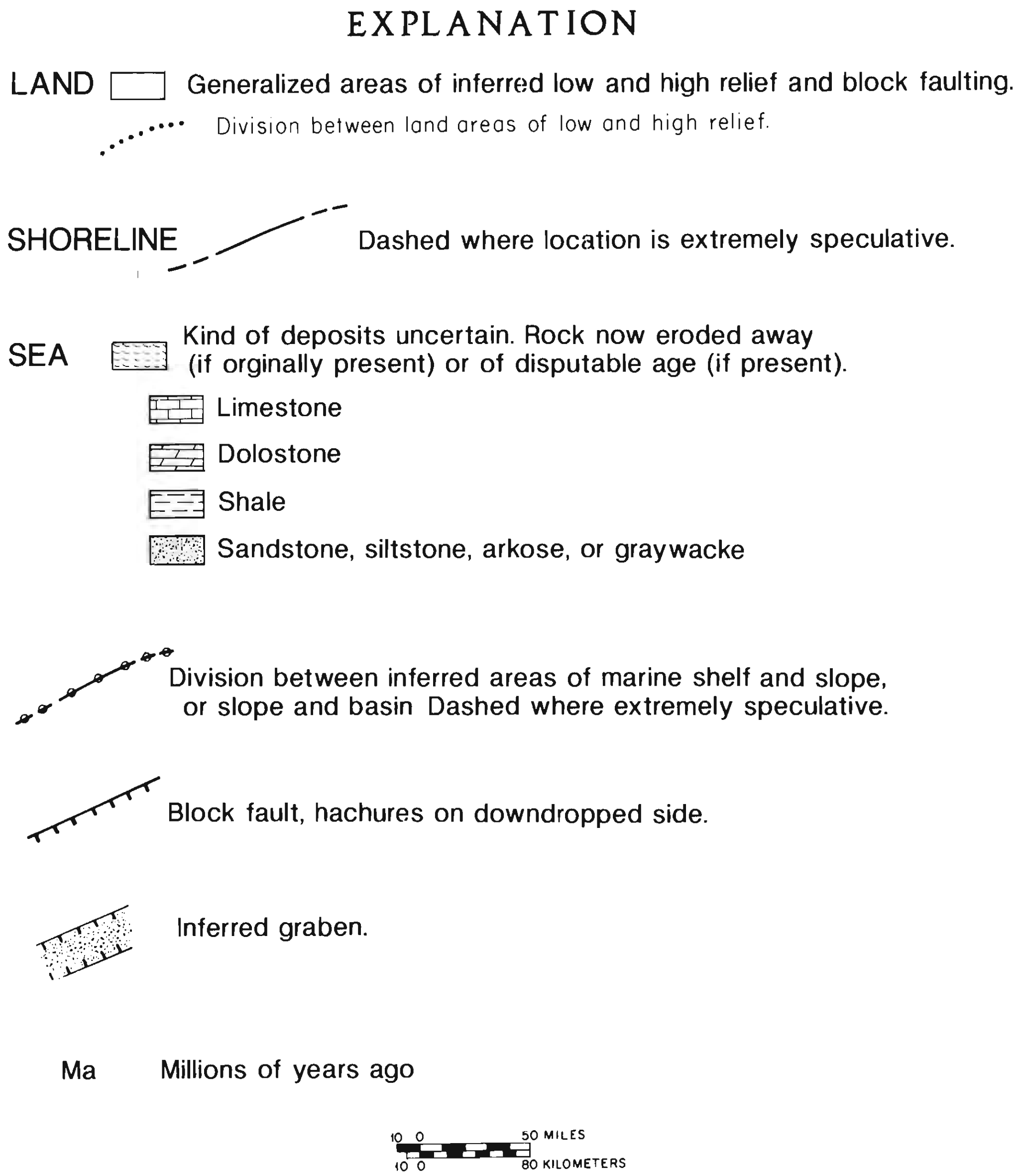


Figure 7.3. C *continued*

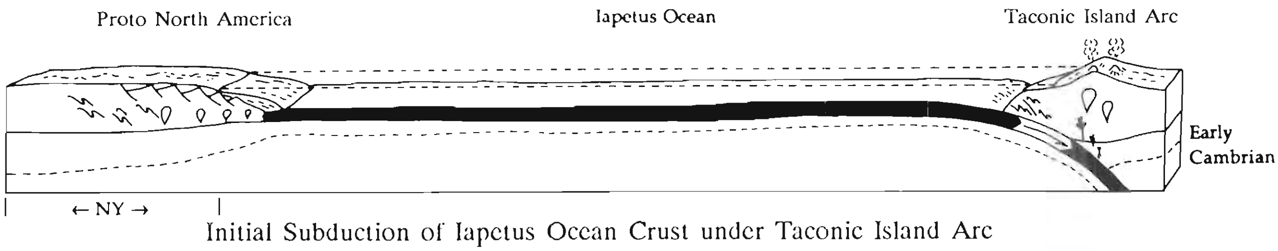
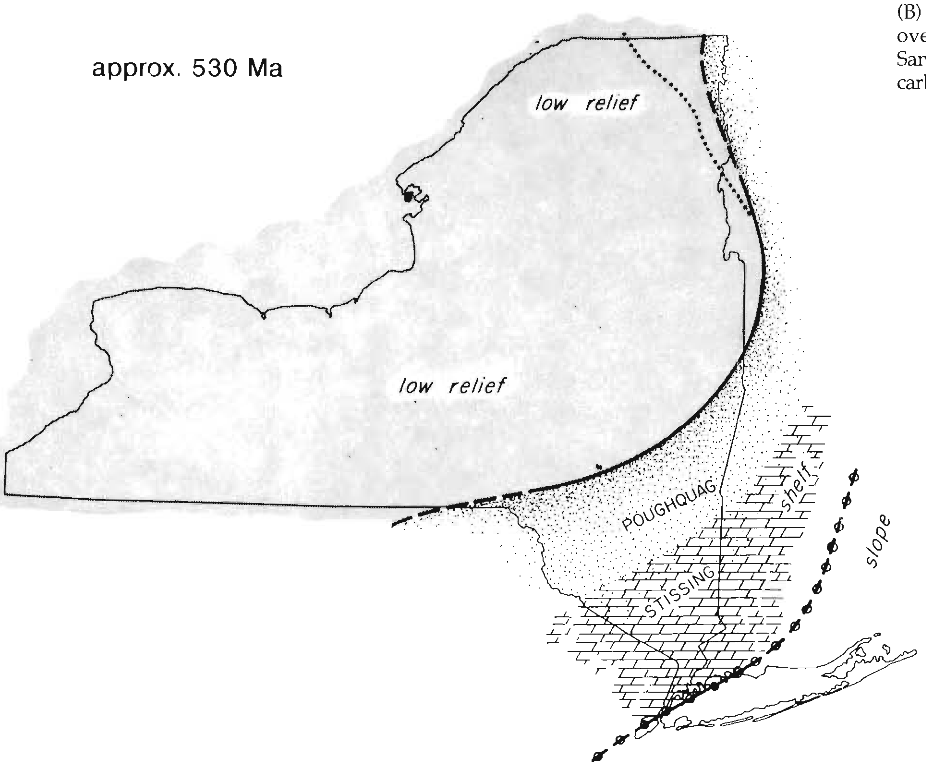


Figure 7.4. Deposition of the sedimentary rock of Package One during the Cambrian through Early Ordovician. (A) Subduction has begun in the Iapetus Ocean; the western part of the ocean is closing, and a volcanic island arc builds above the subduction zone. A continental shelf, slope, and rise develop on the eastern edge of proto-North America.

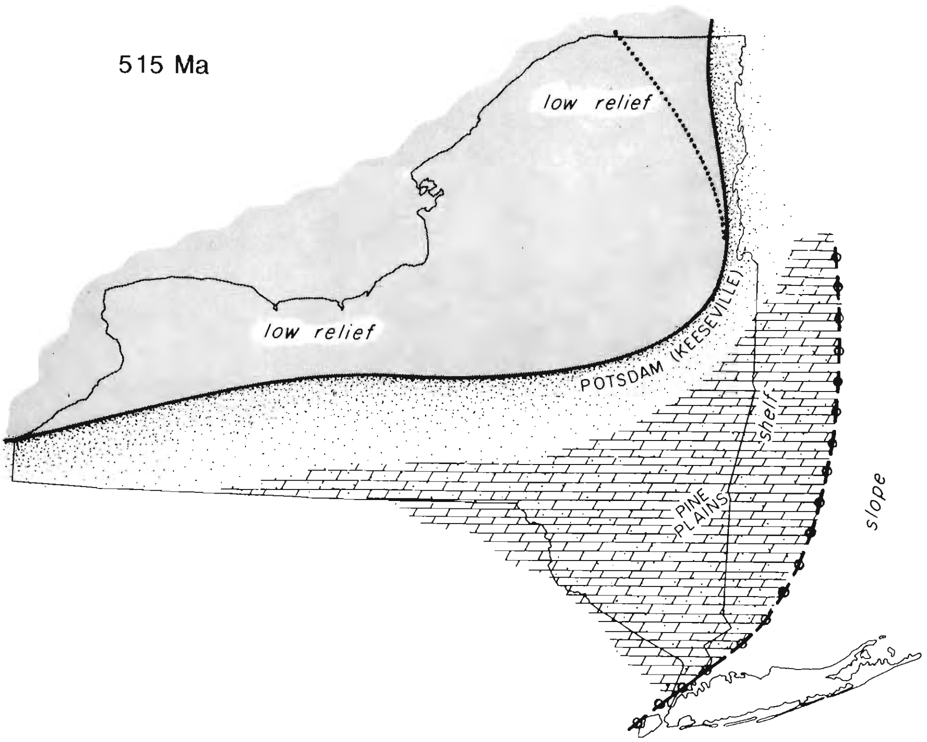


(B) The shore zone begins to advance over eastern proto-North America. Sand is deposited in the shore zone, carbonate sediment farther offshore.

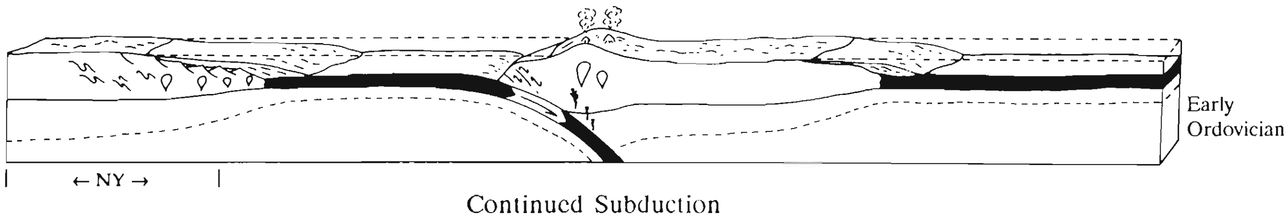
Rocks of Package Two: Middle through Late Ordovician Time

The Middle and Late Ordovician rock record in the northern lowlands is most nearly complete in the Finger Lakes-Mohawk Valley region (Columns 2 and 3 on Plate 3). The units in this package are shown on the geologic map and legend (Plates 2 and 3) by light blue with diagonal stripes, light brown, pale orange, and yellow-orange with red dashes. In the eastern Mohawk Valley and southern Catskill region, there is a reddish-brown map unit of this age as well. These rocks are described in Table 7.3. The largest area of bedrock of this package lies southwest of the Adirondacks and extends along the south shore of Lake Ontario. Patches of the lower two map units in the package crop out in the Champlain Valley (see Table 7.4 for description).

The lowest map unit (blue, striped diagonally) has several sedimentary formations. We find limestones at the bottom of the pile. Higher, there are shale layers alternating with layers of carbonate rock. The next higher map unit



(C) The shore zone advances farther onto proto-North America. A layer of sand is left in its wake. The sand deposit is progressively covered by carbonate sediment offshore.



(D) The western part of the Iapetus Ocean narrows as the island arc approaches proto-North America. Sediments cover the widening continental shelf and extend to the ocean floor as continental slope and rise deposits.

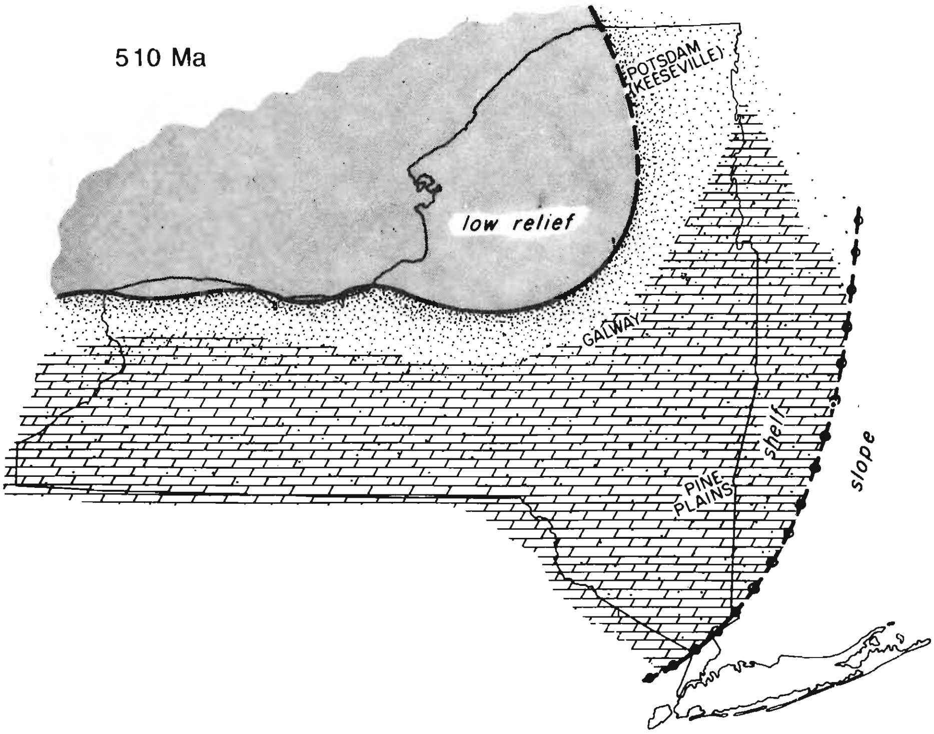
(pale brown) includes a widespread thick layer of dark shale or shale and siltstone at the bottom. In the Mohawk Valley and west, the amount of coarser grained material gradually increased through time; siltstone and sandstone become more abundant upward in this unit. The third map unit (pale orange) in Package Two contains layers of well sorted sandstone and of shale. This unit forms the caprock[4] of the Tug Hill Plateau east of Lake Ontario. The topmost map unit in this package (yellow-orange with red dashes) is shale and siltstone. It crops out south of Lake Ontario. In contrast to the rock layers below it, which were deposited on the sea floor, this topmost unit was deposited above sea level in a river delta system.

[4]*Caprock* is the hard rock layer that forms the top of a cliff.

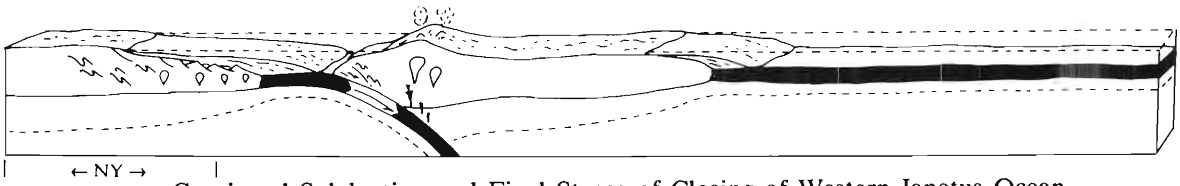
The Sedimentary Record

The oldest rocks in Package Two in the northern lowlands are limestones of the Chazy Group (see Column 7 on Plate 3 and Table 7.4). They were deposited in the early part of the Middle Ordovician and occur only in the Champlain Valley of New York and in the northern St. Lawrence Valley of Canada (Figure 7.5).

Why is the Chazy Group found in so few places? There are two possible explanations. The Chazy sea may have extended only onto the eastern margin of proto-North America, so the limestone was formed only in restricted areas. Or this limestone may originally have been more widespread but was eroded away later.



(E) The shore zone continues to advance over eastern proto-North America. Sandstones of the Potsdam Formation that we now see in outcrop are deposited. Sediments offshore thicken and keep the continental shelf waters fairly shallow.



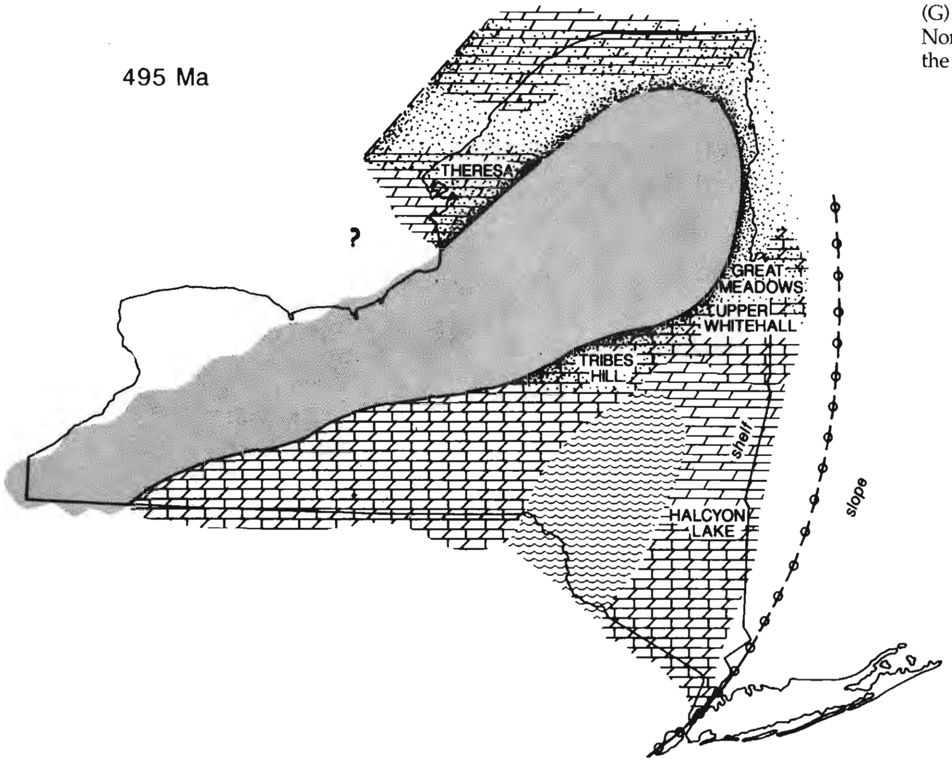
(F) The island arc nears the edge of the continental crust and continental rise deposits of proto-North America.

Regardless of its extent, the Chazy sea supported a host of new creatures: new kinds of brachiopods, specialized nautiloids,[5] trilobites, and clams (see Figure A.3). Snails were common, especially the large, tightly coiled form called *Maclurites* (Figure 7.6). The first bryozoans appeared and became important reef-builders (see Figure A.3). Another new arrival, the *stromatoporoids*, a group of sponges that resemble colonial corals, built moundlike reefs. During this time, the first true corals appeared as well. The oldest known coral reef in the world is found on Isle La Motte in Lake Champlain. Echinoderms (primarily cystoids)[6] were common in areas around the reefs.

An unconformity separates the Chazy Group from younger Middle Ordovician limestone units (see Column 7 on Plate 3). Later in the Middle Ordovician, carbonate sediments were deposited across much of New York State. This deposition resulted in the formation of the Black River Group (Column 2 on Plate 3; Tables 7.3 and 7.4) and the Orwell and Isle La Motte limestones (Column 7 of Plate 3; Table 7.4). Much of this material was fine-grained carbonate—a *lime mud*. It contains very little clay and silt derived from the land. Lime mud is formed when shells and other hard parts of animals and plants disintegrate after death. Feeding by predators and the action of waves and currents help this process along.

Black River Group limestones contain many fossils,

[5]*Nautiloids* are squid-like animals with shells.
[6]*Echinoderms* include modern-day crinoids, starfish, and sea urchins and their ancient relatives. A *cystoid* is an extinct type of echinoderm that grew attached to a solid sea bottom like a crinoid (see Figure A.3).



(G) Sea level drops, and eastern proto-North America begins to emerge from the sea.

burrows of invertebrate animals, and sedimentary structures. These features are the clues to the various environments in which sediment was deposited. Mud cracks and abundant vertical burrows suggest mud flats that were exposed to the open air at low tide. Colonies of *Tetradium* coral, on the other hand, indicate an environment that was continuously underwater. Beds of *fossil hash*—broken and worn pieces of shell—tell us that life was abundant in this sea and that there were occasional storms. (Storm waves stir up the bottom sediment and separate the coarser material—fossil hash—from the finer lime mud.)

Among the fossils found in these limestones are brachiopods and pelmatozoans[7], clams and ostracodes (see Figure A.3), and several kinds of trilobites (Figures 7.7 and 7.8).

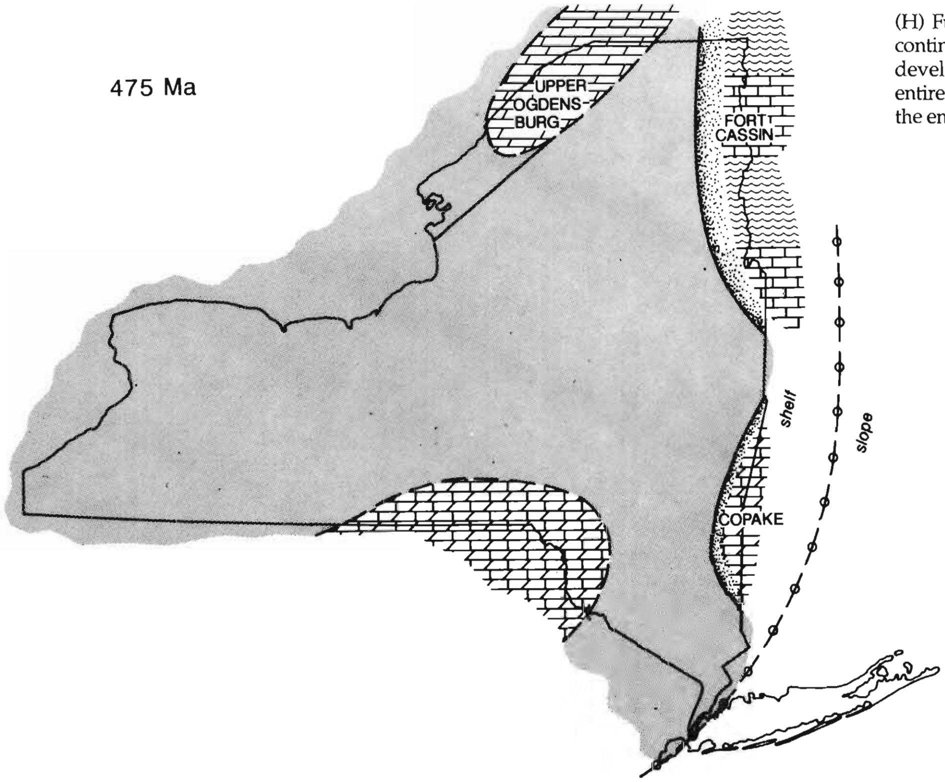
Studies of the earth's paleogeography[8] conclude that our part of eastern proto-North America was 20 degrees south of the equator in the Middle Ordovician. This information suggests that the sea water was warm. The deposition of limestone and the kinds of fossil animals and their abundance in the rock record support this idea of a tropical climate.

An unusual feature of this sequence of rock is the presence of bentonite in thin layers. *Bentonite* is a kind of rock that is altered from volcanic ash. It is made of *montmorillonite*—a type of clay that expands remarkably when wet. The trained eye can spot very thin layers of bentonite in an outcrop because they weather with a distinctive "popcorn" texture. We have no evidence of volcanoes in eastern proto-North America at this time, so where did this bentonite come from? Volcanic ash fell in our quiet Middle Ordovician sea after being blown in from an offshore island arc, to be discussed later.

Above the bentonite layers, we find a significant change in the rock of the northern lowlands. This next higher part of the sequence (the Trenton Group in Columns 2 and 3 on Plate 3 and the Glens Falls limestone in Column 7; Tables 7.3 and 7.4) contains thin layers of shale that alternate with thicker layers of limestone. What's significant about this arrangement? It turns out that the clay and silt that form this shale came from the *east*. All the sand, silt, and clay in the rock below this level, down through the Cambrian section, had come from the west. Proto-North America itself was their source. Now we must have land offshore to the east.

What caused deposition to alternate between carbonate and land-derived mud? Here are some possible answers. In the western part of the northern lowlands,

[7]A *pelmatozoan* is an echinoderm, with or without a stem, that lives attached to a solid sea bottom.
[8]*Paleogeography* refers to the geography of past geologic ages.



(H) Further sea level drop exposes the continental shelf sediments to erosion to develop the Knox Unconformity. The entire area of New York is exposed by the end of the Early Ordovician.

Figure 7.5. Limestone of the Day Point Formation, Chazy Group, south of Chazy, Clinton County. The rock is coarse textured and contains many fossils. It also displays cross-bedding; compare this photo with Figure 7.1 to recognize this feature.

we find layers of fossil hash in the limestone. We think these layers were formed when storm waves churned up the sediment on the bottom. The waves and currents caused by the passing storm separated the coarser material from the fine and left the two sizes of sediment in different layers. With time, some of the fossil hash layers were cemented, and this cementing made the sea bed firm, at least in places. Organisms that need a hard bottom on which to grow colonized such a layer. So we find fossil hash layers encrusted by the kinds of organisms that need a firm foundation. These organisms include varieties of bryozoans, corals, echinoderms, and brachiopods (see Figure A.3). This community is covered by a very thin layer of dark shale. The shale appears to have smothered it. How could such a thin layer do that? Answer: when a layer of mud compacts to shale, its thickness is reduced to only one-tenth that of the original mud. The clay and silt that form the shale layer were probably deposited slowly, whereas the carbonate became a fossil hash bed in a single storm.

In Column 3 of Plate 3, you can see that the middle part of the Trenton Group passes eastward into the limestone and shale of the Dolgeville Formation. The Dolgeville Formation is another sequence of limestone beds alternating with shale beds, but both the shale and limestone beds have the same thickness. Each is about 10 cm thick. The carbonate sediment in these limestone beds originally formed near the east edge of the Trenton shelf of western New York. Something (big storms, earth-

Figure 7.6. Abundant specimens of the gastropod *Maclurites magnus* Le Sueur found in the Crown Point Limestone, Chazy Group, southwest of Chazy, Clinton County.

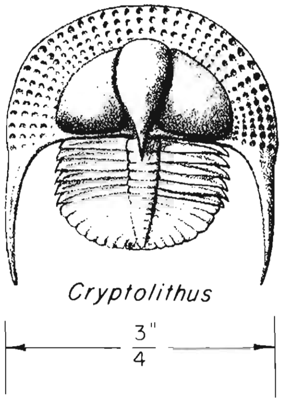


Figure 7.7. The trilobite *Cryptolithus tesselatus* (Green), common in Middle Ordovician limestones and shales.

quakes) occasionally disturbed the sediment pile near the shelf edge so it slumped downslope toward the basin to the east. In the process of slumping, the sediment mixed with water to form a *turbidity current*. This current then flowed along the bottom down the slope toward the basin. In this way, carbonate moved off the shelf and suddenly invaded the slope environment. The carbonate bed was deposited in just a few hours or days. Mud (silt and clay) continued to be deposited on the slope and in the basin to form shale, and after an interval of time (years to hundreds of years) another turbidity current brought in another carbonate

Figure 7.8. The trilobite *Isotelus gigas Dekay*, common in the limestones of the Middle Ordovician Trenton Group.

layer. This process eventually built up the sequence we call the Dolgeville Formation.

To find the environment in which the Dolgeville Formation was deposited, look at the diagram labeled *Depositional Environments* (in the lower left corner of Plate 3). Compare this diagram with the legend above it and find the patch that represents the Dolgeville Formation. It is colored green on the small diagram, representing the slope environment that lay between the shelf environment of the Trenton Group (blue) and the basin environment of the Utica Shale (brown).

The Dolgeville is easily recognized in the road cuts on the New York State Thruway west of the Little Falls exit in Herkimer County. Some of the limestone beds in the unit prominently display small, sharp folds. These road cuts also display the black shale (the Utica Shale) that lies on top of and east of the Dolgeville.

The different kinds of limestone found in the northern lowlands each reflect a different environment of deposition. A variety of environments existed on the shallow shelf; water depth was a major control over environment. Tidal flats, quiet lagoons, turbulent shallows churned by waves and currents, the deeper and quieter outer shelf where the bottom was disturbed only by the biggest storms, and the yet deeper water of the slope are all recorded in these limestone units.

Hundreds of meters of black shale lie on top of the sequence of alternating limestone and shale. This shale (called the Utica Shale, described in Table 7.3) was formed from mud eroded from land to the east; this mud gradually spread westward, until all of the carbonate environments were blanketed. Where did all this mud come from? We'll come back to that question later.

The kinds of fossils in the limestone sequence are different from those in the thick shale sequence. These two sequences record environments so different that they contained entirely different animals. Brachiopods, corals, bryozoans, and trilobites (see Figure A.3) are common in the limestone sequence, but they are largely missing in the overlying shale sequence. Instead, we find only scattered remains of graptolites and trilobites of a different kind (see Figure A.3). All of the fossils we find in the shale sequence are of swimming or floating organisms rather than the bottom dwellers so common in the limestone. What caused this dramatic change?

The shale is dark colored because it has a lot of finely dispersed organic matter and pyrite (iron sulfide—chemical composition FeS_2) in it. The presence of these materials tells us that there was little oxygen at the ocean bottom. The environment was poisoned by hydrogen sulfide. Nothing could live there. When creatures died in the water above, they settled to the poisonous bottom. There they remained, because there were no scavengers to eat them and no oxygen to promote decay.

As we move from west to east along a rock layer of the same age, we pass from limestone, to interlayered limestone and shale, to shale. (On Plate 3, follow a horizontal time line from the Trenton Group through the Dolgeville limestone and shale into the Utica Shale.) If we do, we can see that all three environments existed at the same time in different places. How do we know? Some species of graptolites occur in both the Trenton Group and the Utica Shale. These fossils permit us to conclude that these rock bodies are the same age.

Most of our rock record for Late Ordovician time is in western New York. A complicated suite of rock units of this age occurs in the Mohawk Valley and west (see Columns 1, 2, and 3 on Plate 3 and Table 7.3). The shale basin began to receive increasing amounts of coarser material—silt and sand—in the Middle Ordovician. Through time, this coarser material gradually spread from east to west. A careful study of Plate 3 will show you this arrangement. Look first to Column 3. Toward the end of the Middle Ordovician, sand and conglomerate were deposited to the east (Quassaic); sand, silt, and mud westward (Schenectady); and mud in the basin farther west (Utica). (The Quassaic and Schenectady are rock units that lie east of the northern lowlands, but they were formed at the same time by related processes.) The formations of the Lorraine Group appear higher in the Mohawk Valley sequence. Upward and westward through this group, the sediment gradually becomes coarser—from shale and siltstone (Frankfort), to siltstone and shale (Whetstone Gulf), to sandstone, siltstone, and shale (Pulaski), to sandstone with minor shale (Oswego). This last unit is the coarsest grained of the group. It is made up of clean (mud-free) sandstone beds separated by thin shale. The sandstone has the characteristics of nearshore and beach deposits.

These features of the rock record suggest that the deep Middle Ordovician basin was filled in slowly from east to west. The fossils in the formations of the Lorraine Group support this conclusion—upward through the rock sequence the life forms are from progressively shallower water.

By referring to the geologic map and legend (Plates 2 and 3), you can see that the youngest Ordovician rock in New York crops out on the Tug Hill Plateau and west along the shore of Lake Ontario. This unit, the Queenston Shale (described in Table 7.3), has a distinctive reddish color. It is largely shale, but it contains beds of siltstone and sandstone. The Queenston Shale has the features of an enormous delta that spread westward across the State. We call this delta the *Queenston Delta.* The eastern part of the outcrop belt appears to have been deposited above sea level. The western part contains a few marine fossils. The Queenston is easily eroded, and good exposures are scarce. However, the unit is well exposed low in the cliffs of the Niagara Gorge from the Whirlpool downstream to the villages of Lewiston and Queenston and in the Genesee River Gorge at Rochester. Its reddish color makes it easily recognizable in these outcrops.

The Queenston Delta in New York is part of a huge apron of sediment that spread west to the mid-continent and as far south as Virginia. The sediment was eroded from highlands that lay just east of New York and extended southward. Where did all this sediment come from? Traditionally, geologists have concluded a renewed uplift of the mountains built by the Taconian Orogeny provided a source for all the sediment. A new idea suggests that sea level dropped in the Late Ordovician. Such a drop would permit a delta to build rapidly across the newly exposed sea floor. Perhaps some of its sediment was eroded from earlier marine deposits.

What brought about this new interpretation? Recent work in Africa and South America indicates that deposits were made there by continental ice sheets during the Late Ordovician. Such huge ice sheets store a lot of water as ice and snow. Where does all that water come from? Because the oceans contain 99 percent of the earth's water, they must be the primary source for the water in continental ice sheets. The level of our modern oceans would rise over 100 meters if the ice sheets that now cover Antarctica and Greenland were to melt completely. Conversely, if new continental ice sheets formed, sea level would drop worldwide. Such a drop in sea level as a result of a major glaciation may have influenced the formation of the Queenston Delta back in the Late Ordovician.

Interpretations

What caused all these developments? Let's look at the major geologic events at that time. During the Middle and Late Ordovician, a major mountain-building event, the Taconian Orogeny, was taking place farther east. The Taconian Orogeny can explain the changes we see in the bedrock of the northern lowlands. Even though sedimentary rocks of the northern lowlands were not deformed, their origin was strongly affected by the events to the east.

When a volcanic island arc began to collide with proto-North America in the Middle Ordovician, it rode up over the eastern edge of proto-North America. Its weight caused the margin of proto-North America to sink, slowly at first (Figure 7.9).

Volcanic ash blew in from the east. The relentless advance of the volcanic island arc across the margin of proto-North America bent the continental shelf downward to form a basin. The basin deepened until it was

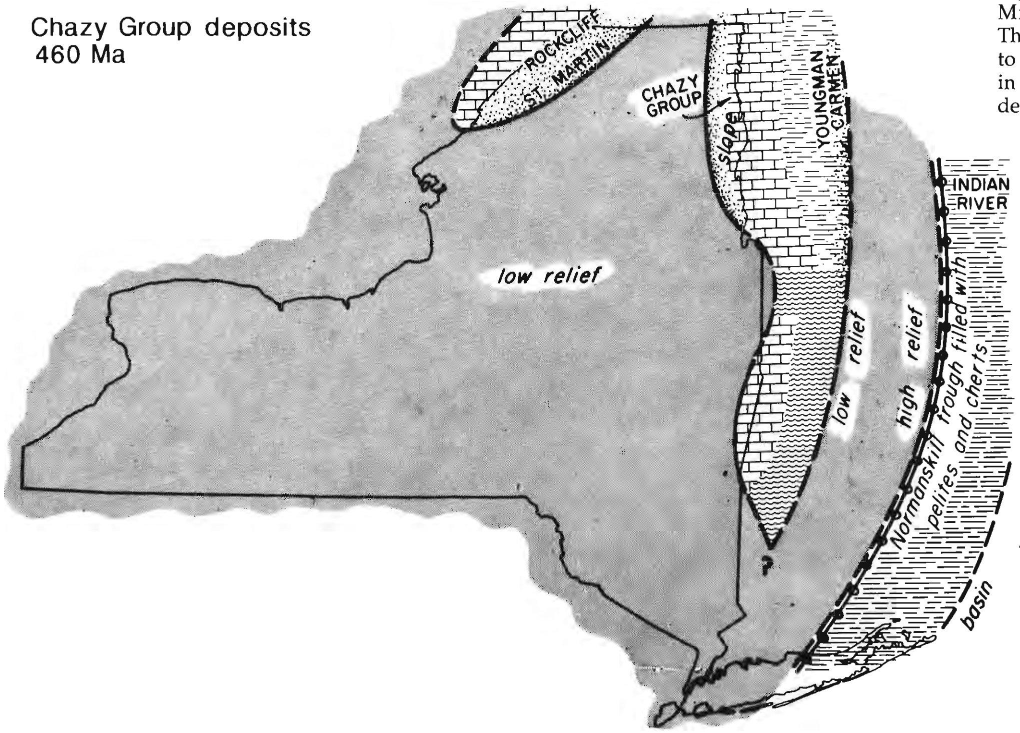
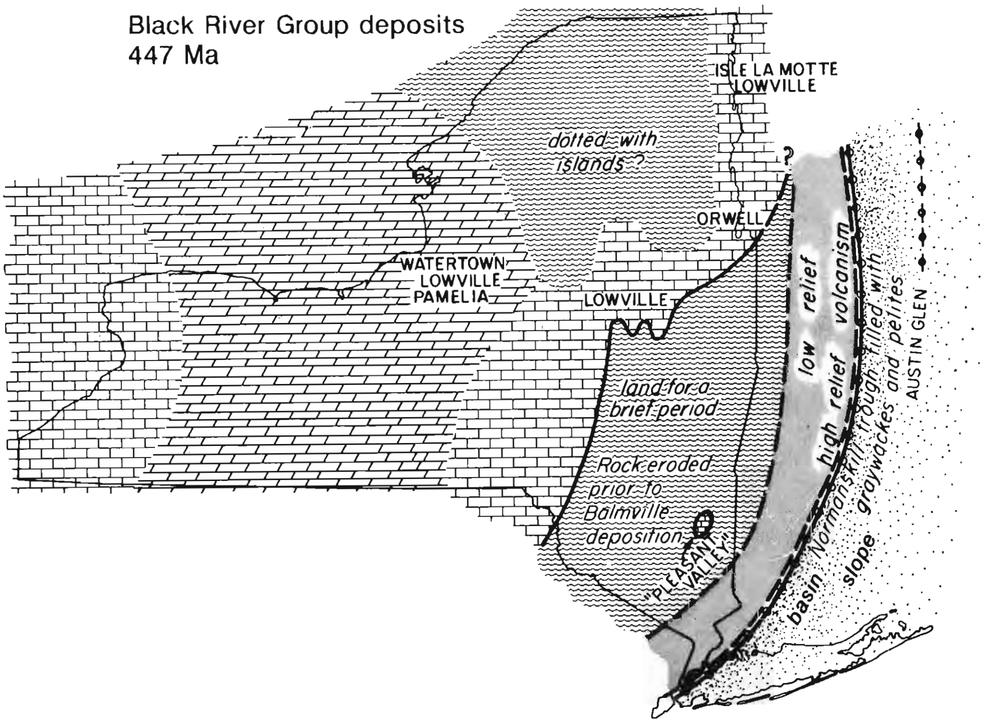
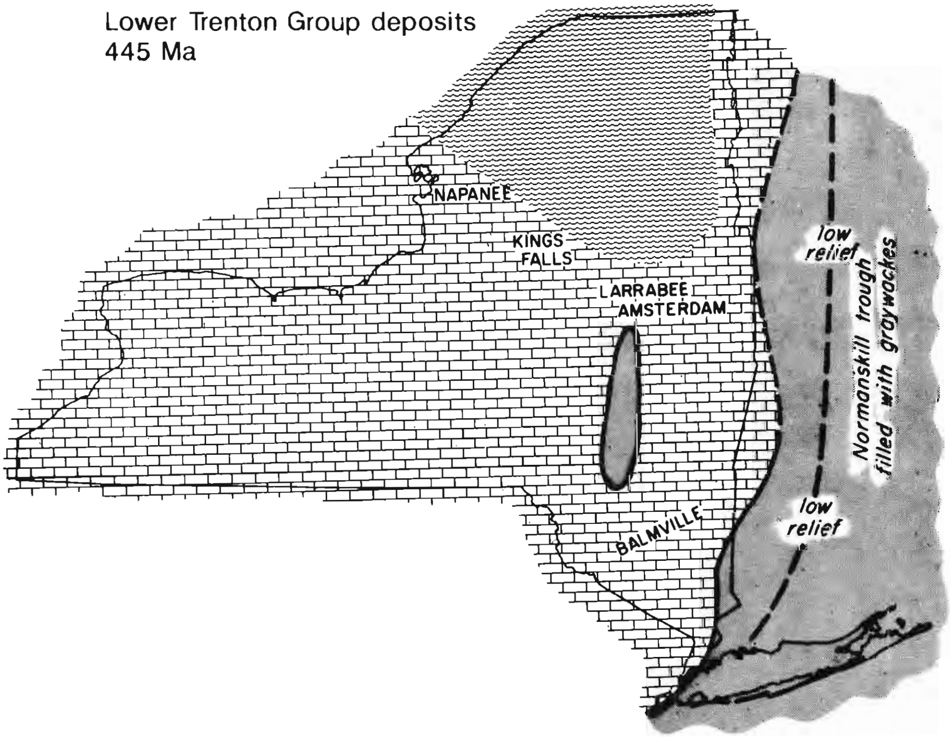


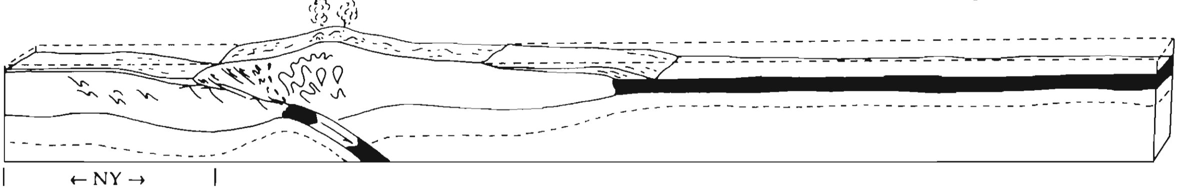
Figure 7.9. Geography during Middle Ordovician time. (A) The edge of the continent begins to be submerged again by a rise in sea level. The Chazy Group is deposited in eastern areas.



(B) The Black River Group is deposited. The western part of New York is now submerged, and the water becomes progressively deeper toward the west. Volcanic ash is blown into the area from the volcanic island arc to the east.

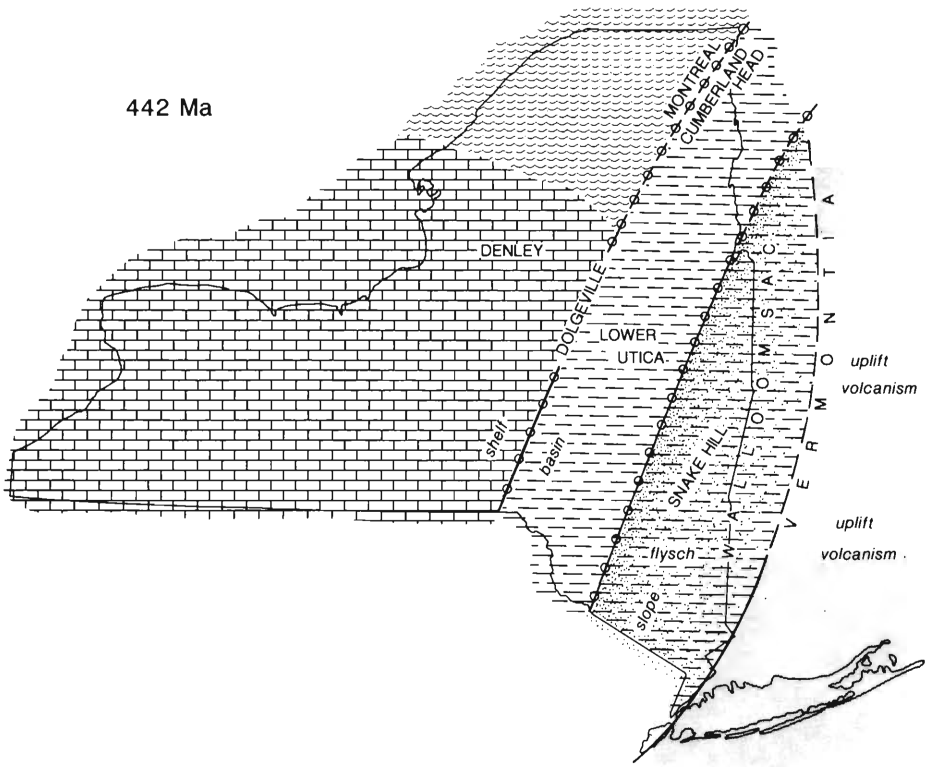


(C) Most of New York is now submerged, except for some areas in the east-central part of the State. Carbonate sediment predominates.



Taconian Orogeny - Collision of Island Arc and Proto North America

(D) The collision between the volcanic island arc and the continent is well under way. Sedimentary rocks originally deposited far to the east are thrust into eastern New York. The eastern part of what was earlier a carbonate shelf is now depressed to form a basin. The ancestral Taconic Mountains develop.



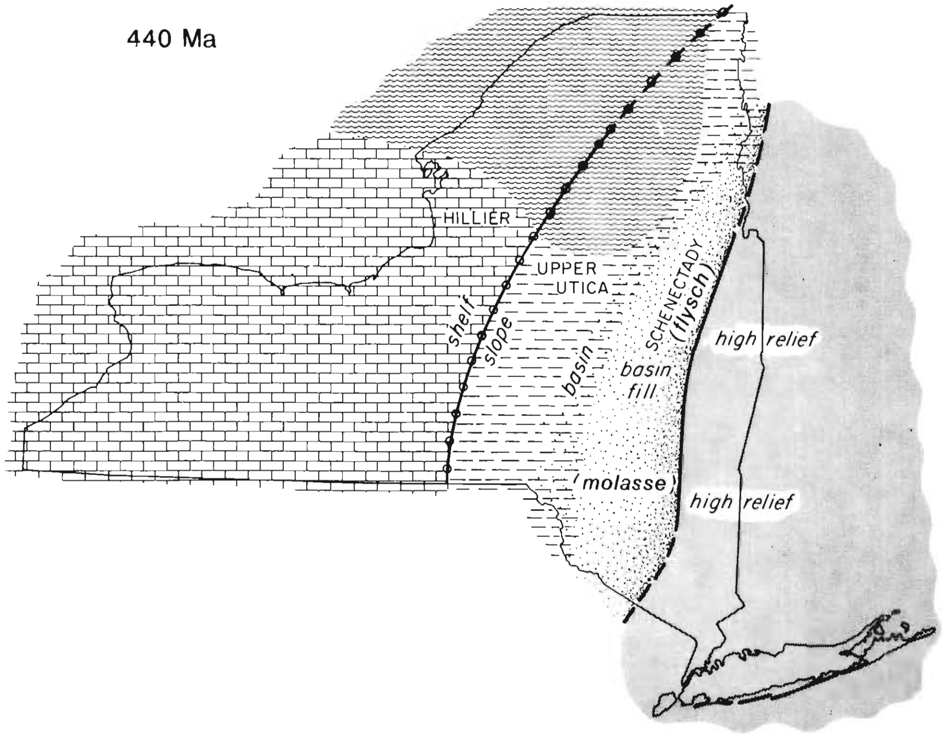
(E) Mud eroded from the ancestral Taconic Mountains pours into the basin. Today, this mud is the Snake Hill Formation and Utica Shale. Farther west, deposition of limestone continues. This sediment will eventually become the upper part of the Trenton Group.

more than 500 m deep, the deepest environment we know for the Ordovician of New York.

Sediment eroded from the volcanic island arc and its accretionary prism poured into the deepening basin. As the collision went on, it built a huge range of mountains along the east coast of proto-North America. Sediment eroded from these ancestral Taconic Mountains continued to pour into the deep basin. Water circulation was poor in the deep basin, and there was not enough oxygen to support much life. The mud deposited here was black from organic matter that rained down from the surface water and from fine-grained pyrite that grew within the mud. Carbonate sediment continued to be deposited on the shallow shelf to the west. Eventually, this shelf became basin.

Toward the end of Ordovician, the mountains had been largely eroded away and the basin was filled. But then, sediments once again poured into the area from the east to form the Queenston Delta. Where did these sediments come from?

The land to the east may have been uplifted again, and this uplift increased the speed of erosion. But there is



(F) The filling of the basin continues, and coarser material accumulates in its eastern part. These coarser deposits are known as the Quassaic and Schenectady Formations.

another possibility. Major glaciers in the southern continent of *Gondwana* (modern Africa, South America, India, Australia, and Antarctica) may have locked up enough water to make sea level drop around the world. A drop in sea level would have exposed the eastern part of New York to erosion. This material may have been reworked to form the Queenston Delta.

In any case, the sediments from the east piled up until they filled in this deep basin.

Summary of the History

The rock record of the Middle and Late Ordovician tells a more complicated history than that of the Early Ordovician. The major events are summarized in Figures 7.9 and 7.10. After the Middle Ordovician began, the eastern part of the continent began to sink below sea level again. The formations of the Chazy Group are the earliest records we have of this sinking. (See Column 7 on Plate 3 and compare it to the other columns.) Through the first half of Middle Ordovician time, the record suggests that deposition was spotty in eastern New York. In the Mohawk Valley region and west, however, carbonate sediment accumulated on a shallow shelf to the end of middle Ordovician time (see Columns 2 and 3 on Plate 3). This sediment became the limestone formations of the Black River and Trenton Groups. Volcanic ash layers in the Chazy and Black River Groups provide evidence that a volcanic island arc was offshore. About halfway through the Middle Ordovician, the eastern part of the region was bent downward to become a basin. This basin was gradually filled with the sediment of the Snake Hill and Utica formations. As time passed into the Late Ordovician, the basin expanded westward. The Trenton carbonate shelf sank, and the basin developed above it. Eventually, sediment filled the basin to sea level and above. This last event is recorded in the rock of the Queenston Formation.

Study the geologic map and legend (Plates 2 and 3) and the *Depositional Environments* diagram in the lower left corner of Plate 3. With these events in mind, find the Middle and Upper Ordovician formations on the diagram. This diagram shows the environments in which sediments were deposited across the State (in those places where we have a record). For example, find the Trenton Group on the diagram. East of it is a small green patch that represents the Dolgeville Formation. Draw a horizontal line through the Trenton and Dolgeville and eastward across the diagram. This line passes through depositional environments that existed side by side. This procedure lets you visualize the geography of that time; then, you can follow the changes in geography through time.

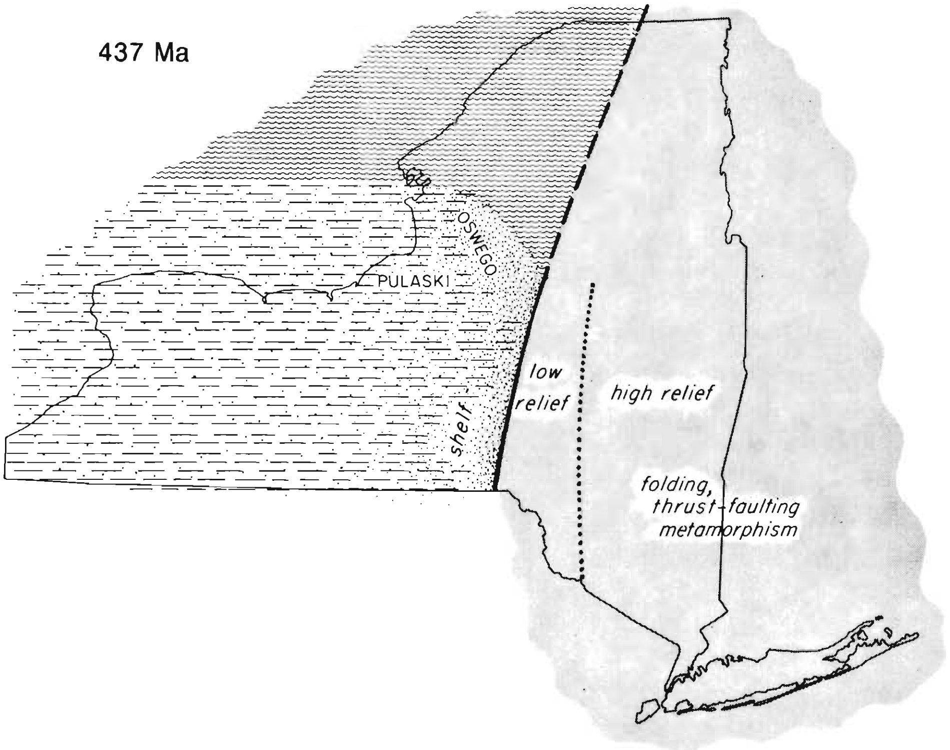
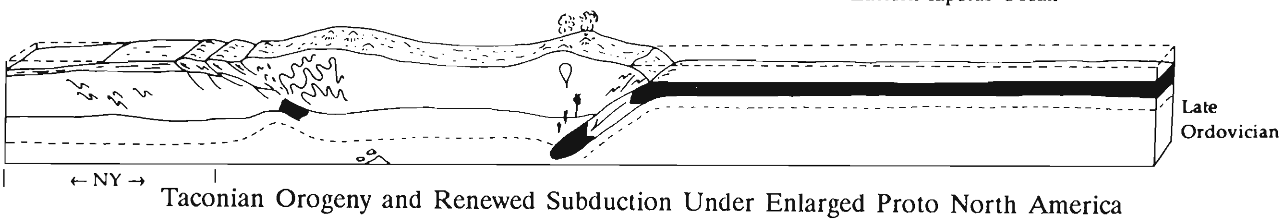


Figure 7.10. Geography during Late Ordovician time. (A) Sediment has been filling the basin. Its eastern part is filled to sea level or above. Mud and sand are deposited on the shelf in western New York (Pulaski Formation). As the sediment fills the basin to sea level, the shore zone moves from east to west, leaving a layer of sand (Oswego Formation)



(B) The ancestral Taconic Mountains continue to supply mud and sand. This material accumulates above sea level and builds an apron of poorly sorted fine-grained sediment over the shore zone deposits. This apron is the Queenston Formation, which is the youngest Ordovician unit in New York.

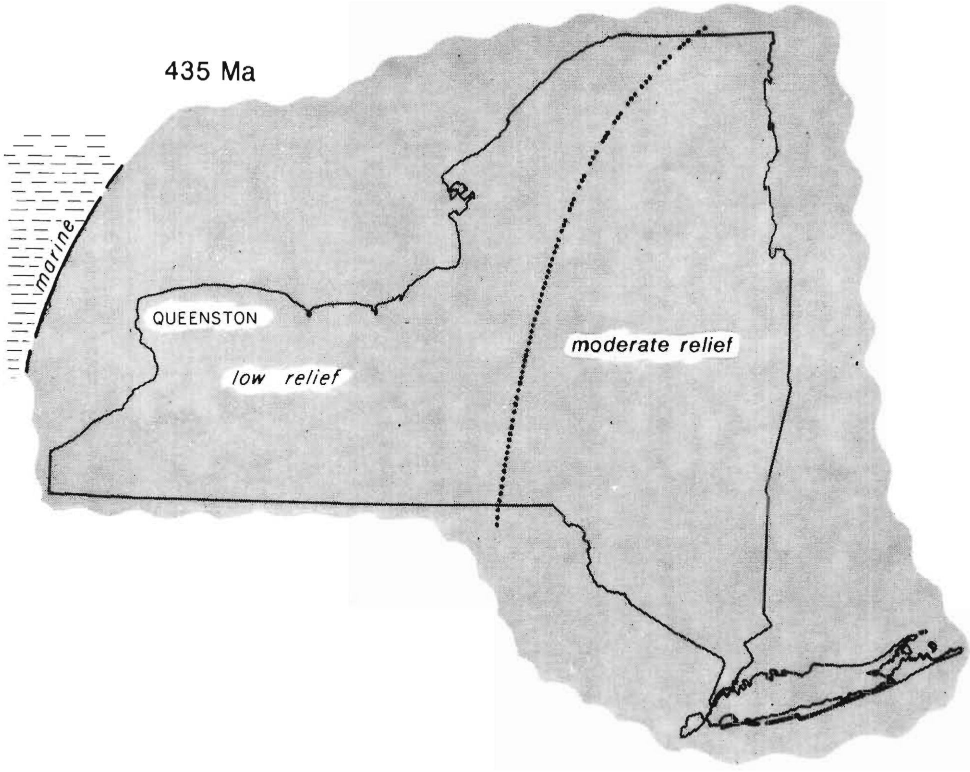
Rocks of Package Three: Silurian Time

There was a great change in animal life between the Ordovician and the Silurian. Many animals that thrived in the Ordovician became extinct.

There are few places in the world with a continuous rock record from the Ordovician into the Silurian. New York State is no exception. Silurian rocks lie on top of Ordovician shale, and there is an unconformity between them. In some places, rocks formed from an Early Silurian delta lie on top of rocks formed from the Late Ordovician Queenston Delta. They look very much alike, and it's hard to recognize the unconformity between the two.

Silurian rocks in the northern lowlands are exposed only in the Ontario Lowlands (Columns 1, 2, and 3 on Plate 3; they are described in Tables 7.5, 7.6, and 7.7). They run in a wide band that extends east from Niagara Falls. This band narrows down to nothing east of Canajoharie. To the south they slope gently beneath the great mass of Devonian rocks exposed on the Allegheny Plateau (see Figure 1.1).

Devonian layers rest on top of Silurian rocks everywhere in New York State except in Albany and Greene Counties and at places in Columbia County. There, the Devonian layers rest on Middle Ordovician or older rocks. Underground in south central New York, the Sil-



(C) This apron of fine-grained sediment spreads across the shelf area as the Queenston Delta.

urian rocks reach their maximum thickness—610 m. They are the thinnest Lower Paleozoic rocks found in New York State.

The Silurian rocks represent a short interval of geologic time—a mere 30 million years. Though the Silurian Period is the shortest in the Paleozoic Era, it has a very varied history. Sediments were deposited in ever-changing environments on land and near the shore. As the Silurian progressed, there was more limestone and dolostone and less sandstone, siltstone, and shale.

The dramatic mountain-building of the Ordovician was over. Even so, Silurian sediments and fossils tell intriguing stories.

The Sedimentary Record

Silurian rocks were formed in a variety of environments. In fact, there were more different environments in the northern lowlands during Silurian time than at any other time in New York's history. Red sandstones and siltstones and some green and red shales were deposited on the land near the ocean. Ripple-marked and cross-bedded sandstones and conglomerates were formed on the beach. They also formed just offshore in shallow water where the sediments were disturbed by waves. Silts and muds with mud cracks and marks left by burrowing creatures accumulated on the flats between high and low tide. Limestones, fossil hashes, lime mudstones, and shales accumulated in the sea below low tide.

As we mentioned above, there is no rock record from the end of the Ordovician through the earliest part of the Silurian in most of the world. We think that this unconformity was formed because these regions lay above sea level.

The oldest of New York's Silurian rocks make up the Medina Group. These rock units are represented by reddish purple on the geologic map (Plate 2) and Columns 1 and 2 of the legend (Plate 3); they are described in Table 7.5. Early in the Silurian, an inland sea spread a thin layer of clean white quartz sand across the western part of the State (Whirlpool Sandstone). The sand was deposited as dunes and beaches on the shore of the sea by wind and water. The sea advanced from west to east. It finally reached as far east as Medina. There are beautiful exposures of these sandstones in Niagara Gorge. The white sand was later covered by a layer of mud (Power Glen Formation). Still later, the mud was covered by red, green, and mottled sandstone, siltstone, and shale (Grimsby Formation).

The red and green sediments of the Grimsby Formation may have been part of a delta. There are many clues that they were deposited in shallow, turbulent water. The rocks contain ripple marks, cross-bedding, mud cracks (Figure 7.11), and conglomerate. There are also fossils of common beach-dwelling animals—clams, snails, and worms. Above the Grimsby Formation, a relatively uniform layer of white quartz sand was deposited. This sand (now sandstone of the Thorold and Kodak Formations) extends from Hamilton, Ontario, to Oneida County.

We know little about life in these Early Silurian seas. The most common animals were worm-like creatures that dug horizontal burrows and a smooth brachiopod called *Lingula*. We have also found fossils of clams, snails, ostracodes, and an occasional nautiloid (see Figure A.3).

Above the Medina Group is a beach deposit of quartz pebbles, which have been cemented into conglomerate. This conglomerate shows us that the beach of the shallow Silurian sea was beginning to advance eastward again.

This conglomerate is the oldest layer in the Clinton Group, a key rock interval that contains a wide variety of environments. In fact, geologists have had to divide the Clinton Group into 26 separate rock units. The rocks represent time of the Early Silurian. They are represented by pink with red stripes on Plates 2 and 3; they are described in Table 7.6.

Some of the units in the Clinton Group have a spectacular number and variety of fossils. They probably formed in warm, clear, shallow seas. Other units have only a few fossils. One black shale unit appears to have been deposited in a foul, almost lifeless setting with little oxygen. One shale unit with many fossils lies underneath a limestone layer with no fossils.

We find thin but widespread layers of limestone on top of some major unconformities in the Clinton Group. These limestone layers are especially noteworthy. They contain many fossils as well as *hematite*, a kind of red iron ore.

The hematite probably formed in depressions on the shallow sea floor. Another kind of iron ore, called *siderite*, formed in slightly deeper water. Both types of ore are important to us in our study of Paleozoic rocks. Where sea level fell and the water became shallower, we find hematite. Where sea level was raised and the water became deeper, we find siderite. Thus, these two differ-

Figure 7.11. The sediment-filled mud cracks in this rock indicate that it was deposited in very shallow water and was exposed from time to time and dried in the open air. (Rosendale Dolostone Member of the Rondout Formation, near Kingston, Ulster County.)

ent kinds of iron ore serve as markers that help us figure out when the seas advanced and retreated.

Hematite iron ore has been used since the end of the 1700s. It was first mined to make iron, then used for red paint pigment. These deposits of iron ore supported the steel towns of the past, such as Troy and Buffalo, before huge ore deposits were discovered in Minnesota. They extend south through the Appalachian Basin to Alabama. There, they are much thicker and are still mined for iron ore. (For more information, see the section on metals in Chapter 15.)

Sediments in the Clinton Group were eroded from a source in the east. How do we know? Water can carry large particles only a short distance. The smaller the particle, the farther it can be carried. Thus, sediments are generally coarsest and thickest close to their source. The Clinton rocks are coarsest and thickest in the east. Fossils give us another clue. As we move from west to east the fossils change from deeper water animals (brachiopods and bryozoans; see Figure A.3) to shallower water animals (clams). Even farther east, we find beach deposits with few fossils.

The environments in the lower part of the Clinton Group teemed with life. The tops of some shale layers are so crowded with broken brachiopod shells that they are called "pearly layers." In one limestone, another kind of brachiopod is as crowded as oysters in modern commercial oyster beds (Figure 7.12). Mats of bryozoans cover the tops of other limestone layers.

The middle part of the Clinton Group contains fewer fossils with less variety. These rocks are found only in the eastern part of the northern lowlands, between Herkimer and Oswego Counties. They may never have been deposited farther west. It is also possible that they were deposited there and have since been eroded away.

In central New York, the middle Clinton Group rocks include green and gray sandstone and siltstone that formed in the sea. These rocks alternate with layers of shale. Farther east, we find red sandstone and siltstone with quartz pebbles. They formed close to shore and alternate with layers of green shale. The most numerous fossils are ostracodes, clams, and brachiopods (see Figure A.3).

In the upper part of the Clinton Group, we find a layer of black shale. Poor circulation produced an environment that had little oxygen. It contained a great deal of iron and was poisoned by hydrogen sulfide. Few animals could survive in this foul setting. Bottom-crawlers avoided it. Swimmers ventured into it only rarely, and then probably by accident. Certain floating animals, on the other hand, lived in the more normally oxygenated surface waters. When they died, they settled into the black ooze on the bottom. Thus, only a few fossils are found in this shale.

However, the fossils we do find there are very important. A particular kind of graptolite (see Figure A.3) is found both here and in the Silurian rocks of Europe. Using the graptolite fossils, we can match up this shale with European layers of the same age.

This shale was formed from a layer of black mud that accumulated in deep water. The sedimentary layers below it formed before the water deepened. The layers above it were formed as the water again became shallower.

This inhospitable environment ended as abruptly as it had begun. A layer of limestone lies on top of the shale. It formed in shallow seas that were warm and clear. There were small reefs built by algae and bryozoans. Abundant brachiopods and trilobites occurred with them. Masses of broken crinoids piled up between the reefs (see Figure A.3). The area had returned to more normal conditions.

On top of that limestone is a layer called the Rochester Shale. It is made of alternating layers of limestone and calcareous[9] shale. It contains more fossils than any other Silurian formation. In fact, of all the rocks in New York State, only two Middle Devonian units contain a greater number and variety of fossils.

The types of animals that appear in the lower Clinton Group reach their peak of diversity and abundance in the Rochester Shale. There are over 200 species, including 84 species of bryozoans. We find many ostracodes, some of them elaborately ornamented. There were hosts of stalked echinoderms[10]—cystoids, blastoids, and crinoids—and even larger numbers of brachiopods. Although trilobites were on the decline through the Silurian, the surviving families were still important. The *tentaculitids*, a group of tiny, cone-shaped, ringed shells, became important. Corals, snails, clams, and nautiloids, though less abundant, also continued to evolve and were abundant. (See Figure A.3 for drawings of many of these types of animals.)

As we move east along the outcrop of the Rochester Shale, it gradually changes into a sandstone unit (Herkimer Sandstone). This sandstone contains ripple marks and mud cracks. It was formed in shallow water and on beaches. In it, we find fossils of clams and brachiopods as well as the trails left by worms and trilobites (see Figure A.3). These fossils are typical of shoreline deposits.

In western New York, a thin layer of limestone lies on top of the Rochester Shale. It lacks fossils. It does, however, contain some areas of contorted sediments. We don't know what caused these areas. It is possible that they were caused by living things.

There is an extreme contrast between this apparently lifeless limestone and the fertile Rochester Shale. This contrast is puzzling. Why did life disappear in this area?

[9] *Calcareous* means partly composed of calcium carbonate.
[10] *Stalked echinoderms* are echinoderms that grow attached to a solid sea bottom by a stalk.

Figure 7.12. Abundant specimens of the brachiopod *Pentamerus oblongus* Sowerby found in the Wolcott Limestone, Clinton Group, Wayne County.

Did the sea became much more salty? Did the temperature change drastically? Either or both of these things may have happened. We don't know.

Whatever brought on these lifeless conditions, they did not continue long. The overlying rock layers, also limestones, are called the Lockport Group. They are represented by pink with blue stripes on Plates 2 and 3 and are described in the lower part of Table 7.7.

The lower Lockport was formed in warm, clear, shallow waters. These seas sustained a variety of animals. There were reefs, built mainly by corals.[11] Honeycomb corals, chain corals (Figure 7.13), tube corals, and solitary horn corals were all present (see Figure A.3). There were also some reef-building bryozoans (see Figure A.3), but they were not as important as the corals. Around the reefs, we find the broken remains of many crinoids. These crinoid fragments were scattered there by waves that pounded the ancient reefs.

Fossils are rare higher up in the Lockport. Either living conditions were unfavorable, or the fossils were destroyed after the rocks were formed. The few that we do find are mostly mollusks[12]. Snails are the most common. We also find nautiloids (see Figure A.3) and clams.

Thousands of people gaze at the Lockport Group each day as they admire Niagara Falls and the Niagara Gorge. This tough carbonate rock forms the Niagara Escarpment. The cliff faces north and extends east from Hamilton, Ontario, to Medina. We can see the Lockport Group, especially the lower part, for almost this entire distance. Both above and below the earth's surface, the Lockport Group is consistently about 60 m thick.

The rocks in the Niagara Gorge are the *reference section* for the Early Silurian in eastern North America. This term means that the Niagara Gorge rocks serve as a standard for Early Silurian time. Scientists try to match up Early Silurian rocks from other areas with units of the same age in the Niagara Gorge. This procedure allows us to tell where they fit in the history of the period.

The Lockport Group is a gold mine to mineral collectors. The corals had cavities between them, which became open spaces in the rock. Minerals like quartz, calcite, gypsum, dolomite, sphalerite, galena, pyrite, and fluorite formed in many of these open spaces. None of these minerals is commercially important; the rock is used widely for crushed stone.

After the Lockport Group was deposited, there was a

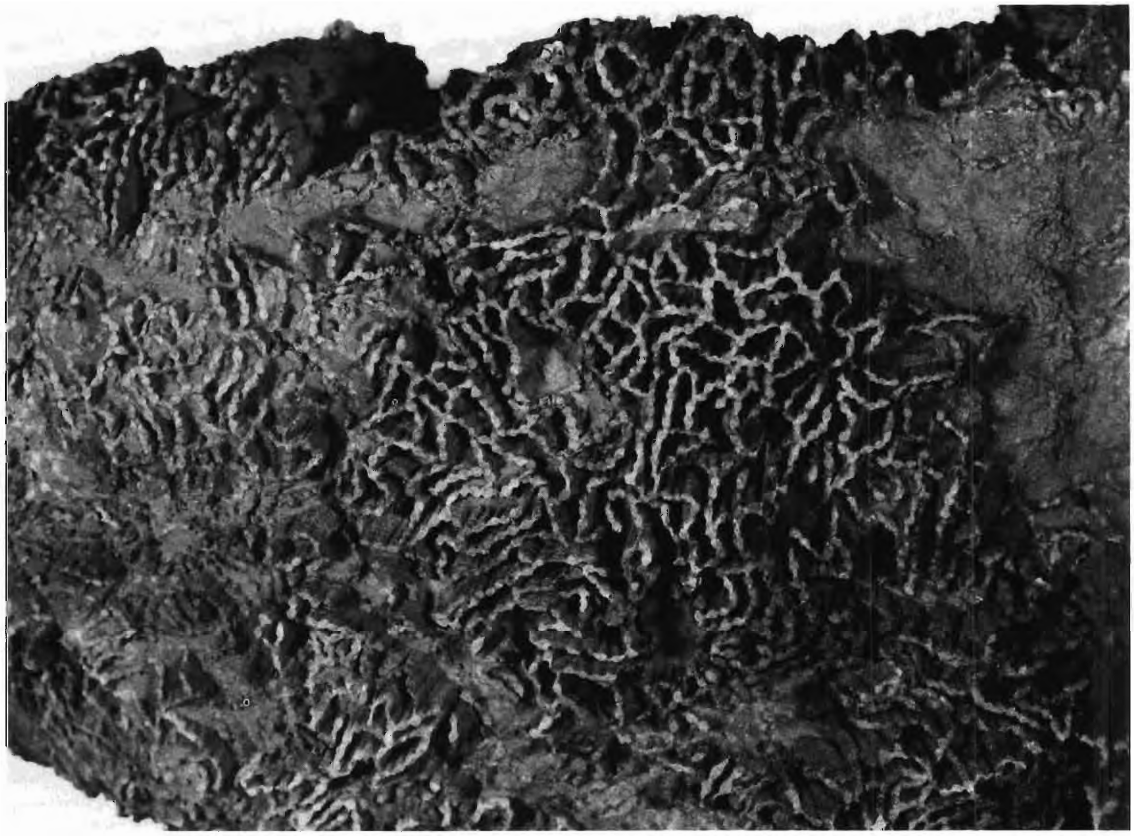


Figure 7.13. The chain coral *Cystihalysites*. (Found in the Glasco Limestone Member of the Roundout Formation near Kingston, Ulster County.)

[11]This situation contrasts with earlier rocks, which contain reefs built by algae and bryozoans.
[12]*Mollusks* have a soft body and a hard shell. Some examples are snails, clams, and squids.

change in the kind of sediments that form the Silurian rocks. Earlier in the Silurian, most of the sediments eroded from the land were quartz sand. Later on, however, sand becomes scarce. Instead, we find finer sediments, like silt and clay. Why did this change occur?

Maybe there was a change in the landmass being eroded. If erosion completely removed a quartz sand layer, new sediments would come from the layers underneath. If the underlying layers were made of clay-rich sediments (shale and siltstone), we would see finer sediments being deposited.

That is one possibility. However, there is another, more likely explanation. The energy of waves and currents in the water helps determine what kind of sediments are deposited. Higher energy waves and currents can carry fine sediments, like silt and clay, a long distance. Therefore, coarser sediments, like sand, settle out quickly and are deposited near the source. On the other hand, even fine sediments will settle out in low energy environments. In these places, we find silt and clay deposited as well.

We think that the rock in the northern lowlands region represents low energy water conditions in the Late Silurian. Thus, finer grained sediments were deposited in the region. There is another fact that supports this idea. Much more sediment piled up during Late Silurian time than in the earlier part of the period. This situation is what we would expect from lower energy conditions. The marine water would deposit all of the sediments it was transporting, not just the coarser ones. Thus, they formed thicker deposits.

Above the Lockport Group is a thick sequence of dolostones, shales, and evaporites[13] called the Salina Group. It is represented by solid pink on Plates 2 and 3 and is described in the middle part of Table 7.7. These rocks were probably deposited in very shallow water, on tidal flats, or just above high tide. The Salina Group dates from the Late Silurian.

In east central New York, the lower part of the Salina Group contains red and green silty shale. As we move westward, it gradually turns into gray shale, dolostone, and evaporites. The red shale was deposited near the seashore. The gray shale accumulated in a shallow sea. There are several units of rock salt (*halite*, an evaporite) as much as 3 or 4 m thick.

In the middle part of the Salina Group, we find gray or green shale and dolostone with very few fossils. Layers of halite as thick as 30 m alternate with layers of dolostone and shale. Salt from this formation has been used for hundreds, perhaps thousands, of years.

Native Americans first discovered salt springs where water ran through the salt layers. By the 1800s, a thriving salt industry was vital to the local economy. The mine at Retsof is still one of the largest producers of rock salt in the world.

Other evaporite minerals are also mined. In western New York, the mineral gypsum is extracted from layers of anhydrite that alternate with layers of Silurian shale. (*Anhydrite*, chemical composition $CaSO_4$, is a mineral that turns into gypsum when it is exposed to water.)

The salt layers in these rocks could not have formed in the open sea. The sea contains enough water to keep the salt dissolved. Circulation must have been restricted. Perhaps a major barrier cut one area off from the rest of the sea. The water left behind would start to evaporate. The pool would become saltier and saltier. Eventually, enough water would evaporate and rock salt and gypsum would be deposited.

Even in very salty water, like today's Great Salt Lake or Dead Sea, some animal life endures and thrives. The highly salty Silurian seas also had inhabitants. These inhabitants included the *eurypterids*, one of which is now the New York State fossil (Figure 7.14). Some New York rocks contain many well-preserved eurypterids. These extinct scorpion-like animals grew to lengths of 2.5 m.

Some other creatures were also able to endure the very salty seas. They included species of scorpions, ostracodes, brachiopods, a few snails, small clams, and worms (see Figure A.3).

However, most of the animals from this time lived in normal sea water. Their fossils appear only in a few rock layers formed when the saltiness was less. When enough fresh water flowed into the sea, the saltiness went down and these animals thrived.

When water evaporated faster than sea water of normal salinity flowed in, the sea became concentrated and highly salty. Deposits of rock salt, shale, and dolostone continued to form in highly salty seas nearly to the end of the Silurian Period.

Late in Silurian time, water circulation improved dramatically. These new conditions were recorded in the rocks described in the top part of Table 7.7. A land barrier in the southeast had worn down enough to let in much more normal sea water. Brachiopods, corals, bryozoans, and ornamented ostracodes multiplied (see Figure A.3). Their remains piled up as lime muds and reef carbonates.

In very latest Silurian and earliest Devonian time, another inhospitable environment appeared. Dolostones, rich in clay but containing few fossils, were deposited over much of New York.

[13]*Evaporites* are sedimentary rocks made of mineral salts that were dissolved in water. As the water evaporates, the evaporites form.

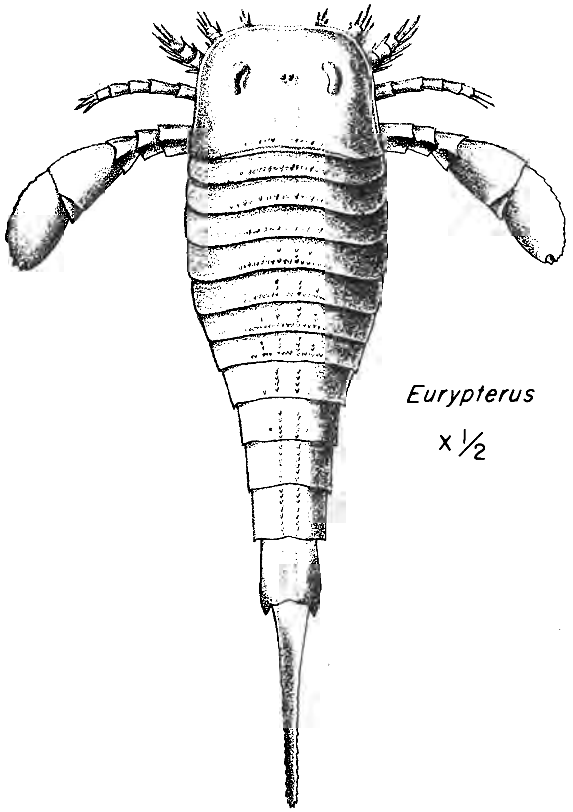


Figure 7.14. *Eurypterus remipes* Dekay, a eurypterid that lived in New York during the Late Silurian. *Eurypterus remipes* is the New York State fossil.

Interpretations

Shallow seas covered New York's northern lowlands region throughout much of Silurian time. At the beginning of the Silurian Period, about 438 million years ago, most of New York was near sea level. Much of the State was covered by red mud flats. In the eastern highlands, erosion broke down the ancestral Taconic Mountains into sand and mud. These sediments were redeposited in the western part of the State.

Early in Silurian time, a sea advanced eastward as far as Medina, then shrank westward again until it lay past the border of the State. Several million years later, the sea once more moved eastward, this time as far as Oneida and Utica. Sands, silts, and muds accumulated on deltas, beaches, and tidal flats early in Silurian time. As the water deepened, these sediments eventually gave way to carbonates—limestones and dolostones.

Near the end of Silurian time, poor circulation and evaporation produced large, very salty pools and tidal flats. Eurypterids thrived and layers of salt accumulated.

What geologic events were happening during the Silurian Period?

The Taconian Orogeny was over by the beginning of the Silurian Period. The island arc was securely welded to proto-North America. The ancestral Taconic Mountains had been quite thoroughly eroded. Some tectonic activity continued far to the east of New York, along the plate boundary.

New York State itself was a quiet sea basin, much like the shallow ocean that lies between Australia and New Guinea today.

What caused the sea to move back and forth throughout Silurian time? We don't know for certain. The shoreline was bent very gently up and down. This bending may have been related to the movements of plates to the east.

The Northern Lowlands Fossil Record: Cambrian, Ordovician, and Silurian

Invertebrate organisms dominated the seas in the Cambrian, Ordovician, and Silurian Periods. Fish—the first vertebrates—had appeared in the Late Cambrian. By the end of the Silurian, they had become relatively abundant.

In Lower Paleozoic rocks, we find fossils of many marine creatures. There were brachiopods, clams, worms, snails, trilobites, corals, bryozoans, nautiloids, graptolites, echinoderms, tentaculitids, and ostracodes (see Figure A.3).

The evolution of life took many important steps in the Cambrian, Ordovician, and Silurian Periods. Many of these steps are reflected in the rocks of the northern lowlands. Here, we will mention only a few of the most important discoveries based on that rock record.

During the Middle Ordovician, a host of new creatures appeared in the seas. A new invertebrate group, the bryozoans, was important. So were the coral-like sponges known as stromatoporoids. True corals also appeared in this period. The oldest known coral reef in the world is found in Lake Champlain.

One Silurian shale contains more than 200 different species—a remarkable variety. Other Silurian rocks contain hosts of ostracodes and stalked echinoderms and even larger numbers of brachiopods. In the Silurian, trilobites were on the decline, but still important. Tentaculitids were common in Silurian communities. Corals, snails, clams, and nautiloids evolved and were diverse and abundant in the shallow waters. This large variety of invertebrates lived in the seas and competed for food and survival.

With such intense competition, it is hardly surprising that life began to move into a different environment at this time. Air-breathing arthropods (insects, spiders, etc.) began to evolve. They eventually colonized the land in the Late Silurian.

Upper Silurian rocks are of particular interest to paleontologists. They tell the story of a great evolutionary advance—the development of the fish. In the Silurian, a number of more modern kinds of fish developed. For example, armor-skinned fish (or *placoderms*) are found in rocks from the Late Silurian. They continued to thrive into the Devonian. In fact, the Devonian is sometimes called "The Age of Fishes."

New York's Early Devonian fossils are very different from the Late Silurian fossils. Animal life changed significantly over a short period of time. These changes happened at least partly because animals were adapting to changes in the environment.

Land plants had appeared by the end of the Silurian; their record may extend as far back as the Late Ordovician.

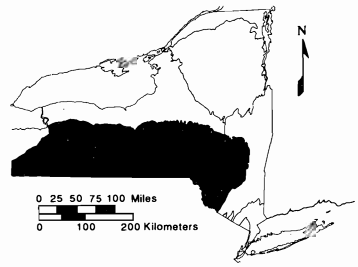
Review Questions and Exercises

Most of the bedrock in this region is which type—igneous, sedimentary, or metamorphic?

The bedrock in this region can be divided up into three "packages." What separates these packages? What kinds of environments do they represent? What was happening in geologic history at those times? How did those events affect the environments in which the rocks were formed?

Chapter 8
Oldest Forests and Deep Seas

Erie Lowlands and Allegheny Plateau[1]



Summary

The bedrock of the Erie Lowlands-Allegheny Plateau region consists of flat-lying layers of sedimentary rock. This rock records the history of the region during the Late Silurian and Devonian. The rocks of the Upper Silurian (dolostones, evaporites, and shales) and the limestones and shales of the Helderberg Group are the oldest part of this record. From them, we learn that a warm, shallow sea covered most of New York at the beginning of the Early Devonian. We can reconstruct a number of major depositional environments from the variety of rock found in these formations. Above this interval dominated by carbonate rock, we find an unconformity that records the retreat of the sea from the area and the erosion of the exposed Helderberg Group. The Tristates Group records the sea's return, clear water at first, and later muddy. At the end of the Early Devonian, erosion removed almost all of the Tristates Group from western New York. The Onondaga Limestone, which forms the lower Middle Devonian, tells us of a widespread shallow sea with coral reefs and a great variety of bottom-dwelling animals. The Tioga ash beds within the upper Onondaga are clues to volcanic eruptions far to the southeast. The ashes are a sign that an episode of mountain-building was beginning. The next Middle Devonian rocks are those of the Hamilton Group. These rocks record a massive influx of mud and sand that were eroded from a new mountain range to the east during the early part of the Acadian Orogeny. The Tully Limestone above the Hamilton Group marks a pause in this great influx of sediment. An unconformity in the middle of the Tully emphasizes this pause. The Late Devonian began with a renewed influx of mud, sand, and gravel from the east, which continued until the end of the period. This influx was the result of the continuing Acadian Orogeny. Within the Genesee, Sonyea, West Falls, Canadaway, Conneaut, and Conawango Groups, we find a number of major varieties of rock that record different depositional environments. These settings range from the piedmont in the east to the floor of the sea basin in western New York. Their distribution shows how the shoreline and related environments advanced haltingly across the State as a huge sedimentary apron. This apron, called the "Catskill Delta" complex, grew westward and crowded the sea out of the region.

Description of the Erie Lowlands and Allegheny Plateau

The Erie Lowlands is the low, flat area southeast of Lake Erie. (See Figure 1.1 and the Physiographic Map on Plate 4 of the *Geological Highway Map*.) To the south, the land rises gently from lake level (175 m above sea level) to the Portage Escarpment (300 to 460 m above sea level). Sandstone layers form this *escarpment*, or cliff, because they resist erosion better than the layers above and below them. The escarpment is the boundary between the lowlands and the Allegheny Plateau to the south.

The southern half of New York State (west of the Hudson River and south of the Mohawk River and Erie Canal) is part of the Allegheny Plateau. (See Figure 1.1 and the Physiographic Map on Plate 4.) Sandstone and shale layers of Middle and Late Devonian age form the

[1]Adapted from a manuscript by L.V. Rickard.

bedrock here. They are part of the "Catskill Delta" complex and were deposited in marine waters that ranged from a deep basin to near sea level during the Acadian Orogeny. (See Chapter 3 for more information.) Millions of years later, these layers of rock were uplifted to their present height well above sea level. They were tilted only slightly by the uplift. After the uplift, erosion carved the plateau into the hilly upland we see today.

The Shawangunk Mountains form the southeastern border of the Allegheny Plateau in New York. These mountains form a steep ridge, called a *hogback*, that runs from Kingston southwest to Port Jervis. (See the Physiographic Map on Plate 4.) This ridge is made of the Shawangunk Conglomerate, which dips toward the northwest. The conglomerate resists erosion strongly because it is nearly pure quartz. It is made of quartz sand and pebbles held together by quartz cement.

The eastern and northeastern border of the Plateau is the Helderberg Escarpment. (See the Physiographic Map on Plate 4.) The limestones of the Helderberg Group, which resist erosion better than the layers above and below them, form this escarpment.

The Allegheny Plateau is relatively high and rugged. The highest points are in the Catskill Mountains, where the Wall-of-Manitou rises 915 m above the Helderbergs and 1130 m above the Hudson Lowlands. The highest peak is Slide Mountain—1282 m above sea level.

This region was once low and flat. It had been eroded to a nearly flat plain by the middle of the Cenozoic. Then, this surface was uplifted to form the Allegheny Plateau. Streams flowing across the plain began to carve it into the hilly terrain we see today. The western part of the region was carved into ridges. The eastern part was higher after uplift, and stream erosion carved away all of the rock except the high peaks of the Catskill Mountains.

The Catskills' highest peaks all have about the same elevation. How did this situation come about? *Geomorphologists* (geologists who study landforms and the processes that produce them) have proposed two explanations. Some say that the tops of the present mountains were once part of the flat surface of the plain before it was uplifted. Following regional uplift and erosion, parts of this plain still remain uneroded between the stream and river valleys. Therefore, the mountain tops wound up at the same height. The second, more recent explanation is that the Catskill high peaks are all formed of rock that is more resistant to erosion that the underlying rock. The peaks have been eroded, but they have all worn down at the same rate. Therefore, they continue to have very similar heights.

Most of the streams in the region flow southwest into the Allegheny, Susquehanna, and Delaware Rivers. The exceptions are Cattaraugus Creek, which flow west; the Genesee River, the Finger Lakes, and Schoharie Creek and others of the Mohawk River drainage, which flow north; and Catskill Creek and other, small streams along the edge of the Catskills, which flow east (see Figure 11.1B).

The Finger Lakes occupy troughs that are cut into the northern edge of the region. During the Pleistocene Epoch, huge ice sheets advanced across New York State many times. The ice widened and deepened former river valleys to make the Finger Lake troughs. In fact, the ice dug two of the lakes, Cayuga and Seneca, so deep that their bedrock floors now lie below sea level.

The Pleistocene glaciers picked up and carried along huge amounts of mud, sand, gravel, and boulders. When they melted, they left this rock debris behind. Such glacial deposits are 180 to 300 m thick in the valleys of the Schoharie Creek, the Finger Lakes, the Genesee River, Chautauqua Lake, and Cassadaga and Conewango Creeks (see Figure 11.1B). Elsewhere in the region, glacial deposits are rarely thicker than 15 m.

The Valley Heads Moraine (see Figure 12.3) is a long ridge south of the Finger Lakes that runs east to west. It is the major drainage divide of central New York. A *drainage divide* is a relatively high ridge that separates streams and rivers that flow in one direction from those on the other side that flow in a different direction. The streams and rivers north of the moraine flow generally north and eventually run into the Great Lakes, then into the St. Lawrence River to the Atlantic Ocean. Streams and rivers south of the moraine flow into south-flowing rivers. There is one exception—the Genesee River, which crosses the moraine.

The Valley Heads Moraine was built by the last Pleistocene ice sheet as it retreated across New York State. When the ice halted temporarily in its retreat, it built the moraine along its southern margin. A small region to the south, which is now Allegany State Park, escaped being covered by the last ice sheet.

See Chapters 12 and 13 for more information on the effects of the Pleistocene glaciers.

Rock of the Allegheny Plateau

The Devonian formations of the Allegheny Plateau represent 50 million years of history. They are the bedrock for a large portion of New York State: south of the Mohawk River and Barge Canal and west of the Hudson River (Figure 8.1). This rock contains remarkable

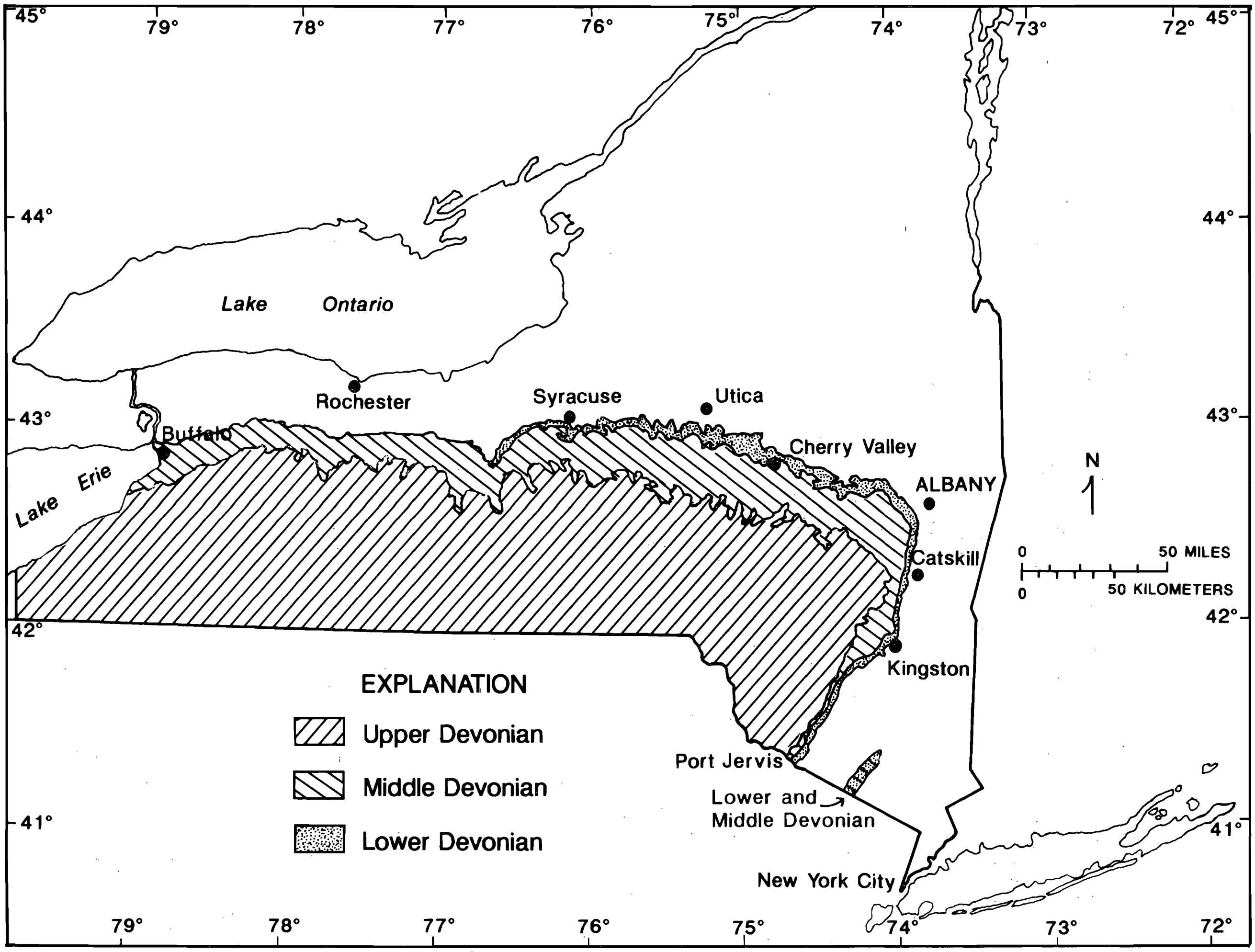


Figure 8.1. Outcrop map of the Lower, Middle, and Upper Devonian rock units in New York State. Notice that the Lower Devonian formations do not extend into the western part of the State. An unconformity cuts across these formations, as you can see on Plate 3. Erosion removed the Lower Devonian units from western New York before sediment was deposited there in Middle Devonian time.

and abundant fossil remains. Among the fossils are some of the earth's first forests, some fearsome fish, and many brachiopods[2] and other invertebrate animals. The first air-breathing fish, from which all other vertebrates have evolved, appeared during the Devonian. However, we have not yet found their remains in New York.

Layers of Lower Devonian rock *crop out* (that is, appear at the land surface) in the eastern part of the Allegheny Plateau from just east of the Hudson River to Cayuga Lake. (The Helderberg and Tristates Groups are Lower Devonian; Plate 3 gives you a more detailed picture of where they are.) Middle Devonian rock makes up most of the Catskill Mountains and extends west to Lake Erie. We find some Upper Devonian units high in the central Catskills, but most Upper Devonian rocks are found in the south-central and western parts of the State. The youngest Devonian rocks in New York are found in the western part of the State along the Pennsylvania border. (See Figure 8.1 and Plate 3.)

Rock of Early, Middle, and Late Devonian age crops out in belts that run east to west across central and western parts of the State The oldest belt is in the north and the youngest in the south (Figure 8.1). This pattern arises because the layers dip gently southward. As the erosion surface of the land intersects the gently tilted layers, it creates the east-west belts shown on the geologic map (Plate 2).

The Devonian rock is about 2450 m thick near the eastern edge of the Catskill Mountains. It gradually decreases to about 1000 m thick near Lake Erie. The Devonian

[2]See Figure A.3 for drawings of brachiopods.

section is thickest in southeast New York, where it is more than 3,050 m thick.

Much of the rock in the Catskill Mountains was deposited by rivers near sea level rather than by sea water. This rock commonly has reddish and greenish colors. The remains of land plants, a few clams, and rare mites, ticks, and spiders are the only fossils in this part of the section. In the rest of New York, most of the Devonian beds were deposited in a *marine* (or sea) environment. They are remarkable for the fossils they contain. The fossils are abundant, well preserved, and represent many different kinds of living things.

The Devonian sequence contains many different kinds of sedimentary rock in a complicated arrangement. (You can get an idea of how complicated by looking at Plate 3. The Devonian rock is represented by various shades of green.) This complex rock record reflects a complex history.

Early Devonian History

About 410 million years ago, at the beginning of the Devonian Period, a shallow sea covered much of New York. Indeed, most of the eastern edge of proto-North America came to be flooded by sea water. This sea lay in the *Appalachian Basin* (Figure 8.2). From the Late Ordovician through Middle Silurian, marine waters were limited to the western and central parts of New York. Their record can be seen, for example, in the rocks that form the Niagara Escarpment (see Chapter 7). The shoreline of this sea began to move eastward and reached the Helderberg Mountains in the very Late Silurian. The shoreline crossed the area of the modern Hudson River and eventually extended east to the edge of the continent during the Early Devonian. These sea waters merged with the nearshore waters that formed the eastern edge of the Iapetus Ocean. Later, in the Middle Devonian, the sea expanded west to cover some of the central parts of the continent as well.

We reconstruct the history of the Early Devonian from evidence in the oldest Devonian rock. The earliest Devonian rock is a limestone and shale unit called the *Helderberg Group*. It appears at the surface in eastern and southeastern New York, where it reaches a thickness of 135 m. It can be seen especially well in the impressive cliffs along the north and east edges of the Helderberg Mountains southwest of Albany. These cliffs, called the *Helderberg Escarpment*, run from Albany west to Auburn. They form the northern boundary of the Allegheny Plateau in this area and overlie uppermost Silurian strata (Figures 8.3 and 8.4).

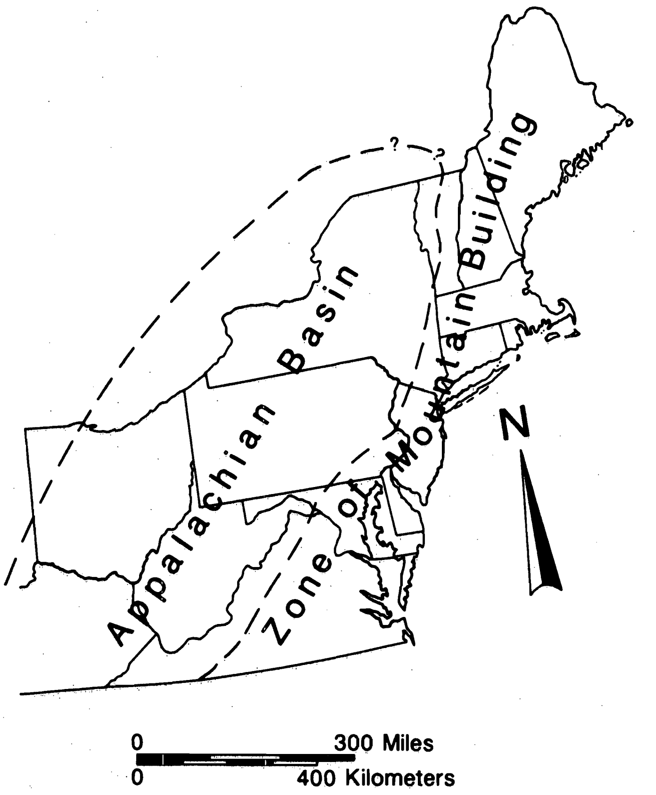


Figure 8.2. Map of the northern part of the Appalachian Basin during Middle and Late Devonian time. Sediment eroded from the mountains on the east was deposited in the Basin as the "Catskill Delta." (See Figure 8.14 for the location of these deposits.)

Early Devonian sedimentary rock probably once covered northeastern New York, but erosion has removed it from this region. Early Devonian rock occurs at great depths in southern New York State, where it is buried by younger deposits.

The Helderberg Group includes many types of limestones. They were deposited in a shallow sea surrounded by a low, flat landscape. How do we know what the landscape was like? Highlands tend to erode quickly and produce large amounts of mud, sand, and gravel. We don't find much of this kind of sediment in the Helderberg limestones, so we conclude that there were no highlands nearby. In other words, the landscape was low and flat.

The sea in the Appalachian Basin began to deepen in the Late Silurian; as a result, its eastern shoreline moved farther east, and its western shoreline moved farther west. This movement of the shorelines continued in the Early Devonian. As the sea very slowly spread over the land, it deposited the calcareous sediments[3] that later became an important part of the Helderberg Group.

[3]*Calcareous sediments* are composed of calcium carbonate (chemical composition $CaCO_3$) and often made up largely from the hard parts of animals and plants—for example, shells. Limestone, a kind of *carbonate rock*, is formed from calcareous sediments.

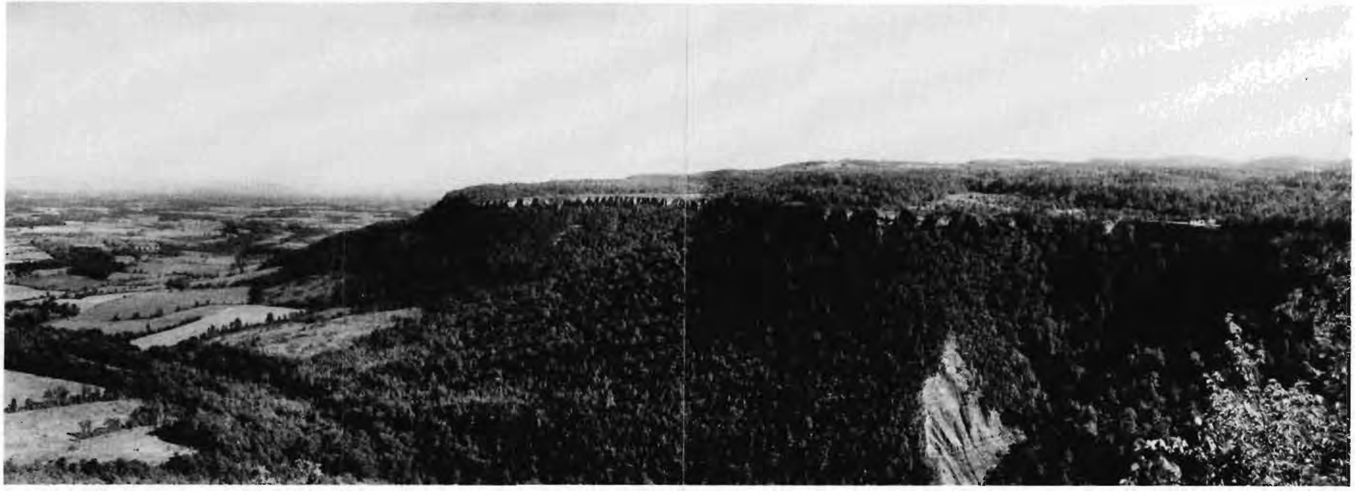


Figure 8.3. The Helderberg Escarpment in John Boyd Thacher State Park, southwest of Albany in Albany County. Lower Devonian limestones of the Helderberg Group form the cliff. They lie on top of Middle Ordovician shales and sandstones of the Schenectady Formation.

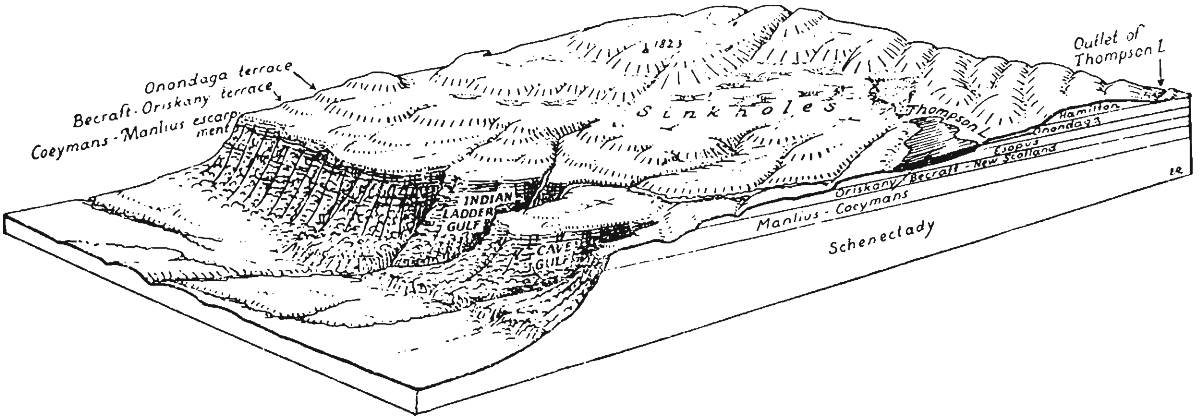


Figure 8.4. This block diagram of the Helderberg Escarpment shows the relationship between the bedrock units and the land surface. The escarpment exists because the limestone of the Manlius and Coeymans Formations (part of the Helderberg Group) is more resistant to erosion than the sandstone and shale of the underlying Schenectady Formation. Locate the place on Plate 3 where the Helderberg Group lies directly on top of the Schenectady Formation. There is a large gap in the rock record in this area.

How do we know that the sea was deepening and its shorelines moving as the Helderberg Group was formed? The answer to that question requires a long explanation.

Each of the different types of limestone in the Helderberg Group formed in its own environment. Figure 8.5 shows the environments where these limestone layers were deposited and how they were arranged. How do we know about these environments? We look for certain clues in the rock layers.

Different types of sediments are deposited at the same time in a wide variety of sea environments. For example, fine limy[4] muds settle out in the deep, quiet water far from shore; some beaches are formed of shells along the sea shore. Wind and waves work the sediment along the shore into a variety of deposits. How do we know about all these differences? We study how sediments are deposited in modern seas.

The layers formed in different environments vary in a number of ways. They may have different colors. They may be coarser or finer grained. They may be made of

[4]*Limy* means rich in calcium carbonate (which is also called *lime*).

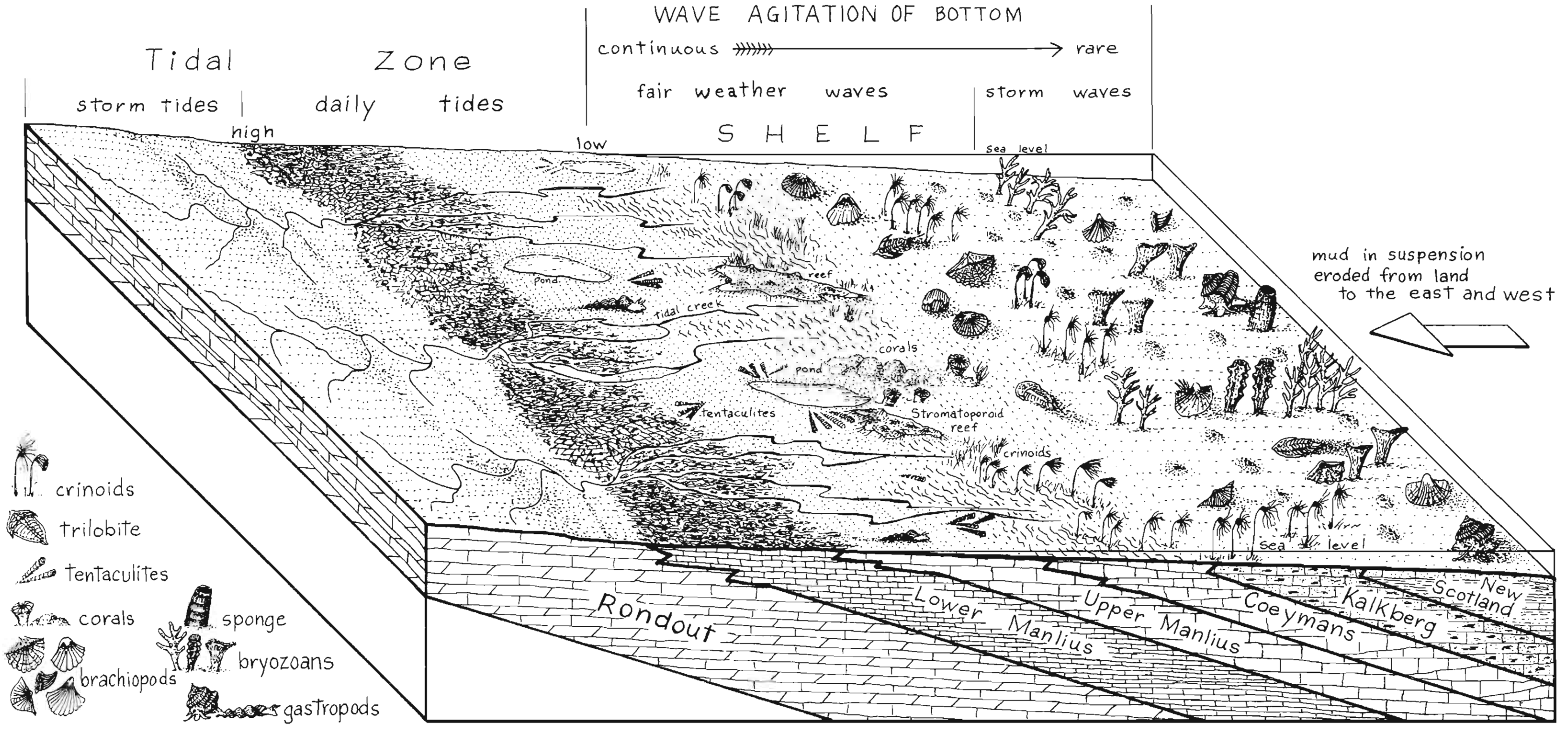


Figure 8.5. Diagram relating depositional environments to the different facies of the Helderberg Group. The water depth increases from left to right. The arrangement of the facies—Rondout through New Scotland—indicates that the depositional environments have been moving from right to left as the deposits accumulated. You can verify this fact by drawing a line through the facies below and parallel to the sea floor. This line will represent the sea floor at an earlier time. Notice that the depositional environments on that earlier sea floor were to the right of the present ones. Compare this figure with Figure 8.6.

sediment eroded from the land (mud, sand, or gravel), or sediment formed in the sea (commonly calcium carbonate), or a mixture of both. The layers may be thick or thin. The *sedimentary structures* (features formed as the sediment was deposited, such as wave or current ripples and cross-bedding (see Figure 7.1)) are different in different environments. When we study the deposits in different modern environments and compare them with layers of sedimentary rock, we often find striking similarities. When a layer of rock looks like a modern layer of sediment, the similarity can be used as evidence that both were deposited in similar environments. Therefore, we can deduce what the environment was like from the appearance of a rock layer.

The fossils in the rock also give us valuable clues to the environment. We can tell the difference between animals and plants that lived on the sea bottom and animals that swam or floated in the waters above. Many creatures that are at home near the shoreline cannot venture into deeper water. By looking at the fossils of the animals and plants that lived there, we find out more about what conditions were like.[5]

Taken together, all the features of a sedimentary deposit—the sediment, sedimentary structures, and fossils—give it a distinctive character or appearance—called its *facies*. Each facies reflects a particular *depositional environment* (that is, an environment in which sediment is deposited). Each environment has a particular water depth, sediment size, and other distinctive characteristics. Each environment is home to a distinct community of plants and animals.

You can think of a facies as the combination of features that identifies the environment of a deposit. In a similar way, a combination of facial features lets us recognize a person's face. Just as closely related people can be similar in appearance, closely related environments can produce deposits with similar facies.

Now we come back to the question of how we know that the shorelines moved and the sea deepened as the Helderberg Group was being deposited. In general, here is how we figured it out. We look at a single facies. We notice that in younger layers it is farther east and west than in the older layers. This arrangement tells us that the shorelines were gradually creeping eastward and westward over time. Then, we look at the rock at one place. We notice that the facies reflect shallower water in the older rock and deeper water in the younger rock. This arrangement tells us that the sea was gradually getting deeper through time. Because the rock of the Helderberg Group records a sea that was growing deeper and shorelines that were creeping eastward and westward, we know that it was deposited in an expanding sea.

Now let's look at the rock in a bit more detail. The Helderberg Group is a series of seven limestone-rich formations.[6] In these formations, we find five major facies; each is named for the formation where it first occurs: Lower Manlius, Upper Manlius, Coeymans, Kalkberg, and New Scotland (Figure 8.5 and 8.6). The facies are listed in Table 8.1. The environment represented by each facies is described in the last column of the table. Notice how the water gets deeper as time goes by.[7] The earliest facies shown were deposited near the shore, just above high tide or between high and low tide. Later facies were deposited in deeper environments farther offshore, first in shallow water, then in deeper.

The five facies of the Manlius, Coeymans, Kalkberg, and New Scotland Formations are partly repeated in the upper part of the Helderberg Group. The Becraft is like the Coeymans, the Alsen is like the Kalkberg, and the Port Ewen is like the New Scotland (Figure 8.6).

After the limestones of the Helderberg Group were deposited, the sea withdrew from the State and exposed the newly formed beds to erosion. How do we know? The unconformity[8] above the Helderberg Group resulted from this erosion. (The unconformity is represented by a pale yellow area on Plate 3.) The sea withdrew first from the northern and western parts of New York. Because the rock there was exposed first and longest, it had the greatest chance to be eroded. Thus, more of the early deposits were removed north of Kingston and in the western part of the State than elsewhere. At Cayuga Lake, only the oldest of the Helderberg formations remain. Farther west, we don't find any at all. Either the Helderberg formations were never deposited that far west or erosion has destroyed them completely.

Later in the Early Devonian, the sea readvanced. The sedimentary rocks formed in this sea are called the *Tristates Group*. We find the Tristates Group mainly in eastern and east-central New York, just like the Helderberg Group that lies underneath it (see Plate 3). The only formation of the Tristates Group in western New York is the Bois Blanc Limestone. It is a thin layer, rarely more than 1.2 m thick. It does not form a continuous sheet but is found in patches.

[5]We have to be careful when we interpret fossils, though. From time to time fossils don't match the environment. For example, after a shallow water animal dies, ocean currents may carry its remains into deeper water. If it became a fossil there, we would find it in an environment where it didn't live.

[6]The limestones from the Manlius, Coeymans, and Becraft Formations are used to make *portland cement*. Portland cement is made by heating a mixture of certain rocks and minerals together in a kiln. For more information, see Chapter 15.

[7]If the sequence is undisturbed, the bottom rock layer is the oldest. Therefore, this table lists the oldest formation at the bottom and the youngest at the top.

[8]When rocks are eroded and younger sediments are deposited on the eroded surface, it leaves a gap in the geologic record because some rocks have been destroyed by erosion. The surface in the rock that represents this gap is called an *unconformity*.

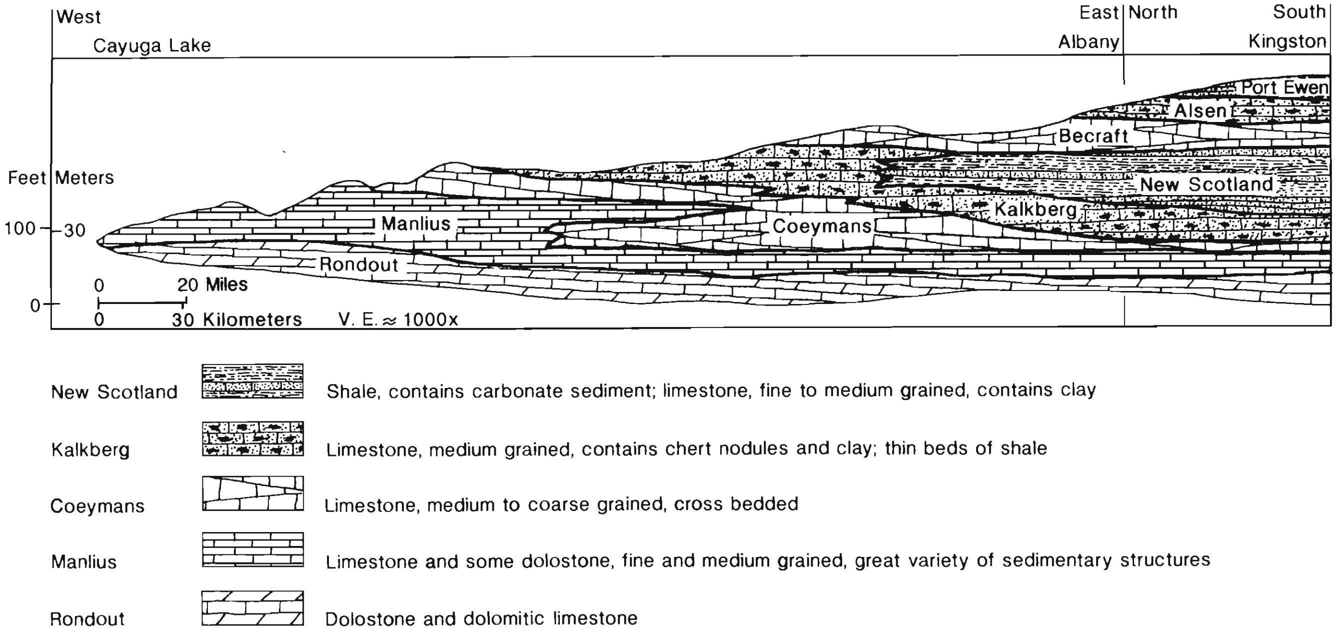


Figure 8.6. Diagrammatic cross section of Lower Devonian formations along the outcrop belt, west to east across central New York State, and north to south along the Catskill Mountain front. The arrangement of the formations shows that the depositional environments of the formations moved as the deposits accumulated. Compare with Figure 8.5. Notice that the Coeymans and Becraft Formations are made up of the same kind of rock. What does this fact suggest about their depositional environments? The Kalkberg and Alsen Formations and the New Scotland and Port Ewen Formations are paired in the same way. Notice that the vertical scale of this cross section is much larger than the horizontal scale. The vertical exaggeration is about 1000 times. We have to exaggerate the vertical dimension in drawings like this one in order to show details because the thickness of sedimentary formations is small compared to their width and length. (Note: A *diagrammatic cross section* is a cross section that is drawn to explain or illustrate a point, rather than to present a realistic picture of the appearance of the subject.)

In eastern New York, the Tristates Group is 100 m thick at Catskill and becomes thicker to the south (225 m at Port Jervis). Except in southeastern New York, there are unconformities above and below the Tristates Group.

Table 8.2 contains a description of the formations of the Tristates Group. Some of these formations strongly resemble some formations in the Helderberg Group. These similarities are indicated in the facies column on the table.

The Port Jervis Formation at the base of the group is found only near Port Jervis. The rock of this formation is similar to that of the New Scotland Formation of the Helderberg Group. Above the Port Jervis is the Glenerie limestone. To the west, the Glenerie becomes more and more sandy until it gradually becomes a sandstone. This sandstone unit is called the *Oriskany Sandstone*.

The Oriskany lies upon the eroded surface of the Helderberg Group (see Plate 3). Remember that the sea withdrew after depositing the Helderberg limestones and exposed them to erosion. The farther west we go, the longer the rock was exposed. Thus, as we move west, the Oriskany lies on top of older and older layers of the Helderberg Group.

The Oriskany Sandstone is found below the surface in south-central New York State. Although it does not appear at the surface, it is well known in this area because it produces large quantities of natural gas. The gas fills the pore spaces between the quartz sand grains in the sandstone and is trapped there by an impermeable rock layer above. People looking for oil and natural gas frequently drill down into the Oriskany Sandstone.

The Esopus, Carlisle Center, and Schoharie Formations form the bulk of the Tristates Group. The rock of these units was formed largely from sand and mud eroded from the land. These formations are as thick as 135 m and occur only in eastern and southeastern New York.

The Esopus, Carlisle Center, and Schoharie Formations are very different from the Glenerie and Oriskany formations beneath them. This abrupt change reflects a change in the environment. The water in the Appalachian Basin

Table 8.1
Helderberg Group

Formation	Facies	Rock Types, Grain Size, Sedimentary Structures	Fossils	Environments
Port Ewen	New Scotland	see New Scotland, below	see New Scotland, below	see New Scotland, below
Alsen	Kalkberg	see Kalkberg, below	see Kalkberg, below	see Kalkberg, below
Becraft	Coeymans	see Coeymans, below	see Coeymans, below	see Coeymans, below
New Scotland (Fig. 8.7)	New Scotland	fine- to medium-grained limestone that contains clay shale that contains calcium carbonate thin to medium layers of uniform thickness	high number & variety of sea bottom dwellers	deepest water of the Helderberg Sea; below motion of fair-weather waves; bottom agitated by storm waves
Kalkberg (Fig. 8.7)	Kalkberg	medium-grained limestone rich in clay & silica chert thin to medium layers	high number & variety: bryozoans brachiopods crinoids corals trilobites mollusks ostracodes	deeper water at or near lowest point reached by fair-weather waves bottom occasionally agitated
Coeymans (Fig. 8.8, 8.9)	Coeymans	clean medium- to coarse-grained limestone scattered small coral and stromatoporoid reefs uneven, medium to thick layers cross-bedding	moderate number pelmatozoans corals brachiopods mollusks trilobites ostracodes	shallow water shelf vigorous wave motion well-agitated bottom
Upper Manlius (Fig. 8.10)	Upper Manlius	fine- to medium-grained limestone slightly uneven, medium to thick layers scour & fill, birdseye, ripple marks, cross-bedding	low to moderate number & variety stromatoporoids brachiopods mollusks ostracodes trilobites	shallow water near the shore & near low tide moderate wave motion--protected by a barrier
Lower Manlius (Fig. 8.11)	Lower Manlius	fine-grained limestone & dolostone medium to thin layers; some laminations alternating layers of shale rich in carbonate sediments scour & fill, birdseye, desiccation cracks	low number & variety stromatolites oncolites ostracodes brachiopods gastropods tentaculites	between high & low tides and shallow water below low tide

Figure 8.7. In this road cut in Greene County, you can see the Kalkberg Formation (center right) and, on top of it, the New Scotland Formation.

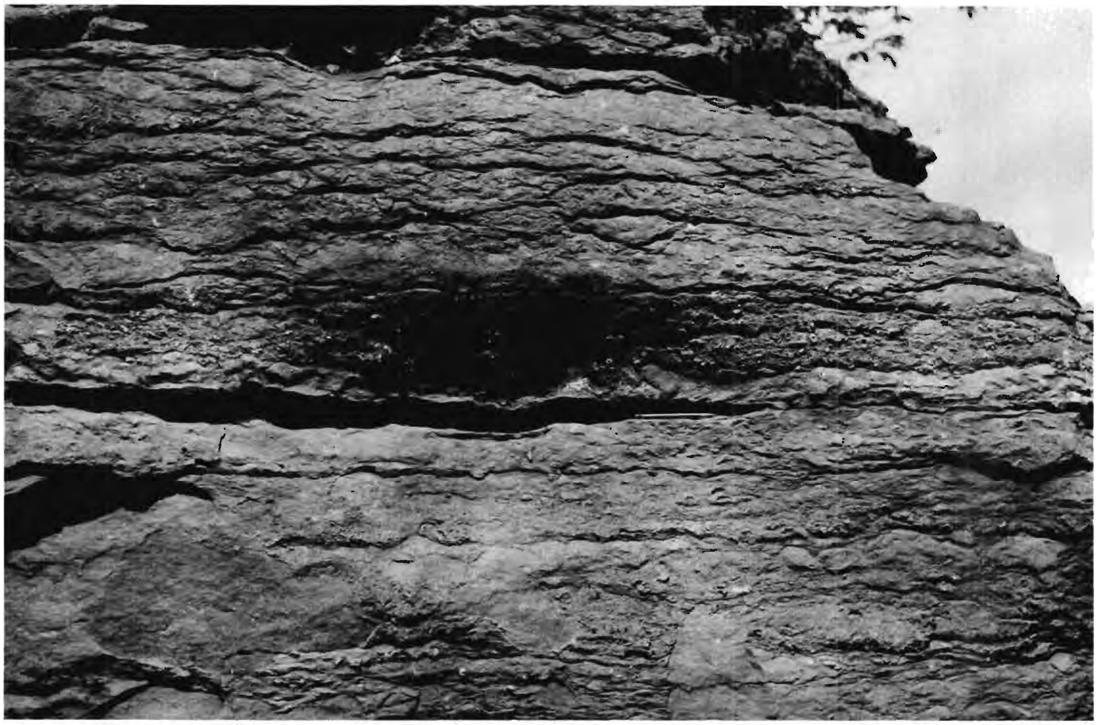


Figure 8.8. Thick, coarse-grained limestone beds of the Lower Devonian Coeymans Formation are seen in this Albany County road cut.

Figure 8.9. This coral reef, called the Knoxboro reef, is found in the Lower Devonian Coeymans Formation in a field in Oneida County. Because it contains abundant fossil shell debris, the rock has a coarse texture and lacks distinct layers.

suddenly became deeper after deposition of the Glenerie-Oriskany. Look at the "Environments" column in Table 8.2. Notice the change between the Glenerie and the Esopus. The water suddenly became much deeper; mud was deposited instead of sand. This mud became the Esopus Formation. The next higher formation, the Carlisle Center, is mainly siltstones. They were deposited in somewhat shallower water. Both the Esopus and Carlisle Center Formations were formed from sediment washed from the land and carried by streams into the Early Devonian sea.

Unlike the Oriskany Sandstone, the Esopus and Carlisle Center Formations contain few fossils of animals with shells or other hard parts. The sea bottom was so soft and the water was so muddy while the Esopus and Carlisle Center were being deposited that few animals with heavy shells could live. We find only one common indication of life in that environment. It is a *trace fossil*[9] called *Zoophycus* that looks like the outline of a rooster's tail on the surfaces of rock units. It was made by a worm-like animal that moved through the sediment in long, curved arcs as it ate mud (Figure 8.12).

The Schoharie Formation is a fine- to medium-grained sandstone that contains some limy material. It also contains abundant body fossils in its uppermost layer. The Schoharie is similar to the Carlisle Springs Formation. However, the sediments are coarser grained and seem to have been deposited in shallower water. As the water grew shallower, brachiopods, cephalopods, and clams (see Figure A.3) appeared on the sea floor. They are preserved as fossils in the top of the formation.

Middle Devonian History

At the end of the Early Devonian, the inland sea of the Appalachian Basin continued to become shallower and shrink. Eventually, it withdrew temporarily from most of New York State; as it went, it exposed the Schoharie Formation to erosion. In the western part of the State, much

[9] A *trace fossil* is a track, trail, or burrow made by an animal or plant root that is preserved as a fossil when the sediment becomes rock. The skeletal remains or impressions of plants and animals are known as *body fossils*.

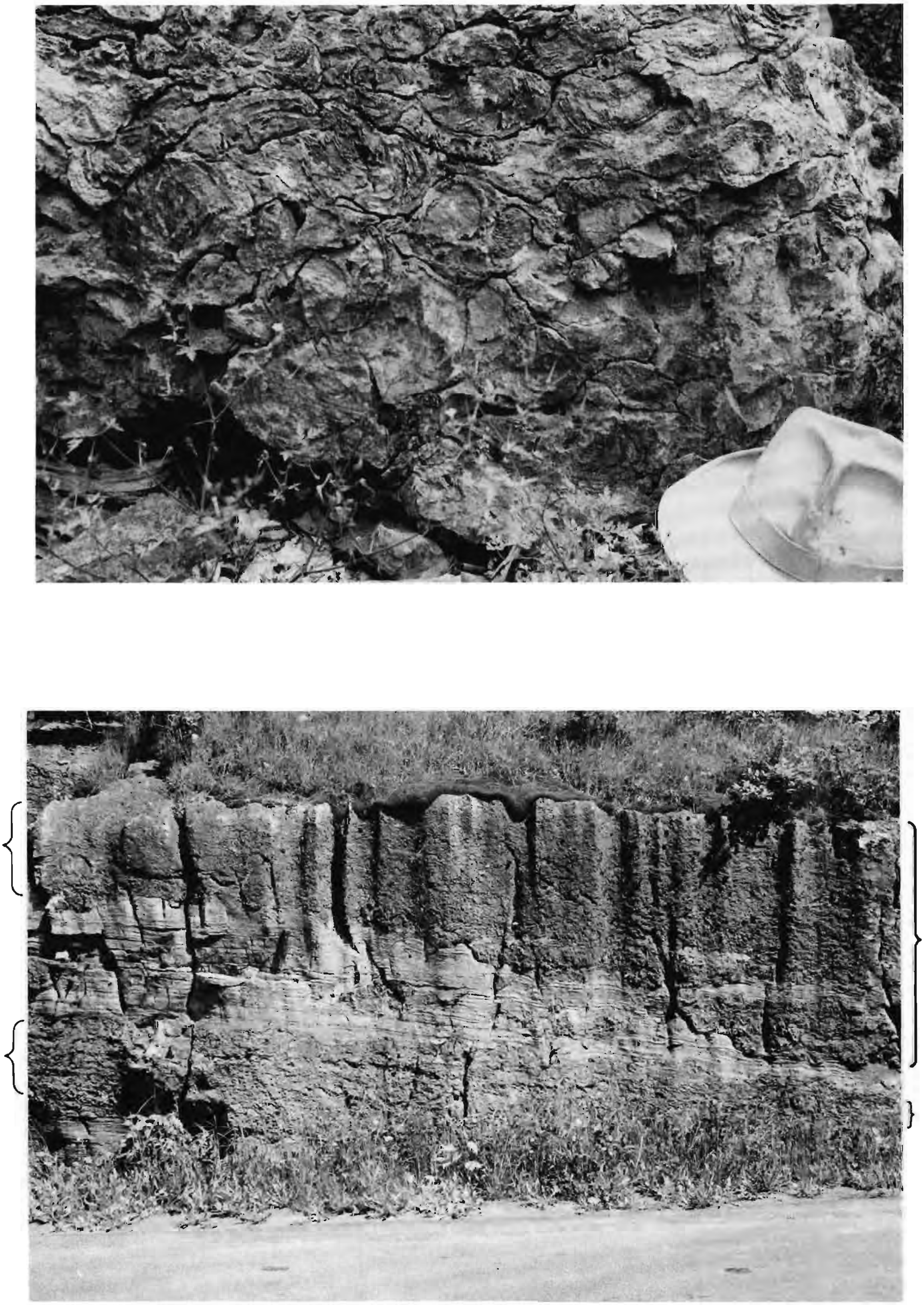


Figure 8.10. These two photos show stromatoporoids in the Manlius Formation. In (A), you can see large, spherical stromatoporoids found in Herkimer County. In (B), you can see small, irregular stromatoporoids in the layers indicated by the brackets. Found in Albany County.

Figure 8.11. These fossils, which have the technical name *Tentaculites gyracanthus* (Eaton), may be members of an extinct group related to mollusks. They are found in the Thacher Member of the Lower Devonian Manlius Formation in Schoharie County.

of the Early Devonian record was destroyed. Only patches remain (see Plate 3).

The Middle Devonian began about 390 million years ago, when a warm, shallow sea again covered New York from the present Hudson River to Lake Erie and farther west. This sea was home to a host of invertebrate animals. Corals were particularly abundant and built reefs in many places. There were also vertebrates—a number of jawless and shark-like fish lived in these waters.

We read this history in the Onondaga Limestone, the first rock unit deposited in the Middle Devonian sea. This limestone unit ranges from 20 to 75 m thick, and throughout much of New York State it lies on a major unconformity. (It is this unconformity that shows us that the sea withdrew temporarily at the end of the Early Devonian.)

As we move west from Cherry Valley, we find the Onondaga Limestone on top of progressively older rocks—the Carlisle Center, the Oriskany, and various formations of the Helderberg Group (Kalkberg, Coeymans, and Manlius). In west and west-central New York, it lies on rock of Silurian age. Near Buffalo, patches of the Bois Blanc Limestone lie between the Silurian formations and the Onondaga Limestone. You can see how the layers stack up on Plate 3.

However, in eastern and southeastern New York, the Onondaga Limestone lies on the Schoharie Formation with no unconformity. The sediment seems to have been deposited continuously here, without any breaks. Thus, the sea must have remained in eastern and southeastern New York through the Early Devonian and into Middle Devonian time.

The facies of the Onondaga limestones are similar to facies in the Helderberg Group. The Onondaga Formation is divided into four members: the Edgecliff, Nedrow, Moorehouse, and Seneca. You can find descriptions of the members in Table 8.3; their locations are shown on Plate 3.

The Edgecliff Member contains corals, as indicated in Table 8.3. We can see these coral reefs in outcrops of the Edgecliff Member. By drilling underground into the Edgecliff Member, we have learned that corals are also present there. These corals have many holes in them. Some of the holes are spaces between coral heads; others are the small tubes in which the coral animals lived. If natural gas is produced underground, these holes can trap and store it. The coral reefs make the Edgecliff Member a source of gas.

In the upper part of the Onondaga Formation, we find several layers of clay. They have a special origin: they are

Table 8.2
Tristates Group

Formation	Facies	Rock Types, Grain Size, Sedimentary Structures	Fossils	Environments
Schoharie Formation	New Scotland	siltstone that contains calcium carbonate and fine quartz sandstone	trace fossils with body fossils present only at top of formation brachiopods cephalopods corals	below fair-weather wave base well oxygenated bottom agitated by storm waves
Carlisle Center Formation		siltstone that contains a small amount of calcium carbonate	rare body fossils some trace fossils	moderately deep water soft bottom little current activity bottom rarely agitated
Esopus Formation		dark gray shale rich in silica chert	rare body fossils some trace fossils	deep water soft bottom little oxygen little current activity bottom rarely agitated
Glenerie Limestone	Kalkberg	limestone rich in silica	moderate number, similar to those found in Kalkberg Formation	deeper water near deepest level reached by fair-weather waves bottom occasionally agitated
Oriskany*		quartz sandstone that contains calcium carbonate	large, thick-shelled brachiopods	shallow water near the shore vigorous wave and current motion well agitated bottom
Port Jervis Limestone**	New Scotland	medium-grained limestone rich in clay & silica	similar to those found in New Scotland Formation	deep water below motion of fair-weather waves

*The Oriskany lies to the west of the Port Jervis, not on top of it.
**Found only near Port Jervis, NY.

made from layers of ash spread by powerful volcanic eruptions over eastern proto-North America. The clay layers, called the *Tioga ash beds*, show us that there were at least three large volcanic eruptions during the early part of the Middle Devonian. We can trace these clay layers all the way to the Midwest, so we know the volcanic eruptions spread ash over a very wide area. Because they are so widespread, the ash layers are very useful in matching the ages of rock bodies that are far apart. A volcanic eruption lasts for only an instant of geologic time. Thus, if we can trace a volcanic ash into widely separated areas of the country, we can use it for very precise time correlations.

The Onondaga Limestone was the last thick, widespread deposit of limestone in the Devonian of New York. It is relatively resistant to erosion compared to the rock above and below it, so it commonly stands above the rest of the landscape as an escarpment that runs east to west across the State. It is quarried extensively in New York, mainly for crushed stone, which is used in concrete and for other purposes.

An abrupt change in environment stopped deposition of the Onondaga Limestone. Sometime in the early part of the Middle Devonian, the continent of Avalon collided with proto-North America (see Chapter 3). This collision caused a great new mountain-building event called the

Figure 8.12. The surface of this layer in the Lower Devonian Carlisle Center Formation shows feeding burrows of a marine worm called *Zoophycus*. It was found near Cherry Valley, Otsego County.

Table 8.3
Onondaga Formation

Formation or Member	Facies	Rock Types, Grain Size, Sedimentary Structures	Fossils	Environments
Seneca Member	New Scotland	shale that contains calcium carbonate and fine-grained limestone that contains much clay less pure (contains much clay) with several thin volcanic ash beds (Tioga ahs beds)	brachiopods, including some with pinkish shells shells, called <u>Chonetes lineatus</u> sea floor animals similar to those found in New Scotland Formation	deeper water, below motion of fair-weather waves bottom agitated by storm waves
Moorehouse Member (Fig. 8.13)	Kalkberg	fine- to medium-grained limestone thin to medium-thick layers varying amounts of chert	many fossils of sea floor animals	shallow, quiet water at or near lowest point reached by motion of fair-weather waves bottom occasionally agitated
Nedrow Member*	New Scotland	medium-grained limestone (upper) shale that contains calcium carbonate (lower)	platyceratid gastropods and sparse fossils of sea floor animals	similar to New Scotland facies
Edgecliff Member	Coeymans	medium- to coarse-grained limestone medium to thick layers chert blanket-like layers built by corals, scattered coral reefs	similar to those found in Coeymans Formation rugose & tabulate corals pelmatozoans brachiopods trilobites mollusks	shallow water shelf vigorous wave motion well agitated bottom

*The Nedrow Member occurs in central New York. To the east and west, it gradually become a cleaner limestone with chert in it. There, it is more like the rest of the Onondaga Limestone and less like a separate member.

Acadian Orogeny. Mountains started to rise in New England and the Canadian Maritime Provinces. As the collision went on, it caused faulting, folding, metamorphism, and igneous intrusions.[10] In the area where the Onondaga Limestone was being deposited, the orogeny caused an abrupt deepening of the water. This deepening brought about a drastic change in the environment of the sea floor and, hence, an abrupt change in the kind of sediment deposited there.

The Acadian Orogeny eventually transformed the eastern part of proto-North America into the rugged, lofty Acadian Mountain range. In some areas of southeastern New York, we can see sedimentary layers that were highly deformed and metamorphosed in the Acadian Orogeny. Their twisted and contorted condition shows us the intensity of the event. The indirect effects of the Acadian Orogeny were even more widespread.

Erosion immediately attacked the newly built mountains, and streams carried tremendous quantities of sediment from the mountains westward toward the sea. This process went on through the Middle and Late Devonian.

Figure 8.14 shows the general location of major river systems that flowed from the mountains into the Appalachian Basin in the Late Devonian. How do we know where the rivers were? On their way to the sea, the rivers dropped some of the sediment they carried. They dropped the coarser particles first, at the foothills; they continued dropping finer and finer sediment along their courses to the sea. These processes built an *alluvial plain* between the hills and the shoreline. Where the streams

[10]Chapters 3 and 4 have more information about continental collisions and mountain-building.

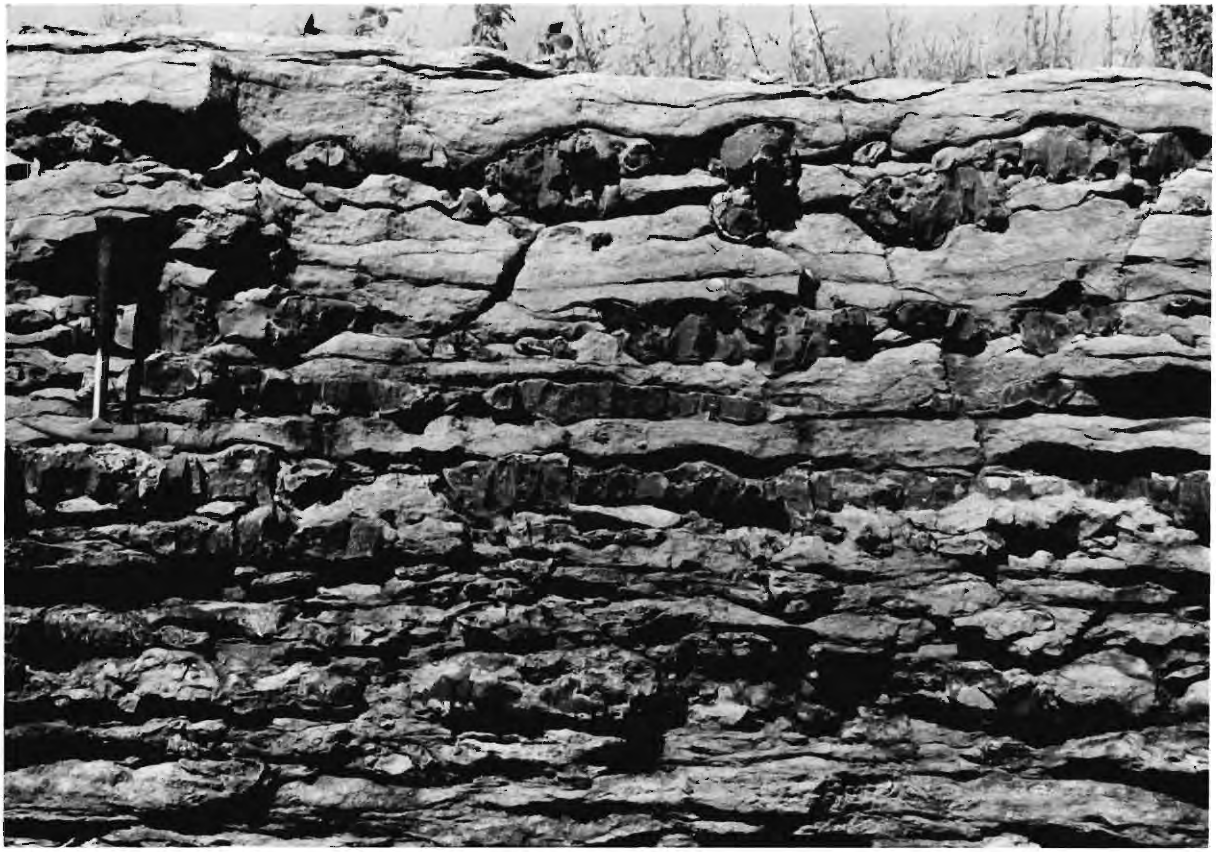


Figure 8.13. This photo shows the Moorehouse Member of the Middle Devonian Onondaga Limestone in Otsego County. It includes knobby chert in the layers of limestone.

met the sea, they built deltas of sand and mud. Between the shore and the mountains, the rivers changed their courses from time to time. Thus, the alluvial plains grew sideways and overlapped. The deltas grew out into the sea; they also grew sideways and overlapped. Eventually a huge apron of sediments was formed (Figure 8.14). By looking at the thickness of these deposits and the grain size of the rock in various places, we can deduce approximately where the rivers flowed.

Figure 8.15 will give you a rough idea of the geography at this time. The sedimentary apron extended from the mountains, across the shore, and well out into the sea. As sediment filled in the eastern edge of the basin, the shoreline moved west and the sea retreated. This process continued throughout the Middle and Late Devonian. By the end of the Devonian, the shore was in the western part of the State.

To examine this movement in the Middle and Late Devonian, see the small diagram labelled *Depositional Environments* on Plate 3. Notice how the shore zone (yellow) and the other environments push westward across the State over time. The ragged edges in the diagram show that this movement was not steady and continuous through time. It went by fits and starts, with occasional temporary retreats.

This great apron of sediment became layers of sedimentary rock. We can see these layers in many outcrops in the Catskill Mountains. These outcrops contain many clues that tell us in which environments the sediment was deposited. It was from such clues that we figured out the picture described above—a system of rivers flowing generally westward from a high mountain range on the east to a sea on the west.

We call the sedimentary apron the *"Catskill Delta."* But this great wedge of sedimentary rock is not really a single delta. It was built by many rivers that carried sedi-

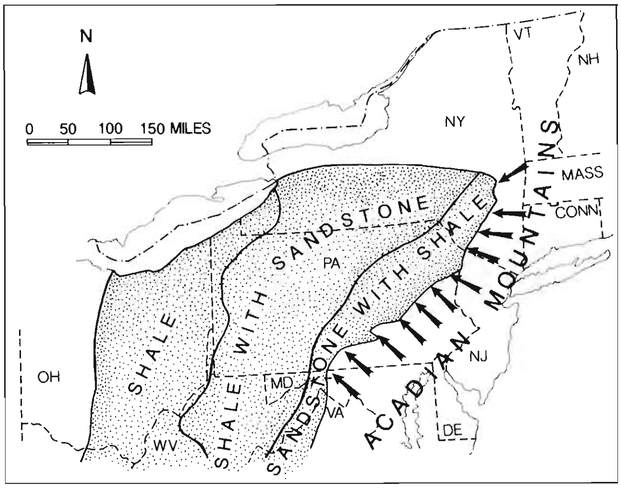


Figure 8.14. Map of the area where "Catskill Delta" deposits exist today. They originally extended farther north across New York, but erosion has removed them from that area. The Acadian Mountains of Middle and Late Devonian time were the source of the sediments of the "delta." The arrows represent a system of large rivers that carried sediment from the mountains to build the "delta." (Modified after W.D. Sevon, Fig. 3 and 6, Guidebook, 53rd Annual Meeting of New York State Geological Association, 1981.)

ment from the west side of the Acadian Mountains (Figure 8.14). We put quotation marks around it to remind ourselves that "Catskill Delta" is not a precise term.

The "Catskill Delta" grew—sometimes rapidly and sometimes slowly—throughout the Middle and Late Devonian. Sediment was washed down from the Acadian Mountains, and the floor of the sea basin was sinking. Both of these things happened at varying rates. How fast the "delta" grew westward and thickened upward depended on how much sediment was washed from the mountains and how fast the sea floor was sinking.

Several factors affected the amount of sediment eroded from the mountains. When the Acadian Mountains grew rapidly and became very high, erosion would be more rapid. When they were worn down to lower elevations, erosion would be slower. Changes in climate would also change the rate of erosion, perhaps drastically if annual rainfall changed markedly. The building of the "delta" took tens of millions of years, so there was time for many variations.

At the same time, the floor of the inland sea was sinking at changing rates. When the sea floor sank slowly, the sediment would fill in at the edge of the basin and push the shoreline westward. When the sea floor sank faster than the sediment could accumulate at the basin's edge, the shoreline would remain in one position or the sea would advance eastward. When the shoreline moved eastward, it covered the newly formed layers of non-marine sediment by depositing marine sediment on top of them. The back-and-forth movement of the shoreline produced alternating layers of marine and non-marine sediment.

The oldest rock in the "Catskill Delta" is found in the Hamilton Group. The Hamilton Group extends across New York State from the Hudson River to Lake Erie. In the east, it is 850 m thick. In the west, it is only 80 m thick. The Hamilton Group includes a number of formations, which are shown on Plate 3. These formations were deposited in five major depositional environments. The formations and facies are described in Table 8.4.

Remember that the "delta" grew by filling in the sea. As the rivers delivered sediment to the sea, marine waves and currents took over and began to move some of it around. These processes tended to sort the sediment into its various grain sizes. Much of this work was done during storms. The storms would churn the shallow water near shore and put a lot of fine-grained sediment into suspension. Currents then moved it around before it was dropped.

The finer material was deposited farther offshore. Finer grained sediment settles more slowly than coarser grained. Thus, fine material stays in suspension longer than coarse. Weak currents and waves will drop coarse grains but can move fine material. Currents and waves tend to become weaker offshore as the water deepens. As currents or waves weaken, they drop the coarser material first, and the fine material is carried farther.

In Table 8.4, notice that the lowest part of the Hamilton Group, which lies directly on top of the Onondaga Limestone, is the black shale of the Marcellus Formation. It was formed from fine black mud deposited in the deep part of the basin where the water was stagnant and had very little oxygen in it. As we mentioned above, a sudden deepening of the inland sea stopped deposition of the Onondaga Limestone. This event also brought about the stagnant basin environment where the Marcellus Shale was deposited. This deepening probably was related in some way to the rapid mountain building to the east. The basin apparently sank rapidly to compensate for the rapid mountain building. As the Acadian Mountains eroded, coarser sediments—silty mud, silt, and fine sand—advanced across the basin and buried the fine mud that formed the shale. In eastern New York, these sediments were later replaced by even coarser ones—muddy sand (together with red and green mud), then quartz-pebble gravel. This succession of sediments crept out into the sea to form the lower part of the "Catskill Delta."

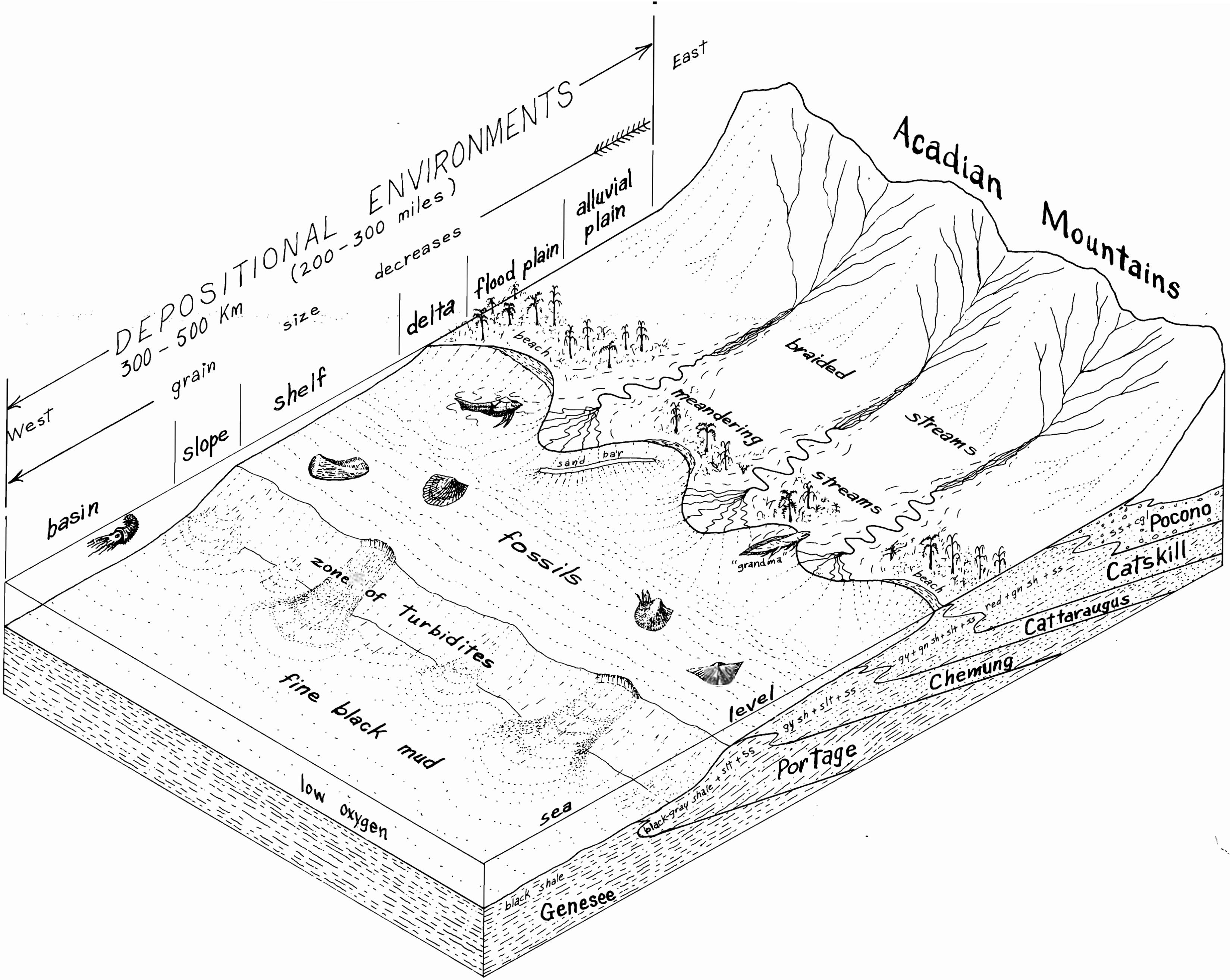


Figure 8.15. Diagram of the depositional environments of the "Catskill Delta" and the facies that were deposited in them. The arrangement of the facies (Genesee-Pocono) shows that the environments have moved from right to left through time as the sediment has filled in the edge of the sea. This process could be reversed by a rise in sea level, which would move the shore zone toward the right. (In this oversimplified diagram, the Pocono facies looks as if it were underneath the Acadian Mountains. It was actually deposited at the foot of the mountains.)

Table 8.4
Middle Devonian Shales, Sandstones, and Conglomerates

Group, Formation, Member, Beds, or Facies	Facies	Rock Types, Grain Size, Sedimentary Structures	Fossils	Environments
Thin limestone units at several levels within the group	New Scotland	limestone rich in clay shale that contains calcium carbonate	high number & variety corals brachiopods bryozoans all types of mollusks crinoids trilobites ostracodes	deeper water below motion of fair-weather waves well oxygenated
Skunnemunk Conglomerate*	Pocono (named after the Pocono Formation of northeast Pennsylvania)	thick layers coarse at the bottom, gradually become finer grained from bottom to top: top: silty shale finer grained sandstone very coarse pebbly sandstone (purple or maroon) bottom: conglomerate pebbles in conglomerate are mainly white quartz or quartzite; also include red and green shale, greenish quartzite, buff sandstone, pink sandstone		braided streams at foot of growing mountain range
Catskill** facies	Catskill	red, green, & gray shale, mudstone & siltstone alternating layers of impure quartz sandstone and pebbly sandstone sandstone is medium to coarse grained sandstone layers gradually become finer grained from bottom to top cross-bedding, root traces, mud cracks, scour & fill	relatively few overall in places, common plants and clams, and very rare fish fossils	delta above sea level flood plain and river channels
Hamilton Group	Hamilton	gray shale, mudstone, siltstone mudstone siltstone fine- to medium-grained sandstone flat-pebble conglomerate concentrations of fossil shells laminations, cross-bedding, ripple marks, flute & groove casts, convoluted bedding	high number & variety of shelled animals brachiopods bivalve mollusks	deep part of basin open shelf underwater part of delta channels dug by underwater currents tidal flats offshore bars
Marcellus Formation	Marcellus	very thin layers of black or very dark gray shale thin layers of limestone rich in clay shale splits easily into thin sheets abundant calcareous nodules or concretions abundant pyrite	low number & variety of bottom-dwelling & swimming animals ammonoids conodonts styliolinids brachiopods	deep part of the basin far from land poor circulation limited oxygen

*Found in southeastern New York.
**Found only in eastern New York.

From time to time, the sediment supply was interrupted. At those times, the "delta" would stop growing, and the sea water became less muddy for a time. This environment permitted organisms that produced calcium carbonate to thrive. Their remains accumulated on the sea floor as layers of calcareous sediment. And indeed in the Hamilton Group, we find several thin but widespread limestone layers. We use these limestone beds as markers to separate the Hamilton Group into the formations shown on Plate 3. As you can see in Table 8.4, these limestones contain much clay, so we know that mud (clay) was being washed in from the land. When less mud and sand were deposited, we find limestone rich in clay. When more mud and sand were deposited, it diluted the calcareous sediments and formed limy shales or limy sandstones.

Where the limestone disappears, we know that the sea had again become so muddy that the organisms that produced calcium carbonate couldn't survive or their remains had been too diluted to form limestone. The limestone of the Hamilton Group contains some of the most magnificent Devonian fossils ever found. Here we

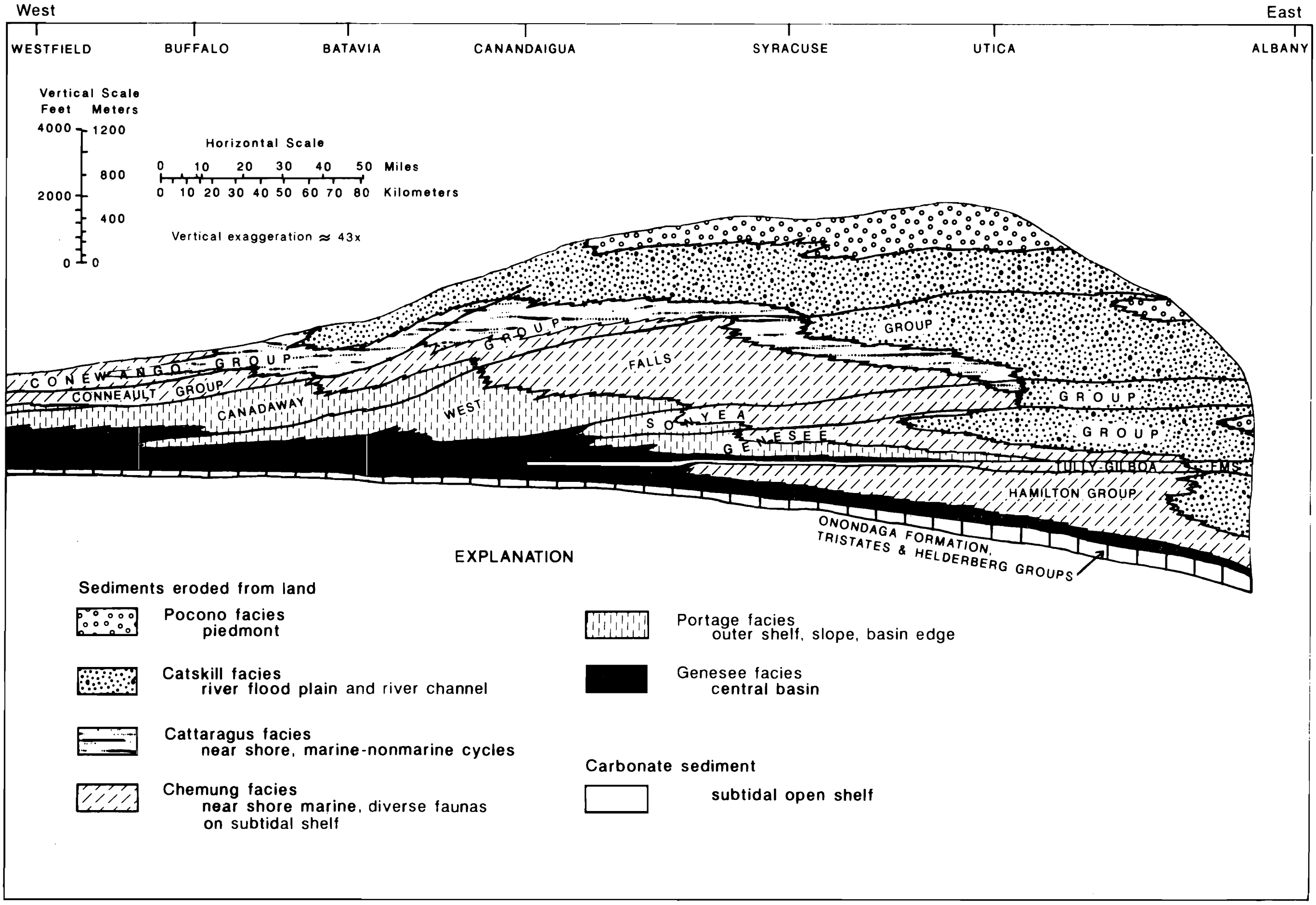


Figure 8.16. Diagrammatic cross section of the "Catskill Delta" east-west across New York State. This diagram is a composite that uses information from the outcrops in New York and in northern Pennsylvania. The cities listed across the top of the diagram generally are north of the main body of the cross section. A line drawn south from a city will cross the facies shown below it, starting with those facies at the bottom of the diagram. The "delta" deposits are divided into groups. Each group includes several facies. Figure 8.15 shows the environments where the different facies developed. Each group records an episode of the "delta's" construction. For example, as the Genesee Group was deposited, the shore zone moved from east to west as the sediment filled in the sea. An abrupt increase in the depth of the water moved the shore zone back toward the east, and deposition of the Sonyea Group began. The opposing processes eventually built the complex of sedimentary rock we call the "Catskill Delta." Notice that this diagram is distorted because the vertical scale is much larger than the horizontal scale. This vertical exaggeration is necessary to show details. However, it gives a false impression because it exaggerates the thickness relative to the width of the units shown.

find a great number and a great variety of shelled animals that lived on or swam above the sea bottom.

The lower part of Figure 8.16 shows how the different Hamilton facies (described in Table 8.4) are stacked up across the State from east to west. You'll notice that this figure shows no Pocono facies in the Hamilton Group. That is because we find the Pocono only in southeastern New York, which is off the line of this cross section.

Toward the end of the Middle Devonian, construction of the "Catskill Delta" slowed down sharply. This slowing marked the end of deposition of the Hamilton Group. In western and central New York, the sea floor was eroded. This erosion is marked by an unconformity. Along this unconformity, we find many lens-shaped deposits of the mineral *pyrite*. These deposits are shown as the Leicester pyrite on Plate 3. Deposits of this kind are very rare in the geologic record because they are formed in water that lacked almost all oxygen. If oxygen had been present, the pyrite (chemical composition FeS) would have been oxidized into red iron-rich minerals such as *limonite*. We conclude that the erosion of the upper part of the Hamilton Group and the accumulation of pyrite on the unconformity surface happened in deeper sea waters.

Calcareous sediments were later deposited on top of the unconformity. These deposits eventually became the Tully Limestone. The Tully Limestone is 9 m thick. Table 8.5 contains a description. This limestone shows us again that little of the mud or sand eroded from the land reached this area during the late part of Middle Devonian time.

We are uncertain why the flow of sediments from the land slowed down to allow deposition of the Tully Limestone. However, an examination of the Tully Limestone and other sedimentary rocks deposited at the same time suggests an explanation.

The Tully Limestone is found only in western and central New York. Farther east, between the Chenango and Unadilla Rivers, the amount of mud and sand in the limestone gradually increases until the limestone is replaced by silty shale, siltstone, and sandstone. These beds and their fossils represent environments like the ones we saw in the Hamilton Group. They are called the *Gilboa Formation*, a marine unit that is underlain and overlain by sandstones laid down in fresh water or on the land. Heading east from the Schoharie Valley, the Gilboa Formation, in turn, gradually changes into a nonmarine facies—beds that were deposited above sea level. Thus, we can see that erosion of the land didn't stop in the late Middle Devonian, although shorelines moved farther east during deposition of the Tully and Gilboa formations. Enough sediment was washed from the mountains to the eastern part of New York State to continue building the sedimentary apron. However, the shoreline had moved farther east during this interval, and most of the land-derived sediments were deposited farther east in the flooded river mouths and flooded surface of the delta. This situation meant that calcareous sediments, such as the Tully Limestone, could be deposited farther offshore.

Late Devonian History

The Late Devonian lasted from about 375 to 360 million years ago. The major part of the "Catskill Delta" was

Table 8.5
Tully Limestone

Formation	Facies	Rock Types, Grain Size, Sedimentary Structures	Fossils	Environments
Tully*	New Scotland	medium to thick layers of limestone rich in clay	moderate variety of sea bottom dwellers brachiopods corals crinoids pelecypods cephalopods trilobites	depth below fair-weather waves well oxygenated

*The Tully is separated into two parts by an unconformity--the Upper Tully and the Lower Tully. Both parts represent similar environments.

built during this time (Figure 8.16). The structure of the Late Devonian part of the "delta" is similar to that of the Middle Devonian Hamilton Group. The coarsest sediment is in the east, closest to the mountains that supplied it. As we move farther west, the sediment becomes progressively finer.

When sediment is deposited, the water near shore becomes shallower. Water depth controls the environment, so all the environments shift in a seaward direction, following their appropriate water depth. Eventually, the sediment replaces the sea water and builds the area above sea level.

If we select a rock unit in the "Catskill Delta" and follow it from east to west, we see the facies change from non-marine to shallow marine water to deep water. The change from non-marine (rivers) to marine (sea) is a major one for plants and animals, because the chemistry of sea water is very different from that of fresh water. This change in facies shows us the various environments that existed at the same time.

As we move from lower (older) layers to higher (younger) layers, we see the facies change as well. For example, they may change from deep water to shallow water to non-marine. These changes show us that different environments existed in a particular place over time. They show us the history of the growth of the "delta."

The major facies of the Late Devonian and the environments they represent are described in Table 8.6. Figure 8.15 shows the geography for the Late Devonian from the basin floor across the shore zone to the mountain front. This diagram relates the environment where each of the facies developed to the landscape and water depth.

Figure 8.16 is an east-west cross section of the "Catskill Delta" that shows how the facies are distributed. Notice how the non-marine facies—Cattaraugus, Catskill, and Pocono—move westward over the marine facies throughout the Middle and Late Devonian. This was a slow, creeping, halting movement. Frequently the sea would temporarily deepen and bring the shoreline and marine environments back east. Marine facies then could be deposited on top of earlier non-marine facies.

As we saw earlier, a number of factors interact to make the shoreline move back and forth: change in sediment supply from the land; rise or fall in sea level; change in the rate of sea floor sinking. Waves and currents might become stronger or weaker, depending on variations in geography, and move the sediments around in different ways. We can see the effects of all these factors in the overlapping, irregular shape of the facies.

In the Upper Devonian part of the "Catskill Delta," nearly all the rock was made from sediment deposited on land or in fresh water. Geologists have divided this great mass of sedimentary layers into six groups. From oldest (bottom) to youngest (top), they are: Genesee, Sonyea, West Falls, Canadaway, Conneaut, and Conewango (Figure 8.16 and Plate 3). The three oldest groups (Genesee, Sonyea, and West Falls) extend completely across the State. The younger ones are found only in the western part of the State. Either they were never deposited in the Catskills, or they were later worn away by erosion. As you can see on Plate 2, the various groups crop out in the Catskills, the Finger Lakes region, the Genesee River valley, and along the shore of Lake Erie.

We'll describe the lower four groups (Genesee, Sonyea, West Falls, and Canadaway) together because they have similar histories. They illustrate the way the "Catskill Delta" developed. All are much thicker in the eastern part of the State (Table 8.7).

The enormous size of the "Catskill Delta," both in thickness and in area, gives us a large problem. How can we tell whether, for example, a reddish sandstone in the eastern part was deposited at the same time as a black clay shale in the western part? The fossil content is not likely to help because the two units represent entirely different environments. In other words, we probably won't find the same kind of fossil in both units—the two environments were home to two different sets of creatures.

One approach to the problem is to carefully examine closely spaced outcrops all the way across the State. Many different geologists have studied parts of the "delta" in this way through the years. However, their conclusions about it have not always fit together.

One feature of the "delta" that has helped sort out the parts of the puzzle are layers of black shale that cross the State in the marine facies. Black shale of this type is deposited in the deeper parts of a marine basin. Only fine mud reaches the area. Commonly, the deeper water in the basin also had a low level of oxygen. Low oxygen allows *organic matter* (the tissues of living things) to accumulate in the sediment instead of breaking down into simpler compounds. In addition, grains and nodules of pyrite (or "fool's gold," chemical composition FeS) grow in dark shales of this type. Organic matter is one of the components that makes the shale black. The other component is pyrite; interestingly, large pyrite grains are golden in color, but very fine-grained pyrite is black in color. When circulation of the bottom water is better, the oxygen content increases and the shale deposited has a lighter color—gray to greenish—because organic matter and pyrite content are low.

There is a relatively uniform sequence of Upper Devonian shale in the western part of the State; thus, we know that a deeper basin environment persisted in this area. Tongues of black shale extend eastward from this main body. A number of black shale tongues lie right on top of other, shallower marine facies in more eastern sites. The upward change to black shale is sudden at these eastern sites. Therefore, we believe that the deeper basin environ-

Table 8.6
Upper Devonian

Facies Name	Environment	Rock Types, Grain Size, Sedimentary Structures	Fossils	Environments
Pocono (Fig. 8.17)	piedmont	conglomerate w/round white quartz pebbles pebbly sandstone & siltstone (purple or maroon) thick layers	rare fossils	braided streams near foot of mountain range
Catskill	river flood plain	red, green, & gray shale green mudstone & siltstone medium to coarse-grained quartz sandstone pebbly sandstone sandstone beds coarser at base and become finer going up cross-bedding in sandstone; scouring, root traces, mud cracks	few fossils overall in places, plant and fish fossils are common	river floodplains with meandering streams shale, mudstone, & siltstone in the floodplains sandstone--in channels
Cattaraugus	near shore marine-nonmarine cycles	gray & green shale, siltstone & sandstone alternating layers of red shale, siltstone, & sandstone gray & green rocks: winnowing, bioturbation, ripple marks red rocks: root traces, mud cracks	low number and variety red rocks contain plant fossils	close to shore, alternately above and below sea level green & gray rocks are marine red rocks are nonmarine
Chemung	nearshore marine, diverse subtidal shelf	gray shale, mudstone, & siltstone fine- to medium-grained sandstone layers of fossil shells flat pebble conglomerate laminations, cross-bedding, ripple marks, flute & groove casts, convoluted sedimentary structures	high number & variety (except in a few environments) of shelled sea animals brachiopods bivalve mollusks	several shallow water environments near shore and in tidal zone: beach, channel, tidal flat, lagoon, swamp, offshore bar, delta, near shore, open shelf underwater: delta, near shore, open shelf
Portage B	open shelf, slope	thin layers of siltstone, cross-laminated, graded turbidites in gray shale	low number & variety of swimmers & sea bottom dwellers	outer part of shelf below motion of fair-weather waves slope
Portage A	base of slope, basin edge	black and medium to dark gray shale, mudstone, and siltstone a few layers of fine-grained sandstone in dark gray shale in siltstone: cross-lamination; casts of grooves, tracks, trails, & flutes convoluted bedding; ripple marks	low number & variety of swimmers and sea bottom dwellers	deeper waters at base of slope to basin margin
Genesee	central basin (like Marcellus)	black shale a few thin layers of dark limestone rich in clay septarian nodules and concretions pyrite shale splits easily into thin sheets	low number & variety of swimmers & sea bottom dwellers: ammonoids conodonts brachiopods mollusks	deep water part of basin far from land very little oxygen near the bottom

Figure 8.17. This photo shows the Twilight Park Conglomerate, an example of the "Pocono" facies of the Upper Devonian, near Haines Falls, Greene County.

Table 8.7

	Thickness at Lake Erie	Thickness in the Catskill Mountains
Genesee	9 m	480 m
Sonyea	15 m	240 m
West Falls	150 m	790 m
Canadaway	335 m	more than 600 m

ment expanded rapidly. Deposition of the black shale tongue would begin everywhere in the expanded basin at almost the same time. If these conclusions are correct, then the base of a black shale tongue is an approximate "time line." In other words, events recorded in the rock at different places just above this time line happened at approximately the same moment in geological time.

What would cause such a sudden expansion of the basin environment? An increase in water depth. And what would increase water depth so quickly? A rapid rise of sea level is one possibility. Another way would be rapid sinking of the floor of the Appalachian Basin. More water would flood in from the ocean to the east, making the inland sea much deeper.

Whatever the cause, a sudden increase in water depth would have several results:

1. The basin environment would expand up the slope and onto the shelf and perhaps even across the old shore zone.
2. The other, shallower depositional environments would move rapidly landward.
3. Low-lying nonmarine environments would be flooded by sea water.

Of course, rivers would continue to carry sediment to the sea. When the increase of water depth slowed or stopped, the sediment would begin to fill in the basin, decrease water depth, and move the environments seaward again.

In western New York, the Genesee, Sonyea, West Falls, and Canadaway groups are each made of a thick layer of black shale with greenish-gray shale on top of it. Tongues of black or very dark gray shale extend eastward from the main body of black shale and mark the base of each of these groups. The lines that separate the groups in Figure 8.16 have been extended eastward beyond the tongues. We use other evidence to mark the base of the groups in the eastern areas.

As we follow a greenish-gray shale above a black tongue from west to east, it gradually changes into a sequence of *turbidites*. Turbidites are beds of siltstones and sandstones that were deposited by *turbidity currents*. (Turbidity currents are density currents caused by churned-up sediment in suspension. They flow downslope along the sea bottom.) As we move farther east, the turbidite sequence changes into other marine facies formed in shallower water (Figure 8.15).

Higher above the black shale tongues, it becomes more difficult to match up the upper parts of the groups. (Remember that each group becomes much thicker and changes facies to the east, but it records the same period of geologic time.) However, there are thin layers of black shale in the upper portion of some groups. Some of these layers continue across the turbidites and help us match up layers from one place to another.

Deposition of each of these four groups began with an eastward advance of the shoreline. As the sea spread east, the water deepened in the east. As a result, the black shale deposited in the deep waters of the basin came to be deposited farther east. This black shale was deposited on top of older deposits that were made in shallower water. These deposits had been formed earlier on the shelf and on the slope between the shelf and the basin. After the sea ceased expanding, deposition again began filling in the edge of the sea and laid down shallower water sediments onto the "delta."

The "delta" then grew until it reached the new sea level, and shallower facies crept across the shelf toward the slope that led down to the basin. When the shore approached the edge of the shelf, sediments piled up near the top of the slope and became unstable. Slumps and storm waves churned them up, put them into suspension, and formed turbidity currents.

Eventually, turbidity currents flowing down the slope into the basin became frequent enough to form the turbidite sequence mentioned above (Figure 8.15). In some of the four groups, though, the shore zone did not reach the top of the slope before the sea level rose again. In those groups, we do not find the turbidites.

The thick black shale at the base of the Canadaway Group represents the last major advance of the sea in the Late Devonian.

The two groups at the top of the "Catskill Delta" complex are the Conneaut and the Conewango. These last two groups were deposited in water that continued to get shallower. By the end of the Devonian, non-marine facies extended almost completely across New York State. Thus, we know that the "delta" had finally grown large enough to push the sea almost entirely out of the State. However, the marine facies were still found in the west.

The Conneaut and Connewango Groups together are 335 m thick in western New York. They are made of gray shale, siltstone, mudstone, and fine sandstone. They contain a moderate variety of fossil shells from marine animals. There are layers of conglomerate at several levels in the Conewango. One is especially easy to see at Panama Rock City in Chautauqua County. In westernmost New York, these two groups form the Chemung facies. Toward the east, the rock gradually changes facies to the red and green Catskill facies in southern Cattaraugus County.

Table 8.6 tells us that much of the Chemung facies, all of the Cattaraugus facies, and much of the Catskill facies were deposited near sea level, either slightly above or slightly below. With this fact in mind, study Figure 8.16 and notice that these facies are hundreds of meters thick in the east-central part of the "delta." Notice also the depositional environments generally moved slowly west through time. What conclusions can we draw? The arrangement of the facies suggests that for millions of years the basin floor sank at about the same rate as sediment was delivered. Then, in the later part of the Late Devonian, the basin was filled faster than its floor sank.

This apparent balance between sediment supply and sediment sink is intriguing. It suggests some cause and effect between the pulses of mountain-building and the sinking of the basin floor. Indeed, some recent studies conclude that it was sinking of the basin floor that caused the sudden increases in water depth in the Appalachian Basin. This sinking, in turn, caused the tongues of black shale to extend eastward far from the central basin. The great influx of sediment that buried the black shale tongues ties this event to a pulse of mountain-building.

Devonian Plants and Animals

There are many fossils in New York's Devonian rock. These fossils show a great variety of living things. This abundance is remarkable when we remember how unusual it is for an animal or plant to be preserved as a fossil.

Only a few of the plants and animals living at a particular time are ever preserved as fossils. It requires a long string of coincidences for any one organism to be preserved. In fact, some kinds of living things may never be preserved at all. They may be too soft or unsuitable in some other way. If they were never fossilized, we will never know that they existed.

New York's Devonian rock contains a great variety and abundance of well-preserved fossils. Clearly, the land and the sea were swarming with life, and the conditions for burial and preservation of plants and animals were good.

Animal life had become much more varied since the earlier parts of the Paleozoic. Corals were extremely plentiful and often large. Broad "carpets" made of bryozoans and crinoids covered the sea floor (Figure 8.18). There were over 700 species of brachiopods (see Figure A.3). (Brachiopods had their greatest variety in the Devonian.) *Pelecypods* (clams) multiplied on the muddy and sandy sea bottoms (Figure 8.19) and developed a variety of types.

The appearance of a new group of cephalopods—called the *ammonoids*—was even more noteworthy. (Figure 8.15 shows an ammonoid swimming in the deep water in the left-hand part of the drawing.) A series of distinctive ammonoid species evolved through time, and we have an unusually good fossil record of Middle and Upper Devonian ammonoids in New York. Therefore, we have been able to determine when a new species developed. This knowledge helps us figure out which Devonian rocks throughout the world are the same age—by matching up the sequence of ammonoids species from different areas.

Conodonts, an extinct group of swimming animals known from tiny tooth-like fossils, also had their greatest

Figure 8.18. This photo shows the crinoid called *Melocrinus paucidactylus* (Hall) from the Lower Devonian Manlius Limestone in Herkimer County. (The crinoid heads are approximately 10 cm long.)

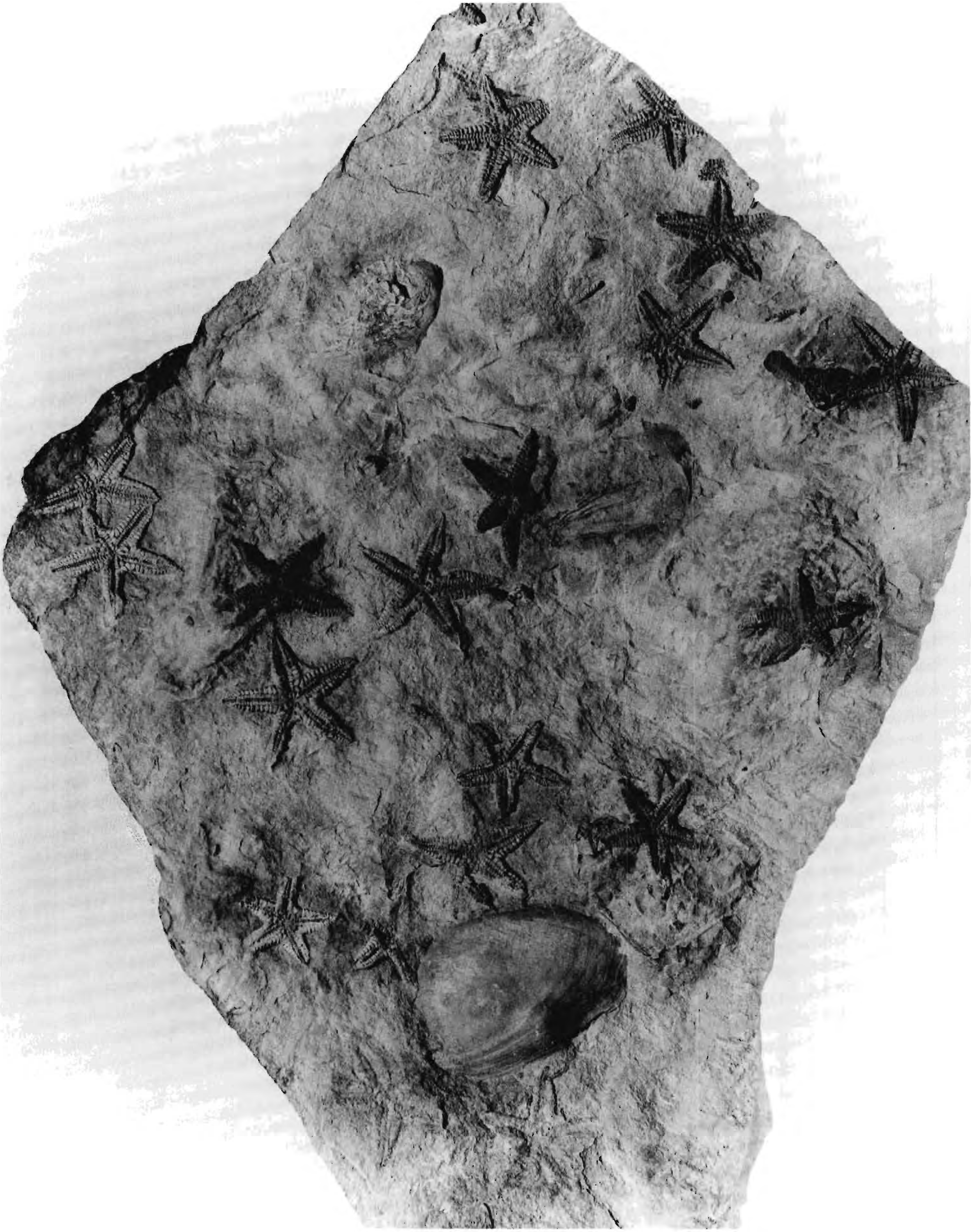


Figure 8.19. These fossil starfish, called *Devonaster eucharis* (Hall), are found in a sandstone slab from the Hamilton Group near Saugerties, Ulster County. Specimens of the pelecypod *Grammysia* are also present. It is possible that the starfish were feeding on the pelecypods. (The starfish are approximately 5 cm across.)

variety in the Late Devonian. Rapid evolution and extinction produced many geologically short-lived species that had worldwide distribution. Because many of the individual conodont species were geologically short-lived, and we can use their first occurrence and how long they survived in different regions to match up rock units of the same age. Because some conodonts had worldwide distribution, they allow us to match up layers from widely separated areas. Thus, conodonts are an ideal group to help us match up rock from different regions.

Devonian fish were especially interesting (Figure 8.20). Several new kinds of fish appeared abruptly. The rapid evolution, increase in diversity, and abundance of fish allows the Devonian to be called *The Age of Fishes*. Shark-like armored fish—some of them 6 m long—were abundant. The first air-breathing fish appeared in the Devonian, and all the higher vertebrates evolved from these air-breathers. Among their evolutionary descendants are the early types of amphibians that first appeared in the Devonian. However, we have not found their remains in New York.

Plant life also became much more varied. For the first time, low-lying land areas were covered by plants. Many of the plants were shrub-like or mosses. However, in some places, forests of tree-like plants developed. The remains of three of the oldest known forests are preserved in the Middle Devonian shale and sandstone near Gilboa, New York (Figure 8.21). These primitive tree ferns once lived on a swampy shore. Their stumps, upright and rooted in the position that they grew, were discovered during excavation for the dam at Gilboa Reservoir.

These trees were the forerunners of a great variety of plants, which would make up large swampy forests during the Mississippian and Pennsylvanian Periods. The remains of these later forests eventually became the Pennsylvanian coal beds of the Appalachian Basin.

The forests that appeared on the "Catskill Delta" changed the low-lying areas of eastern New York into a jungle. The landscape may have looked like the modern forests that grow along some low-lying coasts close to the equator.

Spiders, centipedes, and mites lived in these forests. Their fossil remains were discovered recently in Middle Devonian rock near the Gilboa Reservoir at Blenheim, Schoharie County. Primitive insects and amphibians have been found elsewhere in rock from the Late Devonian. They probably lived in the forests on the younger parts of the "Catskill Delta." The sound of wind in the trees and insect calls first appeared in New York on the "Catskill Delta."

Late Paleozoic History

The Allegheny Plateau contains the only Late Paleozoic sedimentary rock in New York State. It is possible that rocks of Mississippian, Pennsylvanian, and Permian age once covered a large part of the State. However, only scattered patches of Mississippian and Pennsylvanian rock now remain along the western part of the New York-Pennsylvania border. These layers are between 245 and 360 million years old.

Early Mississippian rock in New York is similar to the Devonian sandstones and shales that lie beneath them, and Late Devonian and Early Mississippian rocks can be distinguished only by differences in the fossil species in the rocks. There is no obvious change in facies between the Devonian and Mississippian rocks. This fact tells us that the sea in this region probably lasted from the Late Devonian into the beginning of the Mississippian. There is no rock in New York from later in the Mississippian Period.

The only Early Pennsylvanian rock in New York State is a quartz pebble conglomerate. There are very few fossils in it. This formation is our only clue that a sea existed in New York during that time. The conglomerate, which is well exposed at Olean Rock City, lies on top of Early Mississippian and Late Devonian rock. Rock from the time between the Early Mississippian and the Early Pennsylvanian is missing here.

There is no Permian rock found in New York State. The closest exposures of Permian rock lie to the southwest, in Ohio and Pennsylvania.

During the Late Paleozoic, plant and animal life in the Appalachian Basin changed significantly. Some invertebrates, such as the nautiloids and the crinoids, had many fewer varieties than before. The end of the Permian is marked by a major extinction event. Among the major groups of marine animals, the tabulate and horn corals, graptolites, some bryozoans, cystoids, eurypterids, and trilobites (see Figure A.3) became extinct at this time.

The biggest geologic event in eastern proto-North America in the Late Paleozoic was the Alleghanian Orogeny in the Appalachian mountain belt. This orogeny from the Canadian Maritime provinces south through New York to Texas resulted from the collision of proto-North America and proto-Africa along a transform margin. The collision was part of the formation of the supercontinent of Pangea. (For more detail, see Chapter 3.) This great mountain-building event deformed and uplifted the Appalachian Basin. The deformation during the Alleghanian Orogeny was greatest in the southern and central parts of the basin, where a high and rugged mountain range formed.

EVOLUTIONARY TREE OF FISH

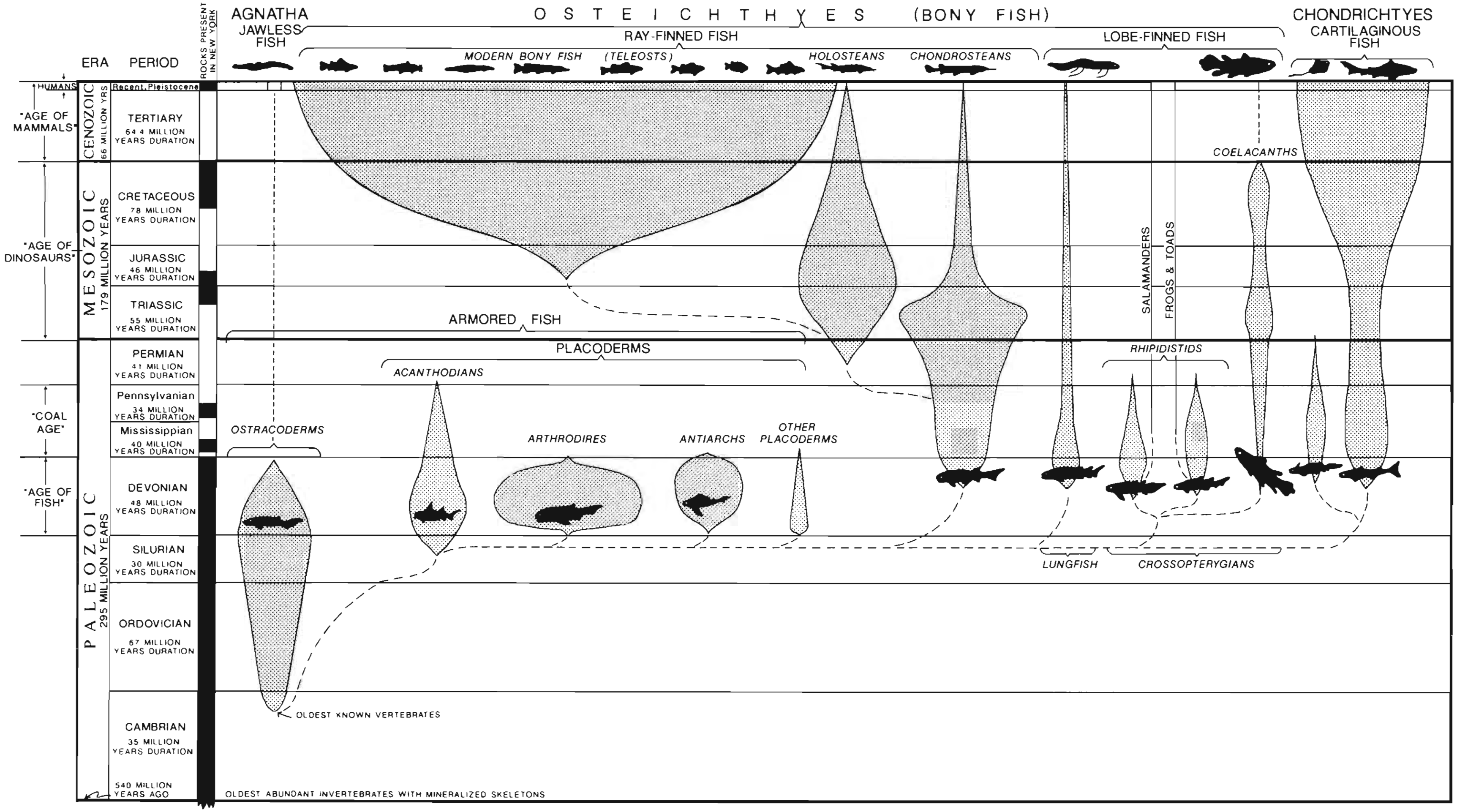


Figure 8.20. Diagram summarizing the history of the evolution of fish. Although this diagram shows sharks and their relatives (Chondrichtyes) as close relatives of lobe-finned fish, they are actually much more closely related to Placoderms.

The rocks of southeastern New York were folded and faulted during the Alleghanian Orogeny. Elsewhere in the State there was regional uplift.

Review Questions and Exercises

Most of the bedrock in this region is which type—igneous, sedimentary, or metamorphic?

Most of the bedrock in this region was formed during what geologic period? What was the environment like then?

What is a *facies*?

What is the "Catskill Delta"? How and where was it formed?

A.

B.

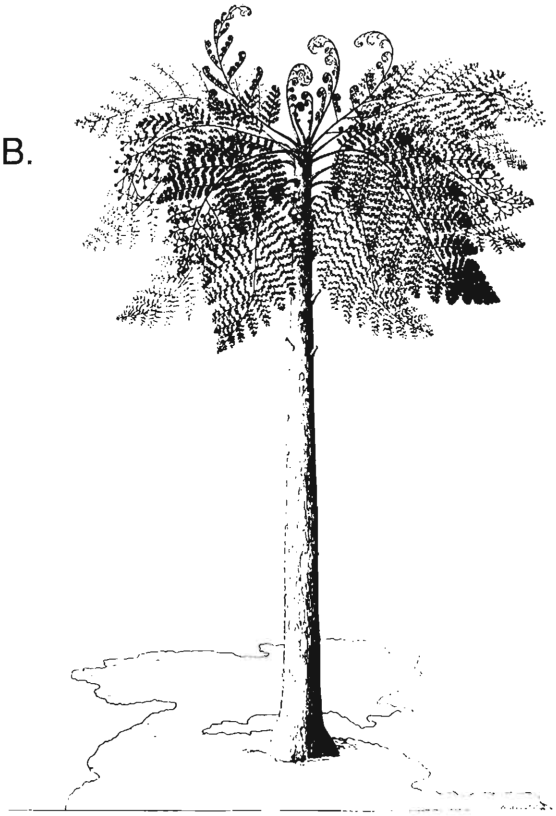


Figure 8.21. These two pictures show the Middle Devonian fossil tree *Eospermatopteris*. These stumps, discovered near Gilboa, Schoharie County, are found in one of the world's oldest known forest. (A) is a fossil stump of *Eospermatopteris*. It is approximately 1 m high. (B) is a drawing of what the living tree probably looked like (published by W. Goldring in 1924). The tree would have been about 8 m high.

Editor's note: The following supplement to Chapter 8 is for students who are interested in a discussion of the subtle structures in the rocks of the Allegheny Plateau. It serves as a case study of the kind of information we can get from close and careful examination of outcrops. A review the Tectonic Map on Plate 4 of the ***Geological Highway Map*** *and the plate tectonic history of New York in Chapter 3 may help you understand this discussion. Also, the Glossary will provide definitions of many unfamiliar terms.*

Deformation of "Undeformed" Rocks: Structures in The Allegheny Plateau

Adapted from text furnished by Professor Terry Engelder, Pennsylvania State University

The structure of rocks in the Allegheny Plateau looks deceptively simple—nothing but nearly horizontal sedimentary rock layers: "layer-cake geology." Folds like those commonly seen in the convoluted rocks of the Adirondacks, the Taconic Mountains, and southeastern New York are absent, and faults are rarely seen. However, despite this simple layer-cake appearance of the rocks of the region, subtle effects of the Alleghanian Orogeny *are* present in most of the rock exposures in central and western New York south of a line between Syracuse and Buffalo (see mustard-colored area on the Tectonic Map on Plate 4). These structures can be seen by the inquisitive eye, and they yield a fascinating structural story. Our goal in this section is to help the reader learn to see these Alleghanian structures, to understand the ways in which they were produced, and to learn what they tell us about the structural history of the Plateau.

Rock Behavior When the Crust Is Squeezed or Stretched

The way a rock deforms depends on the strength of the rock. By strength, we mean a rock's resistance to deformation. When "weak" rocks, such as shale or rock salt, are slowly subjected to increasing stress[11], they deform by flowing, like Silly Putty, modeling clay, or even tar. In contrast, "strong" rocks, such as limestone and sandstone, withstand much greater stress, until finally they deform by breaking. Strong rocks are more brittle.

In the Allegheny Plateau, we can see that the distribution of strong and weak rock layers played a very important role in the way the Plateau deformed. Several basic types of sedimentary rocks are exposed in outcrops of the Plateau: limestone, dolostone, sandstone, shale, and salt. Each of these rock types has a different strength. Limestone, dolostone, and sandstone are strong, whereas shale and salt are weak. It was a layer of salt, which is an extraordinarily weak rock, that had the greatest influence on the way the rocks deformed during the Alleghanian Orogeny.

This salt layer divides the Allegheny Plateau horizontally, like the filling in a two-layer cake. The salt is found in the lower part of the Salina Group of latest Silurian age (see Plate 3). It separates youngest Silurian and Devonian rocks above from lower Paleozoic rocks below. The salt was deposited in a great inland sea that covered an area larger than western New York and northwestern Pennsylvania combined. Both shale and salt deform by flowing, but salt flows much more easily than shale. If we think of the shale behaving like Silly Putty, then we must visualize salt as behaving like a thick split pea soup.

In the Late Paleozoic, the stresses that were produced by the Alleghanian Orogeny pushed northwestward against the rock of the Allegheny Plateau (see the Tectonic Map on Plate 4). The layers below the Silurian salt remained fixed, but the salt layer, which had almost no strength, began to flow. This situation allowed the thick upper layer of Devonian and Carboniferous[12] rocks to slide to the northwest, without folding, like a stiff rug pushed across a slippery waxed floor. The upper section of the Allegheny Plateau thus slid northwestward along a large horizontal fault that developed in the salt layer. This fault, separating the fixed and transported sections, is called a *dècollement*.

Within the layers that slid, which we call *transported* layers, strong units include the Oriskany Sandstone, the Onondaga Formation, and the Tully Limestone, whereas weak units include the Upper Devonian siltstones and shales (see Plate 3). Added together, the weak units are much thicker than the strong units. It is this greater thickness of the weak units that controls most of the structures seen in outcrops of the Allegheny Plateau.

The thickness of the salt beds in the Salina Group exceeds 100 m throughout much of western New York. The salt beds thin out to zero thickness at the edge of the ancient sea. The northern edge of the salt runs east-west along a line south of Buffalo, Rochester, and Syracuse. We find deformation from the Alleghanian Orogeny in the transported layers everywhere above the salt layer. Where the salt layer ends, so does evidence of Alleghanian deformation (see the Physiographic and Tectonic Maps on Plate 4).

[11] *Stress* is the force that is applied per unit of area, such as grams of force per square centimeter or pounds of force per square inch.
[12] *Carboniferous* is another name for the Mississippian and Pennsylvanian Periods combined.

Layer-Parallel Shortening: The Way Rocks Can Deform Without Folding

As the transported rock section was forced to the northwest, it was pushed against the pinchout[13] of the salt. At the pinchout, with no salt to slide on, the upper slab of rock rested directly on the lower slab. Lacking the lubrication of salt, it was anchored there by friction. Despite this fact, compression from the southeast continued to push the slab against the northwest side of the basin. This compression caused the slab to actually become shorter, but *without folding* of the layers. Such deformation is called *layer-parallel shortening* (Figure 8.22). The amount of crustal shortening on the Allegheny Plateau was considerable; an original width of 200 km was shortened by 20 km during the Alleghanian Orogeny.

Layer-parallel shortening occurs in several different ways, depending on the strength of individual layers in the section. Weak shale and siltstone, the most abundant rock types in the Allegheny Plateau, were squeezed together like modeling clay. At the same time, the strong, brittle layers, including the Onondaga and Tully Limestones and the Oriskany Sandstone, broke into giant slabs. These slabs piled up like shingles on a roof (Figure 8.22).

What evidence for layer-parallel shortening can we see in individual rock exposures? We find the evidence in several types of structures, to be explained below: *deformed fossils, pencil cleavage, spaced cleavage, blind thrusting,* and *drape folds.* The first three are associated with flowing in the weak rock layers; the other two are connected with brittle breaks in the strong rock layers.

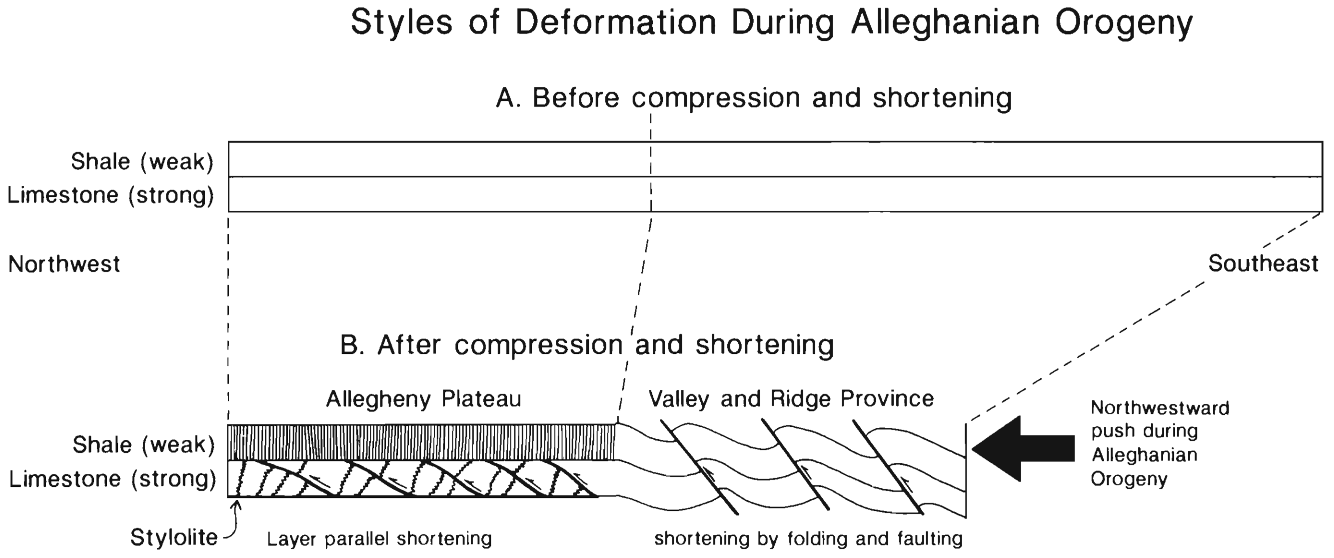


Figure 8.22. Greatly generalized diagram showing some of the ways in which rock on the Allegheny Plateau and the adjacent Valley and Ridge Province deformed when the crust was compressed during the Alleghanian Orogeny. (These provinces are shown on the Physiographic and Tectonic Maps on Plate 4.) In both provinces, the compressed crust became shorter. However, this shortening was accomplished in different ways, for reasons that are still being studied.

The Allegheny Plateau, which is discussed in this chapter, deformed by *layer-parallel shortening,* without folding. As the weak shale was compressed, pore water was squeezed upwards along thin vertical seams. As the water rose, it dissolved and carried away silica (chemical composition SiO_2) and left behind an insoluble seam of clay. The shale tends to break easily, or *cleave,* along these seams, so it is said to possess *cleavage.* (The seams are shown by thin vertical lines in the upper layer in (B).) This process, called *pressure solution,* shortened the layer by removing silica.

As the stronger limestone layers in the Allegheny Plateau were compressed, they, too, shortened by pressure solution. The water dissolved and removed calcite (chemical composition $CaCO_3$) along irregular seams, like those shown in the lower layer in (B). Insoluble clay was left behind in widely spaced seams, producing *spaced cleavage.* These seams are called *stylolites.* The limestone shortened by another process as well: the rock broke into blocks, and these blocks were thrust-faulted westward and stacked like roofing shingles. Arrows in the lower layer in (B) show this westward movement.

The crust in the Valley and Ridge Province, which is not discussed in this book, shortened by folding and faulting, as shown in the right-hand portion of (B), but in a much more complicated manner.

Field studies show that the Alleghanian Orogeny shortened the crust in the Allegheny Plateau by 10 percent and in the Valley and Ridge Province by 55 percent (compare (A) and (B)).

[13]A *pinchout* is the place where a body of rock that has been getting progressively thinner reaches zero thickness.

Deformed Fossils

Of the structures that are found in weak rocks that have undergone layer-parallel shortening, probably the most common and easiest to spot in outcrop are deformed fossils (Figures 8.23 and 8.24). When we see these misshapen fossils on the Plateau, we can tell that the rocks that contain them have been deformed.

It is easiest to see such deformation by finding a fossil of a *crinoid*, an animal related to the modern starfish. Although it was an animal, it looked much like a flower. It was attached by a stem to the bottom of ancient oceans or to other animals (see Figure A.3). When crinoids died, their stems, which consisted of many cylindrical segments, fell apart into many pieces. These pieces, called *crinoid columnals*, appear on bedding planes like small lifesavers. In undeformed rocks, columnals are perfectly circular. In the Allegheny Plateau, however, they have an elliptical shape. The shortened axes of these ellipses line up roughly in a north-south direction. This alignment is good evidence for layer-parallel shortening of the rocks in that direction. It shows that this part of the Plateau was compressed in a general north-south direction. In western New York, the shortened axes of the ellipses are lined up in a north-northwest direction. These alignments are reflected in the "Limit of Alleghanian Deformation" on the Tectonic Map on Plate 4.

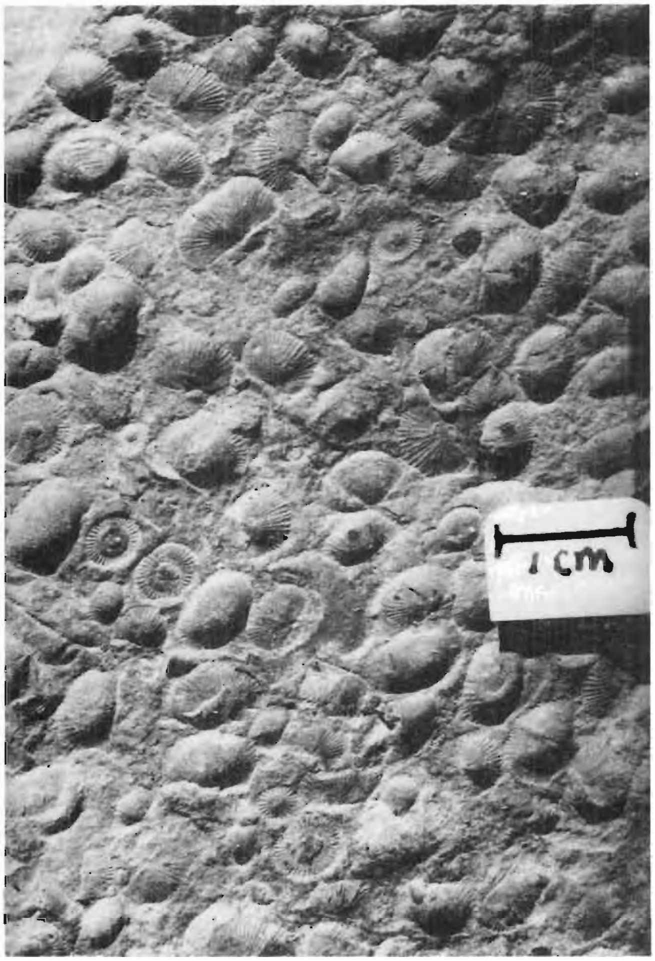


Figure 8.23. This photo is a view looking down on a bedding plane of a Devonian siltstone sampled near Wellsville, New York. Notice that the lifesaver-shaped crinoid columnals that were originally circular have been deformed into elliptical shapes. For a magnified view of a deformed crinoid columnal, see Figure 8.24. Notice also that their shortened axes all have the same orientation or alignment. It is easy to conclude that the rock was shortened along the direction between the upper left and lower right corners of this picture. The other fossils, brachiopods, are also deformed from their original symmetrical shapes (see Figure A.3).

Rock Cleavage and Pencil Cleavage

Rock *cleavage* refers to very closely-spaced parallel fractures (Figure 8.25). Cleavage develops in rocks that are being compressed. Sedimentary rock contains water in the microscopic openings (*pore spaces*) between its grains. When the rock is compressed, the water pressure is raised, and the water is forced upwards along microscopic passageways. As the water rises it dissolves silica (chemical composition SiO_2) in the rock. This process is called *pressure solution*. It results in leaving behind parallel seams of insoluble clay minerals. This removal of rock material by solution along the cleavage planes causes the rock to shorten at right angles to the cleavage. As the rock weathers, it breaks easily along these clay seams to produce very visible cleavage (Figure 8.26). If the rock has thin bedding planes as well as cleavage, the rock breaks along both, to form long narrow pieces called pencils. This kind of cleavage is called *pencil cleavage*. Where exposures contain both pencil cleavage and crinoid columnals, we find that the pencils point perpendicular to the shortened axes of the deformed crinoid columnals. Thus, pencil cleavage also shows that the layer-parallel shortening happened in a north-south direction in the Finger Lakes district.

Spaced Cleavage

Another kind of rock cleavage, called *spaced cleavage*, is a structure found in the Tully and Onondaga Limestones of western New York. Like pencil cleavage, it forms in rocks under pressure, when pore water dissolves part of the rock and leaves an insoluble residue of clay. The mineral that dissolves in limestones is calcium carbonate (chemical composition $CaCO_3$). The insoluble clay seam in limestones are thin, black, irregular surfaces that run through the rock (Figure 8.26). In outcrops of limestone, these irregular structures are called *stylolites*. When lime-

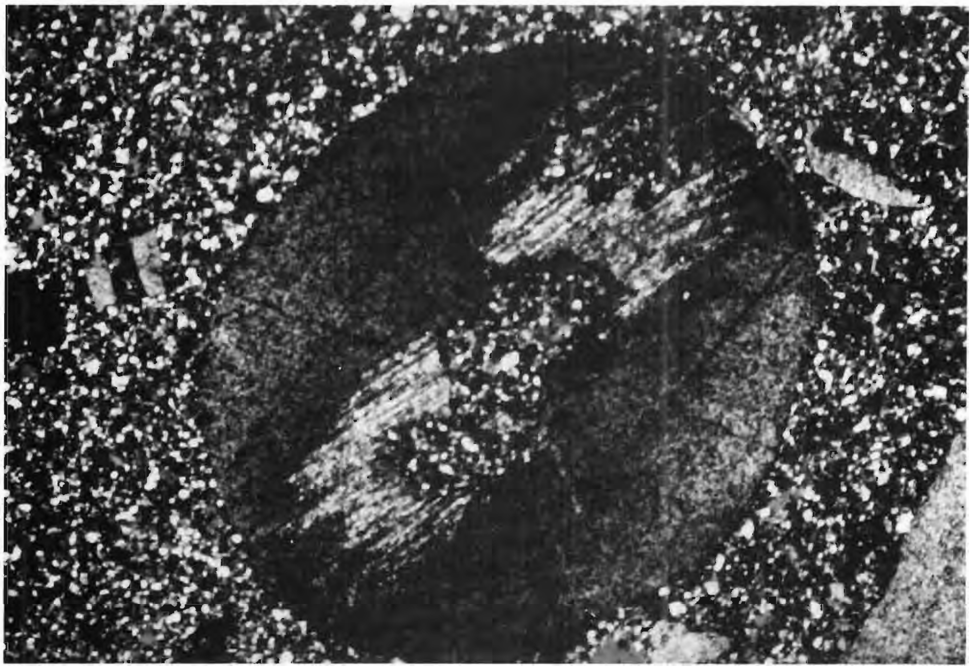


Figure 8.24. Microscope enlargement of a thin rock slice of a deformed crinoid columnal taken from the rock shown in Figure 8.23. The elliptical shape of the crinoid shows the deformation of a fossil that was initially circular in cross section. (This crinoid columnal is about 5 mm in the long direction.)

stones weather, the rock breaks easily along these surfaces. This kind of cleavage is called spaced cleavage because the stylolites form at regular intervals in the rock. The layer-parallel shortening is caused by the solution and removal of calcium carbonate by water rising along these surfaces. The shortening direction is therefore perpendicular to the cleavage, as was the case for the cleavage in shales described above.

Spaced cleavage indicates the same north-south shortening direction shown by deformed fossils and pencil cleavage. However, field studies of the spaced cleavage show that much less layer-parallel shortening has taken place in the limestone layers than in the shale formations that lie on top of it. It is hard to see how one layer could shorten less than one next to it; both would be expected to shorten the same amount. This seeming contradiction suggests that some additional shortening process must also have taken place in the limestone layers. Further field studies confirmed this hypothesis, as described below.

Blind Thrusting

Careful search led to the discovery that while the thick but weak layers of shale shortened by flowing, the thin but strong layers (Tully and Onondaga Limestones and Oriskany Sandstone) shortened equally. They deformed not only by solution along cleavage seams, but also by faulting. Faulted segments were stacked up like roofing shingles. This faulting and stacking shortened the limestone layers in the manner shown in Figure 8.22. We seldom see this faulting at the surface, however, because there are so few outcrops of the Tully, Oriskany, or Onondaga formations in central and western New York. Because the thrust faulting is below the surface and is only rarely seen, it is called *blind thrusting*.

Drape Folds

The faulting and stacking of the thin, strong limestone and sandstone layers created very low mounds beneath the surface. This arrangement caused the overlying shales to drape over these mounds in long, low, wave-like folds, called *drape folds*. Many of these folds are so gentle that they can barely be recognized. We can see them best along the shores of some of the Finger Lakes, where the lake surface provides a horizontal surface for comparison. We find such subtle folds scattered throughout the Allegheny Plateau.

Alleghanian Joints

The most common structures in rocks of the Allegheny Plateau are planar cracks, called *joints* (Figure 8.27). Some of the joints formed during the Alleghanian Orogeny. They are found in both the strong, thin layers of sandstone and limestone and the weak, thick shale cover. The high water pressure that developed in the rocks during the Alleghanian Orogeny became great enough to drive vertical cracks through the rock. The rock literally split when the internal water pressure exceeded the strength of the rock.

Outcrops in the Finger Lakes district all show abundant vertical joints that were formed in this way. They may exceed 300 m in length in cliff faces. In general, Alleghanian joints are oriented north-south; this direction is parallel to the direction of the layer-parallel shortening but at right angles to the cleavage discussed above. Thus, the orientation of these joints can be used as another clue to the direction of compression across the Allegheny Plateau during the Alleghanian Orogeny.

Figure 8.25. This photograph shows the vertical face of a Devonian shale near Scio, New York. Bedding is horizontal, as can be seen along the bottom of the picture. More pronounced, however, is a closely spaced rock cleavage that is perpendicular to bedding. The explanation of this cleavage is given in the text. When a rock like that shown weathers, the rock parts along cleavage planes and bedding planes to produce the elongate rock slivers, or "pencils," shown. This kind of cleavage is called *pencil cleavage*.

Figure 8.26. Spaced cleavage in the Onondaga Limestone near Geneva, New York. The view is looking down on bedding where very irregular stylolites cut vertically through the bed, as shown to the right of the jackknife.

Figure 8.27. Straight, planar cracks called *joints* are seen here cutting siltstones near Ithaca, New York. These joints, which are oriented north-south, are characteristic of many of the outcrops in the Finger Lakes District of New York.

During the Mesozoic Era, some north-south joints in central and western New York became the passageways for magma that moved upward from the earth's mantle. The magma solidified to form *kimberlite dikes*, which are most concentrated in the vicinity of Ithaca. (*Kimberlite* is a dark-colored igneous rock.) Most of the dikes are a few centimeters thick, but some reach several tens of centimeters in thickness.

Clarendon-Linden Fault Zone

Up to this point, we have been discussing structures that formed during the Alleghanian Orogeny. However, some important structures in the Allegheny Plateau formed at other times. These structures include a prominent fault zone and two different kinds of joints.

The most prominent deformation feature on the Plateau is the *Clarendon-Linden structure* located south of Rochester. At the surface, the structure is a north-south-trending fold (see the Tectonic Map on Plate 4). Drill holes show that at depth it is a fault zone made up of three or more segments. We think that the fault zone originated about 650 million years ago, when the Grenville supercontinent was breaking up, or *rifting* (see Chapter 3).

The Clarendon-Linden fault zone cuts through the entire fixed section and probably extends into the *basement rock*—the Proterozoic metamorphic rock that lies under the younger sedimentary layers. Geologists are still debating whether or not the fault zone also cuts the transported upper section of the Plateau.

Below the surface, some of the Middle and Upper Ordovician sedimentary rock units thicken near the Clarendon-Linden fault zone. This fact suggests that downward movement occurred along one side of the fault at about that time to create low areas where sediments piled up thicker than elsewhere. On this basis, we conclude that the Clarendon-Linden fault zone was either still active or again active in Ordovician time.

Evidence also exists that the fault zone may have been active in Devonian time, during the Acadian Orogeny. At the present time, small earthquakes are detected periodically in the vicinity of the Clarendon-Linden structure. These earthquakes suggest that the fault zone is still active. From all these observations, it appears that the Clarendon-Linden fault zone is the most active structure of the Allegheny Plateau. Periodic activity along this zone dates from Late Proterozoic time to the present day.

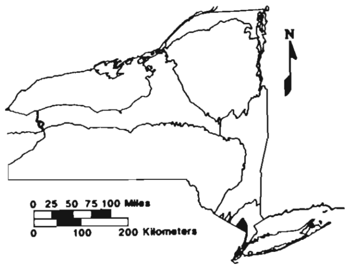
Release Joints

At the time the Allegheny Plateau region was undergoing layer-parallel shortening, sediments were pouring out onto it from a rising mountain range to the southeast that was, at the same time, undergoing vigorous erosion. Later, during the Mesozoic Era, great thicknesses of sedimentary rock were eroded away. Thus rock that was once deeply buried and therefore under great pressure was unloaded and brought closer to the surface. With a lessening of pressure, the rock expanded. This expansion stretched the crust and led to the formation of joints. Joints formed in this way are called *release joints*. These release joints line up roughly east-west in the Finger Lakes district, at right angles to the Alleghanian joints.

Late-Formed Unloading Joints

Other joints formed even later as the rock cooled. These late-formed joints line up roughly east-northeast. This direction is parallel to stresses found in the crust there today. Some geologists have used these late-formed joints to draw a map of the modern stresses in the Appalachian Mountains.

CHAPTER 9
DINOSAUR COUNTRY
Newark Lowlands[1]



SUMMARY

Only the northern part of the Newark Lowlands is in New York State; it lies between the Hudson Highlands and the Manhattan Prong. The region has a gently rolling surface broken by ridges. The Newark Lowlands lie within the Newark Basin, which is filled with the sedimentary rocks of the Newark Group. The Newark Group is divided into the Stockton Formation, the Lockatong Formation, the Brunswick Formation, and the Hammer Creek Conglomerate. The Palisades Sill, a thick layer of igneous rock, intruded the Newark Group 195 million years ago. It forms an impressive vertical cliff along the west bank of the Hudson River. When the Palisades diabase cooled and shrank, vertical fractures broke it into tall, six-sided columns. Another occurrence of igneous rock, the Ladentown Basalt, may have the same source as the Palisades, but the molten rock flowed out on the surface as a lava. Layers of similar basalt probably once lay on top of the Brunswick Formation in New York, but erosion has removed it here. Today, basalt lava flows are well exposed in New Jersey, where they form the Watchung Mountains. The Newark Group is wedge-shaped, and the resistant igneous rocks form ridges. It contains a number of faults and folds. The Newark Basin is the largest of 13 Mesozoic basins along the east coast of North America; these basins formed when the supercontinent of Pangea rifted. The rocks of the Newark Lowlands enable us to reconstruct the Triassic-Jurassic environment of the Newark Basin. By analyzing the gray rocks of the Lockatong Formation, we can tell that they were deposited in a lake that expanded and contracted as the climate became wetter and then drier; we find many such cycles in the rock. The brown rocks of the Stockton and Brunswick Formations were deposited in stream beds and on stream banks. From the distribution of the sedimentary rocks, we conclude that the region consisted of a long, narrow basin with streams flowing from all sides into a central lake. The lake level rose and fell periodically; many plants grew along the shore, and dinosaurs waded in the shallows. Based on radiometric dating of the Palisades Sill and on fossils, we think that the rocks of the Newark Group were deposited over a 35 million-year period during the Late Triassic and Early Jurassic.

INTRODUCTION

The Newark Lowlands lie west of the Coastal Plain and east of the Ridge and Valley Province and Reading Prong[2] (see Figure 1.1 and the Physiographic Map on Plate 4 of the *Geological Highway Map*). The Lowlands extend from the Nyack, New York, area across northeastern New Jersey into Pennsylvania. The New York portion is bounded on the northwest by the Hudson Highlands of the Reading Prong and on the southeast by the Manhattan Prong.[3] Farther south, the Coastal Plain forms the eastern boundary (see Chapter 10).

The Newark Lowlands are lower and flatter than the land to the west because the bedrock, which includes distinctive red sandstone and shale, erodes more easily. The Lowlands have a gently rolling surface that slopes down to the east. This surface is broken by ridges that are made of an igneous rock type called *diabase*, which resists ero-

[1]Adapted from a manuscript by W.B. Rogers.
[2]The Hudson Highlands are part of the Reading Prong. See Chapter 5 for more information.
[3]The Manhattan Prong forms the lowlands of Westchester County and the New York City region. See Chapter 5 for more information.

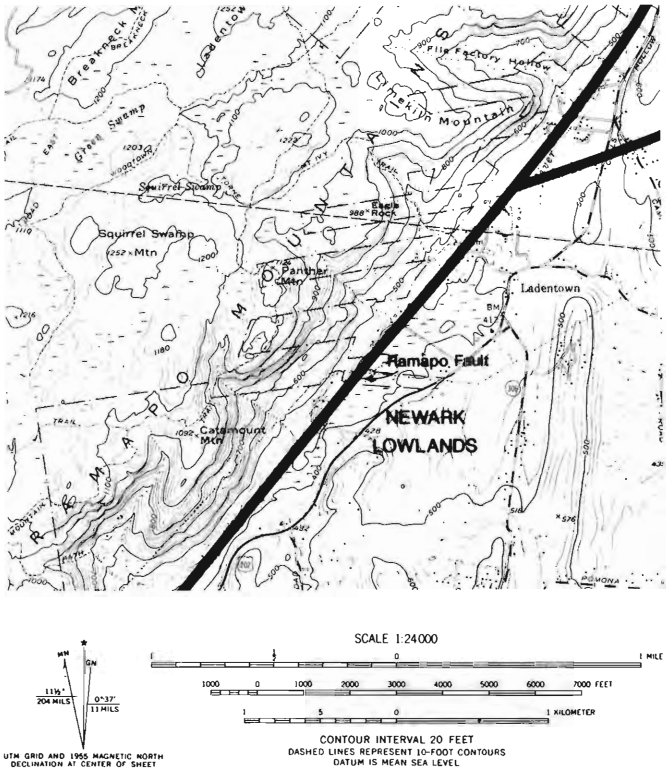


Figure 9.1. Topographic map showing the escarpment formed where the Ramapo Mountains of the Hudson Highlands border the Newark Lowlands on the west. The Newark Lowlands were down-dropped along the Ramapo Fault. The fault lies along the base of this escarpment.

sion. The ridges run northeast-southwest. Streams tend to cut channels in the softer red sandstone and shale between the ridges. Thus, the main valleys, especially in the northern half of the region, also run northeast-southwest and parallel to the ridges. These streams empty into Raritan Bay.

Along the northwest border, the Hudson Highlands rise along an abrupt *escarpment*, or cliff (Figure 9.1). The Hudson River flows along the southeastern boundary, bordered by the Manhattan Prong (Figure 9.2).

Rocks of the Newark Lowlands

The rocks of the Newark Lowlands lie in a large basin called the *Newark Basin* (Figure 9.2). We call the sedimentary rocks in the basin the *Newark Group*. Also present are several igneous intrusions and lava flows.

The Newark Group is divided into four units: the Stockton Formation, the Lockatong Formation, the Brunswick Formation, and the Hammer Creek Conglomerate (Figure 9.3). The lowest and oldest of these units is the Stockton Formation. It contains thick layers of sandstone and conglomerate that are rich in feldspar. These layers alternate with silty and shaley mudstone.

The Lockatong Formation, in the middle of the Newark Group, is not exposed in New York. It contains dark gray to black shales rich in organic materials[4] and limy mudstone. These rocks were probably deposited as sediments in a large lake. The Lockatong contains superb freshwater fossils, especially of fish. The fossils are found in the old Granton Quarry near North Bergen, New Jersey.

The Brunswick Formation consists of reddish-brown shaley mudstone. The mudstone alternates with layers of red-brown sandstone. These rocks gradually merge with the coarse-grained Hammer Creek Conglomerate. This conglomerate contains blocks and boulders (called *clasts*) of various older rocks, mainly Cambrian and Ordovician limestones and dolostones. Some of these clasts are as large as one meter across. We can see the conglomerate best near the western edge of the Newark Basin along the Ramapo Fault.

Of the igneous rocks in the Newark Lowlands, the most prominent is the Palisades Sill. It consists of the rock diabase; it is medium to dark gray when it is freshly broken. Diabase is made mainly of the dark green mineral pyroxene and the light gray mineral feldspar. Together, these two minerals give the rock a dark-colored "salt-and-pepper" appearance. Within the diabase, about 12-15 m above the base, we find a nearly pure layer of the mineral olivine, about 4.5 to 6 m thick.

The Palisades Sill was intruded into the Stockton, Lockatong, and lower Brunswick Formations about 195 million years ago, in Early Jurassic time. The Sill forms an east-facing cliff 120-300 m thick and more than 65 km long, along the west bank of the Hudson River (see Plate 2). It extends from west-central Staten Island to High Tor at Haverstraw, New York. Seen from across the river, the cliff looks like a colonial log stockade (a *palisade*), hence its name (Figure 9.4).

How did the Palisades Sill get its column-like structure? As the rock cooled, it shrank. The shrinkage caused vertical breaks, or *fractures*, in the rock. The fractures run through the rock from top to bottom and break it into tall, six-sided columns. Seen from above, these fractures have a honeycomb pattern.

Another occurrence of igneous rock is at Ladentown. It is *basalt*, which has the same mineral composition as diabase but is much finer grained. The Ladentown Basalt has a smooth, wavy-looking surface and contains gas bubbles[5]. It cooled and hardened at the surface as a lava.

[4] *Organic materials* are carbon-bearing remains of living things, such as plant material that has been partially turned to coal.
[5] This structure is similar to the ancient Watchung lava flows in New Jersey and modern lava flows in Hawaii.

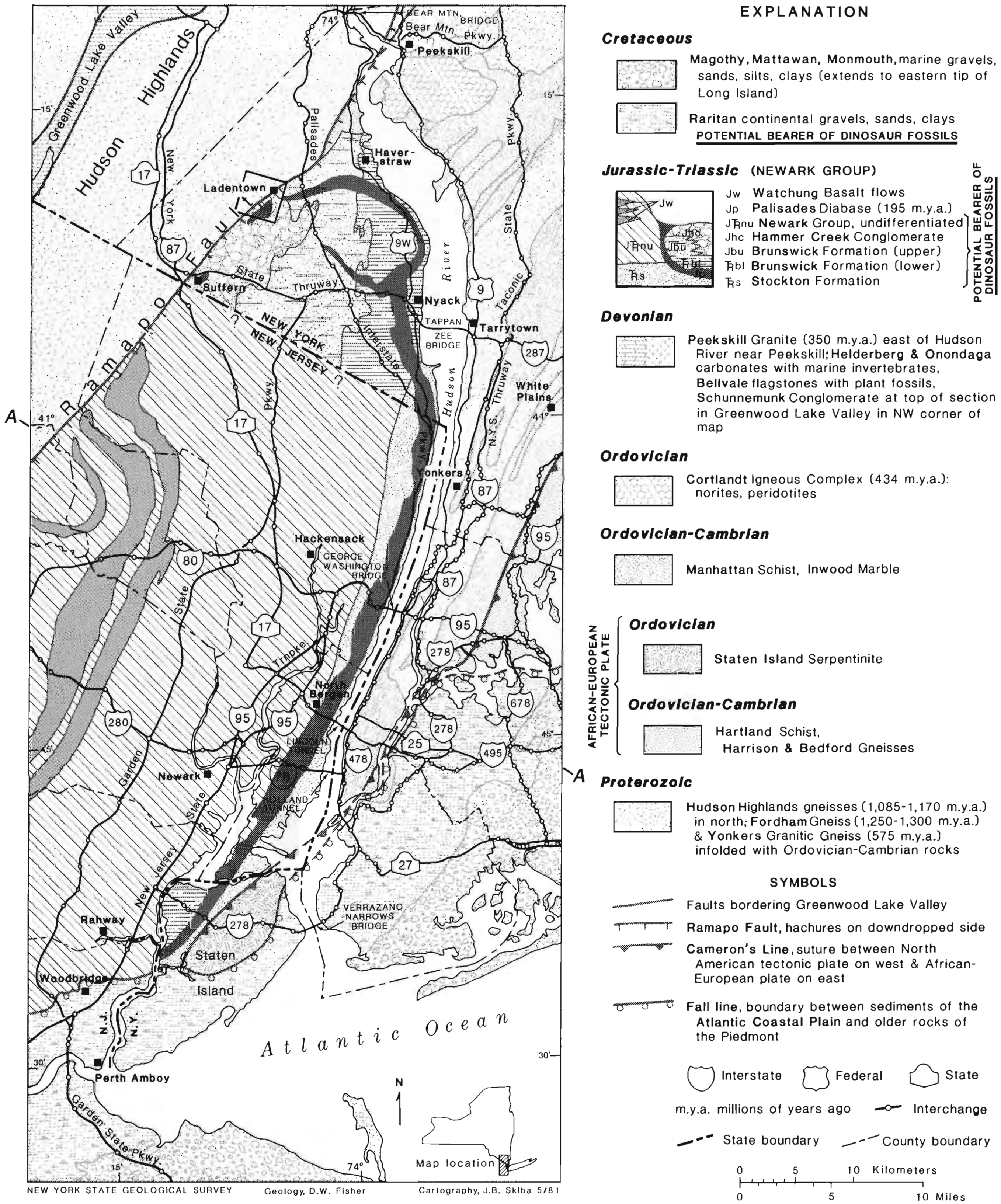


Figure 9.2. Generalized geologic map of the Newark Basin—the oval area between the Ramapo Fault and the Hudson River. It is bordered on the northwest by the Hudson Highlands and on the southeast by the Manhattan Prong east of the Hudson River. Highlighted in the "Explanation" are formations that may contain dinosaur bones and footprints. The box around Ladentown indicates the area shown in Figure 9.1. The cross section in Figure 9.5 follows the line between the letters *A* on the left and right sides of the map.

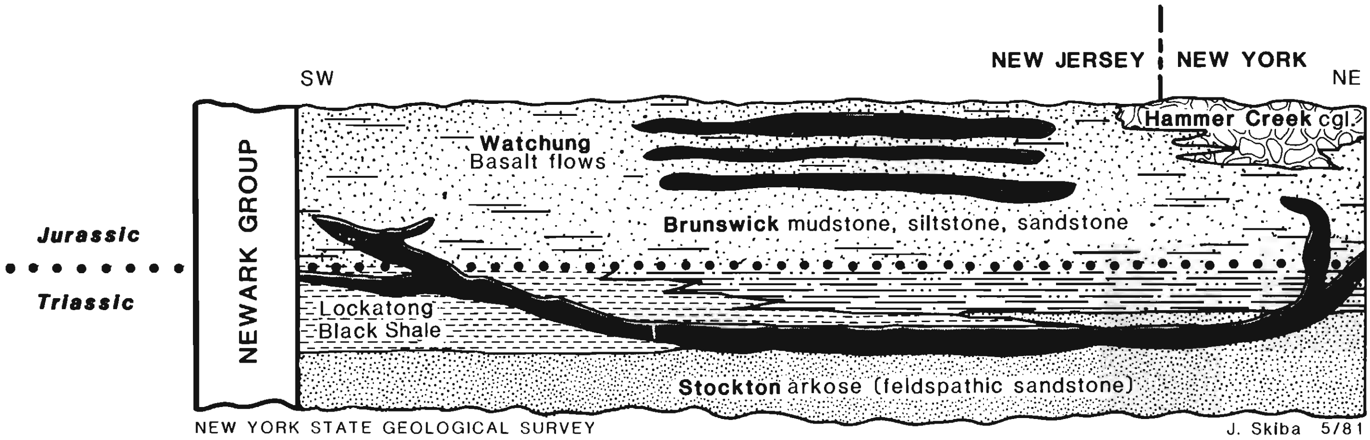


Figure 9.3. Diagram showing the general relationships of rock units in the Newark Group in cross section. These rock units are described in the text. The abbreviation *cgl* stands for *conglomerate*. *Feldspathic sandstone* means sandstone rich in the mineral feldspar.

Figure 9.4. Vertical columns along the face of the Palisades that formed when the diabase sill cooled and shrank during cooling. This view looks northwest from the east side of the Hudson River near the George Washington Bridge. At this point, the Palisades cliff is about 75 m high.

As it did, it shrank and developed curved fractures. Such curved fractures are commonly found in surface lava flows. The Palisades diabase and Ladentown basalt probably came from the same magma.

As the Brunswick Formation in New Jersey was deposited, basalt lava flowed out on the surface several times, each time to be buried by later sediments as the basin subsided (Figure 9.5). These basalt flows are similar to modern flows in Hawaii and older flows in the northwestern United States. The basalt and intervening sedimentary layers probably once extended over much of the Newark Basin. However, erosion has worn much of them away; they are now found only in the western part of the Newark Lowlands.

The basalt flows are much more resistant to erosion than the sedimentary rocks. Thus, they form the ridges called the Watchung Mountains (Figure 9.5).

Structure of the Rocks

The Newark Group is wedge-shaped in cross section (Figure 9.5). The layers slope 10°-15° toward the northwest. Where the sedimentary rocks have been eroded, some of the more resistant igneous layers form ridges that slope to the west. An excellent example of such a slope can be seen along Interstate 95 in the New Jersey meadowlands west of Manhattan. New Jersey Route 3 runs up the west side of a ridge, over the top, and down to the Lincoln Tunnel. The west side of the ridge is a gentle slope up to the summit of the Palisades Sill. This gentle slope is the upper surface of the igneous layer. On the other side of the ridge, however, the highway drops steeply across the Palisades cliff.

Faults bound the northwestern edge of the Newark Basin. In addition, many short north-south faults cross the northern part of the basin and intersect the border fault at angles of 30°-45°.

Folds, usually perpendicular to the border faults, stretch from the northwest edge of the basin about a fourth of the way across it. Many such folds occur along the border faults.

The Newark Basin is the largest of 13 large basins filled with early Mesozoic rocks along the east coast of North America (Figure 9.6). These basins are scattered throughout the Piedmont, New England, and Canadian Maritime Provinces. They are generally long and narrow, and run parallel to the coast. From their shape and position, scientists have concluded that they formed when the continental crust was stretched and broken. This rifting happened when the supercontinent of Pangea broke apart and the present Atlantic Ocean basin began to open and widen during the early Mesozoic (see Chapter 3 and the Tectonic Map on Plate 4).

What Was the Environment Like?

The gray rocks of the Lockatong Formation tell us a lot about the nature of the environment at the time they were deposited. Most of the formation consists of a cycle with three parts. From bottom up, these rocks are: 1) thin to very thick layers of gray siltstone, 2) thin layers of black to green-gray siltstone rich in calcium carbonate, and 3) thick layers of gray to gray-red sandstone or siltstone with cross-bedding (see Figure 7.1), fossil dinosaur footprints, and holes left by roots of plants. These cycles occur over and over again.

Each of the three rock types matches the kinds of sediments we would find in a lake at three different stages of its development. We would find the first kind in a lake that is expanding as the climate becomes wetter, the sec-

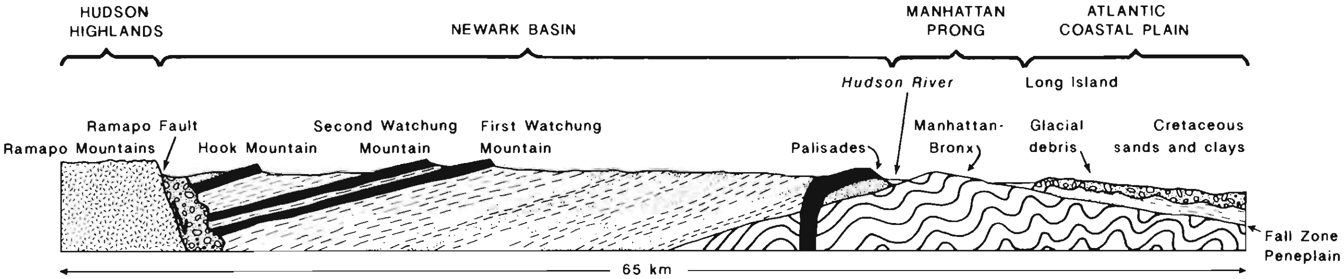


Figure 9.5. Generalized cross section of the Newark Basin. Notice the Ramapo Fault that forms the border between the Ramapo Mountains of the Hudson Highlands and the down-dropped Newark Basin. Intrusions of diabase are shown in black. The sedimentary rocks (shale and sandstone) were deposited horizontally; they were later tilted by downward movement along the Ramapo Fault. (The Hudson Highlands and the Manhattan Prong are discussed in Chapter 5; the Atlantic Coastal Plain and the Fall Zone Peneplain are discussed in Chapter 10.)

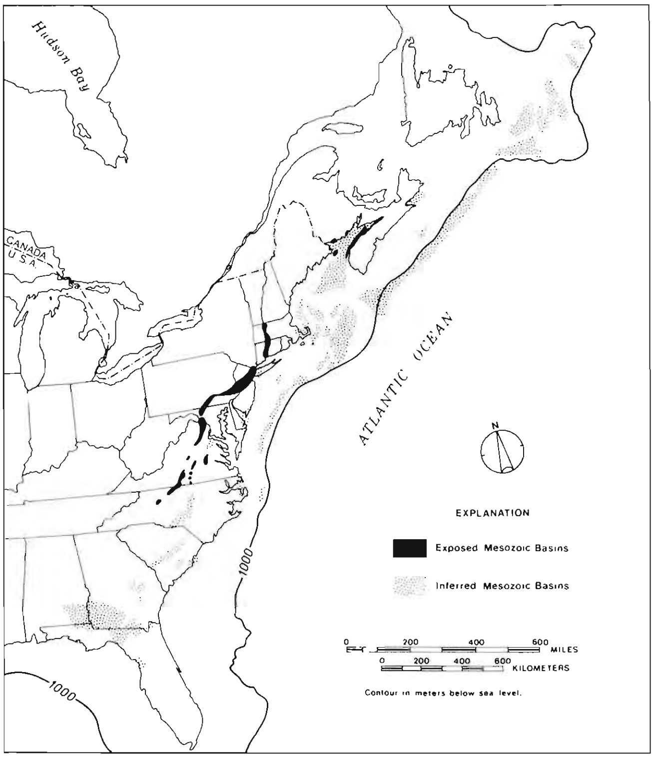


Figure 9.6. Other Mesozoic basins of eastern North America, similar to the Newark Basin. These basins formed when large blocks of crust were dropped down along faults. The basins gradually became filled with Triassic and Jurassic sedimentary rocks and were intruded by diabase. The basins formed because of rifting of the supercontinent Pangea. The Newark Basin is the largest exposed basin in the figure. Notice the inferred basins offshore. The contour line shows where the ocean is 1000 m deep. (See also the Tectonic Map on Plate 4.)

ond kind in a lake that has grown to its largest size in a very wet climate, and the third kind in a lake that had become very shallow as it evaporated under a dry climate.

Many such cycles are found in the center of the basin, where each is about 5 m thick. Toward the edges of the basin, however, the cycles are thinner; their arrangement suggests that they were deposited in shallow lake water close to shore. The fossils we find here support this interpretation. We find many more fossil footprints and remains of land plants at these margins than in the center. What does all this evidence mean? It suggests that the water was shallow enough for animals to walk in. Also, that the shore was nearby—close enough for land plants to fall into the water and be preserved there as organic remains in the sediments.

Most of the brown and reddish brown rocks in the Newark Basin originated as stream sediments. How do we know that? Some of the sandstones have cross bedding, which indicates they were deposited by moving water. The sandstone and the conglomerate are typical of the rocks formed in the stream beds or at the mouths of streams. In the mudstones of the Brunswick Formation, we find the impressions of roots and dinosaur footprints (Figure 9.7). The muds were not deposited in the stream beds, but on nearby stream banks and at stream mouths. In such places, the running water would not wash them away.

When we put all this information together, we can make a good guess about the kind of environment in which the Newark rocks were formed. It was a long, narrow low place in the landscape with streams flowing in from all sides. These streams deposited the sediments that later became the brown rocks in the area. In the central part of the depression was a lake whose shoreline expanded and contracted as the lake level rose and fell. In this lake were deposited the sediments that became the gray rocks of the Newark Basin. The fossils show us that there were many plants along the lake shore and the stream courses. From the footprints, we also know that dinosaurs walked along the water's edge and waded in the shallows.

Radiometric dating tells us that the igneous rocks of the Palisades Sill were intruded into the Newark Group about 195 million years ago, during the Early Jurassic. That age helps us to determine the age of the sedimentary rocks as well. This sill cuts through the lower sedimentary rocks. These rocks must therefore have been deposited before the sill intruded. The upper layers that were not cut by the igneous rocks were deposited after the intrusion took place.

The sedimentary rocks of the Newark Basin have many different kinds of fossils, both plants and animals. We find pollen, spores, and plant remains as well as many holes in the sediments made by plant roots; plants must have been abundant. We have found the footprints and remains of dinosaurs and an early *pterosaur*, or flying reptile. Many of these fossils have been found in New Jersey. So far, the only dinosaur fossils found in New York State are the footprints of the carnivorous dinosaur *Coelophysis* (Figure 9.7). We have also found the remains of clams, arthropods, and fish. From studies of plant and animal evolution through geologic time, we know approximately when these particular plant and animal species lived. Using that information, we are able to conclude that the sediments of the Newark Group were deposited over a 35 million-year period during Late Triassic and Early Jurassic time. An artist's reconstruction of the environment at that time, drawn from information found in rocks of the Newark Basin and rocks of the same age found elsewhere, is shown in Figure 9.8.

Figure 9.7. (A) Evidence that the Newark Basin was once "dinosaur country": three-toed footprints of *Coelophysis* found near Nyack, Rockland County, in the Triassic-Jurassic Brunswick Formation of the Newark Group.

(B) A restoration of this carnivorous dinosaur, which was about 3 m long, and its footprints.

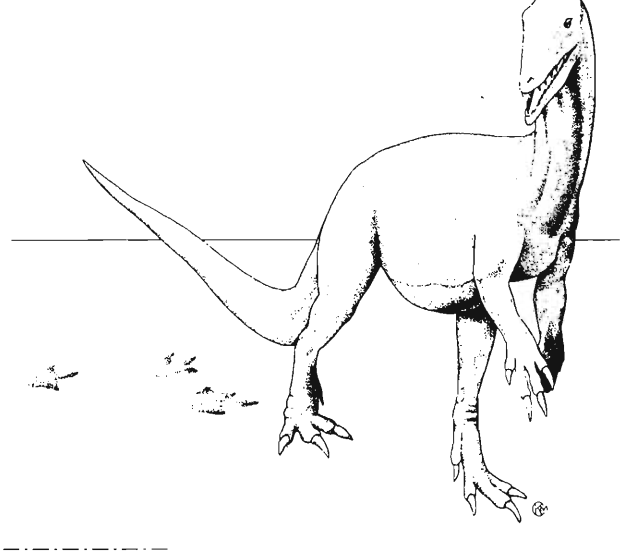


Figure 9.8. The Newark Lowlands, as they may have appeared about 180 million years ago. *Coelophysis*, seen in the right foreground, was about 3 m long.

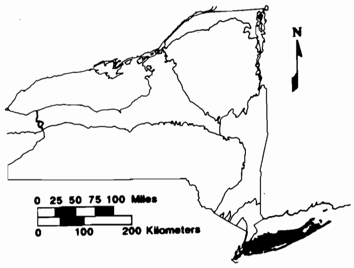
Review Questions and Exercises

Most of the bedrock in this region is which type—igneous, sedimentary, or metamorphic?

There are four major rock formations in this region. Describe them. In what kind of environments did they form?

What was happening in geologic history as the Newark Lowlands bedrock was formed? How did that create the environment where it was formed?

Chapter 10
At the Beach
Atlantic Coastal Plain and Continental Shelf[1]



Summary

Along the eastern edge of the continent is a very gently sloping surface that includes the Coastal Plain and the submerged continental shelf. It lies between higher land to the west and north and the continental slope to the east. The Coastal Plain is generally a flat, low-lying area that slopes very gently toward the sea. The inner edge of the Coastal Plain is the edge of a wedge of Cretaceous and younger sedimentary rocks. Underneath the wedge is an erosion surface of much older rocks—the Fall Zone Peneplain. As the younger rocks wear away, the Fall Zone Peneplain becomes exposed to erosion. We have used various techniques to trace the boundary between the softer sedimentary rocks of the Coastal Plain and the underlying basement rocks of the Fall Zone Peneplain. The sedimentary rocks thicken as we move away from land, so we conclude that the eastern edge of North America is slowly sinking. Of the rocks in this wedge, some were deposited slightly above sea level, and others slightly below sea level. Based on fossil evidence, we think that older rocks are found farther offshore; this conclusion reinforces the idea that the edge of the continent is sinking and the shoreline is creeping inland. The rocks of the Fall Zone Peneplain, all older than Middle Jurassic, have been tilted seaward. The younger rocks above the erosion surface were deposited at a time when the edge of the continent was gradually sinking. The edge of North America was heated and uplifted when Pangea rifted; it has been sinking gradually since then. Sediments eroded from highlands to the west built the wedge of sedimentary deposits as the shoreline gradually crept inland. This process began in the Middle Jurassic and continues today. The Coastal Plain slopes gently toward the sea because the edge of the continent has been sinking. The eroded edges of more resistant layers on this tilted surface stand up as ridges. On the continental shelf, we find channels that were cut by rivers when the shelf was above sea level during the Pleistocene Epoch. We also find broad ridges that mark former positions of the shoreline. Great canyons in the edge of the continental shelf and the continental slope may have been cut by currents filled with churned-up sediment when the shelf was above sea level.

Introduction

The Atlantic Coastal Plain is a very gently sloping land surface near the eastern edge of the continent. It is part of a continuous surface that extends offshore. The underwater section is called the *continental shelf*. The section above the shoreline is called the *Coastal Plain* (see Figure 1.1 and the Physiographic Map on Plate 4 of the *Geological Highway Map*).

The Atlantic Coastal Plain and continental shelf combined run from Newfoundland to Florida (Figure 10.1; see also the Physiographic Map and text on Plate 4). The surface is about 300 km wide for that entire distance. However, varying widths of it are underwater at different places along the coast. North of Cape Cod, for example, the entire surface is submerged. In New York, parts of Long Island and Staten Island are the only parts above water.

The Coastal Plain is bounded by higher ground on the landward side. The eroded Cretaceous rocks of the

[1] Adapted from a manuscript by W.B. Rogers.

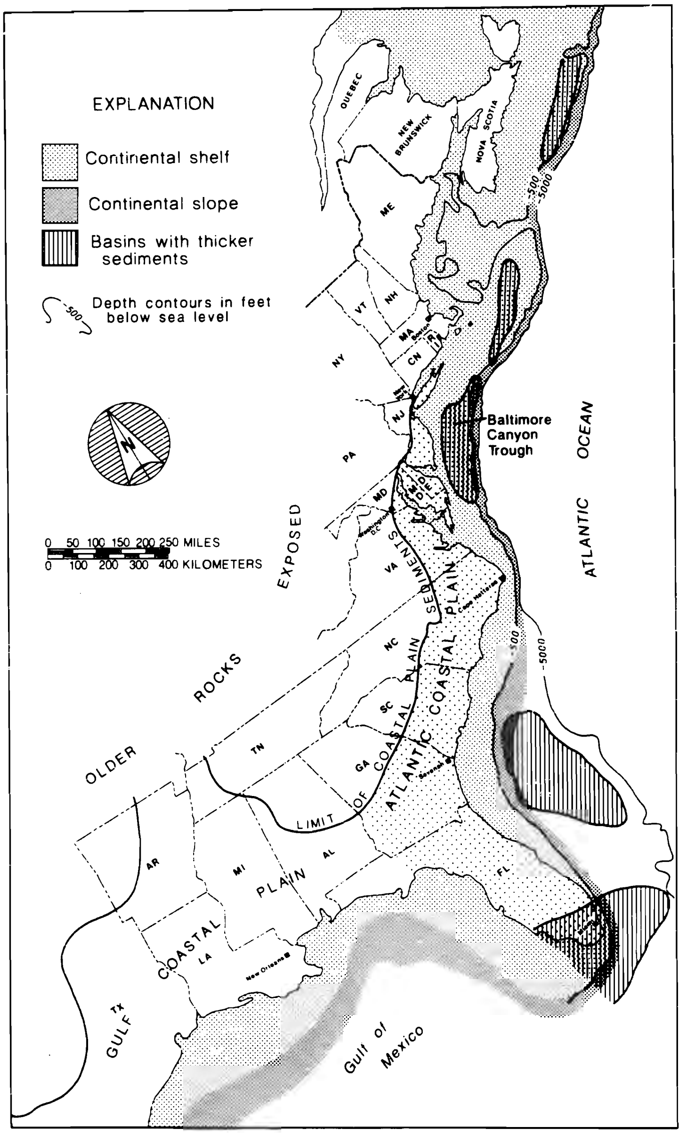


Figure 10.1. Map of eastern North America, showing the Coastal Plain and the continental shelf. Notice that the combined width of the two is fairly constant from Georgia to Nova Scotia. The contact between the Coastal Plain sediments and the bedrock to the west is called the *fall zone.*

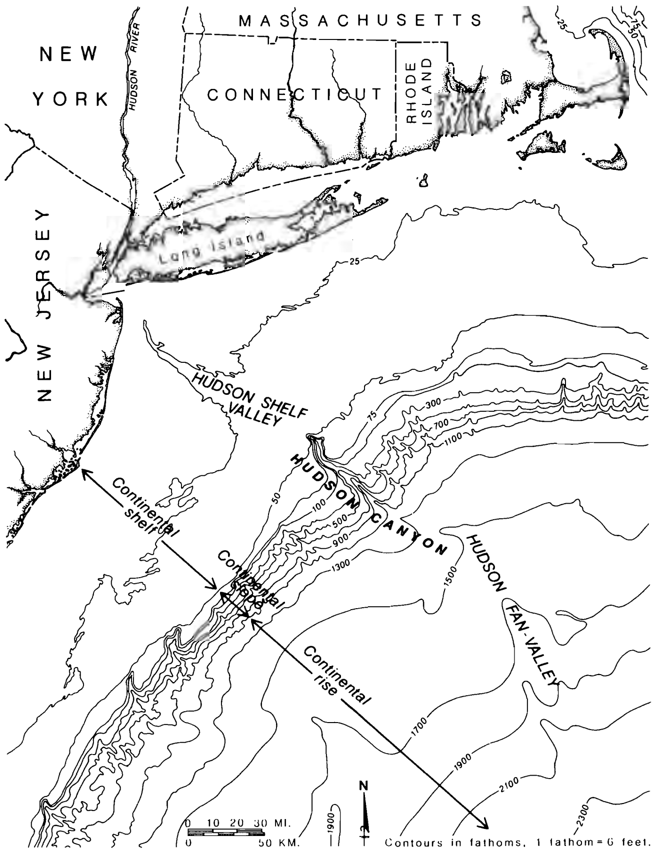


Figure 10.2. This map of the sea floor off the Atlantic coast of North America shows, going seaward, the nearly flat continental shelf, the continental slope, and the continental rise. Contour lines show the depth below sea level in fathoms (1 fathom = 6 feet). The contours reveal the location of the Hudson Shelf Valley on the continental shelf, the Hudson Canyon, and the Hudson Fan-Valley on the continental rise.

Coastal Plain end at this change in topography. The continental shelf is bounded on the east by a gently inclined underwater surface called the *continental slope* (Figure 10.2).

The Atlantic Coastal Plain slopes very gently toward the sea: only about 35 to 85 cm per kilometer.[2] As a whole, it tends to be flat, with rounded, gentle landscapes. In places in New Jersey, the Coastal Plain is more than 105 m above sea level. However, more than half of it in New Jersey is less than 30 m above sea level.

Rocks of the Atlantic Coastal Plain

Cretaceous and Tertiary sediments are part of a wedge of deposits that thins westward towards the inner edge of the Atlantic Coastal Plain. These sediments were deposited in or close to the ocean, some near sea level and some at moderate depths.

Underneath the wedge are older rocks of Early Jurassic to Proterozoic age. These older rocks were eroded to a rather flat surface before the Middle Jurassic. This erosion surface is called the *Fall Zone Peneplain* (see Figure 9.5). The younger and softer sedimentary rocks cover the resistant erosion surface as far west as the edge of the Coastal Plain (Figure 10.1). Beyond that, these older rocks make up the bedrock. The streams that flow eastward across this boundary pass from the resistant rocks of the

[2]The Coastal Plain slopes twice as steeply as the continental shelf. That is still a very gentle slope.

Fall Zone Peneplain to the easily eroded Cretaceous sedimentary rocks of the Coastal Plain. As a result, waterfalls develop there. This boundary of the Coastal Plain is therefore called the *fall zone*.

As the Coastal Plain sediments wear away, the Fall Zone Peneplain is gradually becoming exposed. As the older rocks are exposed at the surface, they also are being eroded. The older rocks slope toward the sea at about 6 m per kilometer. This slope is quite gentle, but the slope of the rest of the Atlantic Coastal Plain is much more gentle.

It was by using the techniques of geophysics that we were able to trace the boundary between the softer sedimentary rocks and the older, underlying *basement* rocks. To find out more about this boundary, we have drilled several holes out to sea beneath the continental shelf. The drilling program, combined with geophysical studies, discovered a large buried trough, the *Baltimore Canyon Trough* (Figure 10.1). This trough is a long basin that lies under the outer part of the continental shelf south of Long Island. The sedimentary rock in the trough appears to be 12 km thick. On the Long Island Platform at the edge of the shelf, the sedimentary rock is about half that thick. At Fire Island on the south shore of Long Island, the sedimentary section has thinned to 600 m.

This information leads us to think that the continent's edge is sinking. As the edge sinks, the sea water reaches farther and farther inland. Thus, it deposits sediments farther and farther inland on the continent. Areas out to sea have been underwater the longest. Thus, we would expect the sedimentary rocks to be thicker as we move away from the land.

Additional details come from deep wells near the edge of the continental shelf. The COST B-3 well was drilled 130 km south of Long Island in the Baltimore Canyon Trough (Figure 10.3)[3]. At a depth of over 4,890 m, the hole had still not reached the basement rock. It stopped in rock of Jurassic age. The rocks from the Early Cretaceous are nearly 2000 m thick in this well, but at the New York shore, they have already thinned to zero thickness.

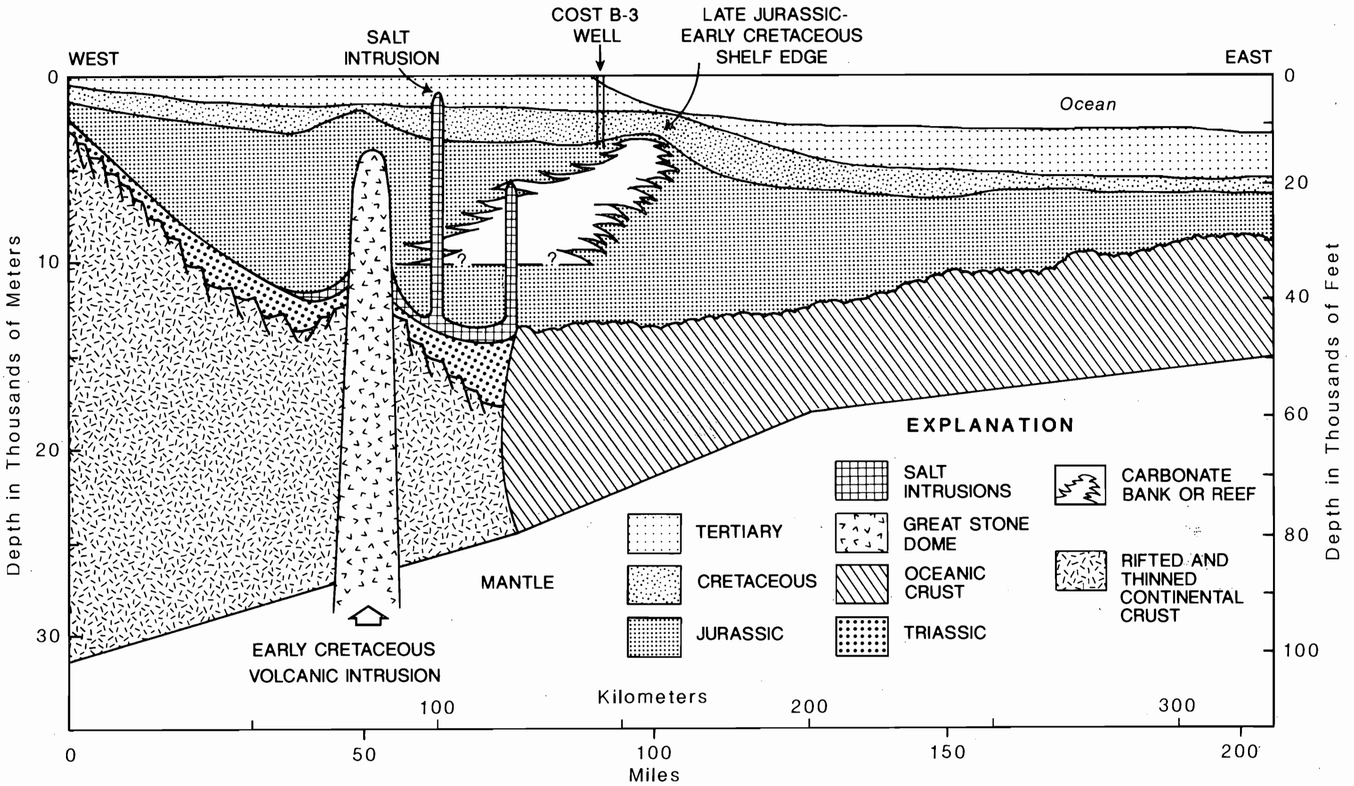


Figure 10.3. Diagram of a cross section of the Baltimore Canyon Trough. The vertical scale is greatly exaggerated. See Figure 10.1 for location of Baltimore Canyon Trough.

[3]*COST* stands for Continental Offshore Stratigraphic Test.

Rocks from the Late Cretaceous are 1000 m thick in the well and 500 m thick at the south shore of Long Island.

These drastic changes in thickness reinforce the idea that the eastern edge of the North American continent is slowly sinking beneath sea level.[4] But there are other reasons for differences in thickness. For example, sediments can, under some circumstances, pile up faster in one place than another during the same time period. In addition, these sediments were deposited on an uneven surface. It was warped and had low spots and high spots. Areas with low basement rocks flooded first as the edge of the sea crept inland, and they received a thicker sequence of sediments. Meanwhile, areas with a higher basement stayed above the water for a longer time. As a result, sediments will be thicker in the areas with a deep basement and thinner in areas with a shallow basement.

Most of the rocks in the sedimentary wedge are sandstone and shale. We also find some clay mixed with carbonate sediments (called *marl*) and a little limestone. Most of these rocks may have been deposited near shore, but slightly above sea level, in rivers and swamps. The rest would have been deposited in shallow water near the shore in an environment like the present continental shelf. The sediments deposited on the shelf contain a green mineral called *glauconite*, which is found only in marine rocks.

The oldest rocks we have found offshore are Jurassic, as shown by the fossils they contain. These fossils, especially pollen and spores, also tell us that sediments piled up almost continuously from the Jurassic through the Tertiary.

This fossil evidence further reinforces the idea that the ocean water is slowly advancing over the edge of the continent. The areas farther offshore have older rocks; this fact shows that they have been underwater longer. Areas closer to shore have younger rocks, which shows that they were flooded more recently.

Geologic History

The rocks of the Fall Zone Peneplain that lie under the Atlantic Coastal Plain are all older than Middle Jurassic. They include rocks of a variety of ages and structures. These older rocks have been warped downward, and this warping makes for a steeper slope for the Fall Zone Peneplain than for the Atlantic Coastal Plain.

Above these basement rocks, we find Jurassic and Early Cretaceous rocks. They were originally deposited near sea level. Today, they are found at much greater depths—5 km below sea level near the edge of the continental shelf. Thus, we deduce that the continental shelf has been gradually sinking as the sediments accumulated. This sinking has allowed a huge wedge of sediment to be deposited along the edge of the continent, a wedge that gets thicker the farther offshore we go.

When Pangea began to break up in the Late Triassic and Early Jurassic (see Chapter 3), eastern North America began to separate from Africa. Convection cells in the mantle transferred heat to the lithosphere in this great area. As the lithosphere was heated, it expanded slightly in volume and floated higher on the mantle as a broad upland. As this upland began to rise, it cracked, and molten rock (*magma*) was injected into the cracks. The convection cells flowed in opposite directions and worked to pull this part of Pangea apart. The Atlantic Ocean began to develop in a rift between eastern North America and Africa. As the edge of the North American continent got farther and farther from the magma that continues, even today, to rise at the rift zone, it cooled, became denser, and gradually sank. As it got lower, the sea crept over its edge.

Sediments were eroded from the highlands in the west and deposited along the seashore. They gradually built up into a wedge of sedimentary deposits. The location of the shoreline varied through time. It depended on how fast the land was sinking, as well as the rate that sediments were deposited. However, more important, probably, was the spreading rate of the growing Atlantic Ocean. During rapid spreading, more lavas were intruded along the rift in the center of the mid-oceanic ridge. This activity increased the size of the ridge and caused sea level to rise. The effect would be the same as piling a ridge of rocks, for example, along the bottom of a bathtub filled with water. The final effect of all these factors was that, slowly but surely, the shoreline crept inland until it reached its present position.

At times, the shoreline was out along the edge of the continental shelf. At those times, sediments poured down canyons on the continental slope to form great sedimentary aprons at its base.

As the shoreline crept landward past the edge of the continental shelf, the shelf began to become covered by sedimentary deposits. These deposits included deltas laid down by streams that flowed into the ocean. They also included near-shore marine sediments. These deposits continued to accumulate through the Middle and Late Jurassic, the Cretaceous, and the Tertiary. This process continues today.

The sedimentary layers that make up the Atlantic Coastal Plain were once horizontal. They now dip gently (between 1/3° and 1°) seaward. This slope was created

[4]According to geophysics, the edge of the continent is on the continental slope. It is there that the crust changes from continental crust to oceanic crust.

by the gradual sinking of the edge of the continent. Some of the sedimentary layers resist erosion better than others. The eroded edges of the harder layers form ridges. They stand up above the softer rocks that have been worn away around them. The ridges and valleys we see on the Atlantic Coastal Plain were formed in this way.

Fifteen thousand years ago, during the Pleistocene Epoch, sea level was 100 m lower than it is today (see Chapter 12). With sea level so much lower, the shoreline was out near the present shelf edge. Rivers flowed to this distant shoreline across what is now the submerged continental shelf. The channels of these rivers were partly filled with sediments as the sea level rose again. However, we can still see them on the shelf. They are called *shelf valleys*. One good example is the Hudson Shelf Valley (Figure 10.2 and the Physiographic Map on Plate 4). It extends from New York Bay across the shelf to the shelf edge, where it merges with the Hudson Canyon.

On the continental shelf, we also find broad ridges. They run generally parallel to the present shoreline. We believe that these ridges are old barrier islands that mark former positions of the shoreline. These islands were flooded as the sea level rose rapidly. Modern currents are gradually wearing them away.

The edge of the continental shelf and the continental slope are cut by great canyons eroded into the sedimentary apron. We don't know exactly how these canyons were formed. However, when the shoreline was close to the present edge of the continental shelf, rivers occupied shelf valleys and flowed to the shelf edge. We think that sediments may have been dumped at the points where the rivers reached the sea near the top of the continental slope. This accumulation caused giant slumps and sediment-laden currents to careen down the continental slope, eroding the underwater canyons on the way.

Review Questions and Exercises

Most of the bedrock near the land surface in this region is which type—igneous, sedimentary, or metamorphic?

How does the thickness of the bedrock in this region vary? How does the age of the bedrock vary?

The variations in age and thickness tell us about a process that is still going on today. What is that process? Why is it happening?

Part III
Surficial Geology

CHAPTER 11
THE MISSING RECORD
Tertiary Period[1]

SUMMARY

During the Tertiary Period, uplift and erosion of eastern North America carved most of the major features of the State's modern topography. Very few rocks or sediments from the Tertiary are found in New York, although they are important units in the coastal plains of the southeastern U.S. From plant remains and tiny fossils in these Tertiary sediments, we learn that the climate was warm during the early Tertiary but began to cool gradually 22 million years ago. The warm climate of the early Tertiary encouraged chemical weathering in the shaping of New York's landscape. By looking at the modern landscape, we can reconstruct where major rivers were during the Tertiary, before the drainage was changed dramatically by the glaciers of the Pleistocene.

INTRODUCTION

The most recent geologic era—the one we're still living in today—is the Cenozoic. It began 66 million years ago, when the extinctions of the dinosaurs and many other species brought the Mesozoic Era to an end. The Cenozoic Era includes the Tertiary Period, plus the Quaternary Period, which is the most recent 1.6 million years.

When the Cenozoic began, New York's bedrock had been formed. But the land surface looked very different from what we see today.

CARVING THE LANDSCAPE

By the Middle Jurassic, New York's bedrock had been eroded down to a flat plain. This erosion surface is called the *Fall Zone Peneplain*. During the middle part of the Cretaceous, the Fall Zone Peneplain was uplifted, and running water began to cut into it. To the east, the Peneplain dipped beneath the widening Atlantic Ocean. There, it was covered by Coastal Plain deposits and is still preserved deep beneath the surface. However, wherever the Fall Zone Peneplain was exposed in New York State, it was destroyed by erosion that accompanied slow uplift along the eastern seaboard.

The modern landscapes of New York developed in the Cenozoic Era. During that time, most of eastern North America continued to be uplifted, weathered, and eroded. As the land was uplifted, water flowed from the high areas down to the seas. The rush of water over millions of years sculpted the features of the landscape.

By the end of the Tertiary, the major features of our modern topography had already been formed. (The circular Adirondack Mountain dome may be an exception. It may have only begun rising at that time.) These features, and especially drainage, were later modified by ice sheets during the Pleistocene Epoch. We'll discuss glacial effects in the next chapter.

TERTIARY ROCK—MISSING ON THE MAINLAND

The sediments from the erosion of eastern North America were deposited during the Tertiary Period. In some western states, sedimentary rocks and igneous intrusions from the Tertiary Period are extensive. However, very little rock of that age remains in New York State. Some exists in nearby areas, though. We find a small Oligocene deposit of a kind of brownish-black coal called *lignite* in western Vermont near Brandon. Some Tertiary rock exists in the Coastal Plain deposits of states to the south and offshore on the continental shelf. From

[1]Adapted from a manuscript by W.B. Rogers.

the amount of sediment on the shelf today, we deduce that several kilometers of rock were eroded from New York and New England during the Cretaceous and early Tertiary.

Reconstructing the Tertiary Climate

With no Tertiary rock exposed in New York State, can we still figure out what happened in our region during that time? Yes, we can, with a little geological detective work. For evidence, we look at the Tertiary sediments on the continental shelf and slope off our shore.

Deep holes have been drilled near the coastline of central New Jersey and on the outer part of the continental shelf south of Long Island to sample to rock there. These samples show us that the Tertiary deposits are about 130 m thick along the shore but much thicker—1500 m—near the shelf edge. Much of this increased thickness was deposited during the middle Miocene Epoch.

We know the age of these deposits by studying the fossils found in them. The fossils are small and unspectacular looking, but they give us a great deal of useful information. They include microscopic plants and pollen as well as one-celled animals. These fossils tell us the age of the sediments and whether they were deposited on sea or on land. They also tell us what the climate was at the time.

Where we find tiny one-celled animals called *foraminifera*, we know that the sediment was deposited in the ocean. In contrast, where we find abundant plant pollen, we know that the sediment was deposited on land.

By identifying the pollen found in the sediments, we can see how the climate changed over time. Each type of plant produces its own kind of pollen. Suppose, for example, we found pollen from spruce and fir trees in one layer and pollen from pine and oak trees in a younger layer. Spruce and fir trees live in subarctic to cool temperate climates, which are warmer than arctic climates, but still fairly cold. Pine and oak trees live in temperate climates that are still warmer and more hospitable. A plant succession like the one described in this paragraph would show that the climate gradually became warmer.

We can find similar climate clues in the foraminifera. The various species change, depending on the temperature and depth of the water at the time.

In a manner like that described above, we have assembled the evidence provided by fossil pollen and foraminifera from the Tertiary Period. From this evidence, we have concluded that the Tertiary climate in northeastern North America varied from humid subtropical to arid and cold.

In most of the early Tertiary, New York was much warmer than it is today—it was between warm temperate and subtropical. The average annual temperature was about 5 degrees higher than today's annual average of 8°C. Frosty mornings were rare, even during the winter. About 22 million years ago, the climate began to cool gradually. At the end of the Tertiary, about 1.6 million years ago, a cool temperate climate was established. This climate was interrupted by four long "cold snaps," which will be discussed in the next chapter.

Tertiary Weathering and Erosion

Temperature and precipitation strongly influenced the shaping of New York State's landscapes during the Tertiary. In warm moist climates, chemical weathering is relatively rapid. Rocks are changed chemically by being exposed to water, oxygen, carbon dioxide, and acids derived from the decay of plants.

In the warm climate of most of the Tertiary, New York experienced deep chemical weathering. Water carried away the dissolved and fine-grained products of the weathering. *Saprolites* were left behind—deeply weathered rock material composed of the resistant grains that did not dissolve. Saprolite disintegrates easily and is eroded quickly by runoff, landslides, and the steady pull of materials downslope by gravity. It also becomes hidden by plant growth. Scattered remains of saprolites have been uncovered during highway construction in the Adirondacks, the Catskills, and the New York City area. These remnants are all that is left of the deep soils formed during the Tertiary.

Almost all of the Tertiary soil was carried away by glacial ice during the Pleistocene Epoch—the subject of the next chapter. However, scientists now believe that the worldwide cooling that produced the Ice Age began in late Tertiary time, at least 10 million years before the advance of the glaciers.

Different kinds of rock erode more or less easily. Granite and some conglomerates and sandstones resist both chemical and mechanical weathering. Because they are not easily eroded, they tend to form uplands. On the other hand, shales and limestones are easily altered or dissolved by weathering processes. They are eroded to form lowlands. Thus, the different kinds of bedrock in New York determined how the landscape was shaped by erosion in the Tertiary.

Tertiary River Systems

The shape of the modern landscape gives us clues to how that erosion happened. Careful study of New York's

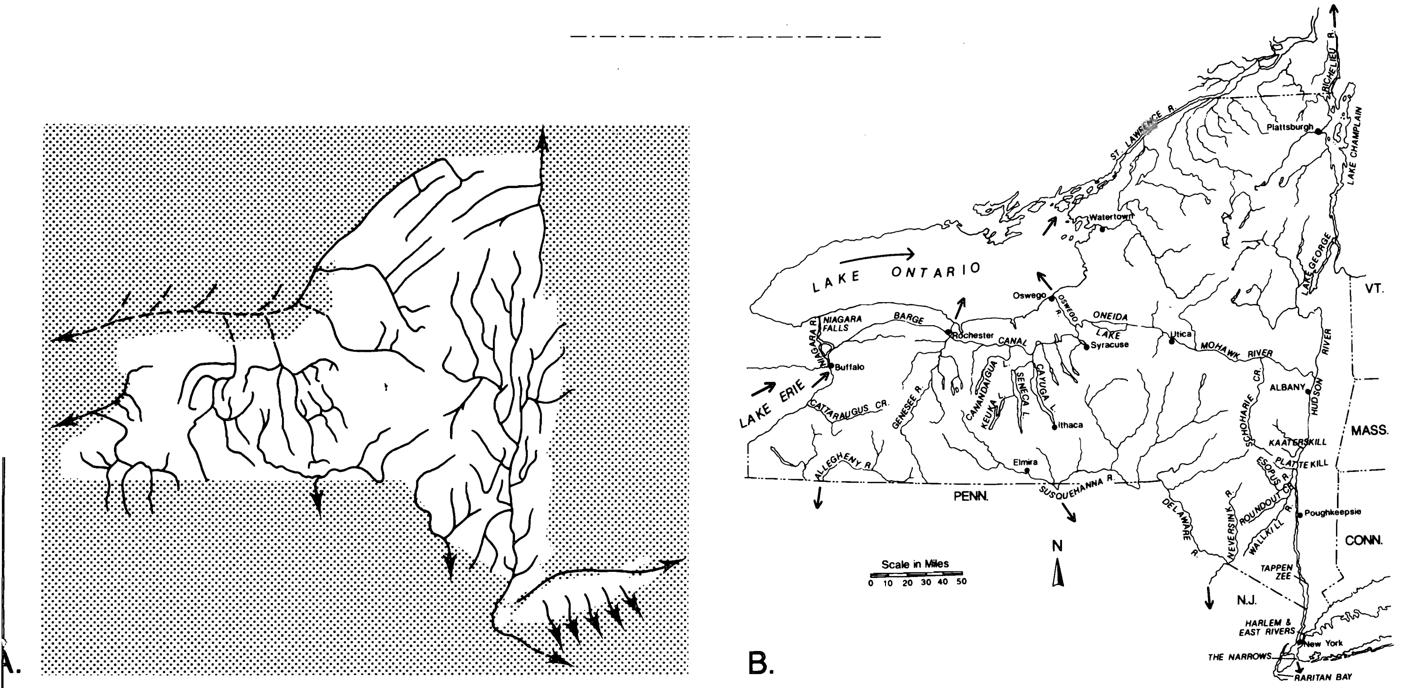


Figure 11.1. The map in (A) is a hypothetical reconstruction of the location of New York State rivers during the Tertiary. The reconstruction is based on the remains we have found of former stream valleys. Compare these rivers with the modern, postglacial rivers in (B). Notice how the drainage divides differ. Notice also that the Great Lakes and Finger Lakes were stream valleys, not lakes, during the Tertiary.

present landscapes lets us deduce earlier drainage patterns. In some places there are V-shaped cuts through upland areas that must have been made by major rivers. However, today these cuts are dry or occupied only by small streams. In other places deep valleys cut in bedrock were later completely filled with sand and gravel. These valleys have been discovered by well drillers.

From information of this kind, we have deduced the locations of major river valleys during the late Tertiary. The reconstructed Tertiary drainage patterns in New York State are shown in Figure 11.1A. For comparison, Figure 11.1B shows New York's modern drainage pattern.

The river that eroded the soft Middle Devonian shales of the Erie Basin has been named the Erian. The river that eroded the weak Ordovician shales of the Ontario Basin has been named the Ontarian. The preglacial Allegheny River flowed into the Erian River, which in turn flowed west into the Mississippi Basin. The Ontarian River drained northwest into Hudson Bay. The preglacial western St. Lawrence and Black Rivers and streams from the western Adirondacks flowed into the Ontarian. So did the rivers that flowed north through valleys in central New York. Today, these latter valleys hold the Finger Lakes.

The preglacial Hudson, Delaware, and Susquehanna Rivers generally flowed south toward the Atlantic Ocean. An eastward-flowing stream, the Sound River, flowed where we find Long Island Sound today.

These ancestral river systems carved the landmasses of New York into the broad outlines of the present landscape. The major hills and valleys were all in place. But if we went back in time, we would not recognize much of the landscape. There was still one large event needed to finish the job. The Ice Age was coming.

Review Questions and Exercises

Where do we find Tertiary sediments in New York? In nearby areas?

What clues tell us about the climate in the Tertiary? What conclusions have we reached about New York's Tertiary climate?

How do we know where rivers flowed during the Tertiary?

CHAPTER 12
THE BIG CHILL
The Pleistocene Epoch[1]

SUMMARY

During the Pleistocene Epoch, which began 1.6 million years ago, climates grew colder around the world for reasons that are not yet clear. Huge ice sheets advanced and retreated several times in the northern hemisphere. The last advance of these ice sheets, which occurred during the Wisconsinan Stage, reached its maximum in New York State about 21,750 years ago. The glacier accomplished spectacular erosion, scraping away soil and loose sediments, wearing away bedrock, and gouging river valleys into deep troughs. It also deposited the rock debris it carried in a variety of distinctive landforms. Glacial debris dammed many rivers and changed the State's drainage profoundly. The Wisconsinan ice sheet retreated from New York about 10,000 years ago. As it melted, it released huge volumes of meltwater. Where glacial debris had dammed valleys, vast temporary lakes were formed. Many of these glacial lakes have long since drained, although small remnants, including the Great Lakes and the Finger Lakes, still exist. At the close of the Pleistocene, meltwater from glaciers around the northern hemisphere raised sea level. The ocean flooded low-lying areas that had been depressed by the weight of the ice. Since then, the land has rebounded, causing the shorelines to shift to their present positions. In spite of the harsh climate during ice advance, a rich variety of plants and animals thrived south of the ice front. Many of the species still exist, but many others have become extinct.

INTRODUCTION

Soils form by chemical and physical breakdown of the underlying bedrock. However, in much of the northern hemisphere, including New York State, the composition of the soil is different from that of the bedrock beneath. The soil, therefore, could not have formed in place. How did New York's soil come to be where it is? How can we explain unusual features of New York's rivers and streams? What unusual landforms do we find, and how did they get here? Why is Whiteface Mountain such a steep-sided peak? Why do ocean tides flow up the Hudson River halfway to Canada? How did the Finger Lakes and the many other lakes in the State come to be? What do the remains of the wooly mammoth and other animals tell us about the past? These questions may seem very different, but the answers are all related. They all have to do with the Pleistocene Epoch—also called the Ice Age.

In this chapter we will discuss what we know about the Ice Age. Why do we think that a continental ice sheet once covered nearly all of New York State? When was the ice here? How do we know which way the ice sheet moved, how thick it was, or how it affected the landscape? These questions and others were asked by geologists in the past, and we continue to seek answers today. From the answers we have so far, we can reconstruct a geologic history of the Pleistocene Epoch.

Nearly all of New York State is covered by a variety of loose rock debris carried southward by glaciers. The glaciers formed in the arctic regions, grew, and merged into large ice sheets that slowly flowed southward into normally temperate zones. Eventually, immense blankets of ice, perhaps 2 km thick, covered much of the northern hemisphere (Figure 12.1). The glaciers changed the landscape at an amazing speed compared to other geologic processes. We see their effects everywhere across New York.

[1]Adapted from a manuscript by D.H. Cadwell.

Figure 12.1. During the Pleistocene Epoch, glacial ice covered most of the northern hemisphere, as shown in this drawing. Sea ice and icebergs filled the polar seas and spread down into the Atlantic Ocean. So much of the earth's water was frozen that sea level was 100 m lower than today. This drawing of the globe, looking down on the North Pole, shows the huge size of the Pleistocene ice cap.

How Did the Ice Age Begin?

The Pleistocene Epoch was a very recent chapter in the earth's history. It began about 1.6 million years ago; it ended only about 10,000 years ago, when the last glaciers melted northward. Or did it end? Some scientists believe that the Ice Age isn't over yet. During the Pleistocene, the ice advanced and retreated several times. Today's warmer climates may be just another interglacial lull; the glaciers could return someday. After all, ice sheets still occupy Greenland and Antarctica. We have no sure way of predicting a future ice age, but it is a real possibility.

About 10 million years ago, during the last part of the Tertiary Period, temperatures around the world began to drop. (We can trace the changes in climate by studying fossil plants and their pollen.) Tropical areas became subtropical. In turn, subtropical areas became temperate. Cooling continued. Eventually, the temperatures in the northern hemisphere became low enough to produce the icy climates of the Pleistocene.

In Pleistocene North America, snow remained on the ground all year long as far south as central New Jersey. This year-round winter happened not just on the cold mountain tops, but even at sea level.

During the Pleistocene Epoch, glaciers expanded dramatically in the northern hemisphere around the world. As the depth of the snow cover increased, vast ice sheets called *continental glaciers* began to flow south from arctic and subarctic regions. As they advanced, they merged with smaller *mountain glaciers* that had formed earlier. These mountain glaciers were streams of ice that flowed down the valleys in mountainous regions. The continental ice sheets that spread across northern North America and Eurasia (Figure 12.1) eventually reached 1 to 2 km in thickness. How do we know? We find, for example, scratches and grooves left by glaciers on the highest peaks in the Adirondacks—1.6 km high. This fact tells us that the ice was thicker than 1.6 km. At the height of the Ice Age, almost one third of the earth's land surface was covered by ice.

How low did the temperature have to drop to produce the Ice Age? Surprisingly, average temperatures worldwide were probably only about 5°C lower than today!

The Advance

Continental ice sheets began to flow south from the arctic and subarctic regions 1.6 million years ago. Once the glaciers started to move, a chain of events sustained the frigid new conditions.

When warm air from the south reached the glacier, it rose over the surface of the ice and cooled abruptly. As the air cooled, the moisture in it condensed and fell as snow. More and more snow piled up. The weight of new snow continuously compacted the snow beneath into ice. The pressure continued to build up and forced the ice to flow out in all directions (Figure 12.2). Centimeter by centimeter, kilometer by kilometer, the glacier crept along. How fast did it move? Some modern glaciers advance a meter or so each day. We can guess that the Pleistocene glaciers behaved in the same way.

Eventually the ice front reached a warmer area—either at a lower elevation or farther to the south. When the average temperature was high enough, the ice along the front melted as fast as the ice behind it pushed forward.

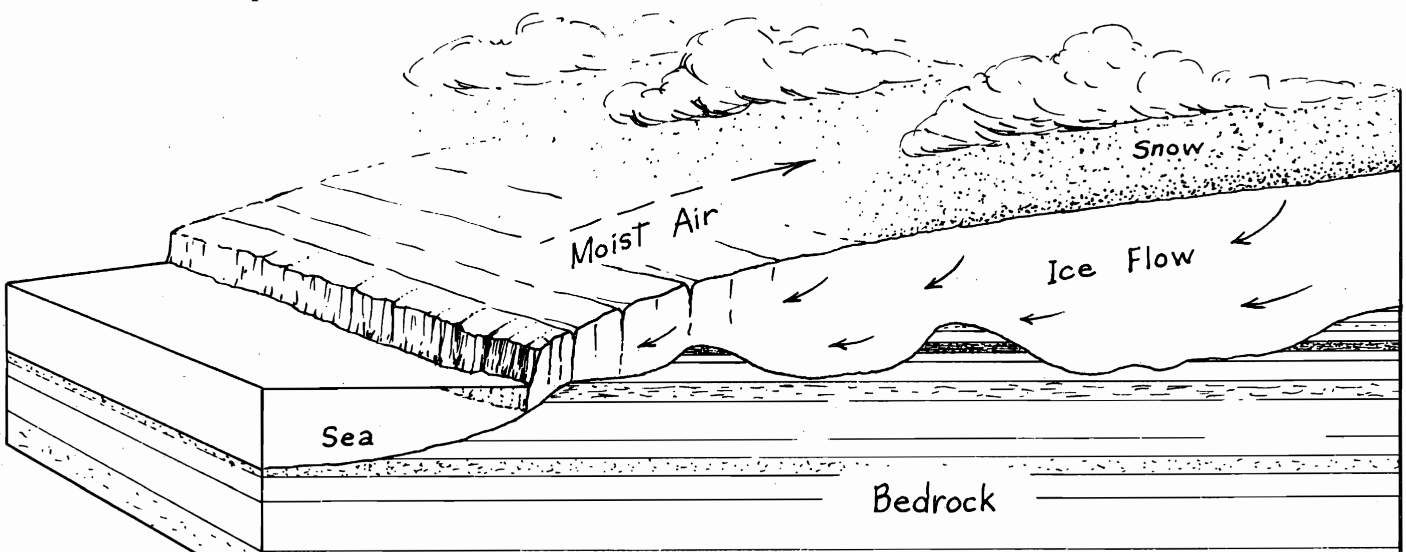


Figure 12.2. This diagram is a simplified cross section of an ice sheet. Notice the snow feeding the glacier behind the ice front and the ice flowing, even riding over low hills. (The vertical scale is highly exaggerated.)

As long as melting balanced forward flow, the glacier's front remained in one place.

The ice sheet that invaded New York is called the *Laurentide Ice Sheet* (Figure 12.3). It started in the Laurentian Mountains of Quebec and the uplands of eastern Quebec and Labrador. Almost all of New York State, nearly 130,000 km^2, was covered by the ice. Even so, that was only about one percent of the total area covered by the ice sheets in North America. About 21,750 years ago, the Laurentide Ice Sheet covered nearly 13 million km^2. Northeast North America looked something like Antarctica does today.

The enormous quantity of water frozen into snow and ice during the Ice Age lowered sea level by about 100 m worldwide. What evidence do we find in New York State for this drop? With sea level that low, much of the continental shelf offshore of New York would have been dry land. Today, we can find channels on the shelf that were cut by rivers. However, the channels are now under the sea and partly filled with sediment (see Chapter 10). Rooted tree stumps have also been found underwater on the continental shelf.

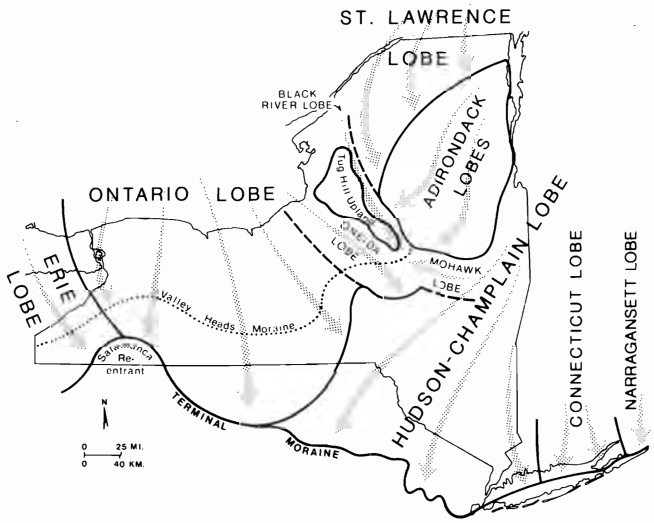


Figure 12.3. This map shows the part of the Laurentide Ice Sheet that covered almost all of New York State. The Terminal Moraine shows the maximum advance of the last ice sheet. Long Island contains two moraines. The island as we see it above sea level is a large dumping ground of glacial clay, sand, gravel, and boulders. The pile of glacial material that forms the Valley Heads Moraine has created a drainage divide across the middle of the State (see Figure 16.1).

The glacier flowed across New York State in connected ice streams, or *lobes*. The Erie Lobe flowed southeast, out of the Erie Basin. The Ontario Lobe flowed southwest across the St. Lawrence and Ontario Lowlands, then changed direction to flow south and southeast into the Appalachian and Tug Hill Uplands. The Salamanca Re-entrant of southwestern New York, where two lobes joined, escaped being covered by the last ice advance. The Hudson-Champlain Lobe advanced through the Champlain and Hudson Lowlands and eventually reached Long Island. Parts of the Hudson-Champlain Lobe spread into the Adirondack Mountains, Mohawk Valley, Catskill Mountains, and Taconic Mountains. It also covered northern Long Island, west of Lake Ronkonkoma. The Connecticut Valley Lobe covered northern Long Island east of Lake Ronkonkoma.

After the continental ice sheet melted, the meltwater raised sea level again—about 100 m. Today ocean tides move up the Hudson River as far north as Albany and Troy. (The salt water does not extend north of Poughkeepsie, though, because the river flow pushes it back.) The Hudson River south of Troy is therefore actually an *estuary*, or arm of the sea. Where it flows through the Hudson Highlands, the Hudson is a *fjord*—a long, narrow bay with cliffs on either side. The water in the lower Hudson is deep enough to accommodate large ships. It was the Ice Age that deepened the Hudson River and enabled Albany to become a port for ocean-going vessels.

How do we reconstruct what the ice sheets did in New York? We look at the many clues they left behind (Figure 12.4). As the glacier advanced, it scratched and grooved the bedrock and streamlined the landscape. Then as it melted, it left great quantities of rock debris in a wide variety of deposits. By examining such clues, we can deduce the directions of ice movement across the State. We find that the ice sheet flowed across New York in "ice streams," or *lobes* (Figure 12.3).

During the Pleistocene Epoch, the Laurentide Ice Sheet made four major advances into the northern United States. Between advances, warm stages caused the ice sheet to retreat back into Canada. During these interglacial lulls, temperatures were probably even a bit warmer than today! How do we know that there were four separate advances? The best evidence for multiple advances comes from glacial deposits in the Midwest. In New York State, however, nearly all traces of earlier glacial stages were removed by the last advance, which happened during the last part of the Pleistocene Epoch, called the *Wisconsinan Stage*. It covered almost the entire State and left almost all the glacial deposits we find here today. The only exception is an area called the *Salamanca Re-entrant* (Figure 12.3), which is part of Allegany State Park. It was ice-free during the Wisconsinan Stage, although scattered evidence suggests that it was covered during an earlier advance.

The oldest Pleistocene deposits in New York are marine gravels found in deep wells on Long Island, soils preserved in a ravine near Cayuga Lake, sediments unearthed in excavations near Otto, Cattaraugus County, and buried soils in wells in the Schoharie Valley. These materials may have been deposited during any of the warm interglacial periods before the Wisconsinan Stage. They may also have been deposited during a temporary retreat of the glacier in the middle of the Wisconsinan Stage.

The glacier affected the landscape through two processes—erosion and deposition. We consider these processes next.

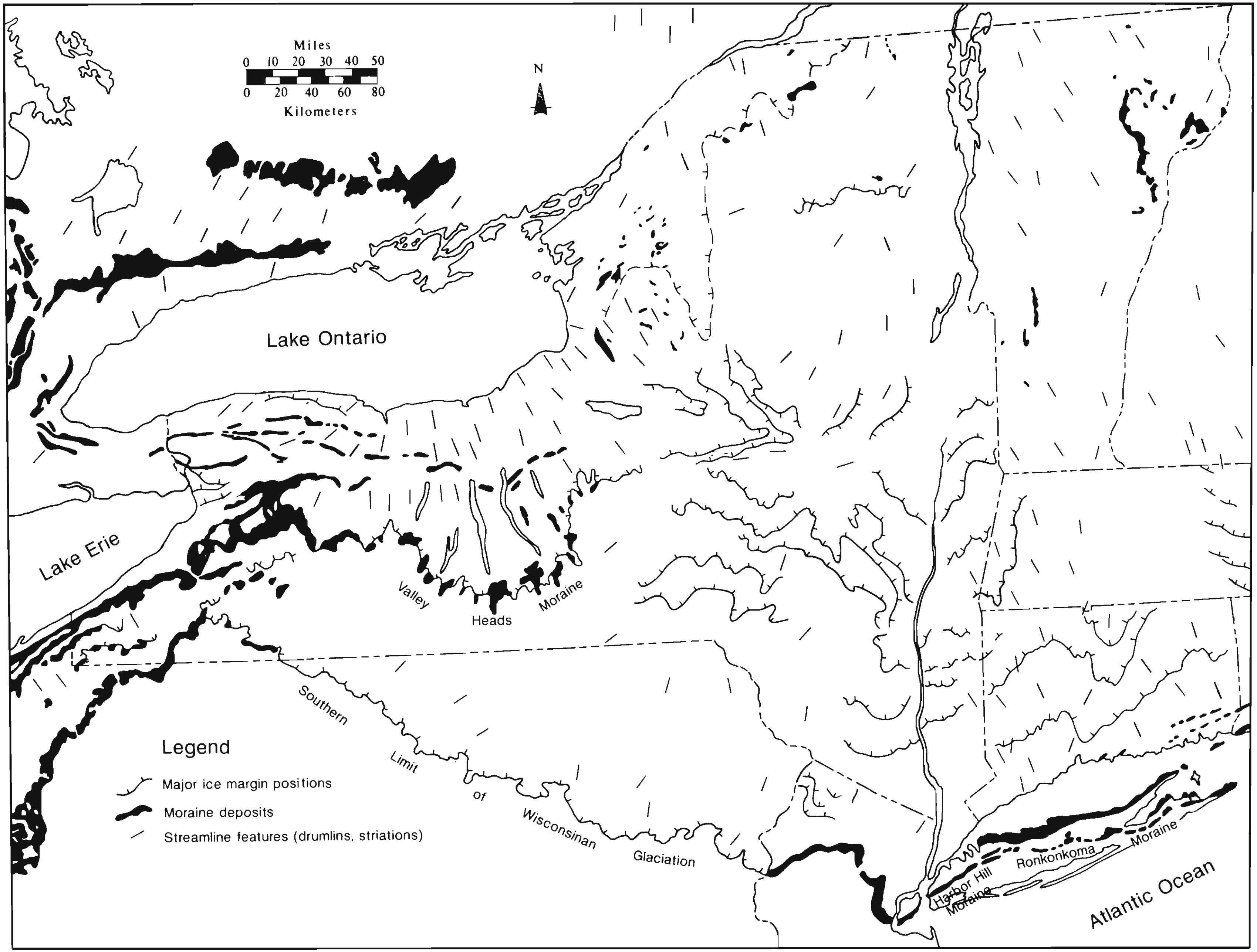


Figure 12.4. This map of New York State and surrounding areas shows the locations of moraine deposits; it also includes features like drumlins and striations that indicate the direction of glacial flow. It was by looking at such evidence that scientists reconstructed the history of the Pleistocene Epoch in New York. The map also indicates position of the edge of the ice sheet at various times.

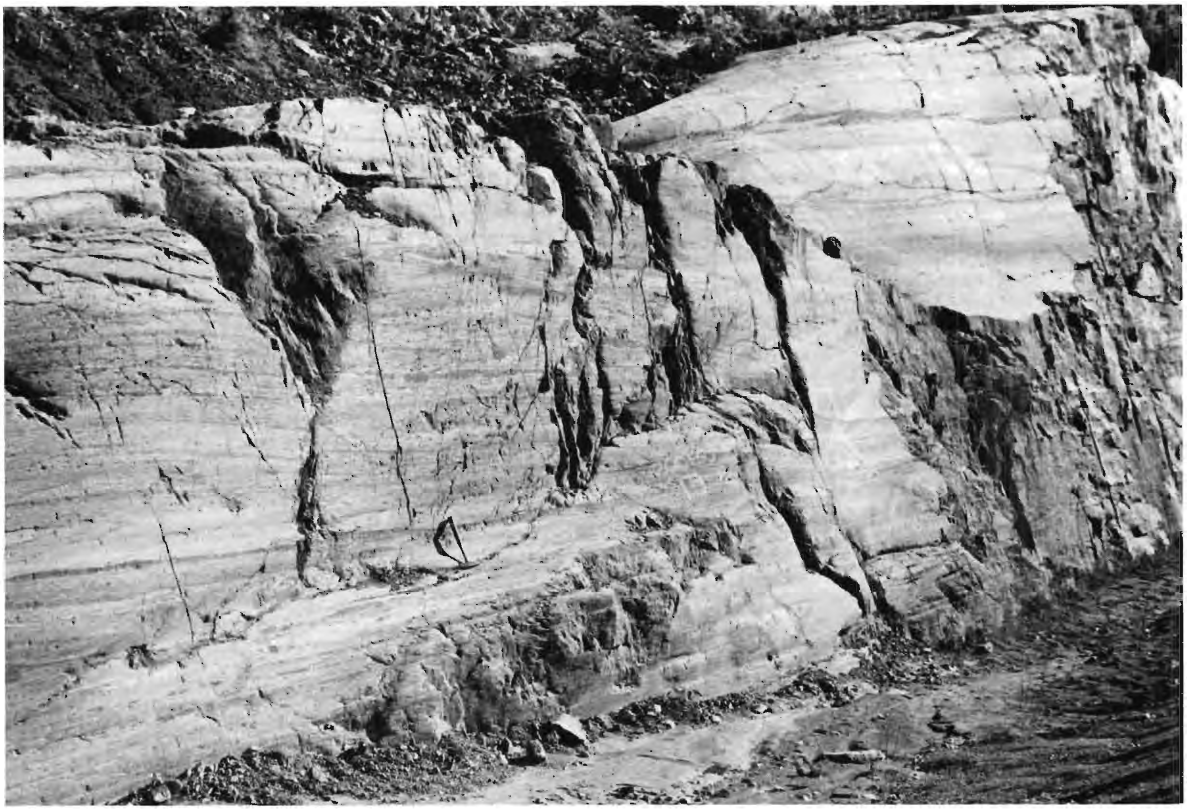


Figure 12.5. The moving glacier sculpted, scoured, and polished this garnet gneiss, found along U.S. Rte. 4, 5.4 km northeast of Fort Ann, Washington County. Note hammer for scale. The rock was polished by cobblestones, gravel, and sand grains that were "cemented" in the bottom of the glacier and dragged across the exposure by the slowly moving mass of ice. Thus, the glacier acted like a giant piece of coarse sandpaper.

Glacial Erosion and the Landforms It Created

The erosion accomplished by the slowly moving mass of glacial ice was astounding. The ice sheet transported millions of cubic kilometers of pre-existing soil and deeply weathered bedrock that had formed during Tertiary time. The glacier also tore free large blocks and pieces of the underlying bedrock. These chunks of bedrock were carried along embedded in the ice.

Filled with mud, sand, gravel, and boulders, the glacier had an underside like a giant piece of very coarse sandpaper. It ground soft shales and limestones into rock flour. It smoothed and polished outcrops of resistant bedrock (Figure 12.5) and scored deep grooves and scratches (called *striations*) into them (Figure 12.6). It rounded and polished knobs of bedrock, called *roches moutonnées* (Figure 12.7). After the ice melted, large boulders, called *erratics*, had been transported kilometers from their places of origin (Figure 12.8). Some of these erratics have striations that were formed as the erratics were dragged along in the bottom of the glacier.

Where glaciers flowed parallel to V-shaped river valleys, they gouged the valleys into deep troughs with U-shaped cross sections (Figure 12.9). New York's Finger Lakes lie in former river valleys carved into U-shaped troughs of this type. Tributary streams that entered these valleys at nearly right angles to the direction of the ice flow were not eroded nearly as deeply by the ice. After the ice melted, the floors of such tributary valleys were left high on the walls of the main valleys. (They are called *hanging valleys*.) Tributary streams formed spectacular waterfalls as they dropped directly from hanging valleys into the steep-walled main valleys. Since the retreat of the ice, running water has gradually worn the rock away, causing the waterfalls to move up the tributary valleys and away from the main valley. Taughannock Falls (Figure 12.10) and several waterfalls and cascades near Ithaca and at Watkins Glen are striking examples of streams that once plunged from hanging valleys; since the ice sheet retreated, these falls have all moved upstream.

The ancestral Hudson River valley was parallel to the direction of ice flow. Where the river flows through the Hudson Highlands, the glacier scoured the valley's

Figure 12.6. Glacial striations on the Larabee Member of the Middle Ordovician Glens Falls Limestone southeast of Chazy, Clinton County. Such striations can often be found atop road cuts where bulldozers have removed the glacial debris that covered the rock. Notice the knife for scale and the arrow indicating north. The directions of such striations give us a major clue in figuring out the directions of ice flow (shown in Figure 12.3).

bedrock floor to a depth of 240 m below sea level. (We base this figure on drill hole tests made for the Catskill Aqueduct tunnel that crosses the Hudson River at Storm King and carries drinking water to New York City.) Many tributaries, including the Mohawk River, occupied hanging valleys and now cascade down a series of waterfalls and rapids to the Hudson River.

While the main continental glacier was retreating, smaller mountain glaciers lingered in highland areas. Mountain glaciers of this type were especially common in the Adirondack and Catskill Mountains. In contrast to the smoothing effect of the huge ice sheet, these mountain glaciers concentrated erosion within stream valleys and sharpened the landscape (as shown in Figure 12.11). In the Catskills and Adirondacks, they carved river valleys into U-shaped cross sections (Figures 12.9 and 12.11) and steepened the valley walls, often forming spectacular cliffs. At the heads of the valleys, the glaciers created large bowl-shaped amphitheaters called *cirques*. The steep walls of cirques formed where the ice dislodged chunks of bedrock from the mountain. In cold climates, rock is broken into smaller and smaller pieces as water flows into cracks, then freezes. In the glacial climate of the Pleistocene, water repeatedly melted and froze. The water expanded as it froze and pried the rock apart along the natural cracks (called *joints*). As the glacial ice flowed downslope, it plucked the loosened blocks of rock, leaving vertical valley walls. Whiteface Mountain in the Adirondacks has several impressive cirques encircling its peak (Figure 12.12).

Glacial Deposition and the Landforms It Created

Erosion was one of the major effects of the Pleistocene glacier. The other was deposition—the dropping of the rock debris that the glacier carried. With these deposits, the glacier dammed rivers and changed their courses. It left vast amounts of mud, sand, and gravel that covered much of the bedrock. It also created a number of distinctive landforms (Figure 12.7).

We have found buried stream valleys in Chautauqua, Onondaga, and Cortland Counties that existed before the glacier advanced. Today, these valleys are filled with over 300 m of glacial debris. West of Glens Falls, the Hudson River meanders for a short stretch across a

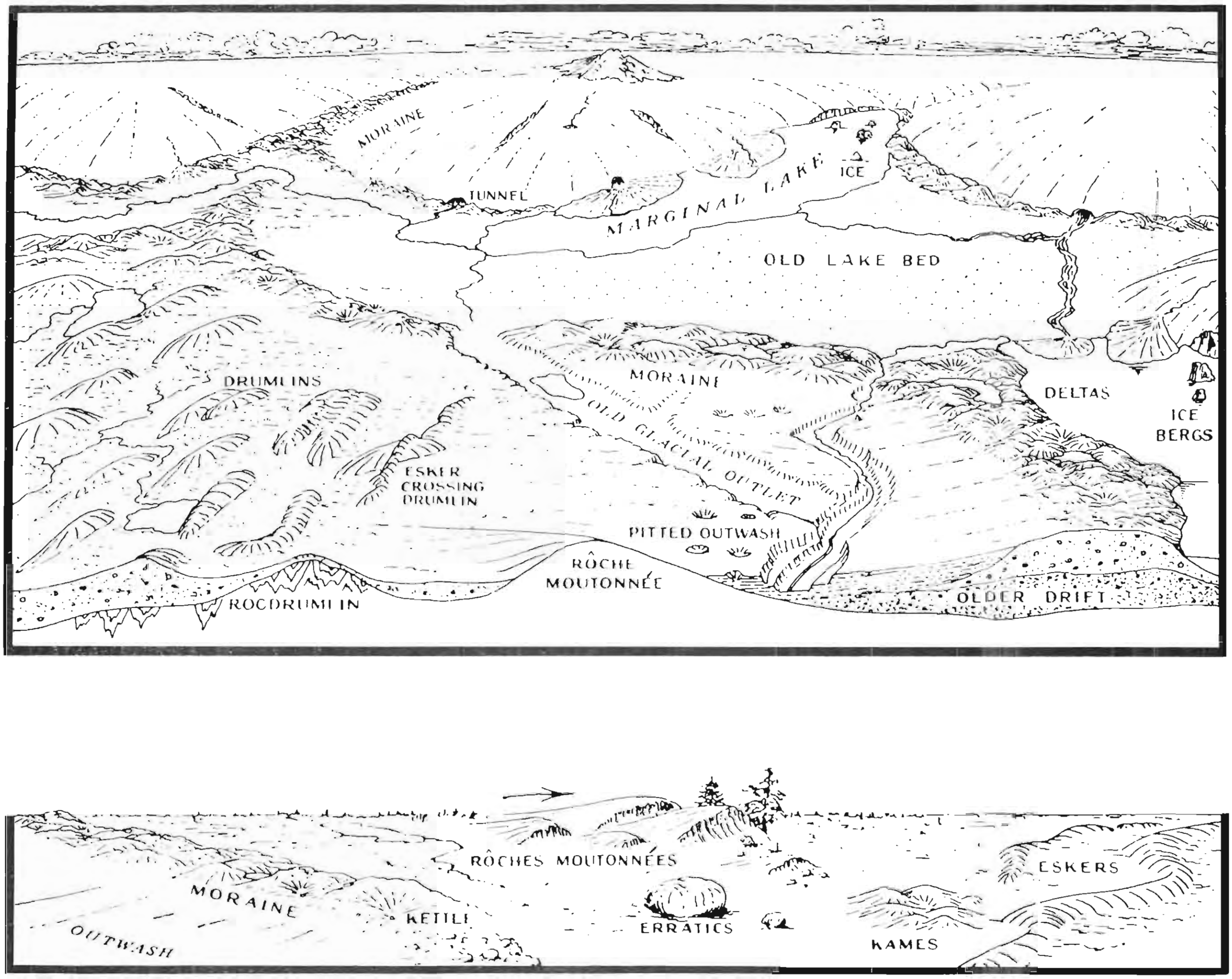


Figure 12.7. These diagrams show various types of landforms and glacial deposits left behind by continental glaciers. We study such features of New York's landscape and compare them with features of areas being glaciated today. With this information, we are able to deduce the glacial history of our State. (From *Geomorphology* by A.K. Lobeck. Copyright© 1939. Published by McGraw-Hill, Inc., New York, NY. Reproduced by permission of McGraw-Hill.)

buried pre-glacial river channel that once drained the Lake George valley. That channel, now filled with glacial debris, passes southward beneath Saratoga Lake and Round Lake. The postglacial Hudson River has cut a new channel to the east.

The most widespread type of glacial debris is *till*. Till is a dense, unsorted mixture of clay, sand, gravel, and boulders (Figure 12.13).

In places, after depositing till, the ice continued to move over it, molding it. In such areas, till deposits are usually streamlined or gently rounded. Cigar-shaped hills of till are called *drumlins*. These hills are steeper on the upstream end—the direction from which the ice flowed (Figure 12.14). Hill Cumorah near Palmyra, where Joseph Smith reported seeing a vision that led him to found the Mormon church, is a drumlin. (It is shown in the lower left corner of Figure 12.15.) Some drumlins have a bedrock core with till plastered on the outside. They are called *rock drumlins*.

The lowland between Rochester and Syracuse is studded with drumlins—some 10,000 of them. (Figure 12.16 shows their general location; see also Figure 12.15 and Plate 1 of the *Geological Highway Map*.) It is one of the greatest drumlin fields in the world.

As glacial ice melted, streams of meltwater flowed over, under, through, and beside the glacial ice. These streams deposited sand and gravel in a variety of forms. Because these deposits were laid down by running

Figure 12.8. Another clue to glaciation, this 2 m erratic, a boulder of metamorphosed anorthosite, is perched on top of Potsdam Sandstone, 1 km northwest of the village of Black Lake, St. Lawrence County. The glacier probably carried this boulder one hundred kilometers or more from its source before leaving it here.

water, they tended to be sorted into layers by size, in contrast to unsorted deposits such as till. An *esker* was formed by a stream flowing in an ice tunnel under or on the surface of a glacier (Figures 12.7 and 12.17). A *kame* is a steep-sided mound of sand and gravel, usually poorly sorted (Figures 12.7 and 12.18). A stream that flowed into a lake between a glacier and the wall of a valley formed a *kame delta* (Figure 12.19).

Huge blocks of ice were commonly buried in the outwash in front of the glacier. When the blocks melted, they left behind *kettle* lakes (Figure 12.20). There are many such lakes in New York State. Some have become overgrown with a mat of floating vegetation and are now quaking bogs. As the vegetation sinks to the bottom and decays, the bogs fill in and become swamps. Still later, the forest encroaches. Poorly drained glaciated terrain has many ponds, lakes, bogs, and swamps.

Moraines include ridges of till piled up or dumped along the edge of the ice. They show where the ice front remained in one place long enough for a ridge of glacial debris to pile up. There are many moraines in the State, as shown in Figure 12.4. An *end moraine* marks the farthest advance of an ice sheet. The end moraine of the Wisconsinan ice sheet is given the special name *Terminal Moraine* (see Figure 12.3). The Ronkonkoma Moraine on Long Island is part of the Terminal Moraine.

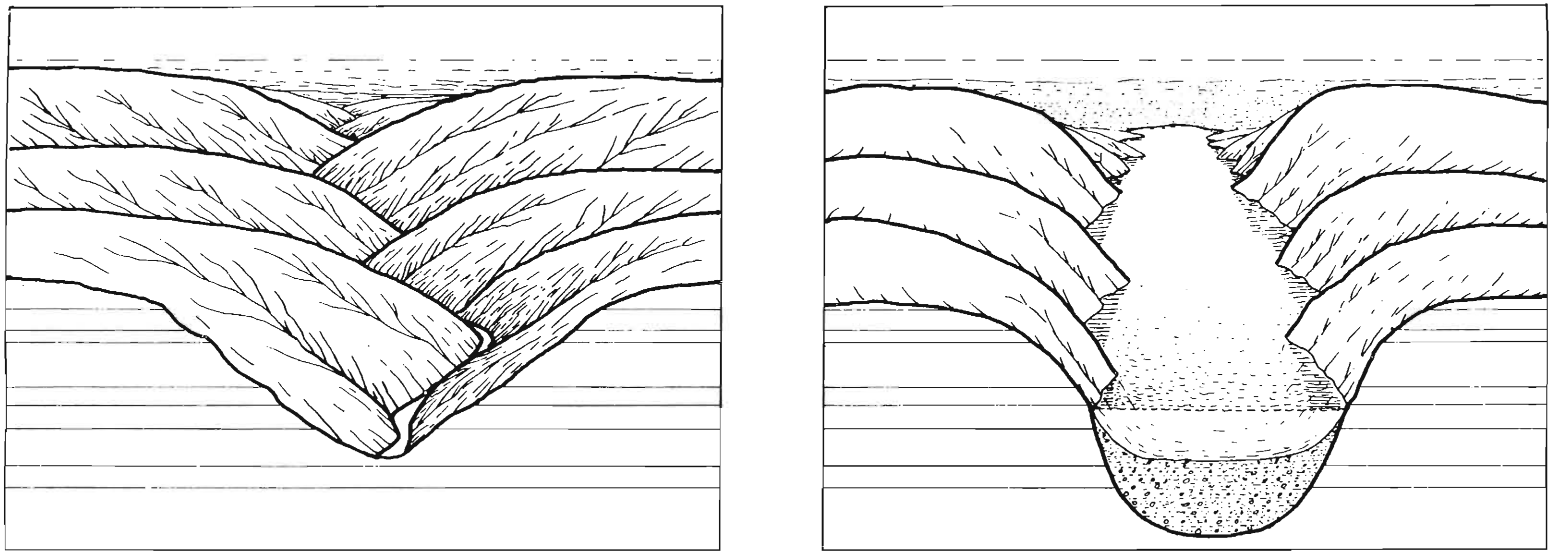
Meltwater streams flowing from the front of a glacier formed a plain of *outwash* beyond the moraine (Figure 12.21B). Outwash deposits were coarser close to the ice and became finer farther away.

At its largest, the ice sheet of the Wisconsinan Stage covered nearly all of New York State and was thick enough to bury the mile-high Adirondack peaks. The southern edge of the ice extended southeast across Pennsylvania and New Jersey to Long Island.

Long Island is made up of mud, sand, gravel, and boulders carried there by glacial advances during the Wisconsinan Stage. Most of this debris was eroded from New York and New England. The part of the island above sea level consists of two moraines, deposited during two advances, with their associated outwash plains (Figure 12.21). These two moraines intersect in western Long Island. South of the moraines we find the outwash deposits carried by meltwater streams.

The Retreat

After Long Island was formed, the climate began to warm. Melting increased. Eventually, although the ice continued to flow southward, melting had speeded up enough that the ice front began to retreat. The ice sheet of the Wisconsinan Stage began its slow retreat to the north about 21,750 years ago (Figure 12.22). It left New York



A B

Figure 12.9. This "before and after" picture shows the results of a glacier flowing down a river valley. The "before" picture in (A) shows the V-shaped valley cut by a river. The "after" picture in (B) shows the same valley after glaciation—broadened and carved into a U-shape by the glacier. When the end of such a glacially broadened valley is blocked by glacial debris, the valley can become a long, narrow lake. This process formed New York State's Finger Lakes.

Figure 12.10. Taughannock Falls, Tompkins County, formed when a tributary stream perpendicular to the direction of glacial flow remained unmodified while the main valley, parallel to ice movement, was considerably widened and deepened. Thus, the tributary was left as a hanging valley after the ice melted in the main valley. The present falls have eroded back 1.5 km from the main valley since the ice left the valley roughly 15,000 years ago.

State about 10,000 years ago and melted completely in Canada approximately 7,000 years ago. The only remnants of the Ice Age still in mainland North America are small mountain glaciers in the western United States and Canada.

Today, the remains of the huge Pleistocene ice sheets—most glaciers of the Canadian and Soviet Arctic islands, Greenland, and Antarctica—cover a tenth of the earth's land. More than three-fourths of the earth's fresh water is frozen in the Antarctic and Greenland ice sheets. If all that ice were to melt, sea level would rise more than 45 m and flood the world's large coastal cities, including New York City and Boston.

During its retreat, the glacier readvanced slightly from time to time. How do we know? By looking at the moraines left during retreat (Figure 12.4).

The melting ice sheets released unimaginable volumes of water. The meltwater flooded lowland areas to make large lakes in front of the glacier (Figures 12.7 and 12.23). These lakes, called *glacial lakes*, are today extinct; they formed between the ice front and bedrock hills or end moraines. The lakes lasted up to perhaps 5,000 years, and their size and depth changed constantly. As the ice front retreated to the north, it opened new outlets for the meltwater flow and for the lake water. About 15,000 years ago, the Hudson River valley was filled with a large glacial lake that we call Glacial Lake Albany. This lake lasted for at least 4,000 to 5,000 years.

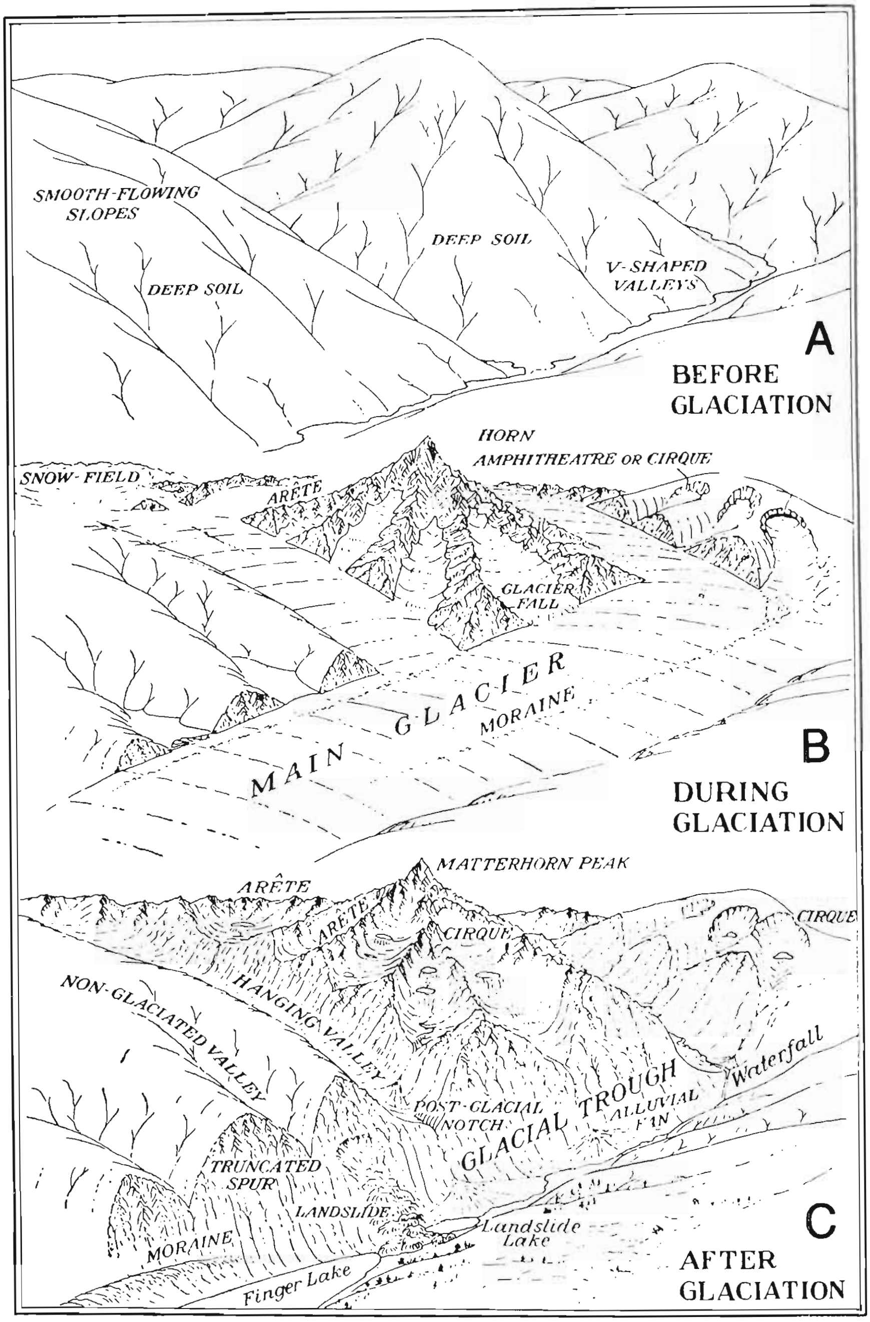
Today, we can tell where the lakes were by the lake bottom deposits they left behind. Many of the lakes lasted long enough for meltwater streams to carry in large quantities of *rock flour*. This very fine-grained material settled out as thick layers of clay in the deeper parts of the lakes. The clay deposits that formed in Glacial Lake Albany have been used extensively to make bricks.

As the streams entered the lake, the coarser material—sand and gravel—was dropped near shore to form deltas. The ancestral Mohawk River built a large delta at the west arm of Glacial Lake Albany where the city of Schenectady now stands. As the lake began to drain, new deltas were built at lower lake levels. Eventually, the lake drained completely, and the wind built a dune field on the former lake floor between Schenectady and Albany north to Glens Falls. The dunes were built from drifting sands derived from the deltas and the lake floor. The dune field between Albany and Schenectady is known as the Pine Bush. These sand dunes have been held in place for thousands of years by a pine-barren vegetation, which is dominated by pitch pine. The tilt of the sand layers in the dunes shows us that the dominant dune-building wind came from the northwest and a lesser component from the southwest.

A major moraine across central New York closed the southern ends of several formerly south-flowing river valleys. The damming of these valleys produced the Finger Lakes. This same moraine, the Valley Heads Moraine (Figures 12.3 and 12.4 show its location), forms an east-west *drainage divide* across the central part of the State. The moraine formed as the glacier receded. This drainage divide can be seen in Figure 16.1, which shows New York State's drainage basins. Streams and rivers on opposite sides of the moraine tend to flow in opposite directions. The moraine has become a drainage barrier between two regions.

Glacial ice in the valleys was thicker and therefore lasted longer than ice in the uplands. It melted slowly in place and became covered with debris carried by tributary streams. Meanwhile, the main ice front continued to retreat.

The receding ice sheet made its last major readvance into northern New York more than 11,000 years ago. The ice readvanced across the Adirondacks and Tug Hill Plateau and across the Erie and Ontario Lowlands (Figure 12.3). In the Erie and Ontario Lowlands, it filled an earlier gorge of the Niagara River with debris and rode over earlier glacial lake deposits.



After W. M. Davis

Figure 12.11. (A) shows the rounded preglacial topography of a mountainous region. (B) shows how mountain glaciers sharpened the topography. In the Adirondacks and Catskills, mountain glaciers didn't last long enough to create a landscape like that shown in (C). The present-day landscape is between (A) and (C). For example, Whiteface Mountain in the Adirondacks begins to resemble the Matterhorn peak in (C), but Whiteface Mountain still retains its original rounded summit, as shown in Figure 12.12. (From *Geomorphology* by A.K. Lobeck. Copyright © 1939. Published by McGraw-Hill, Inc., New York, NY. Reproduced by permission of McGraw-Hill.)

Figure 12.12. Two bowl-shaped cirques are seen in this photo, which looks towrd the east at the summit of Whiteface Mountain. They are separated by a sharp ridge, called an *arête*. A third cirque is out of sight on the other side of the peak. The cirques, steep-walled natural amphitheaters, were formed at the heads of mountain glaciers that surrounded the summit of Whiteface during the Ice Age. These were some of the many mountain glaciers that remained in the Adirondack Mountains after the retreat of the continental ice sheet. The mountain glaciers pried chunks of bedrock off the valley walls and carried away the loosened pieces. If the glaciers had lasted much longer, they would have eroded back to back to produce a sharp horn, similar to the Matterhorn in Switzerland (see Figure 12.11).

Figure 12.13. On the wall of this sand and gravel pit, we can see well sorted layers of glacial deposits. These deposits were left by glacial meltwater. On top of the layers is coarse-grained, unsorted glacial till. Notice the faults in the water-lain layers. These faults formed before the till was deposited. We think that the cause of the faulting was pressure from moving glacial ice nearby. The geologic hammer in the picture is approximately 35 cm long, for scale.

Figure 12.14. One of the thousands of drumlins in New York State. These streamlined hills of glacial till line up in the direction of the glacial flow that shaped them. The steeper end, to the right in

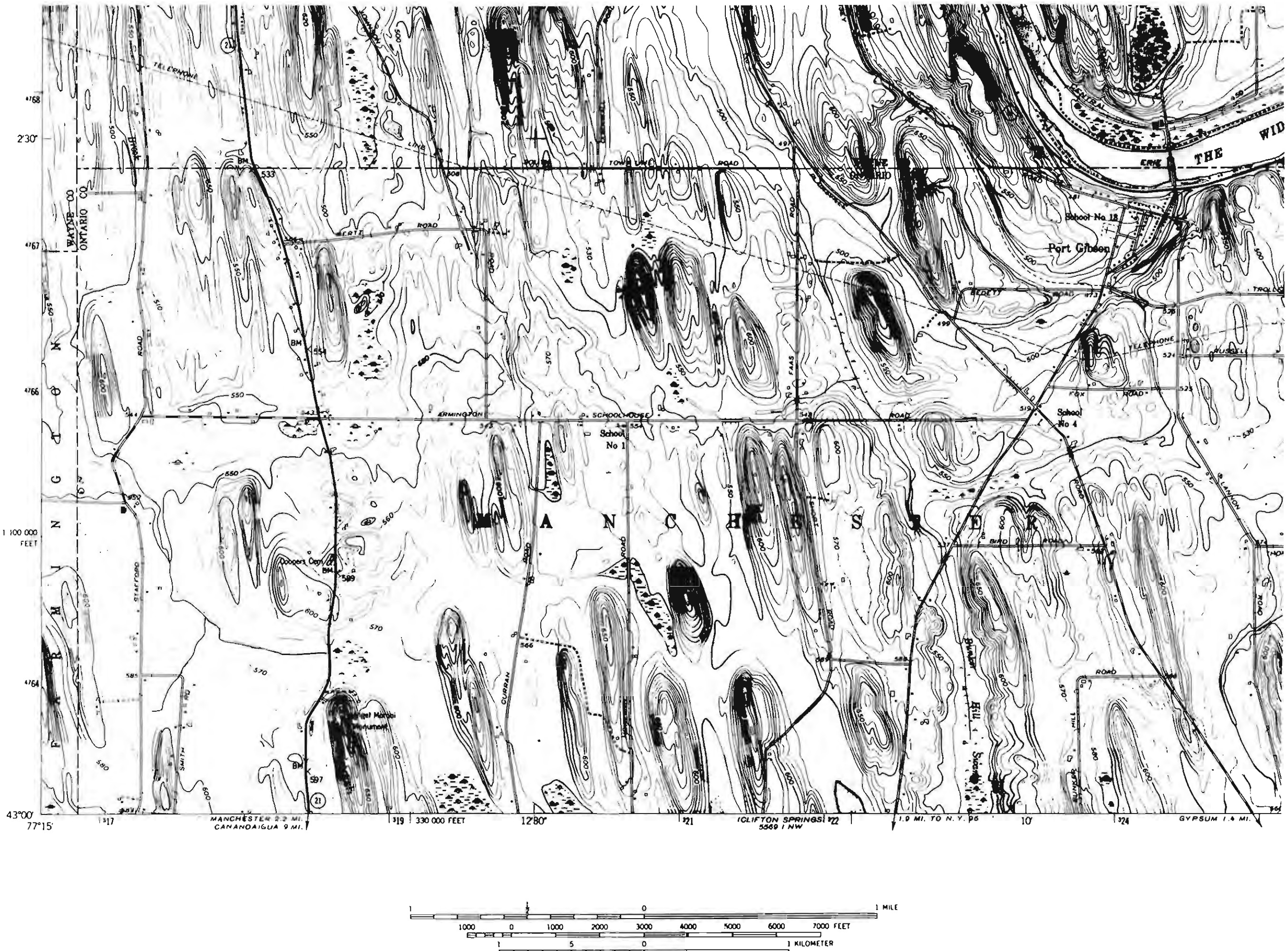


Figure 12.15. This topographic map of a portion of the Palmyra quadrangle shows some of the many drumlins found there.

The largest of the glacial lakes were the ancestors of today's Great Lakes. What remains of Glacial Lake Iroquois, for example, is now Lake Ontario. The shoreline features of these lakes show us that they were huge. (Figure 12.23 shows their largest size.) Ridge Road along the southern shore of Lake Ontario follows a beach ridge of sand and gravel that piled up at the edge of Glacial Lake Iroquois.

The tremendous outflow from Glacial Lake Iroquois flowed east past Syracuse and Little Falls. As the water rushed eastward, it scoured deep circular pits called *potholes* into bedrock at Moss Island in the Mohawk Valley near Little Falls (Figure 12.24). These are some of the best examples of potholes ever found—large enough to climb into.

The glacial ice sheets modified the earlier Tertiary drainage. In some river valleys, it gouged lake basins in the softer bedrock. In other valleys, it built dams by depositing sediments. In this way, the glacier converted the Adirondacks from a land of rivers to a land of lakes.

Through its effects on drainage, the glacier also played an important role in human history. Before highways and railroads were built, water travel was crucial in New York State. It was by far the best means of transportation and communication through the Hudson and Mohawk valleys and west into the Ontario basin. The colonists took advantage of these routes while fighting the Revolutionary War. They used the rivers to move their own troops and supplies but blocked critical waterways to stop the advance of the British.

After the Revolution, the waterways also helped greatly in the industrial development of the State. They were the most efficient way to move goods through New York State. Rivers and streams also became the source of power for grist mills and saw mills.

While glacial ice lay as a thick blanket over New York, the great weight caused the crust to sag. Therefore, as the ice melted, ocean water flooded into the northern parts of the Champlain and St. Lawrence valleys for a short time

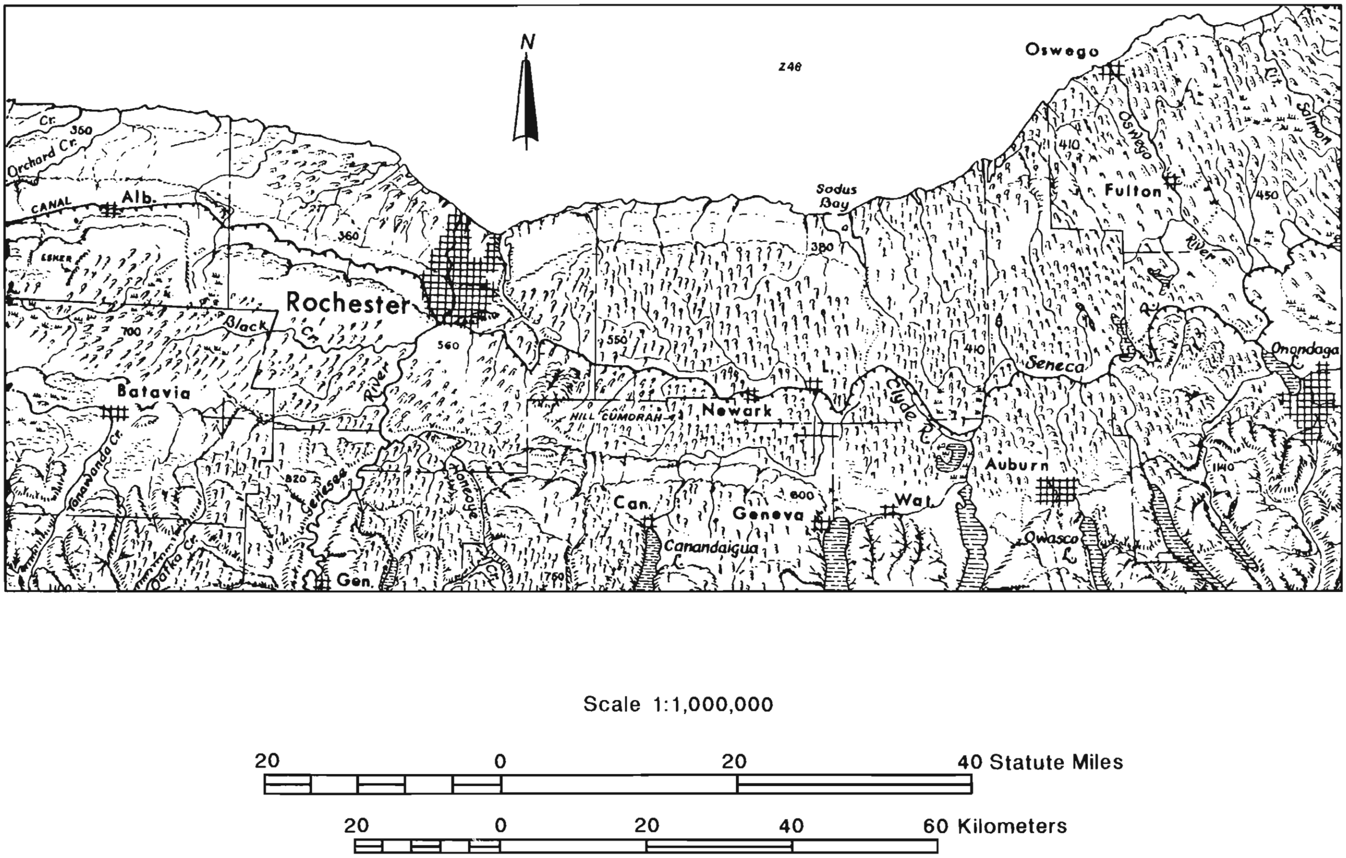


Figure 12.16. This physiographic diagram of central New York State shows the large drumlin fields that extend almost the full width of the Ontario Lowlands. Notice the way the drumlins line up; this alignment shows us the directions of glacial ice movement. (Adapted from James A. Bier, 1964.)

Figure 12.17. An esker 4 km southeast of Defreestville, Rensselaer County, on Rte. 152. This long, curvy ridge snakes along the course once followed by a stream flowing underneath a glacier. The glacial ice formed the walls for the stream; hence, this river deposit makes a ridge.

Figure 12.18. An example of a steep-sided mound called a kame. This one is found 3.2 km northwest of Earlton, Greene County.

(Figure 12.23) to create the ancient Champlain Sea. How do we know about this ancient flood? We find the shells of marine clams and the bones of whales and seals in the glacial sands and gravels in these valleys (Figure 12.25). We also find beach ridges that piled up along the shore of the sea. These ridges are now found as high as 110 m above sea level (Figure 12.26). These features enable us to map the old marine shoreline.

The sea's visit was short lived, geologically. After the ice melted, the land was relieved of the great weight. It began to rebound the way a small boat bobs back up when people step out of it. The rebound gradually raised the area above sea level and forced the sea to withdraw.

Toward the south, the ice had been thinner and the land had been depressed less. As a result, its rebound was less. In northern New York, where the ice had been much thicker, the crust has rebounded as much as 150 m.

Figure 12.19. A kame delta along the east side of the Chenango River Valley near North Norwich, Chenango County. It was formed by a stream flowing between a mountain glacier and the valley wall; it is a special type of stream deposit.

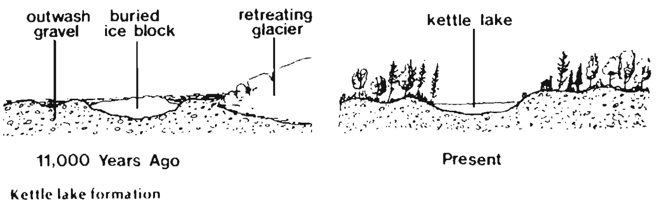


Figure 12.20. This diagram shows how kettle lakes form when an ice block, left behind by a retreating glacier, is buried by glacial outwash deposits. After the glacier retreats, the buried block melts, leaving a hole that fills with water. Debris that once covered the ice collapsed as the ice melted and now covers the lake bottom. Notice how trees and other vegetation have returned to the once barren region. (Drawing by Mike Storey.)

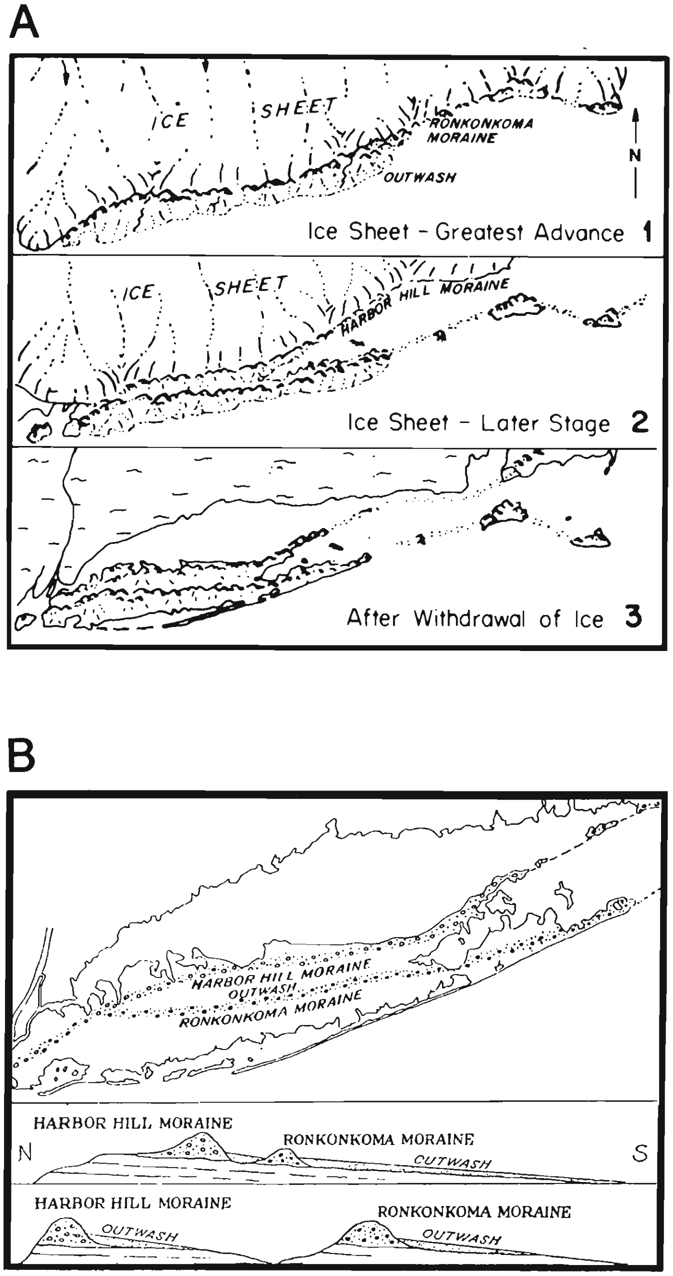


Figure 12.21. Generalized diagram to show the major landforms of Long Island. The island is made of glacial deposits left by the Wisconsinan ice sheet. It consists of two moraines and their outwash plains. The maps in (A) show the two stages when the moraines were built, compared with the present-day situation. (From Isachsen, Y.W., 1980. Continental Collisions and Ancient Volcanoes: The Geology of Southeastern New York. New York State Geological Survey Educational Leaflet 24.) The map and cross sections in (B) show both of the moraines and their outwash plains. (From *Geomorphology* by A.K. Lobeck. Copyright© 1939. Published by McGraw-Hill, Inc., New York, NY. Reproduced by permission of McGraw-Hill.)

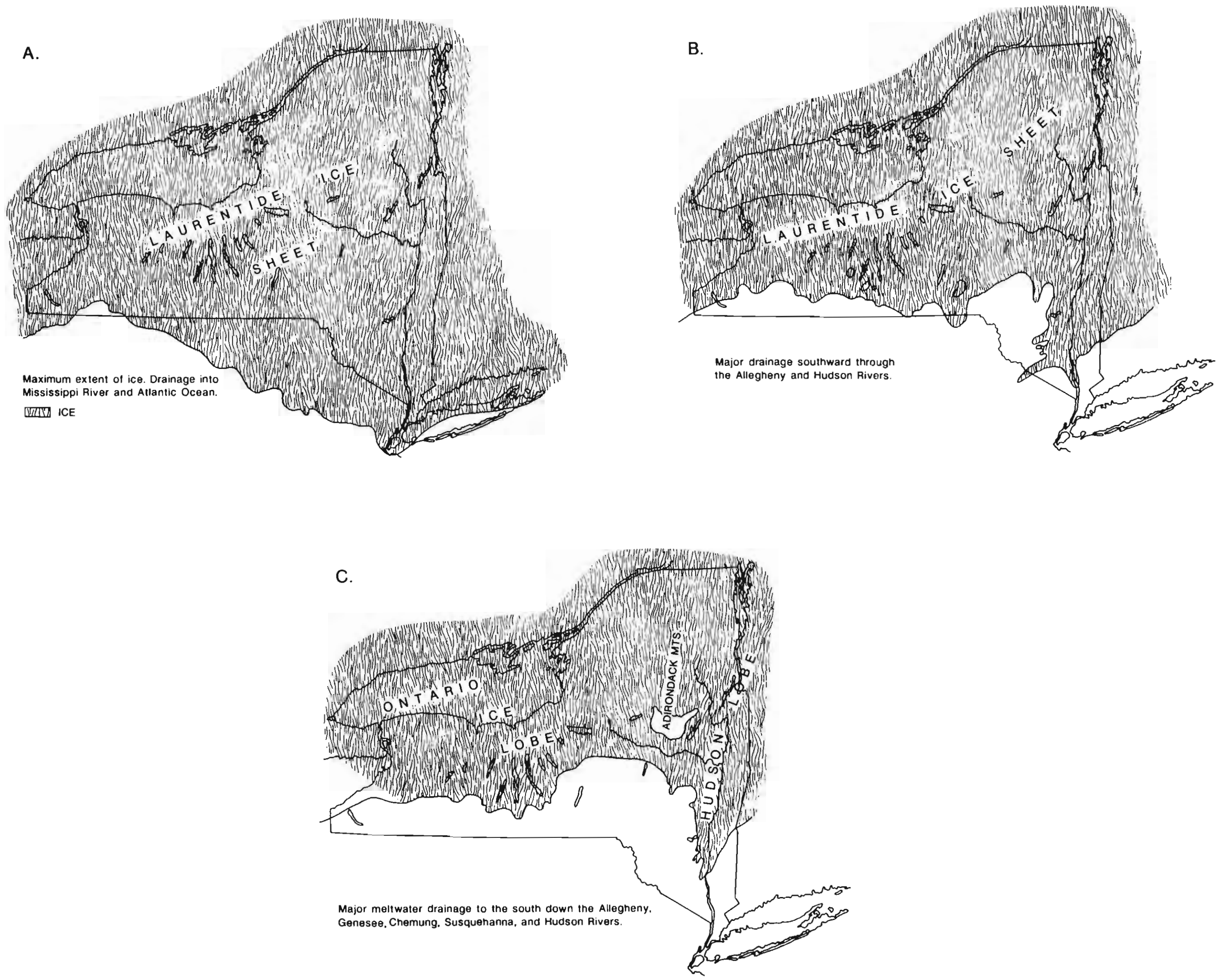
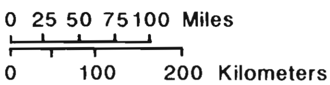
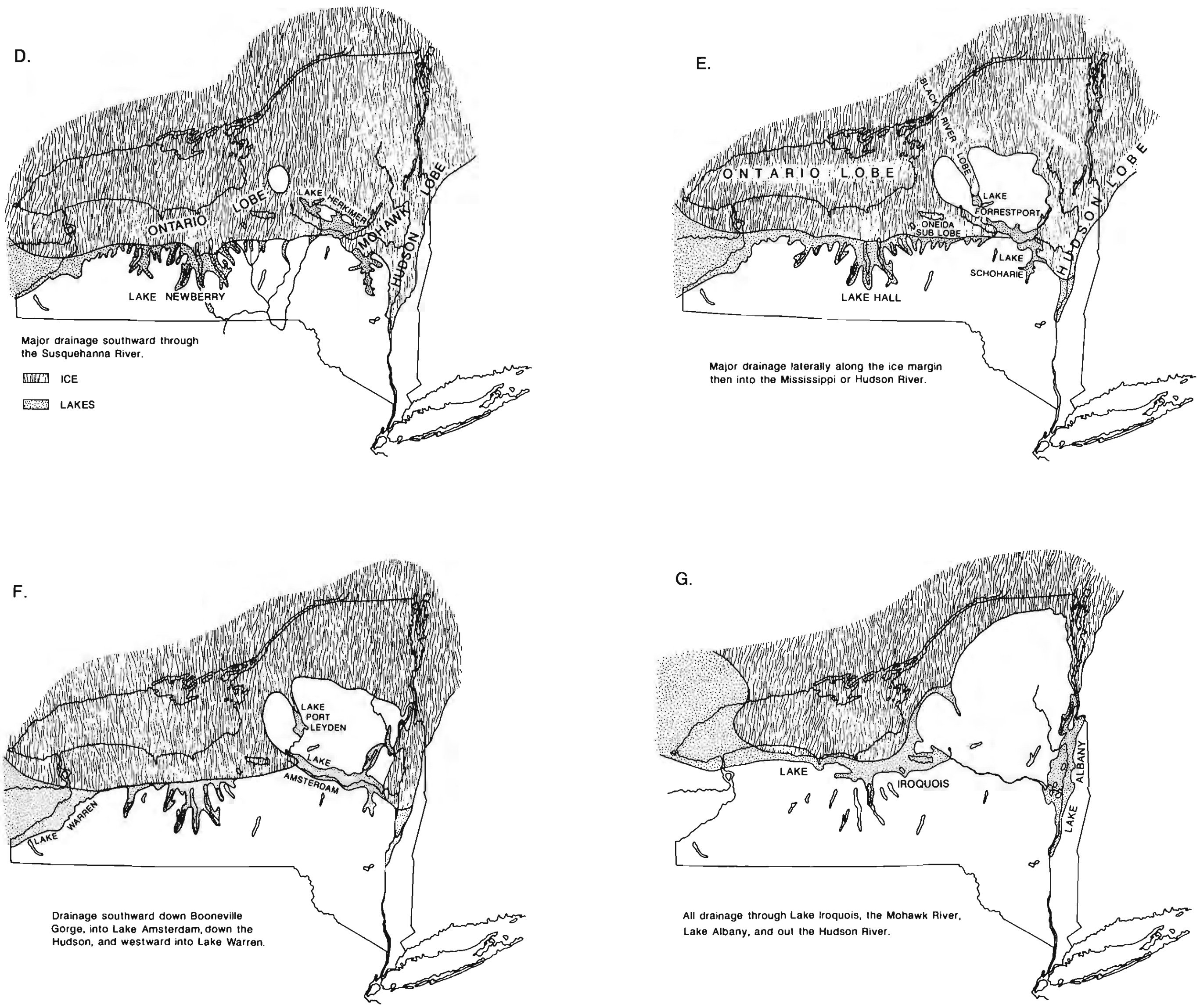


Figure 12.22. These maps show various steps in the retreat of the Wisconsinan glacier. They are based on the glacial deposits we find in New York State and the ages of wood and bone found in these deposits. The ages were found through radiometric dating using the radioactive isotope carbon-14. (A) shows the maximum reach of the glacier, about 21,750 years ago, when the entire State except the Salamanca Re-entrant was covered with ice. (B) shows the situation about 14,000 years ago, when the climate had begun to warm and the glacier had begun to retreat. (C) has been dated approximately 12,000 to 13,800 years ago. It was at this stage that the glacier built the Valley Heads Moraine in central New York (see also Figure 12.3).





The next three stages—(D), (E), and (F)—happened between 11,000 and 13,000 years ago. Unfortunately, few of the features that were built by these stages have been dated radiometrically, so we can't be more precise about the ages. However, we can see that the retreat continued. (G), the final stage in the figure, shows what New York State was like approximately 11,000 years ago. (Adapted from Allers, R.H., 1984. Pleistocene geology of central New York State. In B.J. Tewksbury and R.H. Allers, Hamilton College Field Trip Guidebook: Geology of the Black and Mohawk River Valleys, p. 43-61.)

We can see the results of this uneven rebound throughout northern New York. Glacial lake deposits that were once horizontal now slope up to the north. The effect of this rebound on the Lake Ontario basin is quite dramatic. The differing amounts of rebound have tilted the entire region so that it slopes down from the north to the south. Harbors along the south shore of Lake Ontario slowly grew deeper as the lake basin tilted southward. Harbors on the north shore grew shallower. We find similar tilting in the Lake Champlain basin. Postglacial rebound is now completed in New York State, however.

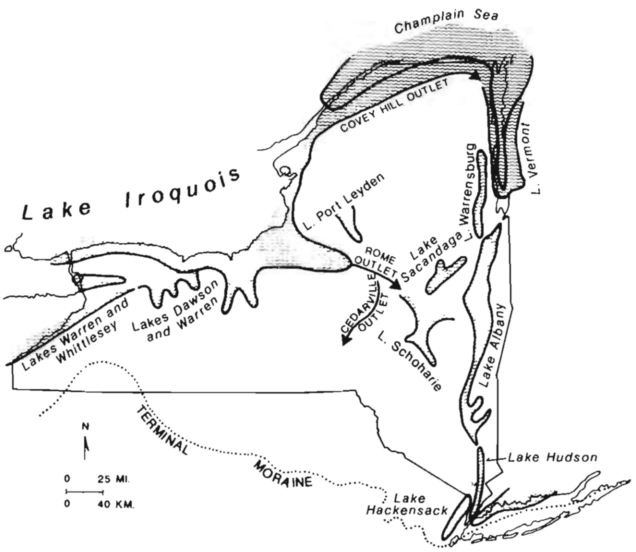


Figure 12.23. These glacial lakes of the Pleistocene formed from meltwater as the ice sheet retreated. The outlets show the directions in which these lakes eventually drained. The Champlain Sea in the north shows the area that was flooded by ocean water as the glaciers melted.

Figure 12.24. This giant pothole is found on Moss Island in the Mohawk Valley near Little Falls. It was scoured into the bedrock by the tremendous outflow from the ancestral Great Lakes rushing to the sea. (Photo by B.K. Goodwin.)

Pleistocene Life

During the Ice Age, colder climates crept down from the north and warmer climates shifted farther south. The climate was similar to modern subarctic regions, such as the barren reaches of the northern Canadian tundra. However, south of the ice front, life was plentiful. A huge variety of plants and animals lived there, including evergreen trees that could withstand the cold. Many of these species still exist today. However, many Pleistocene mammals are now extinct.

Figure 12.25. A close-up view of a groove carved by the glacier in limestone in the Plattsburgh area. The groove contains sand and gravel similar to that left by the glacier. Notice, however, the tiny white clam shells. (They are about 1.5 cm across.) These animals lived in brackish water, not fresh water. Their presence is one piece of evidence that a sea (the Champlain Sea) once covered this area, as shown in Figure 12.23. The sea flooded in as the glacial ice melted and was pushed back as the crust rebounded above sea level.

Figure 12.26. This picture shows a shingle beach. It is just like modern beach ridges found in various part of the world, but this one is high and dry. It marks a former shoreline of the Champlain Sea. After the glacier melted, the sea entered the Champlain Valley via the St. Lawrence River valley, where the crust had sagged under the weight of the ice. This sea lasted only until the unburdened crust slowly rebounded.

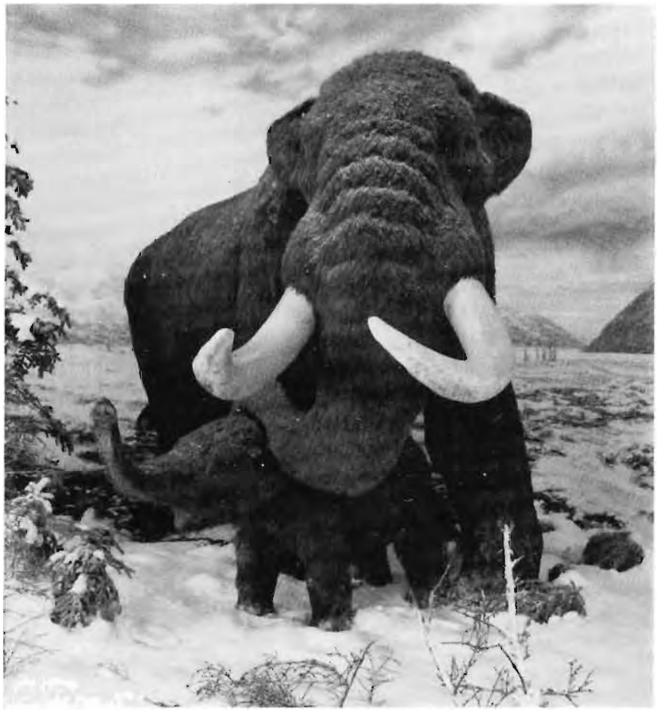


Figure 12.27. The mastodont *(Mastodon americanus)*, which stood about 3 m high, was one of the exotic-looking animals that roamed New York State during the Pleistocene. It is extinct today, but the remains of mastodonts have been found in several parts of the State. This reconstruction is on display in the New York State Museum, Albany.

The wooly mammoth and the mastodont (formerly spelled *mastodon*) are the two largest animals that became extinct. Both were huge, elephant-like beasts with long curved tusks (Figure 12.27). We have found their bones and teeth in peat bogs and at other sites throughout New York State. Mastodont teeth were found in New York as early as 1705.

Some smaller, less exotic animals also became extinct. We have found bones or other remains of ground sloth, bear, musk ox, caribou, moose, moose-elk, peccary (pig), seal, bison (buffalo), deer, elk, horse, giant beaver, and California condor in the Pleistocene deposits of New York (Figure 12.28). The giant beaver and moose-elk are now extinct. We deduce that panther, wolf, arctic fox, wolverine, badger, ptarmigan, and heath hen probably were also part of the State's Pleistocene wildlife. Why do we make this deduction? Because they normally live in the same environments as the animals whose remains we have found.

What caused the great extinctions of large mammals during the Pleistocene? Current evidence indicates that the arrival of human hunters hastened the extinction of late Pleistocene animals in Europe and Asia. Humans arrived in North America later, and North American Pleistocene animals became extinct at a slightly later time. This information indicates that humans probably caused the destruction of many Pleistocene animals.

Review Questions and Exercises

Define the following terms as they are used in this chapter:

mountain glacier	end moraine
continental glacier	Terminal Moraine
Laurentide Ice Sheet	kettle lake
Wisconsinan Stage	glacial lake
lobe	drainage divide

What are the two contrasting processes by which glaciers changed New York's landscape? Define the following terms, and match each with one of the two processes:

cirque	moraine
drumlin	outwash
erratic	rock basin
esker	roche moutonnée
hanging valley	striation
kame	till
kame delta	U-shaped valley
pothole	

Explain why you put each term in that category.

What were glacial lakes? Where were they located? Why were they temporary? What evidence remains of their existence?

What did glaciers have to do with the formation of the Finger Lakes? What was there before the Ice Age? Can you name other large valleys in the region that also run north-south but are *not* lake-filled? Suggest an explanation for their formation. See the Physiographic Map on Plate 4 and a road map.

If a car advances and then retreats, it uses the same process to move in both directions—rolling along on its tires. When the glacier advanced and retreated, though, the processes were different. Explain how a glacier advances and retreats.

Why was sea level lower during the Pleistocene than today? How do we know that it was lower?

What is meant by post-glacial rebound? What evidence do we have that it has occurred?

Name 5 or 10 cities of the world that would be submerged beneath the sea if all of the ice in the world's glaciers suddenly melted. (Hint: Look at a globe or a world map to help you answer.)

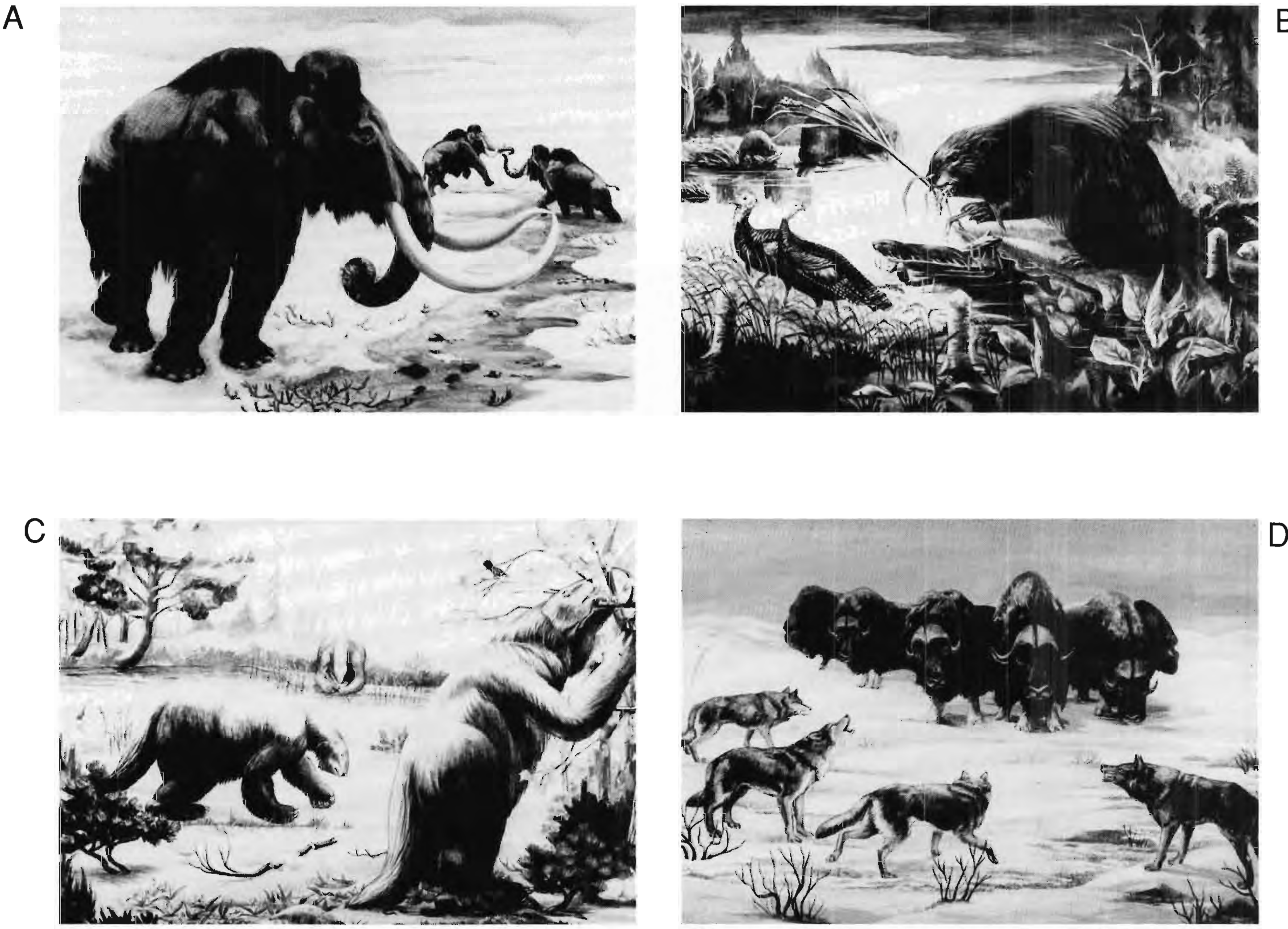


Figure 12.28. Some of the animals that lived in New York State during the Pleistocene Epoch. (A): wooly mammoth. (B): giant beaver with the much smaller modern beaver and wild turkeys. (C): ground sloth. (D): musk oxen and dire wolves.

Figure 12.28 *continued* (E): peccaries, (F): barren ground caribou. (G): woodland bison, which are different from the later plains bison. (Buffalo, NY, was named for a fossil bison, perhaps the only city in the world to be named after a fossil mammal.) (H): woodland caribou.

CHAPTER 13
ICE SCULPTING
Glacial Features of New York State[1]

SUMMARY

Almost all of the glacial deposits in New York State were made during the last advance of the Wisconsinan ice sheet, which occurred during the Woodfordian Substage. The glacier created different kinds of features in regions with different bedrock and physiography. This chapter lists some important glacial features found in each of nine regions across New York State. The regions discussed are the Adirondack Mountains, the Hudson-Mohawk Lowlands, the St. Lawrence-Champlain Lowlands, the Erie and Ontario Lowlands, the Tug Hill Plateau, the Appalachian Plateaus (which include the Allegheny Plateau and the Catskill Mountains in New York), the New England Province (which includes the Hudson Highlands, the Manhattan Prong, and the Taconic Mountains), the Newark Lowlands, and the Atlantic Coastal Plain (including Long Island).

INTRODUCTION

The Pleistocene Epoch was marked by four major intervals of glaciation; some of these intervals had multiple advances of ice. The glacial features we see today in New York State were made by the advances and retreats of the last ice sheet, the Laurentide, during the Wisconsinan Stage. Its last advance occurred during the last part of the Wisconsinan Stage, called the *Woodfordian Substage*. It destroyed nearly all of the signs left by earlier glaciers in our State.

In a few sheltered places in New York we still find evidence of earlier Pleistocene deposits that underlie the deposits of the Woodfordian Substage. Two examples are soils preserved in a ravine near Cayuga Lake and soils near Otto in western New York. These soils are 35,000-60,000 years old and probably formed during a warm interglacial episode. (The last glacier retreated between 8,000 and 15,000 years ago.) We do radiocarbon dating of the plant and animal remains in the soils to find these ages.

As it retreated, the ice sheet of the Woodfordian Substage did not melt uniformly. Sometimes the melting was balanced by the forward flow of the ice; at those times, deposits piled up alongside the stationary front of the ice sheet. Other times the ice readvanced and disrupted earlier deposits and mixed them into new ones. Thus, we have to study each glacial deposit carefully. We need to figure out whether a deposit was formed when the glacier was retreating, when it was standing still, or when it was advancing.

A great variety of glacial deposits are found in New York State. The ice sheets advanced and retreated in different ways and times in different areas. The kind of bedrock and the shape of the landscape in a region strongly influenced the formation of glacial features. For example, the Adirondack Mountains, made up of contorted, hard, metamorphic rocks, have different glacial features than the Allegheny Plateau, with its softer, flat-lying, sedimentary rocks. Because of such differences, we have divided the State into regions (see Figure 1.1) and will look at each region separately.

A list of all the glacial features in each region would be very long. We will discuss only the most important. For an explanation of unfamiliar terms for glacial features, see Chapter 12 or the Glossary.

ADIRONDACK MOUNTAINS

The last glacier moved southwest across the Adirondack Mountains. How do we know the direction? The

[1]Adapted from a manuscript by D.H. Cadwell.

glacier made striations and grooves in the bedrock. It also carved roches moutonnées in the bedrock or left behind rock drumlins. The scratches, grooves, and streamlined landforms point in the direction of the ice movement (compare Figures 12.3 and 12.4).

Till is widespread here, as it is elsewhere in the State, However, in the Adirondacks the till is much more sandy. Why is that the case? The reason is the kind of bedrock nearby. The moving glacier picked up rocks and soil, ground them, and later deposited them. But it didn't carry most of the debris very far—usually less than 15 km. Thus, the till we find in a region is made up of nearby rock. The hard metamorphic rock of the Adirondacks is made of sand-sized or larger mineral grains. Glacial grinding produced sand-sized fragments from this rock. Therefore, the till in the Adirondacks is sandy. In other areas, like the St. Lawrence-Champlain Lowlands, the bedrock is dominantly softer, finer-grained shale and limestone. The glacier ground these rocks into silt- and clay-sized particles. The till in the lowlands is therefore composed of silt and clay, which stick together much better than sand.

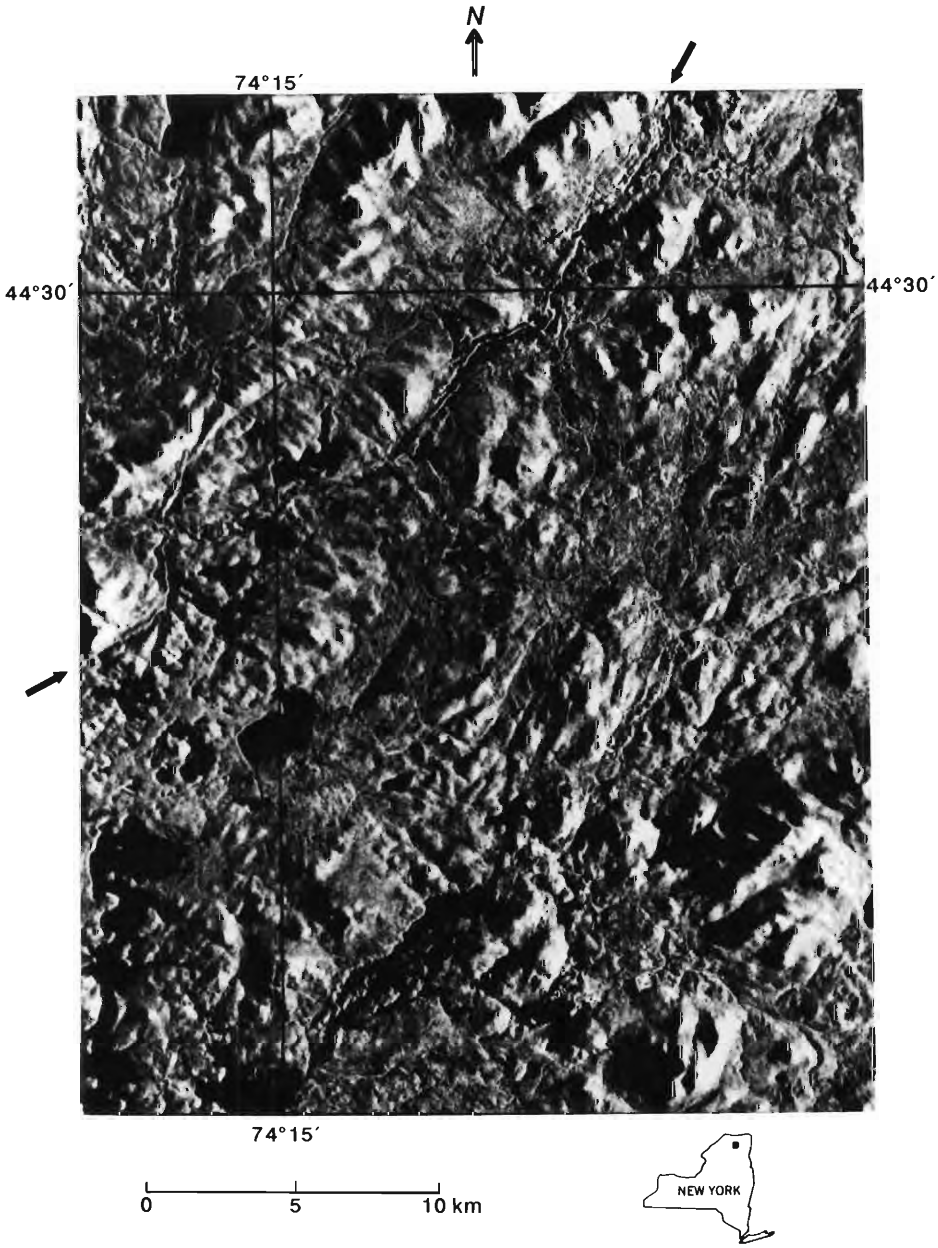


Figure 13.1. This aerial image of a portion of the Adirondacks shows two eskers (indicated by arrows). These long, curving ridges are deposits formed by rivers that flowed in tunnels beneath the ice. Upper Saranac Lake is in the lower left corner of the picture.

Many of the deposits in the Adirondacks were made by water from the melting ice sheet. Long, winding, narrow ridges called eskers are common. Many eskers lie along the shores of Adirondack lakes or project into the lake from the shore. Eskers can be several kilometers long. There are some good examples at Saranac, Tupper, Rainbow, and Cranberry Lakes (Figure 13.1). Eskers are frequently associated with large deltas and kame terraces.

Deltas and sandy beach deposits are clues to vanished glacial lakes. The lakes commonly formed in valleys that sloped downward toward the glacier. They lasted until the glacier retreated far enough to unplug the low places and permit the water to flow out. The lakes then drained.

The Saranac, Placid, Elizabethtown, and Wilmington basins once contained glacial lakes. Before they drained, these lakes overflowed through notches in the southwest rim of their valleys. How do we know that? The overflow formed rivers that left long narrow deposits of sand and gravel in their beds. These deposits end in large deltas, which tell us of another lake downstream.

A very large delta at Forest-port was deposited by water flowing down the Fulton-Chain-of-Lakes and through the Plains area of the Moose River. Glacial Lake Elizabethtown spilled through Underwood Gap into Glacial Lake Warrensburg.

Glacial Lake Warrensburg filled what is now the Schroon River valley. It also stretched from Deadwater Pond to Corinth in the Hudson River valley. The water in this lake was held in by a wall of ice that extended from Glens Falls to Saratoga Springs.

Glacial Lake Warrensburg may have been fed by meltwater from small glaciers that remained behind in the mountains. Why do we infer that? We can still see the cirques formed by these glaciers west of Piseco Lake and on Giant and Whiteface Mountains (see Figure 12.12).

Some ranges in the Adirondack Mountains were at an angle to the direction of ice flow and formed an obstruction to the ice sheet's flow. Such obstructions locally shielded some fragile preglacial soils from glacial erosion. We have found Tertiary soils and deeply weathered bedrock dating from before the Wisconsinan Stage in a number of places where road cuts have been blasted. These Tertiary soils are soft, commonly rust-colored, completely decomposed rock. These exposures therefore quickly deteriorate, but some can be see along Route 9 and the Northway north of Lake George. Others occur near Honnedaga Lake and near Lake Pleasant.

At Tahawus in the Adirondacks also, there are Pleistocene deposits older than the Woodfordian Substage. Here, we have found wood fragments and plant debris more than 40,000 years old in nonglacial lake sediments preserved between two layers of till. This site therefore provides evidence for two episodes of glaciation in the central Adirondack Mountains.

Review Questions and Exercises

How can we tell what direction the glacier moved in this region?

What sort of clues tell us about the locations of glacial lakes?

What is the till like in this region? Why is it different from other regions in the State?

Hudson-Mohawk Lowlands

Between 20,000 and 13,000 years ago, a large lake, Glacial Lake Albany, filled the Hudson Valley (see Figure 12.23). Glacial Lake Albany was 50 km wide at Schenectady, its widest point. It was 320 km long, extending from Glens Falls to New York City. At Albany, it was 120 m deep. Its southern end was dammed by the Terminal Moraine of the Wisconsinan ice sheet, in the New York City area (see Figure 12.3). Its northern end was blocked by the front of the retreating glacier.

At first, the Terminal Moraine extended as a ridge across New York Bay from Long Island to Staten Island (see Figure 12.3). Exactly how Lake Albany drained is still an unanswered question. It may have drained through gaps that developed in the Terminal Moraine. Alternatively, it may have drained farther north, at Sparkill Gap near Nyack: the water could have passed through this narrow gap into the headwaters of the Hackensack River.

Many of the cities and towns of the Hudson Valley are located on deltas built by streams and rivers that drained into Glacial Lake Albany. Examples of such deltas can be found at Croton Point, Newburgh, Kingston, Red Hook, Hudson, Kinderhook, Albany, Schenectady, Schaghticoke, Saratoga Springs, and Glens Falls. On the east side of the Hudson River valley, between Poughkeepsie and Troy, we find old beaches formed on Glacial Lake Albany's shores.

The broad sand plains of today are the ancient lake floors of glacial time. The sand was deposited in shallow water near the shores of the lake. After the lake drained, the wind piled up the sands of the lake floor and beaches into dunes. The Pine Bush between Albany and Schenectady is one such dune field. There are others in Saratoga and Warren Counties. The Northway between Albany and Glens Falls alternately cuts through sand dunes and rides along glacial lake plains.

By looking carefully at the sand in the dunes, we can tell in what direction the winds were blowing. The sloping layers in the dunes tell us that winds generally blew from the northwest.

Moraines are rare in the Hudson Valley, although a large moraine is found northwest of Glens Falls. It was formed between two lobes of the glacier. There is a large channel in it between Fort Ann and Hudson Falls, cut by the water draining from Glacial Lake Vermont.

In the Mohawk Valley, we find clues to the origin of Glacial Lake Schoharie and Glacial Lake Amsterdam. These lakes were created when a tongue of ice called the Mohawk Sublobe occupied the valley near Schenectady. They drained through channels at Duanesburg and West Hill. The channels still exist, but they no longer carry water. The city of Amsterdam is located on a delta built by water flowing into Glacial Lake Amsterdam.

Water draining from Glacial Lake Iroquois in the Ontario Basin flowed over the Glacial Lake Amsterdam and Glacial Lake Schoharie deposits, cutting deep channels. The large size of these channels suggests that they were cut by heavy flows. It may be that water was released suddenly when an ice dam broke.

Whatever the cause, the floods also made the magnificent potholes on Moss Island at Little Falls (see Figure 12.24). They deposited the sand of the Fonda Sand Plain between the Noses and Tribes Hill. When they reached the Hudson Valley, they cut the Ballston Lake, Saratoga Lake, and Round Lake Channels.

Northville, Edinburg, Gloversville, and Johnstown are built on deltas formed by streams that flowed into Glacial Lake Sacandaga. There is also a delta at Saratoga Springs that was built by a large flood of meltwater spilling from Glacial Lake Warrensburg into Glacial Lake Albany through the Kayderosseras Valley.

A number of temporary glacial lakes were formed in the Hudson Lowlands, as the Hudson Lobe readvanced several times. At times it blocked the low points in the northern or eastern parts of valleys and allowed temporary lakes to form in those valleys. Some examples are Lake Tillson in the Wallkill Valley, Lake Elizaville in the Roecliff Jansen Kill Valley, and Lake Durham in the Catskill Valley.

During one brief period of stationary ice, the Hudson Lobe formed the Meadowdale moraine. This moraine was built during a pause in the retreat of the ice front. At the same time, the Hudson Lobe built a kame terrace at Schodack and esker and kame deposits at West Sand Lake.

Review Questions and Exercises

Where was Glacial Lake Albany? What are some of the clues to its existence we see today? What clues tell us about other glacial lakes in this region?

St. Lawrence-Champlain Lowlands

The St. Lawrence Valley is made up of gently rolling farmland. Underneath the soil are glacial sediments deposited during the last part of the Wisconsinan Stage. In places, the glacier molded till into drumlins.

In this region, the ice sheet flowed through the St. Lawrence Valley and into the Adirondacks. When the glacier began to retreat from the lowlands, the meltwater was held in some valleys by the retreating wall of ice to the north. This process created temporary lakes. Today, we find deposits associated with these lakes—kame deltas at Parishville and Stalbird and eskers, including one at St. Regis Falls.

At Chateaugay, there are long, deep channels that no longer carry water. They were created by glacial meltwater as it flowed westward along the edge of the ice into Glacial Lake Iroquois in the Ontario Basin.

As the ice retreated, the long northeast arm of Glacial Lake Iroquois expanded. Beaches and deltas formed along its southern shore. Layers of clay were deposited in deeper, quieter water farther from shore. Potsdam and Malone are built on large Lake Iroquois deltas.

Eventually, the glacier retreated past the northeastern tip of the Adirondacks at Covey Hill near the Canadian border. This retreat provided an outlet that drained Glacial Lake Iroquois abruptly. The roaring torrent carved deep channels. It created waterfalls and plunge pools[2] at Covey Hill. It also eroded the Potsdam Sandstone ledges at Flat Rocks near Altona. Where the flow entered Glacial Lake Vermont, it deposited a large delta near Chazy.

During the Pleistocene, the great weight of the 2 km-thick ice sheet caused the crust and underlying mantle to sag. As the ice melted, the crust slowly rebounded. However, there was a period in between melting and rebound of the crust, during which sea water from the Atlantic flooded the St. Lawrence and Champlain Lowlands.

How do we know that this region was covered by sea water? The retreating glacier had left behind moraines and glacial lake deposits, but on top of these deposits are sands, silts, and clays with abundant marine clams and occasional whale and seal bones as far south as Whitehall. In addition, many of the drumlins in the St. Lawrence Lowlands have boulders on the top. These large stones were left behind when the sea waves swept away the finer sediments.

We have found deltas built by streams that drained north into this Champlain Sea at Malone and Hannawa Falls. Later, northwest winds picked up sand from the delta tops and built dunes. Deltas and sand ridges that formed at the shore of the Champlain Sea can be found from Port Kent to the Canadian border. Such deltas are found at Port Kent and Altona. Well-preserved beach ridges can be seen at Plattsburgh.

In the Champlain Valley, we have found clay and silt without fossils that were deposited in a glacial lake. At higher elevations, we find deltas and beaches from the same lake. This lake, called Glacial Lake Vermont, drained south through a notch called the Wood Creek-Fort Ann Gap. The water poured into the Hudson Valley and carved a channel from Battle Hill to Fort Edward. We can find Lake Vermont deltas at the villages of Morrisonville, Clintonville, Keeseville, Crown Point, and Street Road. There are also beach ridges built by storm waves at Beekmantown. Near Plattsburgh is the Ingraham Esker, a long, snake-like ridge that formed in a meltwater stream beneath the retreating glacier.

The sand deposited in glacial lakes and shallow seas makes rich farmland in the Lowlands. The beaches and

[2]A *plunge pool* is a basin in the bedrock formed at the base of a waterfall by the force of the falling water.

deltas are sources of sand and gravel. They also make good aquifers.[3]

Sand and gravel deposits provide well-drained sites for cities and towns. However, the marine clay is a poor foundation. It has little strength and tends to flow downhill. This property has caused slumps on many hillsides and the collapse of many buildings.

Review Questions and Exercises

What clues tell us what direction the glacier moved in this region?

Where was Glacial Lake Iroquois? Why did it drain? How do we know that?

How do we know the St. Lawrence and Champlain valleys were once extensions of the Atlantic Ocean? Why did that happen? Why are these valleys now above sea level?

ERIE AND ONTARIO LOWLANDS

The Erie and Ontario Lowlands are renowned for their splendid display of drumlins. This drumlin field is one of the largest on earth, extending from Oswego to Batavia (see Figure 12.16). More than 10,000 drumlins rise above the nearly flat plains of the Lowlands. Many of them have been named, for example Chimney Bluffs and LeRoy Island in Sodus Bay, Hill Cumorah near Palmyra, and Mount Olympus at Syracuse. The Ontario Lobe passed across the Lowlands and molded these drumlins from glacial till.

Some drumlins have channels cut in them by meltwater from the retreating glacier. The most spectacular channels are near Syracuse and Newark. The channels were carved as water flowed eastward along the edge of the glacier into the Mohawk Valley. We have frequently found wooly mammoth and mastodont skeletons in peat bogs at the bottom of these old meltwater channels.

Plunge pools are common in the floor of the Syracuse channels. A plunge pool is a basin formed in bedrock at the base of a waterfall, created by the force of falling water. The waterfalls are dry today, but the pools remain. Green Lake, east of Syracuse, is a very fine example.

Many moraines and eskers were formed along the receding ice front. The Pinnacle Hills and Mendon Ponds Kame Moraines near Rochester are among the best known. Other moraines are found near Buffalo, including the Hamburg, Niagara Falls, and Albion Moraines. The Stanwix Moraine lies east of Lake Oneida.

The Erie and Ontario Lowlands also contain one of the finest records of glacial lakes in North America. There are layers of lake sand and silt around many of the drumlins. Old lake beaches lie at the base of the hillsides. Ridge Road runs east-west across the Lowlands along level surfaces and ridges that were built by waves on glacial lake beaches.

These beaches formed the old shoreline along Glacial Lake Iroquois, which once occupied the Ontario Lake Basin. The lake drained eastward into the Mohawk Valley through a wide gap at Rome. There, we find piles of sediments—spits, terraces, and bars[4]—left by the outflow. The city of Rochester is built on a thin layer of lake sediments that cover bedrock. Montezuma Swamp, west of Syracuse, is an unfilled remnant of Glacial Lake Iroquois. Using radiocarbon dating, we conclude that Glacial Lake Iroquois was in existence 12,400 years ago.

Several older lakes, Glacial Lake Warren and Glacial Lake Whittlesey, drained west into the Mississippi River system. We find beaches and deltas at higher elevations along the western edge of the Appalachian Upland. They extend from Pebroke to the Pennsylvania state line. The vineyards of Fredonia grow on these beaches. Tonawanda Creek flows through a clay-filled basin that until 10,000 years ago held a remnant of Glacial Lake Warren. Oak Orchard Swamp is a remnant of Glacial Lake Tonawanda.

Niagara Gorge and Falls are among the best known scenic features in the State (Figure 13.2). About 12,000 years ago, as the glacier retreated, the Niagara River began to flow over the cliff called the Niagara Escarpment. The ancient plunge pool carved by the falling water can still be seen at Lewiston and Queenston. The top layer of the Niagara Escarpment—called the *caprock*—is made of a massive dolostone formation that resists erosion. The dolostone lies on top of the Rochester Shale, a much more erodible rock. The falling water continues to dig a huge plunge pool in the shale and undercut the dolostone caprock. The caprock breaks along *joints* (natural cracks in the rock) and falls down the escarpment in great blocks. Over the past 12,000 years, the falls have crept 11 km upstream because of this erosion. The upper two thirds of the Niagara Gorge, leading to the present falls, was cut after the end of the Pleistocene.

But the present falls are only the latest version of a recurring theme. Before the Woodfordian Substage, an earlier Niagara River cut the St. Davids Gorge, which flows 8 km between the Whirlpool and St. Davids. Today, the gorge is filled with glacial deposits.

[3]An *aquifer* is an underground layer that is porous and permeable enough to let groundwater flow through it.

[4]A *spit* is a small point of land projecting into a body of water from the shore. Spits are commonly composed of sand and gravel that was accumulated by the action of waves and currents. A *terrace* is a relatively flat surface, something like a very broad step. The *bars* we mention here are long, narrow ridges of sand and gravel that accumulated in the floor of a stream.

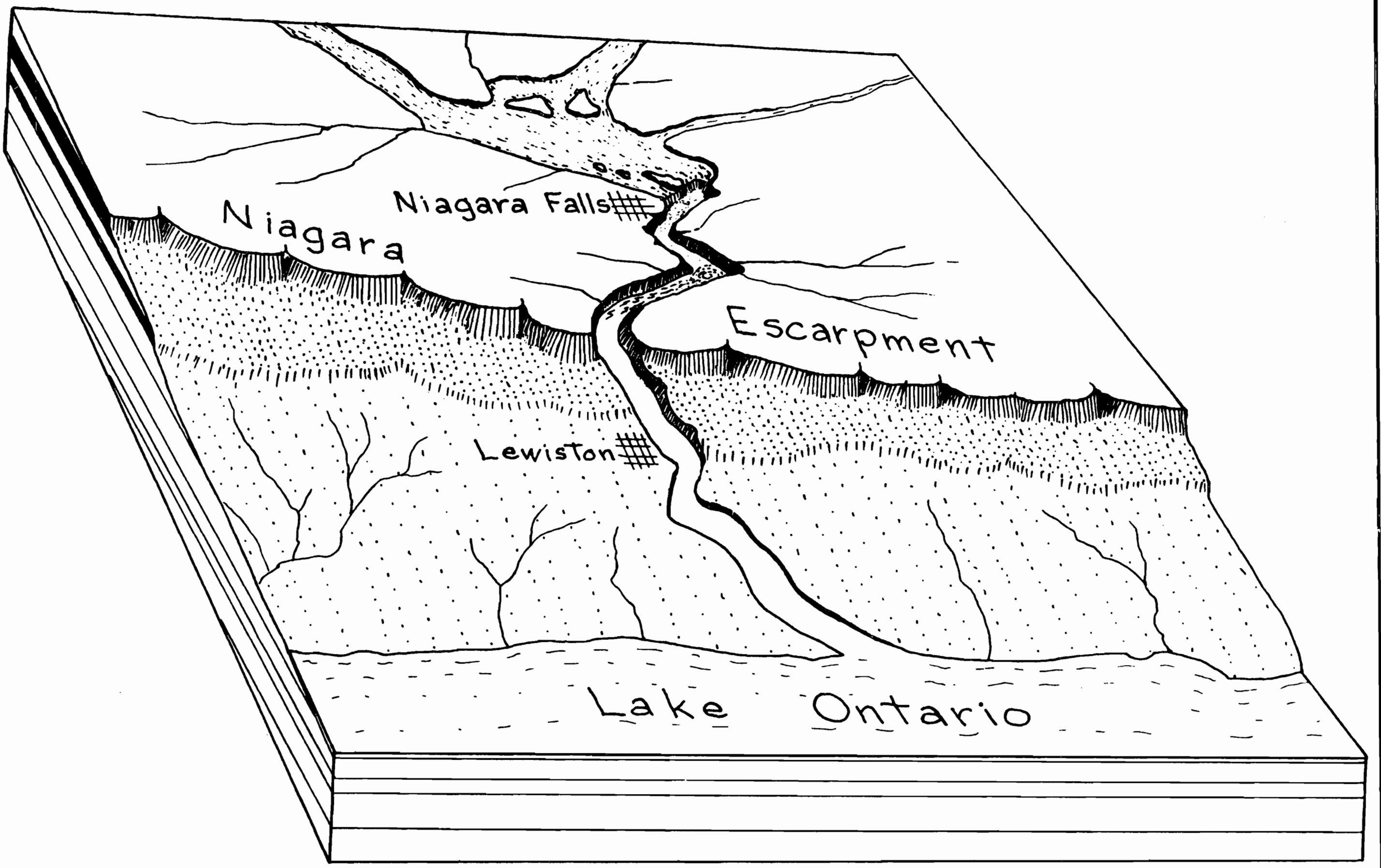


Figure 13.2. Bird's-eye view of Niagara Falls, looking south from the northern shore of Lake Ontario. Notice that the layers of the bedrock, which are c Ordovician and Silurian age, dip south. Notice particularly the Lockport Dolostone (upper dark-colored layer), which forms the Niagara Escarpment and th caprock of Niagara Falls. The Lockport Dolostone resists erosion and lies on top of easily eroded shales. The Niagara River began to flow along its preser course about 12,000 years ago, when the Pleistocene ice sheet melted north from the Niagara Escarpment. Since that time, the Niagara River has cut a gorg 11 km long, and erosion of the caprock continues daily. From the lip of the falls, the Niagara River plunges vertically 53 m. It descends another 22 m in th gorge before reaching the Niagara Escarpment. From there to Lake Ontario, a distance of 9 km, the river falls less than 1 m. The lower third of the Niagar Gorge was cut during the end of the Pleistocene Epoch, the remaining two-thirds, leading upstream to the present falls, was eroded during the Holocen Epoch. (In this drawing, vertical distances are exaggerated two times so that you can see the tilt of the rock layers; they actually dip only 1/4°-1/2°.)

Review Questions and Exercises

What feature formed by the glacier in this region is known worldwide?

How can we tell where glacial meltwater flowed in this region?

What are *plunge pools*?

How did the retreat of the glacier relate to the formation of Niagara Falls?

TUG HILL PLATEAU

The few people who live on the Tug Hill Plateau may sense that it is barely free of the Ice Age because it receives such tremendous snowfalls. The winter storms at Booneville frequently produce the lowest temperatures and deepest snows in the State.[5] The stony soils and short growing season discourage farming. Thus, most of the Tug Hill is covered with forest that has reclaimed abandoned 19th-century farms.

The ice that covered the Plateau during the Wisconsinan Stage formed rock drumlins and scratched the exposed rock surfaces. These traces tell us that the ice flowed southeast.

As the flowing ice thinned, the Tug Hill Plateau divided the glacier into several tongues (see Figure 12.3). It

[5]Such storms happen because the Tug Hill Plateau is an upland that is located downwind from Lake Ontario. This lake has little ice cover during the winter. Water evaporated from its surface falls as snow when the moist air masses rise over the Plateau and cool below the dew point.

caused the Ontario Lobe to split into the Oneida and Black River Sublobes. Similarly, the Hudson Lobe was split into the Adirondack and Mohawk Sublobes.

The lobes dammed the Black River and West Canada Creek and thus created glacial lakes. The largest was Glacial Lake Port Leyden. Water draining from Lake Port Leyden carved the Booneville Gorge.

Review Questions and Exercises

What clues tell us about how the glaciers moved in this region?

APPALACHIAN PLATEAUS

In New York State, the Appalachian Plateaus are subdivided into the Allegheny Plateau and the Catskill Mountains (Figure 1.1). The types of glacial activity in these two areas differed. These differences are related to *relief*—the local difference in elevation between valley floors and mountain tops. The Allegheny Plateau has a relief of 245 to 425 m. The relief is much greater in the Catskill Mountains—600 to 900 m. We'll deal with the Allegheny Plateau first.

Allegheny Plateau

Most of the glacial features in the Allegheny Plateau were formed by the continental ice sheet. Except on steep slopes, the bedrock of the hills is generally covered by one to three meters of unsorted till. In many valleys, on the other hand, layered debris may be up to a hundred meters thick. Such layered debris is deposited by the action of water—either streams or lakes or in conical hills called *kames* that formed when sediment-laden streams flowed off the ice front. The action of the water sorts the sediments into different layers by particle size.

When the edge of the glacier was near the head of the Susquehanna River, meltwater flowed freely to the south. It left outwash deposits of sand and gravel in the valleys. When the glacier had retreated a little farther, it sometimes reached an area where water would normally drain to the north. With that direction blocked by the glacier, however, meltwater would collect in the valley. For a time, the forward flow of the ice balanced the melting, and the glacier continued to deposit sediments along its edge. The result was a massive pile of deposits that blocked the valley. This complex, called the Valley Heads Moraine (see Figure 12.3), today divides the Susquehanna and St. Lawrence drainage basins (see Figure 16.1). Streams north of the moraine flow into the St. Lawrence River system, and those south of the moraine flow into the Susquehanna River system.

We find many magnificent examples of glacial erosion in the Plateau. An outstanding one is a series of U-shaped valleys carved out by the glacier. Today, these valleys are filled by the Finger Lakes[6] and other, smaller lakes to the west (Conesus, Hemlock, Canadice, and Honeoye). The Finger Lakes are the remnants of larger glacial lakes that filled the valleys. These extinct meltwater lakes lay between the retreating ice in the north and the Valley Heads Moraine in the south.

The Finger Lake valleys were widened and deepened by the glacier because they ran in the same direction as the ice flow. Stream valleys that were perpendicular to the main ice flow direction were not deeply carved. In such protected ravines, we may still find debris from earlier glaciers. The valleys of Six Mile Creek and Great Gully, which flow from the east into the Cayuga Lake valley, contain this older drift. Layers of stratified drift occur between the sheets of glacial till exposed in these ravines. Radiocarbon dating of plant and animal remains tells us that this water-deposited material has been there more than 30,000 years. At Fernbank on the west shore of Cayuga Lake a few kilometers north of Ithaca, there are sediments that contain plant remains and shells of freshwater organisms. Radiocarbon dating of the plants and shells tells us that the Cayuga Trough held a glacial lake more than 50,000 years ago.

As the glacier advanced, it carved striations, grooves, and roches moutonnées in the bedrock. Such features are usually found along valley walls and in upland areas.

The glacier also deposited a variety of sediments on the valley floors. Most were left by meltwater flowing from the glacier. Moraines and other deposits formed at the edge of the ice are commonly intermixed till and layered deposits made by meltwater. Many examples of such deposits exist in the Susquehanna River basin. A particularly good place to find them is along the Chenango River at the Chenango Valley State Park. Here, we find till, outwash, kames, eskers, kame terraces, and kettles.

Catskill Mountains

In the Catskill Mountains, many of the glacial features may have been formed by mountain glaciers instead of the continental ice sheet. The glacial history of the Catskills is very complicated, especially where local mountain glaciers merged with the main ice sheet.

In much of the Catskills, we find striations, roches moutonnées, cirques, and U-shaped valleys, all features

[6]The seven Finger Lakes are Canandaigua, Keuka, Seneca, Cayuga, Owasco, Skaneateles, and Otisco.

made by glacial erosion. The glaciers also left deposits behind in the Catskills—moraines, kames, outwash, and kame deltas. In addition, there are many kames, kame terraces, and kame deltas left by the continental ice sheet in the valleys of Schoharie Creek and the Batavia Kill.

A large lake formed in front of the ice in the Schoharie Valley. Between North Blenheim and Prattsville, we can find sand and clay from the lake bottom. We can also find sand and gravel deposited in deltas by streams flowing into the lake.

Review Questions and Exercises

What is *relief*?

What are the two subregions of the Appalachian Plateaus in New York State? How are they different? How were the glaciers that affected the two subregions different?

How did the glacier affect drainage in the Allegheny Plateau? How were the Finger Lakes formed? What was there before the Pleistocene?

What kind of evidence did the glacier leave on the walls of valleys in the Allegheny Plateau? On the valley floors?

What kind of glacial evidence do we find in the Catskill Mountains?

New England Province

The landform types of the New England Province are quite varied. The mountainous areas are rather extensive, as you can see on the Physiographic Diagram on Plate 4 of the *Geological Highway Map*. The entire New England region was covered by ice during the Pleistocene. As the ice retreated, it thinned first over the hilly regions. The higher peaks gradually protruded through the ice. The sun warmed the exposed rock, which was darker than the ice around it. The warm rock in turn caused the ice closest to the mountain to melt fastest.

As the ice melted, it left deposits of sediment on the land. These deposits show us where the edge of the ice was. A number of kinds of glacial deposits are found in the mountainous areas: outwash, kames, kame terraces, kame deltas, and eskers. We also find sediments deposited in meltwater lakes near the edge of the ice, channels eroded in outwash by water flowing over it, and moraines with many kames in them.

Near the Rensselaer Plateau, we can find an excellent example of this ice-melting process. First, the mountains in this upland began to peek through the glacial ice. Then, a large kame moraine was built near Grafton Lakes State Park east of Troy. This kame moraine was formed when meltwater streams deposited sand and gravel between the glacier and the mountain. Large kame deltas are also found at Lebanon Springs and Garfield, eskers and kame terraces at Lebanon Springs and Cherry Plain, and marginal lake deposits in the Hoosic Valley.

Farther south, at the northern edge of the Hudson Highlands, the Shenandoah Moraine formed during the retreat of the Wisconsinan glacier. This moraine is made of layers of glacial drift that was deposited next to the melting glacier. While the ice was at this location, meltwater flowed south along Clove Creek and Foundry Brook toward Cold Spring. The meltwater left numerous deposits. We can see kame deltas and outwash from it along Route 9 near the Dutchess-Putnam County border.

Near Pine Plains, we can find more evidence of a melting glacier. The Pine Plains Moraine can be traced around Stissing Mountain. We can also find an outwash plain left by meltwater flowing south from the Pine Plains Moraine into Wappingers Creek.

Commonly, outwash was deposited by meltwater downstream of the moraine at the ice margin. However, not all outwash plains are connected with such moraines. We find major outwash plains without moraines along Fishkill Creek at Hopewell Junction, in the Harlem Valley at Dover Plains, in the headwaters of the Roeliff Jansen Kill between Hillsdale and Ancram, along the Claverack Creek between Chatham and Mellenville, and in the Batten Kill Valley near Cambridge.

Farther south, in Westchester County, we find numerous signs of the ice sheet's passage. Examples of glacial streamlining, polishing, and striations of bedrock can be seen near Pocantico Hills and Peekskill. Near Shrub Oak is an esker and an erratic that was transported some tens of kilometers by the ice. Another erratic, left perched atop three smaller boulders, is found in North Salem. There are a number of drumlins near Granite Springs and an exposure of outwash in a gravel pit near the New Croton Reservoir.

Review Questions and Exercises

How did the ice sheet begin to melt in this region? What sort of evidence did the ice sheet leave behind as it was melting?

NEWARK LOWLANDS

A small part of the Newark Lowlands is in Rockland County, New York. Sand, gravel, and clay deposited in Glacial Lake Albany cover the Triassic rocks at Haverstraw. A thick wedge of Lake Albany clay lies under the river-bottom sediments of the Hudson River. Drumlins on the Palisades between DeForest Lake and the state line are made of red till. The glacier made this till by grinding up the red Triassic rocks as it moved south-southwest across the region.

Two moraines are found at Tappen. These moraines were built at the edge of the ice in the Nyack-Croton area.

A gap in the Palisades Ridge is found at Sparkill, near Tallman Mountain State Park. This gap may have been an outlet for water from the Hudson Valley and Glacial Lake Albany. From there, the water would have flowed across the sand plains at Northvale, New Jersey, into the Hackensack Valley.

Review Questions and Exercises

Where did the till in this region come from? Why is it different from till in other regions of the State?

What other kind of evidence was left by the glaciers in this region?

ATLANTIC COASTAL PLAIN (LONG ISLAND)

The highest hills of the islands off the southern coast of New England, including Long Island, Block Island, Fishers Island, and Staten Island, are parts of the Terminal Moraine of the Wisconsinan ice sheet (see Figures 12.3 and 12.21). These moraines are made of debris from the bedrock of New England and New York and from the Cretaceous strata underlying Long Island. As the glacier passed over the region, it picked up pieces of rock, ground them up, and then deposited them. Some of these deposits are completely unsorted tills. Others are outwash, deposited as layers of sand and gravel.

Beneath the glacial deposits of Long Island are relatively soft, crumbly Cretaceous rocks. These weak rocks were easily torn apart by the glacier, then redeposited on Long Island as till and outwash. We have evidence on Long Island for two advances of the ice sheet during the Wisconsinan Stage (see Figure 12.4). The end moraine of the first advance is partly buried by the moraine of the second advance. In places, the younger moraine is separated from the older by marine mud. This fact suggests that the two advances were separated by an interglacial period.

Figures 12.4 and 12.21B show the location of the end moraines on Long Island. Lake Ronkonkoma is an excellent example of a kettle lake that formed in the moraine.

We can see some of the glacial deposits of Long Island in the State and county parks in Nassau and Suffolk Counties. An exposure of glacial outwash and underlying Cretaceous rocks can be seen on the north shore of Long Island in Caumsett Park, north of Lloyd Harbor. The bluff along the beach contains layers of sand and gravel, carried from the glacier by a meltwater stream.

The Stony Brook Moraine extends through Sunken Meadow Park along the north shore near Smithtown. This moraine is made of variable amounts of sand, gravel, and till jumbled together. This varied composition suggests that the deposition of this moraine was complicated. However, its glacial outwash streams deposited sand and gravel in well organized layers. In bluffs along the coastline in Montauk State Park, we can see exposures of glacial till.

An end moraine commonly makes rolling hills. The Manetto Hills Moraine in Bethpage State Park, eastern Nassau County, is a good example.

Review Questions and Exercises

How were the highest hills on the islands in this region built? What does that tell us about the advance of the glacier?

What other kinds of glacial evidence do we find here?

CHAPTER 14
YESTERDAY, TODAY, AND TOMORROW
Holocene Epoch[1]

SUMMARY

We are living in the Holocene Epoch. This epoch follows the Pleistocene Epoch. By studying the pollen in Holocene sediments, we have traced a progression of climate from the earlier cold, dry glacial climate to the warm, moist climate of today. River erosion in the Holocene has carved many spectacular features in our State. Although the material eroded in the State eventually ends up in the Atlantic, some is temporarily deposited as deltas into lakes in many places. In other places, rising ocean and lake water drowns the mouths of streams, forming estuaries. Estuaries are common along the south shore of Lake Ontario; the crust has rebounded unevenly from the weight of glacial ice, thus tilting the entire basin to the south. With the melting of the ice, sea level has risen dramatically in the Holocene. This rise has drowned the Hudson River as far north as Troy, as well as the mouths of many of the Hudson's tributaries. Many of the Holocene environments around us change continually. Wind and water currents rearrange the barrier islands, bars, and spits along the shores of Long Island and in Lake Ontario. Lagoons and marshlands develop behind them, and the wind piles up sand into dunes. Along the banks of rivers, floodplains offer sites for towns and good farmland, although some of them flood nearly every year. Landslides are common along steep river and stream banks; they also occur on the very steep slopes of the Adirondack peaks. The Adirondack Mountains continue to rise in the Holocene.

INTRODUCTION

We live in the Holocene Epoch, sometimes called the Recent Epoch. It is the time since the Ice Age, the most recent part of the Cenozoic Era. It began 10,000 years ago, as the Laurentide Ice Sheet retreated north of the Great Lakes. "Holocene" means "completely modern." The name refers to the fact that the plants and animals of this epoch distinguish the modern world from previous times. Because we are still in the Holocene, we can observe its climates and geologic processes. Many of the features that we see daily—streams, waterfalls, beaches, harbors, soil—were formed or modified during the Holocene.

HOLOCENE CLIMATES

Glaciers are gone from New York State. The continental ice sheet left the State about 12,000 years ago. The last mountain glaciers in the Adirondacks probably melted 10,000 years ago. We must travel to the Rocky Mountains, to Alaska, or to the Canadian Archipelago to see remnants of the Ice Age in North America.

As the continental ice sheet retreated, the climate changed rapidly. What clues do we have to the climate 12,000 years ago? The pollen we find in sediments from that time is especially useful. It tells us what kinds of plants grew then. From this information, we can deduce what the climate was like in the early Holocene.

Climatic conditions along the ice front were very severe. Cold wind poured off the glacier. Frigid meltwaters flowed from its front. Scientists have studied the remains of the plants that grew near the ice front. They have found these plants to be sparse and low-growing, such as grass, lichens, mosses, and herbs. This kind of vegetation is just the sort we see today in tundra climates. Soils were very thin and easily eroded. Silt and sand were blown about by the glacial winds. Coarser particles were carried away by meltwater streams.

[1]Adapted from a manuscript by R.J. Dineen.

Farther south, the climate was less influenced by the glacier. Eighty kilometers from the ice front, black spruce, willow, and birch trees grew with the tundra plants. These trees need a warmer, more stable environment to flourish. We have found the bones of mammoth, mastodont, caribou, and elk there, too. Some of these animals died when they were mired in peat bogs that developed in the tundra and the black spruce forests.

As the ice retreated, the tundra vegetation was replaced by white spruce, balsam fir, jack pine, paper birch, and aspen. This change in plants tells us that the cold, dry, glacial climate had changed into a cool, moist one.

Between 10,000 and 8,000 years ago, the spruce forest was replaced by a white pine forest, indicating that the climate had become warmer and drier. As precipitation decreased, streams became smaller and the vegetation more sparse.

Plant remains tell us that about 8,000 years ago the climate changed to the warm, moist climate we live in today. The forest that developed was dominated by red oak, hemlock, hickory, and chestnut. European settlers exploited this "primeval" forest and almost destroyed it. Today, we can see only small remnants of the forest that once covered most of our State. One example is the Great Basin in Allegany State Park.

Holocene Lakes and Rivers

During the past 12,000 years, river erosion has carved many spectacular features. Cohoes Falls migrated upstream almost 5 km from the point where the Mohawk and Hudson Rivers joined. Niagara Falls migrated 12 km upstream. The 2 km-long Ausable Chasm was formed by the upstream migration of the ancestral Rainbow Falls. Lake George, which used to drain south before it was dammed by glacial deposits, now drains northward through a series of cascades into Lake Champlain at Ticonderoga. The Genesee River carved the magnificent Letchworth Gorge and deposited a large alluvial fan at Shaker Crossing near Rochester. The hanging valleys of the Finger Lakes region were also eroded far upstream since glaciers left the valleys.

In the cool, moist climate that developed after the ice retreated, the rivers flowing through the spruce-dominated forests were larger than today. We know their size from the deposits they left behind. Large fan-shaped deposits of coarse sediments, called *alluvial fans*, were made by streams at the foot of steep slopes. We can still see these fans today along the edges of river floodplains. Some good examples are found along the Hudson River between Waterford and Hudson Falls, and along parts of the Susquehanna and Genesee Rivers.

Similar alluvial fans were deposited along the edges of lakes at Bolton Landing on Lake George, at Sheldrake on Cayuga Lake, and at Seneca Point on Canandaigua Lake. Small villages have been built on these fans. Very large alluvial fans were created at the base of high mountains. The sites of Palenville and West Shokan are good examples; these villages were built on large fans at the foot of the Catskill Mountains. The streams that made the fans are still flowing across them. Along the lower Hudson River in Westchester County, Croton Point is a prominent example of an alluvial fan. It extends almost halfway across the river.

Today, most of the material eroded by rivers in New York is transported to the Atlantic Ocean. However, some of it is temporarily trapped in lakes. Kayderosseras Creek, for example, is building a delta into Saratoga Lake. Ticonderoga Creek and the Ausable and Saranac Rivers are constructing similar deltas into Lake Champlain. At Rochester, a large delta was constructed at the mouth of the Genesee River. A rise in the water level of Lake Ontario has since submerged this delta. Canadaway and Cattaraugus Creeks have built similar but smaller deltas in Lake Erie.

Along some streams flowing into lakes, lake level has risen until it is higher than the mouth of the stream. In such places, the stream does not form a delta. The drowned part of the stream is called an *estuary*. Estuaries are common along the south shore of Lake Ontario. Some examples are Irondequoit, Sodus Bay, Little Sodus Bay, and the Genesee and Oswego Rivers.

Why do so many estuaries exist along the south shore of Lake Ontario? The shore has slowly sunk beneath the waters of the lake. The sinking of the shore allowed the lake waters to flood the mouths of streams. But why did the shore sink? The answer goes back to an effect of the continental ice sheet, discussed in Chapter 12. The weight of the continental ice sheet depressed the earth's crust. The crust was depressed more along the north shore, where the ice was thicker, than along the south shore. Since the ice retreated, therefore, the crust has rebounded more in the north. For this reason, the entire lake was tilted to the south. At the same time as water flooded the mouths of streams along the southern shore, the river mouths along the north shore became shallower.

Sea Level in the Holocene

A rise in sea level can also drown part of a river to form an estuary. The Hudson River became an estuary as far north as Troy partly as a result of the Ice Age. The glacial ice widened and deepened the Hudson Valley; later, meltwater flow eroded the valley deeply. As the Pleistocene glaciers melted, sea level rose. Salt water now extends as far north as Poughkeepsie, and daily tides reach as far north as Troy. Large ocean-going ships regularly sail up the estuary to the port of Albany.

As the level of the Hudson River rose, it drowned the mouths of tributaries flowing into it. Catskill, Hudson, and many other Hudson Valley communities are located at the farthest point reached by daily tides on these drowned tributaries. The mouths of streams flowing into the ocean in southern Westchester County and on Long Island were also flooded by the rising sea.

At the peak of the Ice Age, so much water was stored as glacial ice that the sea level dropped around the world. As the ice melted, sea level began to rise again. We estimate that sea level has risen 100 m during the Holocene. About 7,000 years ago, most of the rise had occurred, but sea level was still 10 m lower than today. About 4,000 years ago, the sea reached approximately its present level. However, sea level is continuing to rise about 15 cm each century.

The Holocene Landscapes—Still Changing

By the end of the Pleistocene, huge quantities of sediment had been deposited in glacial lakes, along the shores of the ocean, and on the continental shelf. Long Island is a prime example of such deposits laid down near the ocean (see Chapter 12 for more information). Since then, the sediments along the coast have been continually rearranged by wind and by water currents. Coastal currents have built a series of barrier islands, bars, and spits along both shores of Long Island and also in Lake Ontario. Waves continue to erode cliffs along the shore. Good examples of such cliffs are visible at Montauk Point on Long Island and Hamlin Beach on Lake Ontario. Such erosion provides more sediments to form temporary bars and offshore islands.

An extensive barrier island chain stretches from Coney Island to South Hampton. These islands can be seen on Plate 1 of the *Geological Highway Map*. Individual islands grow as waves erode the cliffs between South Hampton and Montauk. Spits on the North Shore of Long Island partially block the mouths of bays. The coastal islands and spits are very recent in origin. We know their age because they could only have been built after the sea reached its present level about 4,000 years ago. These coastal landforms are like sandcastles in geologic time. Storms can change their shapes overnight.

As these islands and bars grow, they begin to close off small stretches of sea water near the shoreline. The stretches develop into large pools of salt water (called *lagoons*) and wet marshlands. In a similar way, freshwater marshlands have formed on the south shore of Lake Ontario behind barrier islands, bars, and spits between Braddock Heights and Sandy Point. In such environments, the wind piles beaches into dunes. These dunes change in shape as the wind blows. In most places, dune grasses will grow over the dunes and stabilize them unless careless human activity destroys the plant cover.

Floodplains are another kind of constantly changing Holocene environment. They are flat areas beside rivers. They are built of sediment laid down by rivers during flood stages. Towns and villages are commonly built on floodplains. Floodplains also hold some of the best farmland in New York. Some floodplains flood nearly every year. Good examples are the Stockade in Schenectady, parts of the city of Corning, and the village of Schoharie.

Many cities and towns built on floodplains in the Southern Tier were devastated by Tropical Storm Agnes on June 23, 1972. By studying historical records, which tell of recurring floods, we see that this kind of flooding has been going on for a very long time. We also find evidence of repeated flooding in archeological sites on the floodplains.

Landslides are another way that the landscape is changing today. Parts of the St. Lawrence, Erie-Ontario, Champlain, and Hudson Lowlands are prone to landslides. Silt, clay, and clay mixed with glacial deposits form steep banks along many rivers and streams. Flowing stream water erodes the lower part of the bank, especially during storms and spring melts. This erosion undercuts the slope. Landslide-prone soils are less stable when they are wet. They are also less stable when people build on the upper part of a landslide-prone area. We can find the scars left by landslides along many streams. Some good examples are found along the Normans Kill in Albany County, the Bouquet River in Essex County, Catskill Creek in Greene County, and Cattaraugus Creek in Cattaraugus County.

Dramatic landslides also occur on some of the very steep slopes of Adirondack peaks. Several hours of very heavy rain can soak the forest mat so thoroughly that it slides like a giant carpet down the rock face (Figure 14.1). Whiteface Mountain was named from such a landslide scar.

A surprising Holocene development is that the Adirondack Mountains appear to be rising at the present time. This observation is based on precision measurements of the elevation of surveyors' bench marks across the Adirondacks. Elevations were measured for each bench mark when it was installed. When these bench marks were surveyed again several decades later, their elevations were found to be higher. In addition, the elevations had increased more near the center of the Adirondacks than at its borders. This interesting question of Adirondack uplift is still being studied.

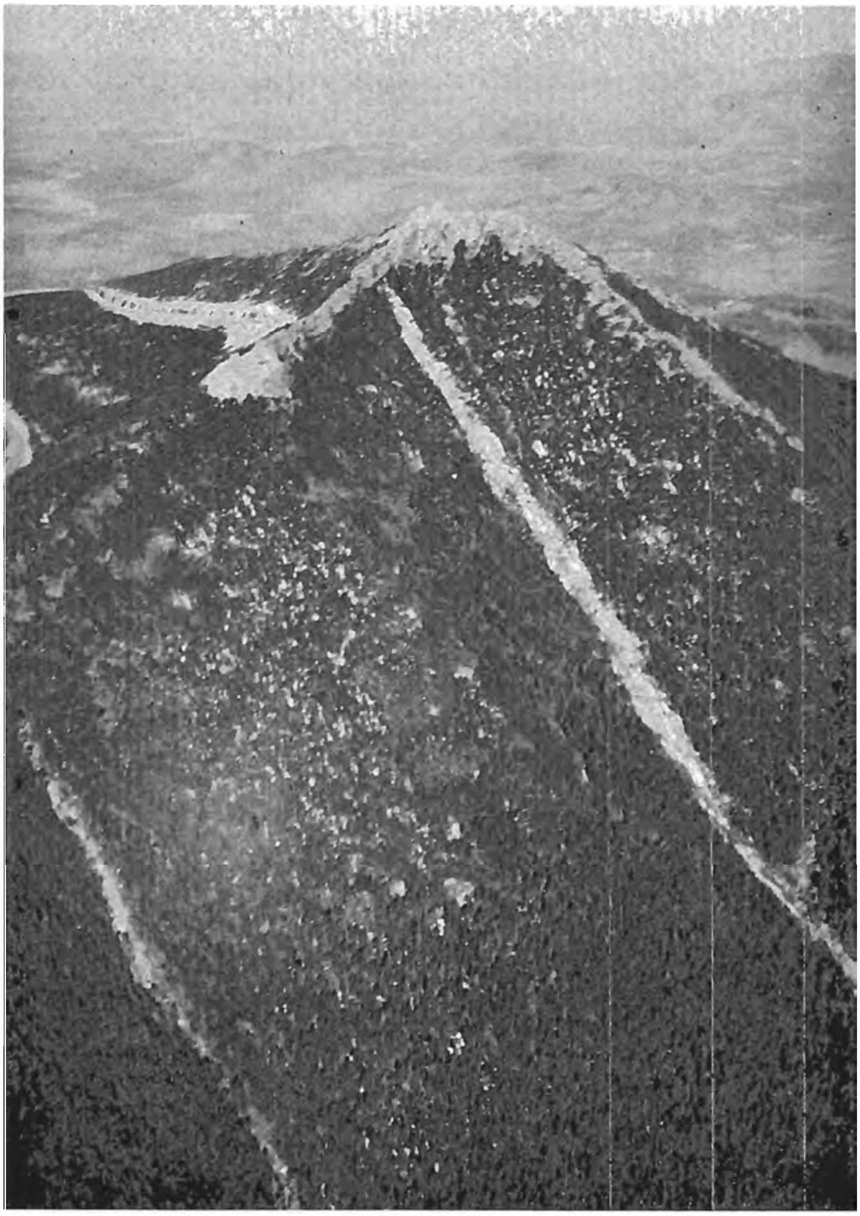


Figure 14.1. In this aerial view of Whiteface Mountain, you can see the long, narrow, light-colored scar left by a landslide. Rock slides like this one can happen on steep, smooth rock slopes. A very heavy, once-in-a-lifetime downpour soaks the carpet of vegetation so thoroughly that it no longer sticks to the rock. Then the forest mat crashes down the mountain.

The slide shown in this photograph is one of 10 that occurred on the mountain on Labor Day, 1971, at about 4:30 p.m. The slides were up to 38 m wide and 5 m deep. The slides were caused by a very heavy local downpour that dropped 7.6 cm of rain in one hour on the summit, while 5 cm fell at the base of the mountain and none in the valley. This odd weather event occurred on a day of record humidity. As the humid air rose over the mountain top, it cooled until it suddenly dropped the moisture it carried.

This photograph was taken looking toward the northeast. Compare it with the photo in Figure 12.12, which was taken from a location just to the left of this one.

Review Questions and Exercises

How did the climate change as the glacial ice retreated and afterwards? How do we know about these changes?

What is an *estuary*? Why do we find many of them on the south shore of Lake Ontario? How did the Hudson River become an estuary?

Name several ways that the landscape is changing today.

PART IV
Geology and People

CHAPTER 15
MONEY FROM ROCKS
Mineral Resources[1]

SUMMARY

Mineral resources are an important part of New York State's economy. This chapter divides them into three categories: nonmetals, metals, and mineral fuels. The nonmetals section covers these resources (in alphabetical order): carbonate rock, clay, emery, garnet, granite, gypsum, halite (common salt), ilmenite (titanium ore), peat, sand and gravel, sandstone, slate, soil, talc, and wollastonite. Each entry answers the following questions: What is it? How did it form? What is it used for? How important is it? Where is it found? In some cases, other significant information on the resource is added. The same format is used in the metals section, which is divided into two entries: iron deposits; and lead, silver, and zinc.

The mineral fuels section discusses New York's oil and natural gas, found mainly in the southwestern part of the State. New York has enough of these resources to contribute to local economies. Oil and natural gas were originally discovered by American Indians, who showed them to European colonists.

The modern oil industry began in Pennsylvania in 1859, with the drilling of the first oil well. An unsuccessful wildcat well was drilled in Allegany County in 1860, and New York's first successful oil well was drilled in 1865 in Cattaraugus County. An oil boom began, and New York's production reached its peak in 1882. The boom ended by the late 1890s. A new technique for extracting more oil from depleted wells started another increase in production, which lasted from 1919 until it reached a second peak in 1938. Since 1942, New York's oil production has declined. Oil in New York is produced from Upper Devonian sandstones—the Canadaway Group and the West Falls Group—and from Upper Silurian and Middle Devonian carbonate rocks—the Akron Dolomite and the Onondaga Limestone. The oil from the carbonate rocks is contained in a structural trap called the Bass Island Trend; the discovery of this structural trap boosted oil production in 1983.

The first natural gas well in the U.S. was drilled in 1821 near Fredonia and the gas used for lighting. In the early days of oil drilling, much natural gas was allowed to escape into the atmosphere, until the invention of a gas-powered well pump in the 1890s. Since the turn of the century, natural gas production has increased. Natural gas has been found in numerous formations, including rocks that do not contain oil, but only some of these formations contain commercial quantities of gas. Formations producing gas in New York (from oldest to youngest) are the Potsdam Sandstone, the Trenton Limestone, the Queenston Shale, the Medina Group (New York's best gas producer), the Akron Dolomite, the Oriskany Sandstone, the Onondaga Limestone, and the West Falls and Canadaway Groups. New York's natural gas will be important to the southwestern and central parts of the State for many years. Depleted natural gas fields are used to store gas produced elsewhere.

INTRODUCTION

New York State is rich in mineral resources.[2] Nationwide, the State ranks between 10th and 15th in the value of nonfuel mineral production. Crushed stone is the leading mineral commodity. It makes up 25 percent of the total value of the State's mineral production. Other commodities that are important in New York's economy are port-

[1]Adapted from a manuscript by W.M. Kelly, H. Bailey, and R.E. Nyahay.
[2]A *mineral resource* is any geologic material that is valuable economically.

land cement, salt, construction sand and gravel, and zinc. There are roughly 2,000 mines in New York, and 85 percent of them are involved in sand and gravel production.

In our discussion, we have divided New York's mineral resources into three categories: nonmetals, metals, and mineral fuels (oil and natural gas).

Note: In other chapters, we have explained unfamiliar words in the text so you would not have to turn to the Glossary many times on each page. In this chapter, though, we have not done so. The question-and-answer format of the first two sections of this chapter makes it easier to look up specific facts rather than to read straight through. Therefore, having to turn to the Glossary will not break up the flow of your reading.

NONMETALS

Carbonate Rock

What is it?
Limestone, dolostone, marble.

How did it form?
Limestone and dolostone are sedimentary rocks deposited in the ocean as carbonate sediments. Marble is metamorphosed limestone or dolostone.

What is it used for?
Mainly construction (concrete, portland cement, crushed stone, highway paving material). In the past, carbonate rock was used for natural cement.
At present, most of New York's carbonate rock is used for concrete, highway paving material, and cement. Of the remainder, some is burned to make quicklime or hydrated lime, which are used in chemistry, industry, and farming, and some is used for miscellaneous purposes (railroad beds, riprap, precast architectural units, ground for use in farming).

How important is it?
Carbonate rock is New York's most valuable mineral resource, critical for modern buildings and highways. Ninty percent of the stone sold in New York State is limestone or dolostone.

Where is it found?
In many places throughout New York State.

Marble—in St. Lawrence County (Gouverneur Marble), Westchester County (Inwood Marble), Dutchess County (Cambrian and Ordovician marbles).

Limestone and dolostone—in long outcrop belts as follows (Figure 15.1):

Devonian Period:
Onondaga Formation: Fine- to coarse-grained, relatively pure gray limestone with many fossils. Frequently contains chert, either in layers or as nodules. Quarried extensively across the State. Used for crushed stone.
Helderberg Group: Fine- to coarse-grained gray limestone, with varying purity and number of fossils. Some formations (Manlius, Coeymans, Becraft) are used for cement and crushed stone. Manlius Formation is fine- to medium-grained limestone with fossils and a small amount of clay. Coeymans and Becraft Formations are usually coarse-grained and relatively free of clay and silica. Other parts of the Helderberg Group (Kalkberg, New Scotland, Alsen, and Port Ewen Formations) are less pure and are used mainly for crushed stone.

Silurian Period:
Rondout Formation: Fine-grained dolostone, containing clay; once used for natural cement near Rosendale. Surface weathers to a buff color.
Lockport Group: Mostly dolostone, with some limestone layers and a moderate number of fossils. Quarried between the Niagara River and Syracuse, mainly for crushed stone.

Ordovician Period:
Trenton Group: Fine- to coarse-grained gray limestone with many fossils; relatively free of impurities, but with many thin shale beds. Used mainly for crushed stone; also used by one cement producer at Glens Falls.
Black River Group: Limestone locally underlying the Trenton Group, finer grained and darker than limestones of the Trenton. Main formation is the Lowville, a relatively pure, fine-grained limestone. Use for crushed stone.
Chazy Group: Fine- to coarse-grained limestone. Quarried for crushed stone in the northern Champlain Valley.
Beekmantown Group: Dolostone containing silica and occasional layers of limestone. Quarried for crushed stone in the Champlain, upper Hudson, and lower Mohawk Valleys.

Cambrian and Ordovician Periods:
Wappinger Group: Dolostone and limestone similar to the Beekmantown. Layers quarried for crushed stone in southeastern New York are probably Early Ordovician.

Other information
About Cement.—There are two kinds of cement. *Natural cement* is made by burning and grinding a special kind of limestone that contains just the necessary amount of clay minerals. The ground rock, mixed with water, will dry into a hard mass. *Portland cement* is different. It is made by heating a mixture of certain rocks and minerals—including limestone—together

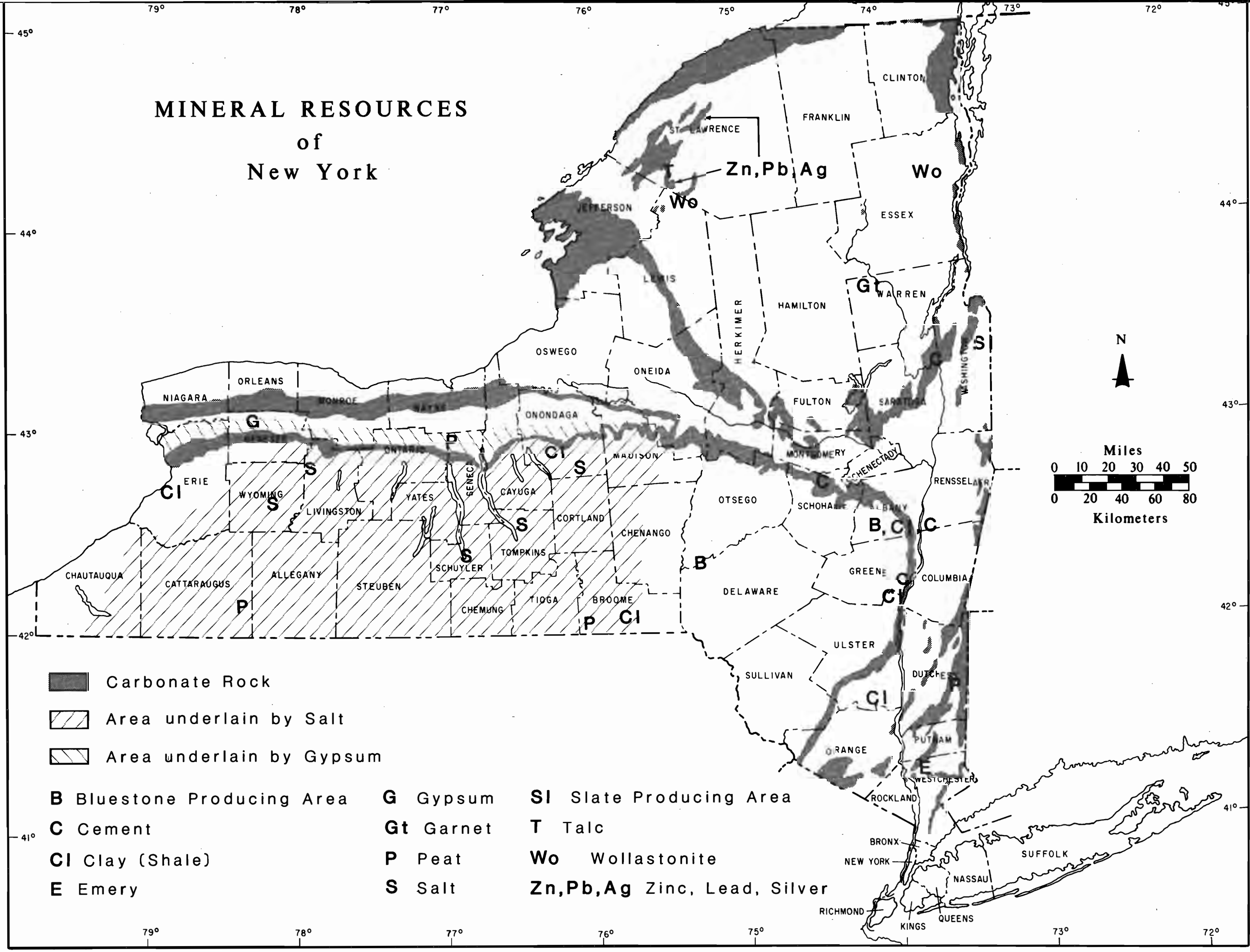


Figure 15.1. Map of the mineral resources (other than oil and natural gas) of New York State. This map shows only those resources that were being exploited in significant amounts as of 1989. Therefore, it does not include some of the resources discussed in this chapter.

in a kiln. Portland cement is manufactured in the mid-Hudson Valley (Albany and Greene Counties) and at Glens Falls. Natural cement was first used to build the Erie Canal. It is no longer produced in New York.

New York is one of the leading cement-producing states. It has a good supply of the right kind of stone, as well as major transportation routes (rivers, highways, railroads) for shipping the bulky product. It is also located near densely populated regions where there is a high demand for cement.

Clay

What is it?
An earthy, extremely fine-grained sediment made of clay minerals.

How did it form?
Clay minerals settled to the bottom in the deeper water of ancient glacial lakes to form layers of clay.

What is it used for?
Making bricks, pottery and stoneware dishes, and lightweight concrete. As a waterproof lining and cover for landfills to prevent contamination of groundwater.

How important is it?
New York has a lot of clay.

Where is it found?
Pleistocene clays (formed in the deepest parts of glacial lakes): Erie County south of Buffalo, middle Hudson Valley between Albany and Newburgh, Onondaga County near Syracuse.

Cretaceous clays: Raritan Formation on Staten Island (no longer used).

Other information
Lightweight Concrete Aggregate.—Concrete is usually made of two substances, an *aggregate* of sand, gravel, or crushed stone and a cement that holds the mass together.

A lightweight concrete can be made by substituting different aggregate material. When clay and shale are heated together in a kiln, they begin to melt and fuse. This melting turns the clay and shale into a sticky mass. Gases are released in the process. These gases form bubbles in the mass and convert it to a froth. When the froth cools and hardens, it forms a very strong, lightweight material that can be used in concrete as a substitute for the heavier gravel and crushed stone. This lightweight concrete is just as strong as regular concrete and is ideal for bridges and modern office buildings.

Emery

What is it?
Metamorphic rock made of the minerals magnetite, corundum, sillimanite, and sapphirine or cordierite (proportions vary).

How did it form?
Molten rock (*magma*) intruded into the Manhattan Schist. Along the contact, heat metamorphosed the schist further and turned it to emery.

What is it used for?
Extremely tough abrasive. Used in industry for grinding and polishing and to make nonslip surfaces for stair treads and some kinds of flooring.

How important is it?
Emery was last produced in New York in 1989. Artificial abrasives replaced emery because they are harder and their composition varies less.

Where is it found?
Near Peekskill, Westchester County. These mines, the only source of emery in the U.S., are now closed.

Other information
Abrasives.—Abrasives are gritty materials. They are used in common household products like sandpaper and emery boards (for filing fingernails).

Garnet

What is it?
A hard red metamorphic mineral. In the Adirondacks, crystals are usually between 2 mm and 2.5 cm across. However, crystals as large as 1 m in diameter have been found at the Gore Mountain garnet mine, which closed in 1983.

How did it form?
When the igneous rocks olivine gabbro and gabbroic anorthosite were metamorphosed, garnet was formed as one of the new metamorphic minerals.

What is it used for?
An important abrasive. Used for sandpaper and powdered abrasive. When broken, garnet from Gore Mountain has a chisel-like edge; garnet sandpaper does not clog when used, so it is desirable for woodworking. Garnet is also used in grinding and polishing glass and metal. Television picture tubes are polished with New York garnet before phosphors are applied. Garnet is also used for sandblasting, filtering water, and in water jet for cutting stone. Garnet crystals can

be used as gemstones, but New York produces very few garnets without internal cracks that are suitable as gems.

How important is it?
New York is a leading producer of garnet. The original Gore Mountain mine was the largest garnet mine in the world; it first produced garnet in 1878. The mining operation shifted to Ruby Mountain in 1983. Garnets from Ruby Mountain make especially high quality abrasives.

Where is it found?
Ruby Mountain near North Creek is the biggest of several garnet deposits in the east central Adirondacks (Figure 15.1).

Granite

What is it?
As used in the stone industry, "granite" refers to a variety of light-colored igneous and metamorphic rocks. In New York State, most commercial "granites" are actually gneisses.

How did it form?
Granite gneiss can form from the metamorphism of intrusive granite, rhyolite lava, or arkosic sandstone.

What is it used for?
Construction—it is crushed for concrete aggregate; some is cut into blocks for buildings or curbstones. Blocks are more valuable.

How important is it?
As a building stone, it was more popular formerly than it is today; the industry declined because of competition from cheaper manufactured building materials. However, granite is a particularly good building stone, and the industry recovers from time to time.

Where is it found?
In the Adirondacks and in Westchester County.

Gypsum

What is it?
A sedimentary evaporite mineral with the chemical composition $CaSO_4 \bullet H_2O$.

How did it form?
Evaporation of very salty shallow seas produced evaporite minerals: gypsum and minor amounts of anhydrite. Burial of these deposits converted them into anhydrite (chemical composition $CaSO_4$). However, when erosion brings anhydrite layers near to the surface, groundwater converts the anhydrite to gypsum.

What is it used for?
It is processed to make plaster and wallboard. It is also a minor ingredient in portland cement.

How important is it?
Very important in building.

Where is it found?
In several unusual layers of the Late Silurian Salina Group (Figure 15.1; see also Plates 2 and 3 of the *Geological Highway Map*). Found in Genesee County; mined and processed in Oakfield, near Batavia. Out-of-state gypsum is processed in Rensselaer, Rockland, and Westchester Counties.

Halite (Common Salt)

What is it?
An evaporite mineral made from sodium and chlorine (chemical composition NaCl).

How did it form?
Evaporation of shallow seas with very salty water.

What is it used for?
New York State salt is used in the chemical industry and for de-icing highways. Salt deposits are being considered as places to store oil, radioactive waste, and sensitive photographic products, because they generally lack fractures and cracks through which liquids can flow.

How important is it?
Very important resource throughout the history of New York. The Retsof mine, near Geneseo, is the largest underground salt mine in the world. It had produced more than 138 million metric tons (138 billion kilograms, or 125 million tons in English units) by 1990. In 1990, New York was the third largest producer of salt in the nation.

Where is it found?
About 3.9 trillion metric tons of rock salt lie under more than 26,000 square kilometers in central and western New York (Figure 15.1). This area stretches from Madison and Chenango Counties in the east to Erie and Chautauqua Counties in the west.
Salt layers are found in parts of the Salina Group—the middle Vernon Shale and the Syracuse Formation (see Plates 2 and 3). They range from 1 m to over 30 m thick and alternate with layers of dolostone and anhydrite-rich shale. Layers are thickest and most numer-

ous in the southern part of Syracuse Formation, along the Pennsylvania border. Like most sedimentary layers in western New York, the Salina Group slopes to the south about 25-50 m per kilometer. At the Pennsylvania state line, it is 1,350 m underground.

Today, salt is produced from brine at six places in Onondaga, Schuyler, and Wyoming Counties. It is mined as rock salt at Myers, on Cayuga Lake, and at Retsof, near Geneseo.

Other information

History of Salt in New York State.—New York's salt industry started in the Syracuse area. A major reason for founding Syracuse during colonial times was to use the salt springs near Onondaga Lake. These salt springs were previously well known among the American Indians.

As demand for salt increased, people drilled wells to try to find more salty water (called *brine*) underground. For quite some time, they failed. Groundwater had dissolved the salt beds for several miles back from the outcrop. Thus, nothing was there to drill into. Eventually, they found a salt layer near Tully, 10 miles south of Syracuse. This discovery set off a new burst of activity.

During the last quarter of the 19th century, brine wells and salt mines expanded rapidly, especially in Livingston and Wyoming Counties.

Ilmenite (Titanium Ore)

What is it?

Ilmenite is a black, shiny mineral made of iron, titanium, and oxygen (chemical composition $FeTiO_3$). Although it could be the source of the metal titanium, in New York it is mined for other uses.

How did it form?

Crystallized from an anorthosite magma. Metamorphosed anorthosite forms large rock bodies in the Adirondacks.

What is it used for?

All of the titanium produced in New York is used to make titanium dioxide—a brilliant white pigment used in paints. As refining techniques improve and costs come down, New York could become able to produce the metal titanium, which is used to make strong, lightweight, corrosion-resistant metal for the aerospace industry.

How important is it?

Mining ceased in 1982.

Where is it found?

Ilmenite is found on the southwest border of the main body of metamorphosed anorthosite in the Adirondacks. Layers are up to 600 m long and 100 m or more thick. These layers dip steeply. The Sanford Lake ore body at Tahawus, Essex County, is worked out; another deposit near Cheney Pond is probably as large and could be used if demand becomes high enough.

Other information

History of Titanium in New York.—The Sanford Lake deposit was discovered in 1826. It contains both ilmenite and *magnetite* (magnetic iron ore). People tried repeatedly to use it to produce iron. They always failed, because they could not separate the ilmenite from the magnetite.

At the beginning of the 20th century, a French chemist, who used Sanford Lake ore in some of his work, discovered that titanium dioxide makes an ideal white pigment for paint. Titanium began to be used more and more for this purpose. However, the Adirondack deposits were not used. The United States purchased most of its titanium ore from other countries until World War II made that difficult. To get the titanium needed for the war, a large mine and mill were set up at Tahawus, and a railroad line was built to carry the ore south. The mining operation continued to be successful after the war because titanium dioxide was needed during peacetime.

Refining Titanium.—The ore from which titanium is refined contains ilmenite (chemical composition $FeTiO_3$) mixed with magnetite (chemical composition Fe_3O_4) In fact, only about 20 percent of the ore is titanium dioxide (chemical composition TiO_2). To purify the titanium ore, these ore minerals are ground very fine and then separated by means of magnetic and floatation separators. *Magnetic separators* are devices that use magnets to help separate magnetic minerals (like magnetite) from nonmagnetic minerals (like ilmenite). *Floatation separators* are tanks of special chemicals into which air bubbles are blown. When ore is added, ilmenite sticks to the bubbles that form a froth on the top of the tank. The froth is collected, and the ilmenite is washed out of it.

After the ilmenite is purified, the leftover magnetite is sold to be used in coal processing.

Peat

What is it?

Partly carbonized remains of swamp and bog plants—mosses, reeds, sedges.

How did it form?

From plants that were submerged after death. Most New York peat formed in old glacial lakes when they were later filled in or partly drained to become bogs or swamps.

What is it used for?
Soil conditioner and mulch.

How important is it?
A minor industry in New York.

Where is it found?
Produced commercially in Dutchess, Westchester, Broome, Seneca, and Cattaraugus Counties (Figure 15.1). If demand increases, other deposits could be used as well.

Sand and Gravel

What are they?
Many kinds of naturally broken rock. Sand and gravel composed of limestone, dolostone, sandstone, and igneous rocks are strong enough for construction; large amounts of weak rocks—shale, slate, and schist—make some deposits of sand and gravel unsuitable for this purpose.

How did they form?
New York's commercial sand and gravel come from glacial deposits.

Molding sands are glacial lake sands that were reworked by wind. They originally contained many shale particles. Over the centuries, these particles weathered into clay that helps bind the molding sand.

What are they used for?
To make concrete for building and highway construction. Molding sand is used to make metal castings.

How important are they?
Vital to building and highway construction. Molding sand is particularly valuable.

Where are they found?
Suffolk, Dutchess, and Rensselaer Counties are leading producers of sand and gravel. Underwater deposits can be brought to the surface by dredging or through pipelines.
Molding sand is found in the Capital District and around Oneida Lake.

Other information
Metal Castings.—Because molding sand contains clay, it can be molded into complex shapes. It will retain those shapes even when hot. Liquid metal is poured into the sand mold and hardens. This process allows us to form the metal into a variety of shapes.

Leading Sand and Gravel Areas.—Suffolk, Dutchess, and Rensselaer Counties are New York's leading producers of sand and gravel. Although they do not have higher quality or greater quantities of sand and gravel than other areas, they are closest to potential markets. Their location cuts down on shipping costs and makes the operations profitable.

Glacial Sand and Gravel Deposits.—The major sources of sand and gravel are glacial deposits: moraines, outwash plains, valley fill, kames, kame terraces, and deltas. See Chapters 12 and 13 for more information about these and other kinds of glacial deposits.

Sandstone

What is it?
In economic usage, "sandstone" refers to graywacke, metamorphic quartzite, conglomerate, and sedimentary sandstones.

How did it form?
Mineral grains and rocky fragments were deposited in bodies of water, mainly ancient seas, but locally in Triassic-Jurassic rift basins in the Ramapo area.

What is it used for?
Cut into blocks for building, flagstone, and curbing. Some sandstones are crushed to make concrete aggregate. Some is used for riprap. Pure quartz sandstone can be used to make high-quality glass, but sandstones in New York contain too much iron and alumina for this purpose.

How important is it?
New York and Pennsylvania are the only sources of bluestone, a particular type of commercial sandstone (Figure 15.1).

Where is it found?
Commercial sandstone locations.—Found widely in New York State; quarried in Orleans County, Delaware County, and around the Adirondacks.

Middle and Late Devonian Period:
Fine-grained graywackes, bluish gray to olive green, called *bluestones*. (For locations of the formations, see Plates 2 and 3.)

Silurian Period:
Medina Sandstone. Used for crushed stone and building stone.

Late Cambrian Period:
Potsdam Sandstone. Used for veneer stone and flagging.

Cambrian Period:
Rensselaer Graywacke. Used for crushed stone. Was once used as building stone.

Potentially commercial sandstones:
Silurian Period:
Herkimer, Thorold-Kodak-Oneida, Shawangunk, Whirlpool. Could be used for crushed stone or building stone.

Ordovician Period:
Oswego, Heuvelton-Mosherville. Could be used for crushed stone or building stone.

Cambrian Period:
Poughquag. Could be used for crushed stone or building stone.

Slate

What is it?
Metamorphosed shale. Colors are red, green, gray green, purple, black, or combined purple and green (called *variegated*).

How did it form?
Metamorphosed shale.

What is it used for?
Flagstones, flooring tile, and roofing.

How important is it?
The New York-Vermont slate belt is the only one in the U.S. that produces colored slates: red, green, purple, and variegated.

Where is it found?
Washington County and across the border in Vermont (Figure 15.1). Most red slate, a popular kind for building, is on the New York side.

Other information
Secondary Cleavage.—Shale splits easily along its sedimentary layers. When the shale is metamorphosed and becomes slate, it develops a *secondary cleavage.* This term means that the slate splits in a new direction that is frequently different from the original layers. We can frequently see the original sedimentary layers where they intersect the secondary cleavage. They form ribbons of different textures or colors on the split slate surface.

New Yorks Slate Industry.—At one time, slate for roofs was a larger part of New York's slate industry than it is today. But the techniques used to quarry and process this slate are old, and this situation has kept costs high. Meanwhile, other roofing materials were developed. Among these materials is asphalt roofing, which uses only small granules of slate on the surface. These low-cost substitutes have taken away much of the market for New York's slate.

Soil

What is it?
Surface layer of the land where plants can grow. Contains both natural minerals and living and dead organic matter.

How did it form?
Mainly from weathering of the glacial deposits that blanket the State. Has been forming steadily since the last ice sheet retreated in New York.

What is it used for?
Agriculture.

How important is it?
A vital resource of the State. All plants depend on the soil, and all animals (including humans) depend on plants for food.

Where is it found?
Throughout the State.

Other information
Soil Formation.—After the ice sheet retreated, soils slowly developed from a thin litter of organic materials on the surface. Gradually, the soils became deeper and more fertile.

The *parent material* of a soil is the weathered product of rock or sediment. The parent material determines some of the chemical and physical characters of soil.

Parent materials that are rich in quartz, such as gneiss, weather and form soil slowly. Shale, on the other hand, weathers and forms soil quickly. Parent materials that are *permeable* (allow air and water to flow through them) will weather quickly. The soil will be deeper in those places where the underlying material is permeable.

Climate and plant communities affect how soils form and how thick they become. For example, warm, moist regions develop thicker soils than dry regions, while the high temperatures and heavy rain of tropical rain forests dissolve away soils almost as fast as they develop. In addition, the slope of the land affects how soils form and are distributed.

Most of New York's soils developed from deposits left by the retreating ice sheet. The ice sheet began retreating in the southern part of the State 21,750 years ago and left the northern part 10,000 years ago. The glacial deposits can range from a few centimeters to a meter or more thick.

The glacial deposits may be *till*—a thick, dense mixture of boulders, gravel, sand, and clay. Till is impermeable, but other glacial deposits may consist of loose, permeable sand and gravel.

Fine-grained deposits (like till or the silt and clay deposited in glacial lakes) tend to be poorly drained. Coarser grained deposits (like sand and gravel) tend to be well drained. The sand and gravel tends to come from such glacial deposits as outwash and kames. See Chapters 12 and 13 for more information on glacial deposits.

The youngest soils of the State formed from sediments deposited by modern streams and rivers.

Talc

What is it?
True talc is a very soft, flaky, white mineral with many uses. New York's industrial "talc," however, actually contains less than 50 percent of the mineral talc. The rest is a mixture of other minerals—tremolite, anthophyllite, serpentine, and dolomite. Because of the presence of these minerals, New York's industrial "talc" is fibrous (made of long, thin, needle-like crystals).

How did it form?
Talc deposits are found near faults and shear zones where tremolite-anthophyllite schists were changed into talc and serpentine.

What is it used for?
Used industrially where a white powdery mineral is needed: as paint extender; as a carrier for insecticide dust; in ceramics; as filler in asphalt roofing, putty, linoleum, and similar products. A company in Jefferson County grinds true talc from out of State for cosmetics.

How important is it?
New York is the fourth largest producer in the nation.

Where is it found?
Gouverneur district, northwest Adirondacks, in narrow, contorted belts of Proterozoic schist (Figure 15.1). Found together with serpentine. Deposits up to 60 m thick occur along an 8 km belt of the schist.

Wollastonite

What is it?
A white fibrous industrial mineral with the chemical composition $CaSiO_3$.

How did it form?
Layers of wollastonite, together with the minerals diopside and garnet, formed when Proterozoic sandy limestone was metamorphosed at high temperature by intruding magma.

What is it used for?
Chiefly used for making ceramic tile, porcelain, and paint, in super-plastics, and for replacing short-fiber asbestos in brake linings and similar uses.

How important is it?
Wollastonite was the basis for a new industry in New York State. More than 99 percent of the wollastonite produced in the U.S. comes from New York.

Where is it found?
Willsboro Mine and Lewis open pit, both in Essex County. Also produced from an underground mine and open pit mine near Harrisville, Lewis County (Figure 15.1).

Other information
History of Wollastonite in New York.—In 1810, wollastonite was found near Willsboro, Essex County. The mineral was then almost forgotten for the next 135 years. After World War II, the deposit was carefully mapped. It was found to be quite large and concentrated. As a result, uses for wollastonite were developed, and a successful mining and milling operation was begun.
Refining Wollastonite.—The deposit consists of layers of wollastonite together with diopside and garnet. The diopside and garnet are weakly attracted by magnets. The milling operation consists of grinding the ore fine and passing it by strong electromagnets. These magnets pull away the diopside and garnet and leave pure wollastonite.

Metals

Most of New York's metal mining is in the Adirondack region (Figure 15.2). Metals produced there today or in the past are iron, zinc, lead, and silver. Copper is the only other metal that has been important in New York's mineral industry. It was mined near Ellenville, Ulster County, by Dutch settlers in the 17th century.

To be profitable for mining, ore deposits have to contain much more metal than we usually find in the crust. It's very difficult and expensive to extract metal from ore when the metal is less concentrated. However, as the economy changes, people may need more and more of a particular metal. When such changes increase demand, people are willing to pay more for the metal. Mine operators then can spend more to mine and refine the ore and still make a profit. At the same time, technology is improving; we are finding better and cheaper ways to extract the metal from the ore. Thus, in the future we may be able to use ore deposits that are too expensive to mine today.

Iron Deposits

What are they?
The common iron ore in the Adirondacks and the Hudson Highlands (Figure 15.2) is *magnetite*, a black magnetic mineral made of iron and oxygen. It has the chemical composition Fe_3O_4.

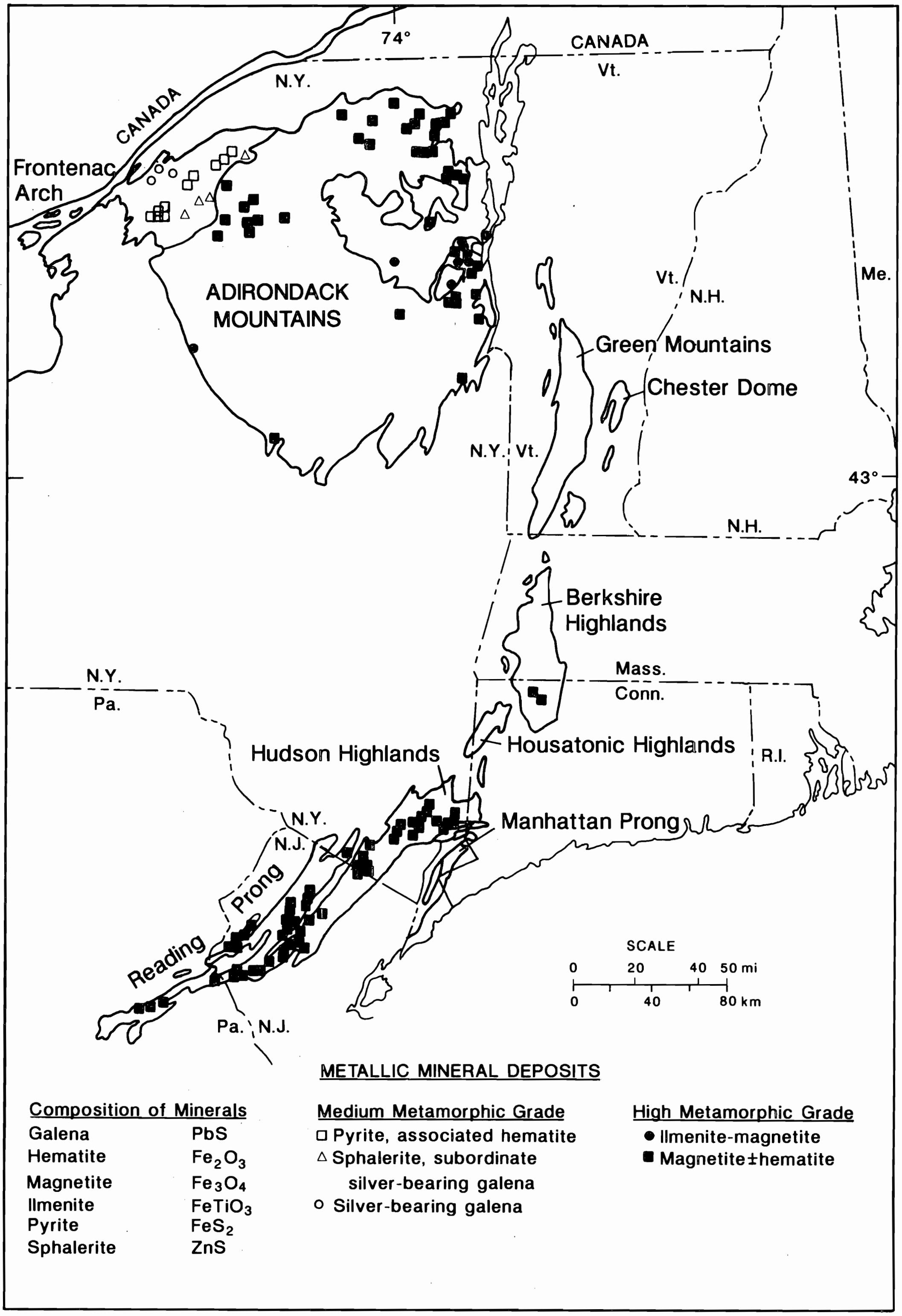


Figure 15.2. Metal deposits in Proterozoic rocks of the northeastern United States.

Hematite, a red mineral made of iron and oxygen (chemical composition Fe_2O_3), was mined in the late 1800s.

Another type of iron deposit is the mineral *siderite*, which is made of iron, carbon, and oxygen (chemical composition $FeCO_3$). In many places, the siderite has been exposed to oxygen and water and changed into another mineral that contains iron and oxygen—*limonite*.

How did they form?

Geologists disagree on how the magnetite deposits were formed. One idea is that they are sedimentary iron deposits that were metamorphosed. Another is that a liquid rich in iron and oxygen solidified along with other molten rock. Some think that hot solutions that flowed through the granitic gneisses deep below the surface dissolved scattered grains of magnetite and concentrated them into ore bodies.

The hematite in the Adirondacks was formed from the mineral pyrite in a rusty gneiss. Some of the iron in the pyrite combined with oxygen to make hematite.

Hematite and siderite beds are found in parts of the Lower Silurian Clinton Group of central and western New York. These sedimentary iron ores were deposited in shallow sea environments and contain fossil shells that are replaced by hematite and siderite. The hematite was deposited in shallower, more wave-agitated, and more highly oxygenated environments than the siderite.

What are they used for?

Magnetite is a major source of iron.

Red hematite from a small underground mine in Oneida County was once used for paint pigment.

Siderite is a source of iron, but New York's deposits are unprofitable to use.

How important are they?

Magnetite is not being mined in New York today. However, large amounts of ore remain in the closed underground and open pit mines. They may become profitable again at some future time.

Layers of sedimentary hematite in New York are seldom more than one meter thick. Though they were mined in the last century, they are no longer profitable.

Siderite deposits were mined in the 1880s. However, they are small and were abandoned.

Where are they found?

Magnetite forms minable layers in some granitic gneisses of the Adirondacks; it was long mined as a source of iron (Figure 15.2). Magnetite also occurs as an impurity in titanium ore in metamorphosed anorthosite (see section on ilmenite, above).

There are closed magnetite mines near Chateaugay, Clinton County; Mineville, Essex County; and Star Lake, St. Lawrence County. The mine at Star Lake was the largest open pit magnetite mine in the world. It was closed in the mid-1970s. Smaller, long-abandoned magnetite mines also exist in the Hudson Highlands (Figure 15.2).

Hematite is found as a sedimentary rock in the Early Silurian Clinton Group (Figure 15.2). Several layers occur near the surface between Wayne and Cayuga Counties and in Oneida County. Hematite mines—now abandoned—lie along a narrow belt in St. Lawrence and Jefferson Counties.

Siderite is found in Cambrian and Ordovician limestones and dolostones in eastern Columbia and Dutchess Counties.

Other information

Magnetite Mining in New York.—Magnetite has a very special property—it is attracted by magnets. Because the needles on compasses are magnetized, they will point toward masses of magnetite. Some of the earliest iron discoveries in the State were made by surveyors when their compass needles were drawn astray by masses of magnetite. Throughout remote sections of the Adirondacks, we can still see abandoned pits dug by early prospectors searching for iron ore.

Since the first underground magnetite mines were opened more than 200 years ago, iron ore has been one of New York's most valuable mineral resources. After the Revolutionary War, New York was one of the most important iron-producing states. It produced as much as one quarter of the whole output of the United States. It competed only with small iron ore deposits in Alabama, Wisconsin, and Michigan.

Then in 1890, rich iron ore deposits were discovered in the Mesabi Range in Minnesota. These new deposits were huge and could be mined cheaply in great open pits; thus, the great costs of underground mining were avoided.

The rich Minnesota ore could also be used directly in the blast furnace. In New York ores, the iron was sparser; the ores had to go through a complicated concentration process before pure iron could be obtained. First, the rocks were crushed. Then, large magnets were used to separate out the magnetite. The concentrated ore was then heated to fuse it into chunks. These chunks could be handled by the blast furnaces where pure molten iron was extracted.

The Minnesota discovery proved to be too much competition for New York ore. Except for a brief recovery during World War I, the State's iron ore production kept declining until 1938.

Then, in the mid-20th century, production made a stronger recovery. One reason was the great increase in demand for domestic iron ore during World War II.

At the same time, the iron ore deposits were starting to get used up. This shortage of iron ore spurred the development of new techniques so that less rich deposits, like the ones in New York, could still make a profit.
Today, however, magnetite is no longer mined in New York. The last mine closed in the mid-1970s.

Lead, Silver, and Zinc

What are they?
The Balmat mine produces the mineral *sphalerite*, which is made of zinc and sulfur (chemical composition ZnS). A by-product is the mineral *galena*, which is made of lead and sulfur (chemical composition PbS). Galena ore also contains small amounts of silver. When the galena is heated to extract the lead, the silver is also recovered.

How did they form?
Marine volcanic rocks containing zinc and lead deposits or scattered zinc and lead minerals were metamorphosed during the Grenville Orogeny. Deposits were concentrated and recrystallized at that time.

What are they used for?
Zinc is used to make tires, galvanized steel (for car bodies), and metal alloys.
Lead is used in batteries, building construction, and communications systems.

How important are they?
Two mines are operating today, although abandoned mines and exploratory holes are scattered throughout the Balmat-Edwards district in St. Lawrence County. The Balmat mine at the southwest end of the region is one of the largest zinc mines in the United States. In 1990, New York was the second largest producer of zinc in the nation.

Where are they found?
Lead, silver, and zinc are mined in the Balmat-Edwards district of St. Lawrence County (Figures 15.1 and 15.2). The zinc and lead ore is found in a belt 12 km long by about 2.5 km wide. It stretches from Sylvia Lake northeast to Edwards. Another rich deposit is mined farther north, at Pierrepont.

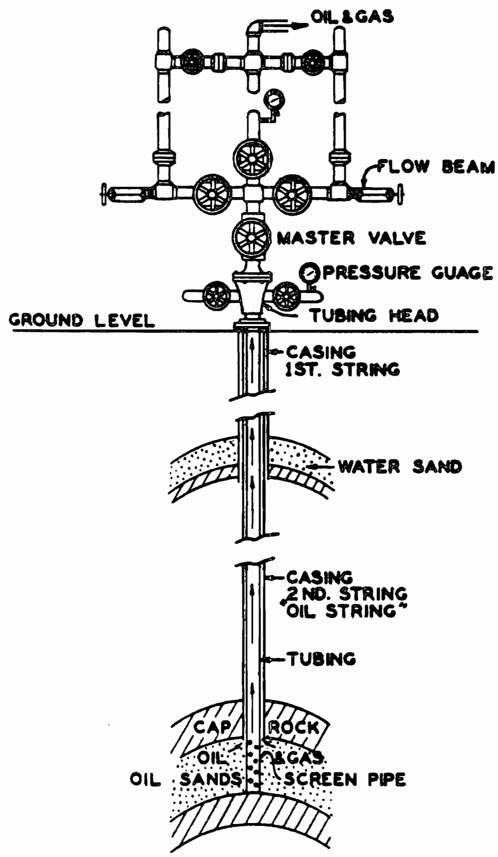


Figure 15.3. A "Christmas tree" consists of pipes and valves on top of a well that control and measure the flow of oil and gas. Pressure gauges measure the pressures produced by the flowing oil or gas. Valves are used to control or shut down the flow of oil or gas. The view below ground level shows the piping or casing through which the oil or gas flows. Three sizes of casing are shown in this diagram. The first, the widest in diameter, extends from the surface to down below the water table. This casing prevents oil or gas from seeping into the soil or water table. The second casing, which fits inside the first, extends from the surface to the caprock. (The *caprock* is the impermeable rock unit that traps the oil or gas in the unit below it.) Inside the second casing goes a third, which extends from the surface all the way down to the producing formation. This casing is perforated to allow the oil or gas to flow to the surface. (From *Oil from Prospect to Pipeline, Fifth Edition* by Robert R. Wheeler Maurine Whited. Copyright© 1985 by Gulf Publishing Company, Houston, Texas. Used with permission. All rights reserved.)

Mineral Fuels: Oil and Natural Gas

Of the three mineral fuels—coal, oil, and natural gas—New York State produces two: oil and gas. Both resources are found primarily in the southwestern part of the State. Native Americans who settled here must have been intrigued by the unique springs and seeps of black petroleum found in this region. However, the history of oil production can be traced back only to the late 1860s. Oil production has now greatly declined. Natural gas production was begun at the turn of the century and the highest modern production was reached in 1986. Both oil and gas occur in the spaces between grains in porous rocks. After gas has been pumped out of these natural reservoirs, the formations can be used for to store natural gas. This new industry is called *underground storage*.

New York's production cannot begin to rival the great quantities of oil and natural gas in the Middle Eastern nations or in other parts of the United States, but oil and gas production continues to fuel local

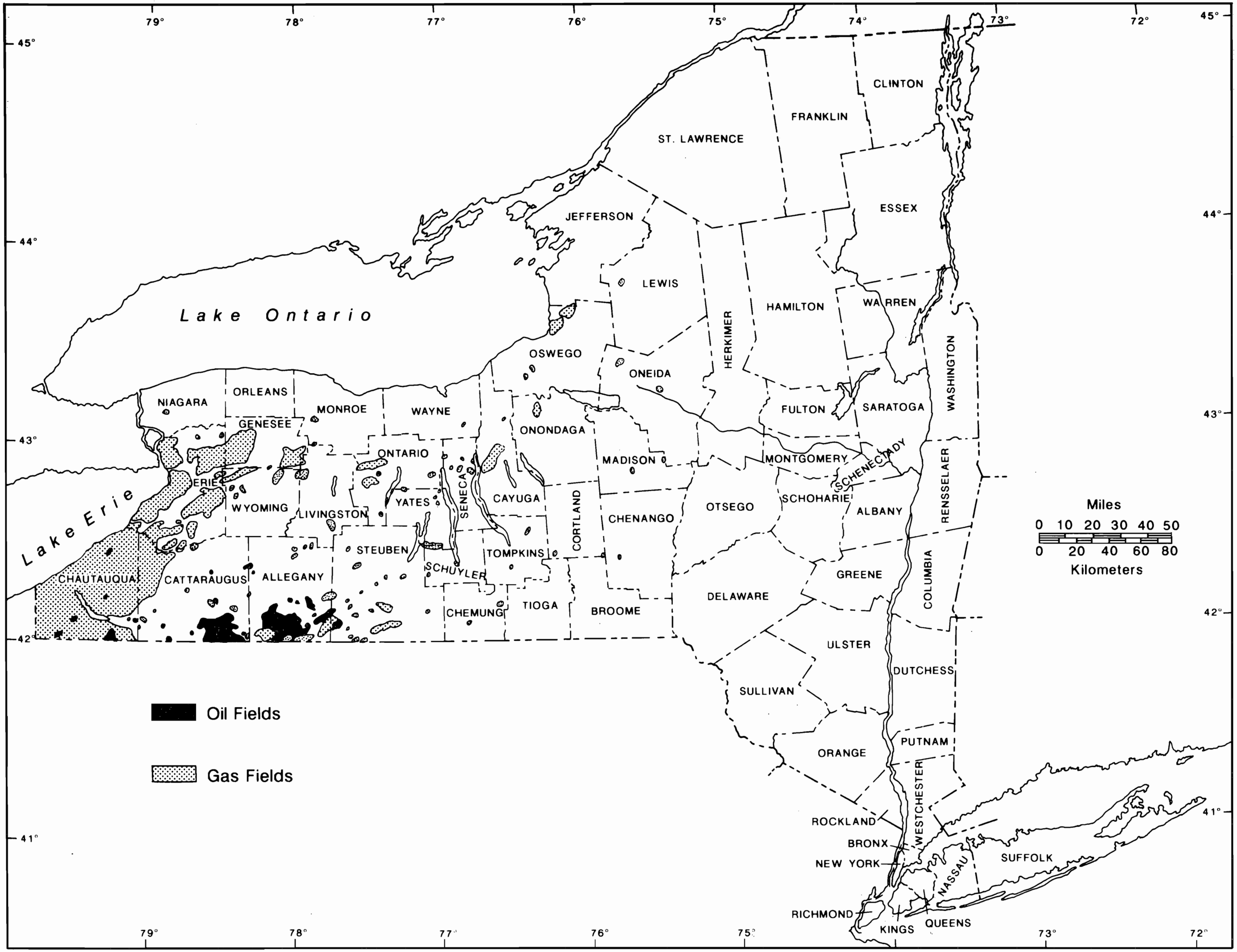


Figure 15.4. This map shows the oil and gas fields of New York State. The black areas represent the oil fields, and the dot pattern represents the gas fields. Notice that gas fields are much more extensive than oil fields. There are fewer fields to the east. Oil- and gas-bearing formations are deeper below the surface and therefore more costly to develop; oil is not known to be present in this region.

economies. In the southwestern part of New York State, particularly in Chautauqua, Allegany, and Cattaraugus Counties, "Christmas trees" dot the landscape. These *Christmas trees* are working oil or gas wells. The term describes the complex structure of valves, pipes, and gauges that sit on top of a completed well (Figure 15.3).

As shown in Figure 15.4, natural gas is found in an area that extends from Chautauqua County northeast to central Erie County, then east toward Cayuga County. New York's oil fields are located mainly in the southern parts of Chautauqua, Cattaraugus, Allegany, and Steuben Counties. A *field* is an area in which a number of wells produce oil or gas from a sedimentary rock formation.

Oil and natural gas were discovered by the American Indians, who found naturally occurring seeps. (A *seep* is a place where oil naturally leaks out through porous material onto the ground surface.) The first written record of natural oil appeared in the diary of a Franciscan missionary in 1627. The Indians had showed him the Cuba Oil Spring in Allegany County. They used this oil for medicine. The local European settlers largely ignored this natural phenomenon until Colonel Edwin Drake pioneered the first commercial well near Titusville, Pennsylvania, in August 1859.

Even before Drake's well was drilled, small amounts of oil had been used for fuel. This oil had been retrieved by skimming it from the oil seeps with wooden paddles or cloth. Colonel Drake's well was important for many reasons. It marked the birth of the modern oil industry. He successfully applied drilling techniques that used casing (see Figure 15.3), previously used in salt wells, to extract oil from the ground. The well was drilled in a area of natural oil seeps. Drake was widely scorned after a few unsuccessful attempts, but he persisted, and a shout proclaiming "They've struck oil!" was heard on August 27, 1859. The true importance of this success was not known at the time, but this well started the first oil boom. As word spread of this discovery, New York State became a target for those in search of oil.

History of Oil in New York State

One of the first entrepreneurs hit by "oil fever" was Colonel Bradford H. Allen. He negotiated the first lease for oil exploration in December 1859 with the American Indians of the Seneca Nation. This lease included over 30,000 acres in Cattaraugus County. In 1860 the first oil "wildcat" hole was drilled. (A well is called a *wildcat* if the well is being drilled in territory that has not previously produced oil or natural gas.) This well was located on the Moore Farm in Allegany County. The hole was originally drilled to a depth of 180 m with no show of oil. The hole was then deepened to 275 m, but again no oil was found. Drilling a hole to this depth took six to nine weeks at that time in the history of well drilling. This well was considered a deep wildcat hole for the time; the Drake well had hit oil at only 21 m deep.

The first known producing oil well was drilled in 1865 by Job Moses in Cattaraugus County. It produced seven barrels of oil a day from the Upper Devonian Bradford Third Sandstone of the Canadaway Group (Figure 15.5).

During these early years, oil was sold by the barrel, but the size of barrels varied. The buyer provided the barrel; therefore, the buyers could get more oil for their money if they provided barrels a bit larger than the regular barrel. This practice soon angered the oil producers. On August 30, 1866, in Venago, Pennsylvania, a meeting of oil producers unanimously adopted a resolution to standardize the oil barrel at 40 gallons, plus two gallons to cover leakage and evaporation. This standard 42-gallon barrel is still used today to measure oil production. A "standard" barrel is 55 gallons in other industries.

As the lone oil producer of the State, Job Moses profited greatly. Moses developed the oil industry in Cattaraugus County. The town of Limestone developed from small, sleepy community of 200 to a town of more than 1200 with the growth of oil production. East of Cattaraugus County, the oil boom was starting to take off. O.P. Taylor, called the father of Allegany oil fields, developed the first oil wells in Allegany County. The chart in Figure 15.6 shows that New York oil production reached its peak, 6.7 million barrels, in 1882. By the late 1890s, the oil boom was over and many towns went bust. This was one of the first boom-and-bust cycles in the oil and gas industry; there have been many since. As oil production declined, oil developers started to pull casing from depleted wells and abandon them.

At the same time, strangely, the rate of oil production was increasing from wells nearby—without the discovery of new oil fields. A new method had been discovered: *waterflooding*. This process consists of injecting water into a depleted field. The water created pressure that forced the remaining oil to a selected well.[3]

The "five-spot" flood pattern, with four water input wells on the corner and an oil well in the center, became the standard waterflooding practice; it is still used today. Waterflooding was legalized in New York in 1919. As a result, leasing of land to produce more oil from existing wells increased. Wildcat drilling also increased. As shown Figure 15.6, production of oil increased from 1919

[3]The production of oil by flushing remaining oil from a depleted field by waterflooding is called *secondary recovery*. The production of oil by drilling a new well is called *primary recovery*.

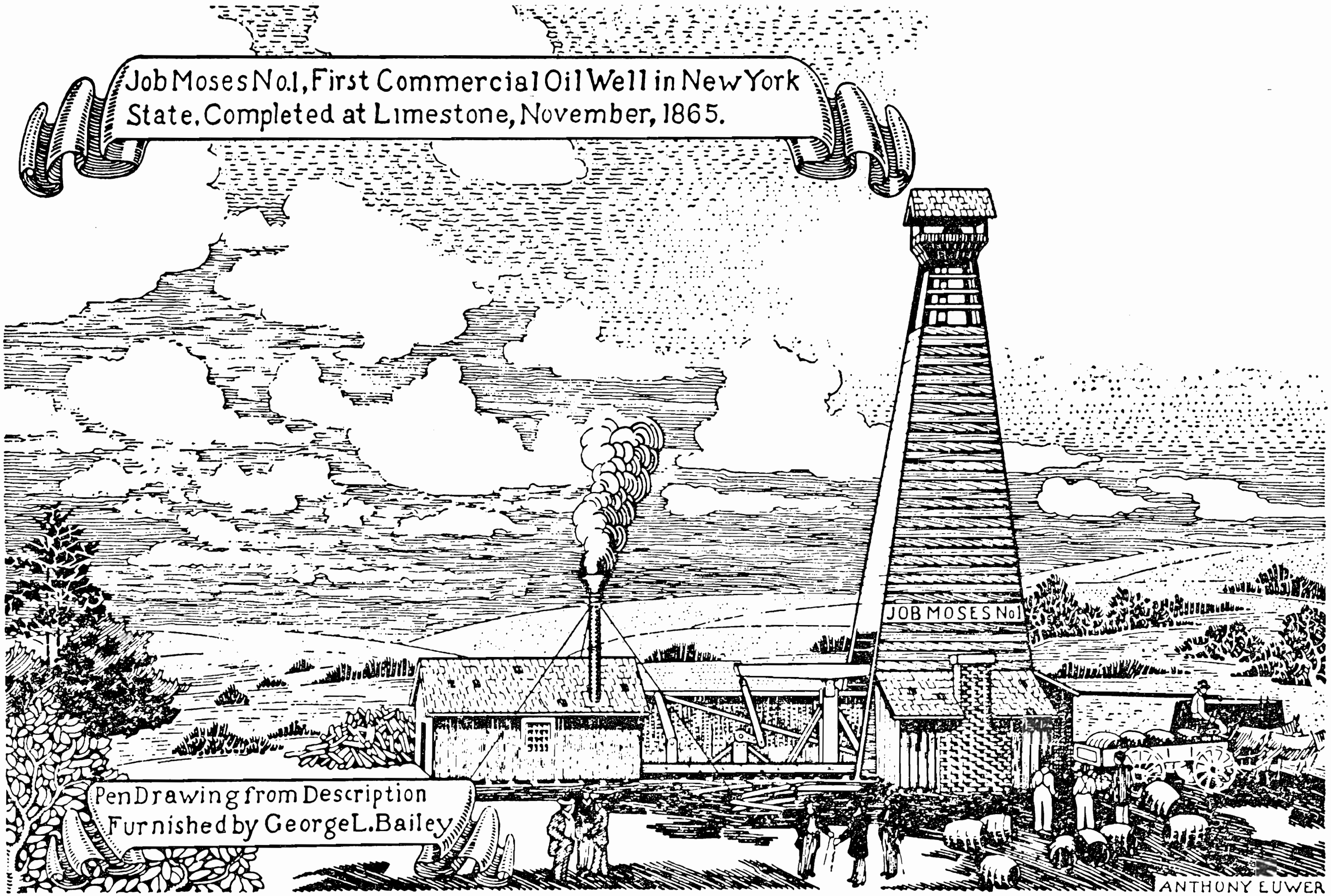


Figure 15.5. Drawing of the first commercial oil well in New York State, the Job Moses No. 1, in Limestone, Cattaraugus County. This early well was drilled by steam power. Notice the oil transported in barrels and the wooden tower, called a *derrick*.

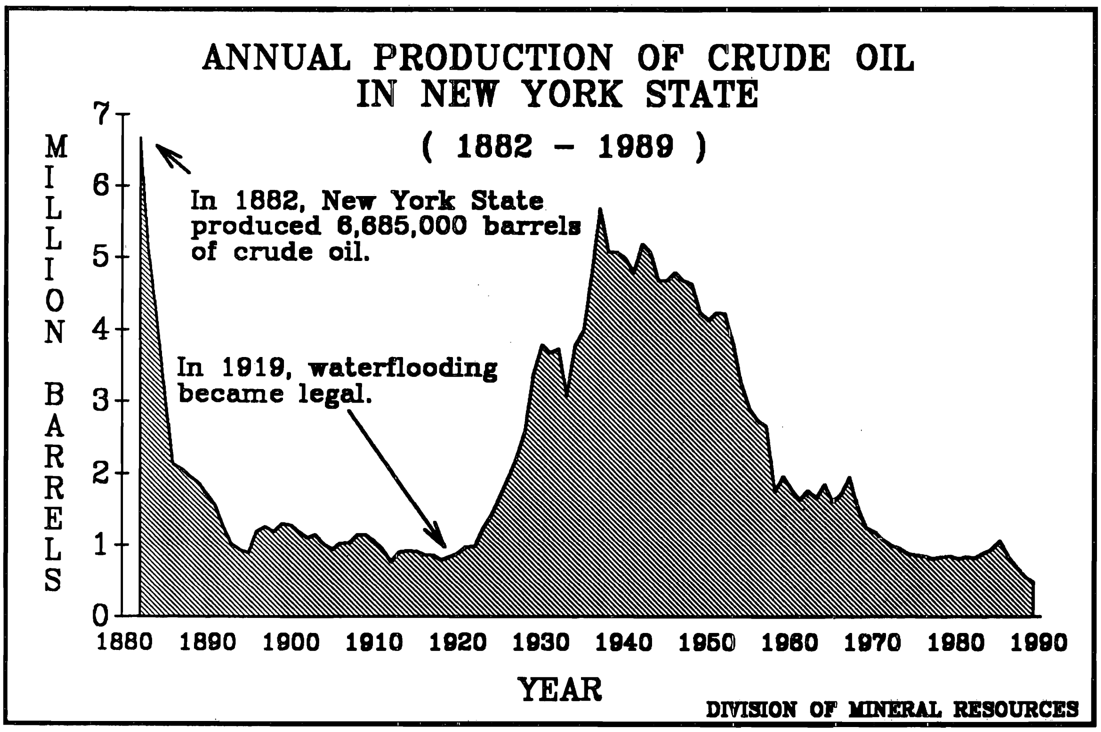


Figure 15.6. This graph shows the annual production of crude oil in New York State. The number of barrels of oil, in millions, is plotted on the vertical axis, and the year is plotted on the horizontal axis. The peak year was 1882, when 6.7 millions barrels of oil were produced. After waterflooding was legalized in 1919, production increased again, reaching 5.5 million barrels in 1938. Production continued at approximately this rate until the early 1950s, when it began to decline. The decline continued until 1983, when oil was first produced from the Akron-Onondaga Formations. (Graph supplied by New York State Department of Environmental Conservation.)

until it reached a second peak, 5.5 million barrels, in 1938.

Since 1942, the amount of oil produced in New York State has declined. In 1989, it reached a record low of just under 500,000 barrels. Most of the oil produced is from New York's *stripper wells*—wells that produce less than 10 barrels of oil per day. It is estimated that between 1.5 million and 9 million barrels of oil could still be recovered. A few projects (called *tertiary recovery*) have been tried that use the injection of steam, carbon dioxide, or gasoline to recover the oil that remains in place after waterflooding. These projects proved to be unprofitable while the price of oil was low. If oil prices rise, however, they might become profitable. One recent advance that could possibly increase New York's oil production is the technique of drilling oil wells horizontally.

Oil-Bearing Rocks in New York

Oil in New York is produced from Upper Devonian sandstones, and from Upper Silurian and Middle Devonian carbonate rocks (Figure 15.7; see also Plate 3). Oil found in the Canadaway Group and the West Falls Group (Figure 15.7) is stratigraphically trapped in shallow permeable sandstone lenses (Figure 15.8). The permeable sandstone that contains the oil is surrounded by impermeable sandstones (called *tight sands*). The pore space between the grains of these tight sands is small and few spaces connect the pores. Therefore, the amount of oil that can be trapped in these rocks or move through them is low. These rocks were the source for nearly all of New York State's oil until the discovery of "The Bass Island Structural Trend" in 1981.

The oil-bearing rocks of the Bass Island Trend are the Upper Silurian Akron Dolomite and the Middle Devonian Onondaga Limestone. The Bass Island Trend was named after the Bass Island Formation in Ohio.

Before 1981, natural gas and minor quantities of oil had been produced from the Akron Dolomite, but it was not considered an important producing formation. In 1978, however, a geologist doing subsurface mapping discovered a long, narrow, structurally complex anticlinal trend that extends from southwestern Chautauqua County to southern Erie County (Figure 15.9). The oil along this trend is structurally trapped by reverse faults. (The Tectonic Map on Plate 4 of the *Geological Highway Map* may help you discover what tectonic event might

COMPOSITE PALEOZOIC STRATIGRAPHIC SECTION
FOR SOUTHWESTERN NEW YORK

PERIOD		GROUP	UNIT	(rock type)	Thickness	Production
Penn.		POTTSVILLE	OLEAN	(ss,cgl)	25-30 m	
Miss.		POCONO	KNAPP	(ss,cgl)	15-30 m	
DEVONIAN	UPPER	CONEWANGO		(sh,ss,cgl)	215 m	
		CONNEAUT	CHADAKOIN	(sh,ss)	215 m	
		CANADAWAY	UNDIFF. +	(sh,ss)	335-425m	Oil, Gas
			PERRYSBURG# DUNKIRK	(sh,ss) (sh)		Oil, Gas
		WEST FALLS	JAVA NUNDA RHINESTREET	(sh,ss) (sh,ss)	115-380m	Oil, Gas
		SONYEA	MIDDLESEX	(sh)	0-120 m	
		GENESEE		(sh)	0-135 m	
	MIDDLE		TULLY	(ls)	0-15 m	Gas
		HAMILTON	MOSCOW LUDLOWVILLE SKANEATELES MARCELLUS	(sh) (sh) (sh) (sh)	60-185 m	 Gas
			ONONDAGA	(ls)	10-70 m	Gas, Oil
	LOWER	TRISTATES	ORISKANY	(ss)	0-10 m	Gas
		HELDERBERG	MANLIUS RONDOUT	(ls,dol)	0-3 m	
SILURIAN	UPPER		AKRON	(dol)	0-5 m	Gas, Oil
		SALINA	CAMILLUS SYRACUSE VERNON	(sh,gyp) (dol,sh,salt) (sh,salt)	135-465m	
		LOCKPORT	LOCKPORT	(dol)	45-75 m	
		CLINTON	ROCHESTER IRONDEQUOIT	(sh) (ls)	40 m	Gas
	LOWER		SODUS REYNALES	(sh) (ls)	25 m	
			THOROLD	(ss)	1-2.5 m	
		MEDINA	GRIMSBY WHIRLPOOL	(sh,ss) (ss)	25-45 m 0-10 m	Gas Gas
ORDOVICIAN	UPPER		QUEENSTON OSWEGO	 (ss)	335-455m	Gas
			LORRAINE UTICA	(ss,sh) (sh)	275-305m	
	MIDDLE	TRENTON- BLACK RIVER	TRENTON GP. BLACK RIVER GP.		130-190m 70-170m	Gas
	LOWER	BEEKMANTOWN	TRIBES HILL	(ls)	0-170 m	
CAMB.	UPPER		LITTLE FALLS GALWAY POTSDAM	(dol) (dol) (ss)	0-105m 175-410m 25-150m	 Gas Gas
PROTEROZOIC			GNEISS, MARBLE, QUARTZITE, etc.			

\+ Includes Glade, Bradford 1st, Chipmunk, Bradford 2nd, Harrisburg Run, Scio, Penny and Richburg.

\# Includes Bradford 3rd, Humphrey, Clarksville, Waugh & Porter and Fulmer Valley.

Figure 15.7. Chart summarizing the Paleozoic rocks found in southwestern New York. The oldest rocks are on the bottom and the youngest rocks on the top. This chart also lists approximate thicknesses of each formation (in meters) and whether or not any oil or gas was produced from each formation. The following abbreviations are used for rock types: cgl (conglomerate), dol (dolostone), gyp (gypsum), ls (limestone), sh (shale), ss (sandstone).

have created this structural trap.) Oil production up to 2,400 barrels per day have been reported from these rocks. Oil from this trend boosted production in 1983, when over 1 million barrels were produced.

New York's oil production is declining. With current technology, it may last only into the late 1990s. New York's natural gas industry has a shorter history than the oil industry, but a brighter future.

History of Natural Gas in New York State

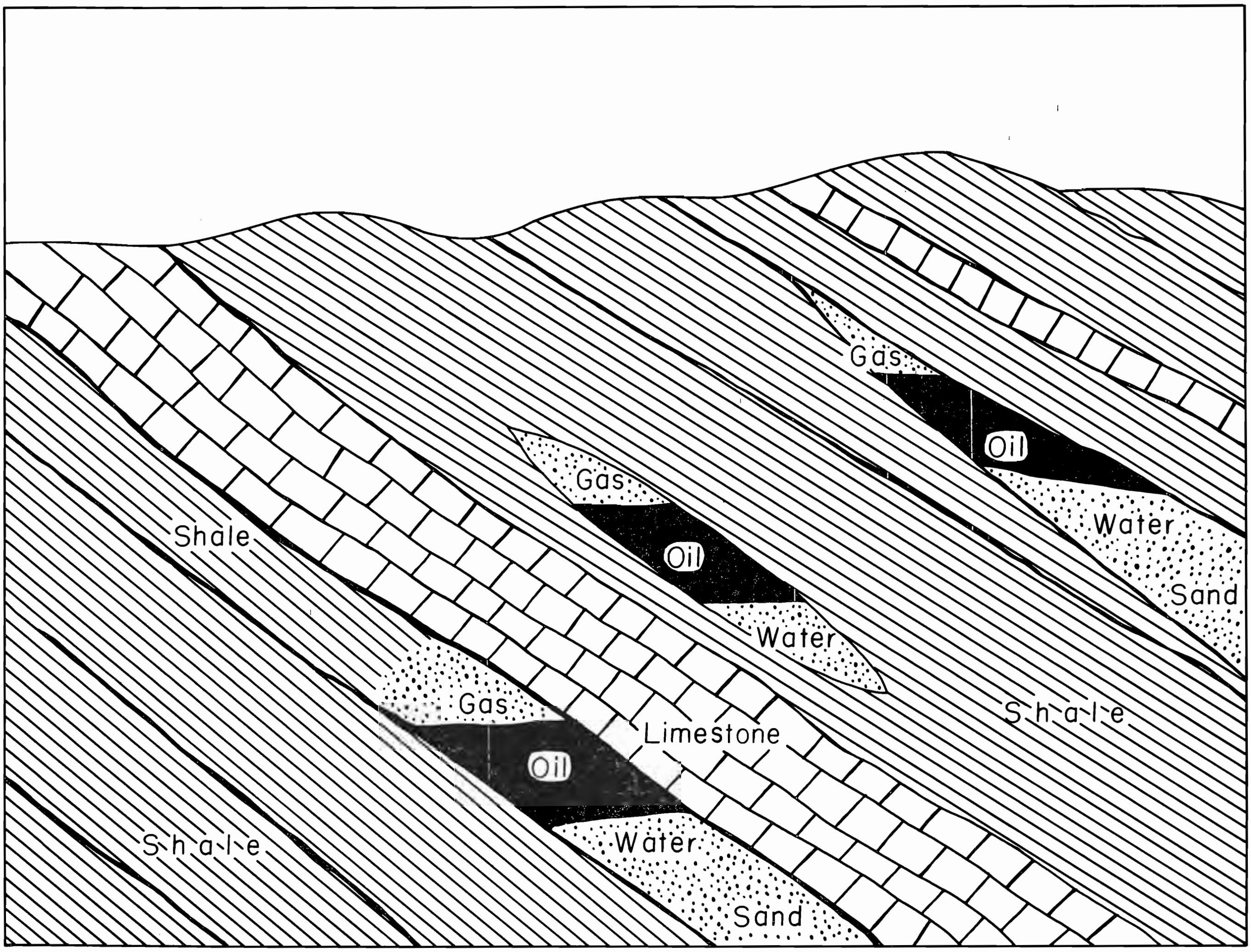
Europeans first learned of natural gas in New York in 1669, when American Indians showed French explorers a gas vent near the present city of Canandaigua in Ontario County. The first known occurrences were associated with naturally occurring oil seeps.

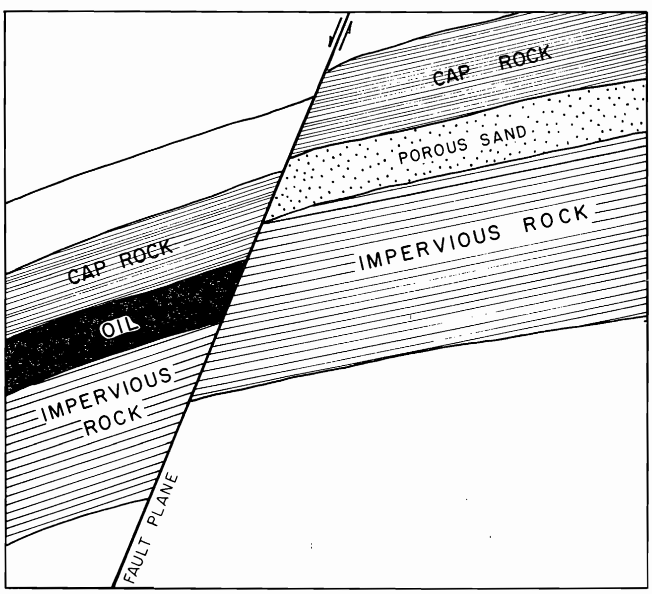
In 1821, William A. Hart drilled the first natural gas well in the United States. The well was located next to a water spring that had natural gas bubbling in it. This spring was located on the Canadaway Creek in the Chautauqua County town of Fredonia. Fredonia gained international fame because it was the only city in the world at the time to use natural gas for lighting. The natural gas was supplied mostly by the Hart well, but other holes were driven to supplement this supply. The Hart well was productive until 1858. Many shallow gas wells were drilled in the region to provide independent lighting and heating for local land owners.

In the mid-1860s, as oil drilling began, much natural gas escaped from the wells into the atmosphere. The drillers realized that natural gas might be a byproduct of oil production. Therefore, during these early years, whenever natural gas was found, it was thought that oil would be found also. It soon became common practice to let the gas blow into the air until oil flowed from the well—a very wasteful practice. In the 1890s, as New York oil production declined and became costlier, a new invention gave the wells new economic life. The gas cylinder engine was fueled by natural gas. They were used to power well pumps more efficiently and cheaply than the steam-powered pumps used earlier. Natural gas production has increased gradually since the turn of the century (Figure 15.10). Large supplies of natural gas were discovered in rocks without oil.

Natural Gas-Bearing Rocks in New York

As shown in Figure 15.7, natural gas has been found in numerous formations, from the Upper Cambrian Potsdam Sandstone to the Upper Devonian Canadaway Group. However, commercial quantities have been found only locally in some of the formations. Gas shows





are found in some strata. (A *gas show* is an appearance of gas in the cuttings, samples, or cores that are taken when a well is drilled.) As we review the rocks that contain natural gas, we will start with the Upper Cambrian Potsdam sandstone and go up the section (Figure 15.7; see also Plate 3).

The Upper Cambrian Potsdam sandstone is the oldest rock in New York State with natural gas. It lies on top of the Proterozoic basement rocks. On top of the Potsdam Sandstone lies the Upper Cambrian Galway and Ticonderoga Formations, which grade upward from sandstone to dolostone. Gas shows have been found mainly in the sandstones.

Stratigraphically upward, the next natural gas-bearing rocks are of Ordovician age. Commercial quantities of natural gas have been produced from the Middle Devonian Trenton and Black River Groups in the past. The limestone-rich Trenton Group is the gas-bearing formation in this group. Wells drilled into this unit have produced gas since the early 1880s. The major gas fields of

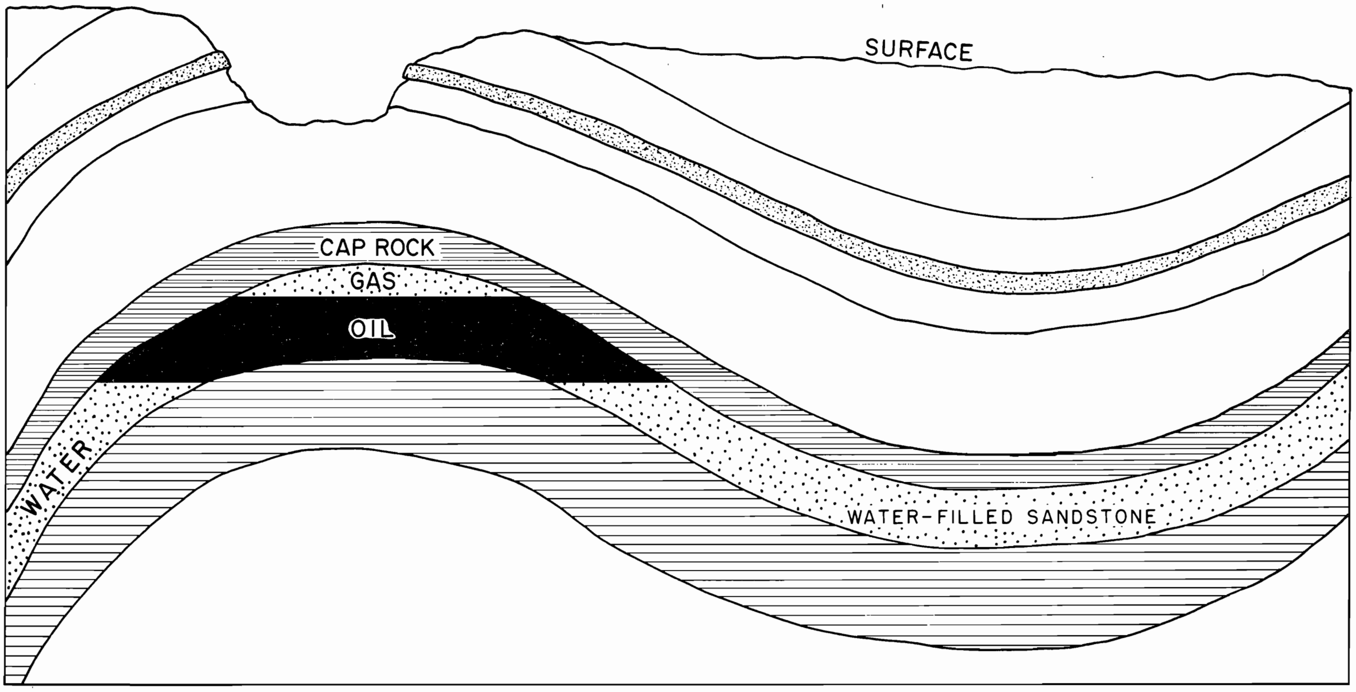


Figure 15.8. In order to be recoverable, oil or natural gas has to be trapped in an underground rock formation. This formation has to be both *porous* (having a large amount of pore space to contain the oil or gas) and *permeable* (able to let the oil or gas flow through it). However, it has to be surrounded by material that is *impermeable*, so that the oil or gas can collect underground. We divide these traps into two sorts: stratigraphic and structural. In a *stratigraphic trap*, the oil or gas is held in by the properties of the rock itself. (A) shows three stratigraphic traps: pockets of permeable sandstone that occur in the middle of impermeable rock layers. The sandstone can hold oil or natural gas. A *structural trap* is a pocket created by faulting (B) or folding (C) of the rocks.

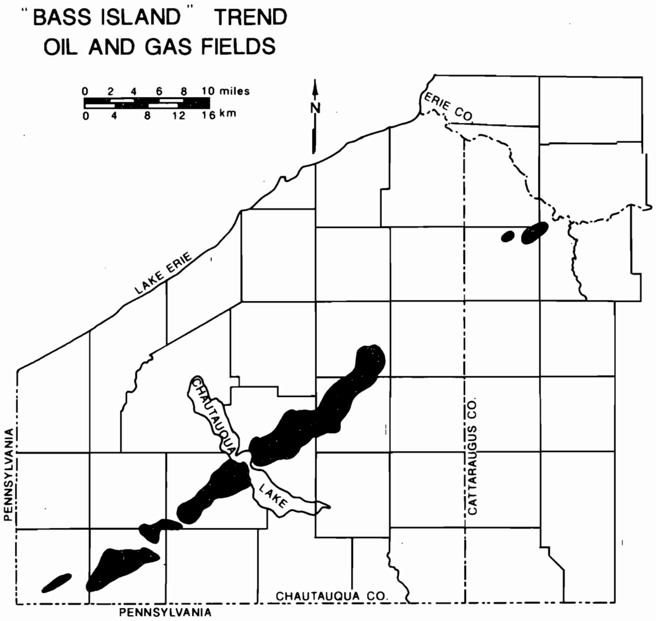


Figure 15.9. This figure shows the oil fields of the Bass Island Structural Trend. The oil fields extend from southwestern Chautauqua County northeast into Cattaraugus County. The oil is found in a long narrow band that is nearly 100 km long and 3 km wide. The oil here is structurally trapped in a complex fault zone.

the Trenton Limestone are near Sandy Creek, Pulaski, and Baldwinsville. In the 1960s, major oil companies drilled a series of cores to the Proterozoic basement throughout the State looking for oil. The Trenton Limestone had many natural gas shows, but they were ignored. Average well depths range from 180 to 2,200 m below the surface.

The Upper Ordovician Queenston Shale is a good source of natural gas. Average well depth is approximately 580 m. Current estimated reserves are nearly 450 BCF (billion cubic feet). Major fields of the Queenston Shale are near Fayette-Waterloo and West Auburn.

Above the Queenston Shale lies New York's richest source of natural gas, the Medina Group. The Lower Silurian Medina Group, called the "bread and butter" of the New York State natural gas industry, has estimated reserves of more than 2.5 TCF (trillion cubic feet). There are 63 Medina gas fields found throughout 17 counties in the State (Figure 15.11). The largest is the Lakeshore field. This field alone encompasses all of Chautauqua County and parts of Cattaraugus County. The average well depth varies from less than 300 m up to 1,400 m.

The Medina Group has low porosity; therefore, a technique called *hydraulic fracturing* is used to increase the

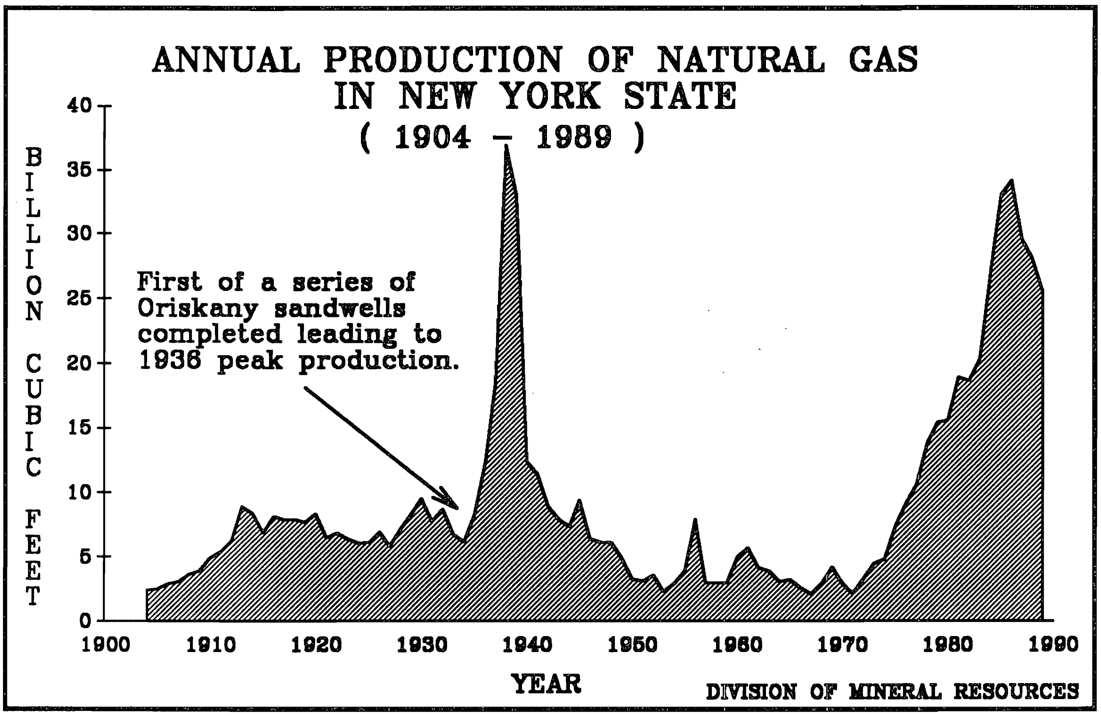


Figure 15.10. This graph shows the annual production of natural gas in New York State from 1900 to 1990. The amount of gas, measured in billions of cubic feet, is plotted on the vertical axis, and the year on the horizontal axis. The peak production year for natural gas was 1938, when 40 billion cubic feet were produced. This peak was due to the discovery of a new gas field, the Wayne-Dundee field in Schuyler County. The gas was structurally trapped in the Lower Devonian Oriskany Sandstone. The next peak year occurred in 1986, when approximately 34 billion cubic feet were produced. This increased production was largely from the Bass Island Structural Trend. (Graph supplied by New York State Department of Environmental Conservation.)

flow of natural gas. Hydraulic fracturing is done by adding fluid, commonly water, under high pressure to cause the rock to split. Openings thus created allow the flow of natural gas to increase. Sand is sometimes added to the water to keep the fractures open. High pressures—4,000 pounds per square inch—are needed to accomplish this fracturing. Large pumps mounted on tractor-trailer trucks are used to accomplish hydraulic fracturing at the Medina wells.

The Medina Group is divided into three producing strata (see Plate 3). The Whirlpool Sandstone (nicknamed the "White Medina") overlies the Queenston Shale. A greater volume of natural gas is produced from the Whirlpool Sandstone than from the other formations in the Group. Above it, the Power Glen Shale is sandwiched between two sandstones, the Whirlpool Sandstone and the Grimsby Sandstone (also called the "Red Medina"). Gas shows also occur in the Irondequoit Limestone, but no major quantities have been found in this formation.

Both oil and natural gas are produced from the Upper Silurian Akron Dolomite. Most of the natural gas production occurs in the Bass Island structural trend. Initial gas flows were gauged at 60,000 cubic feet of gas per day.[4] Average well depth varies from 760 to 900 m.

Exploitation of the Lower Devonian Oriskany Sandstone was largely responsible for New York's highest recorded production of natural gas—40 million cubic feet—in 1938 (Figure 15.10). The largest field at the time was the Wayne-Dundee field, located in Schuyler County. The Oriskany Sandstone is being explored for gas in Allegany and Cattaraugus Counties. While most of the huge gas reserves of this formation have been tapped, the field is still useful. Structural traps in the Oriskany Sandstone are now used to store natural gas produced elsewhere (Figure 15.12). During the summer months, gas from pipelines is injected into wells in the Oriskany Sandstone. This gas is extracted for heating needs in the winter.

Overlying the Oriskany Sandstone is the Onondaga Limestone of Middle Devonian age. Today, the natural gas produced from this limestone is mainly from the Bass Island trend. In the past, commercial amounts have been produced from pinnacle reefs. A *pinnacle reef* is a

[4]After the initial flow from a natural gas well, there is a rapid decrease in the amount of gas produced.

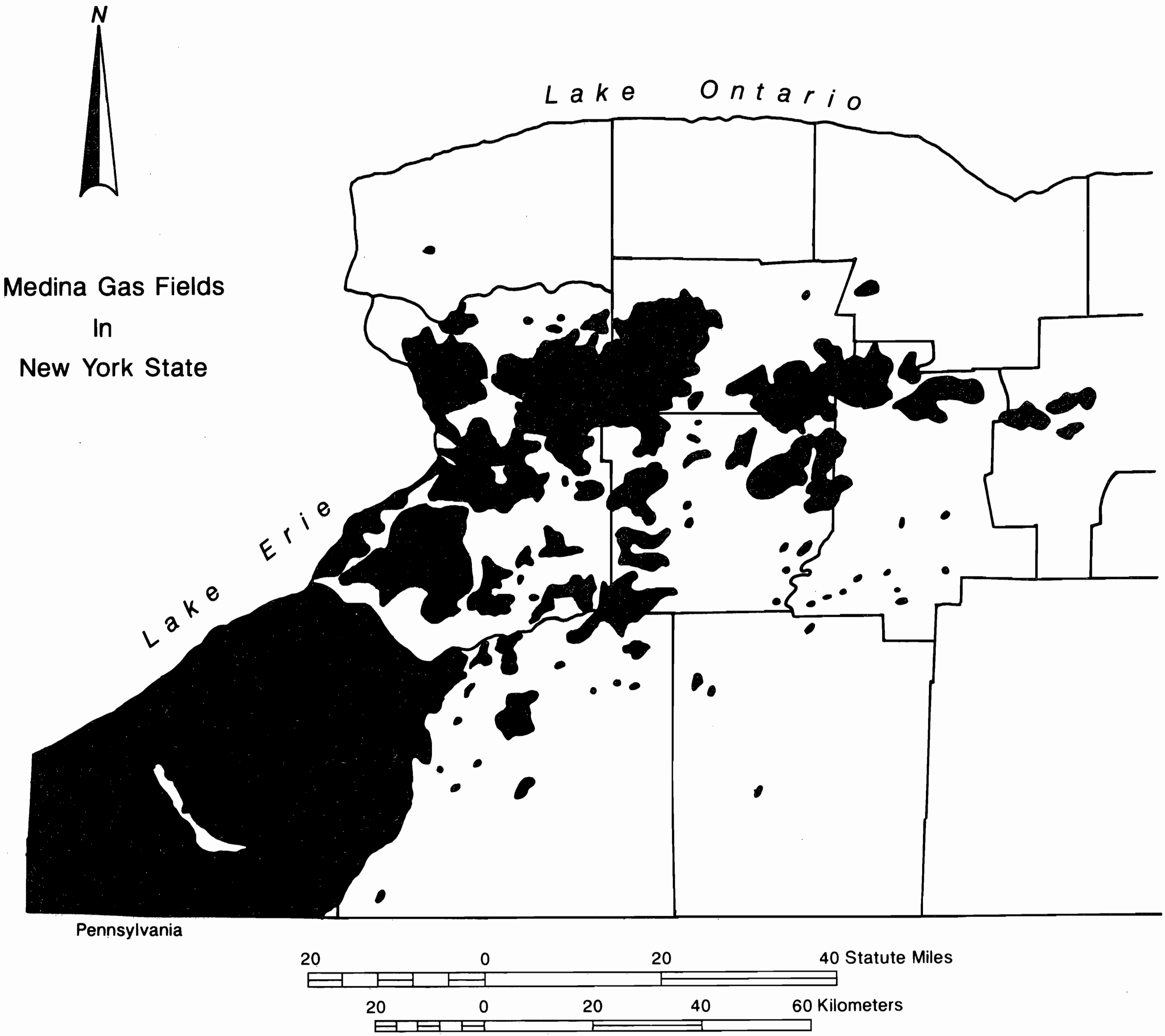


Figure 15.11. This figure shows the area in which natural gas is produced from the Lower Silurian Medina Sandstone. This area stretches across 17 counties. The natural gas fields are the black areas.

high buildup produced by corals and other marine organisms. The total pore space between this fossil debris that forms the reef is large. The first pinnacle reef was discovered in the town of Jasper, Steuben County, in 1967. These pinnacle reefs are presently being considered for use as underground storage sites. Small quantities of natural gas have been produced from the Tully Limestone further up the stratigraphic section.

Finally, the Upper Devonian West Falls and Canadaway Groups are sources of natural gas. It was from these Groups, particularly the Dunkirk Shale, that the first natural gas was commercially extracted in 1821. The Dunkirk Shale gives off a petroleum odor when broken from a fresh outcrop. The same odor is associated with many limestones in the State (and even with highly metamorphosed marbles in the Adirondacks!).

UNDERGROUND STORAGE IN NEW YORK STATE

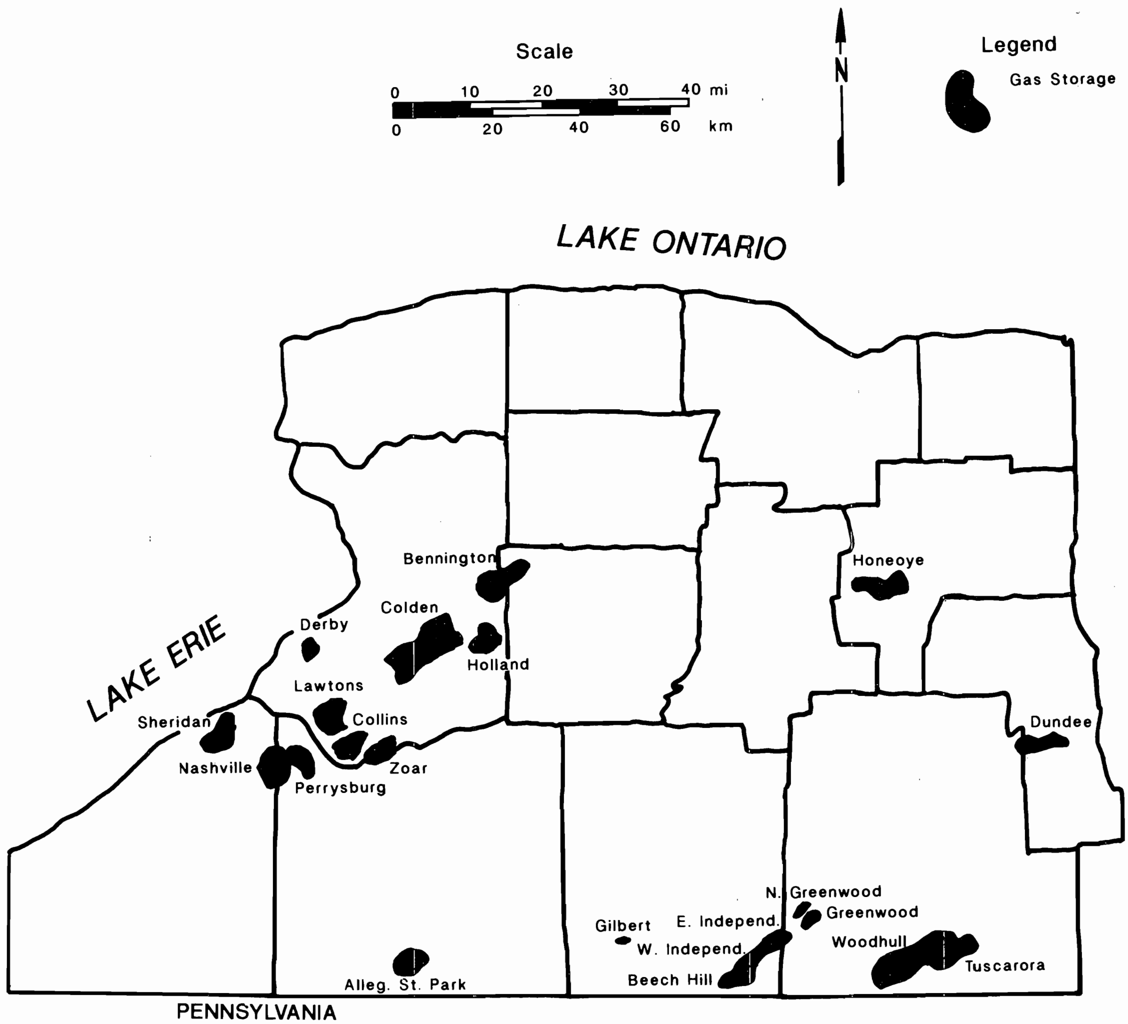


Figure 15.12. This figure shows the underground storage areas of natural gas in New York State, along with their names. These storage areas are former gas fields. They have been converted to natural gas storage because they can hold large amounts of natural gas.

New York State's natural gas industry has a much brighter future than does oil production, because gas reserves are very much greater than oil reserves. Most of the natural gas produced is used locally. With more efficient extraction practices, natural gas will be a viable source of energy for southwestern and central parts of New York State for a long period of time.

New York State has 21 natural gas storage fields (Figure 15.12). Underground storage fields were developed to take advantage of the large porous reservoirs left after the natural gas was extracted. The Onondaga Limestone and Oriskany Sandstone are prime formations targeted for storage fields. New York State developed the first underground storage facility in the nation in 1916 at the town of Zoar Valley. With natural gas becoming increasingly popular as a heating source, additional underground storage facilities will be needed to supply areas farther away from the resource.

New York State is only a modest producer of oil and natural gas, but the history of these industries is rich and colorful. From Job Moses's first oil well in Limestone, New York, to the most favored Medina Formation, New York's long period of productivity continues.

Review Questions and Exercises

Name several mineral resources that are important in New York State's economy.

What important mineral resources are found in your part of the State?

Select three of New York's mineral resources. Describe what they are, where they are found, what they are used for, and how important they are to the State's economy.

Which is more important to New York State's economy: oil or natural gas? Why?

What is waterflooding? Why is it important to oil production?

Is the pinnacle reef a structural or stratigraphic trap? Explain.

Once the natural gas reserves in a formation have been used up, what can that formation be used for?

Chapter 16
Water, Water Everywhere
Hydrogeology[1]

Summary

Hydrogeology deals with surface water—rivers, streams, and lakes—and groundwater—water that has soaked into the ground.

The rivers in New York State drain nine major drainage basins. New York's lakes are temporary features. They were created mainly by the Pleistocene glaciers and, more recently, by the construction of artificial dams. Lakes reflect the chemical makeup of nearby rock and soil, so some are more susceptible to acid rain than others. New York State receives its greatest precipitation in late summer and its least in winter; however, rivers are not always highest at times of greatest rainfall. One concern of hydrogeology is flooding and how to control it. Groundwater can provide a continuing supply of water for people if they neither overdraw it nor pollute it. The water table—the level below which all openings in soil and rock are saturated with groundwater—rises and falls with the amount of rain and the amount of water that has been pumped out of any given local area. The largest aquifers in New York State are Pleistocene sand and gravel deposits and, on Long Island, Cretaceous Coastal Plain deposits.

As demand for water rises, the danger of groundwater pollution rises as well; both individuals and industry have to take care not to contribute to the problem.

Surface Water

Hydrogeology deals with water—both water at the surface of the ground and water that has soaked down into the soil. We will discuss surface water first.

Surface water refers to water in rivers, streams, springs, and lakes. New York has many large rivers. The largest are the St. Lawrence, Niagara, Hudson, Susquehanna, Delaware, Genesee, Oswego, and Allegheny (see Figure 11.1B). The Richelieu River in Quebec is also important in New York's drainage: the water from Lake Champlain flows north into the Richelieu and eventually into the St. Lawrence River. All these rivers are sources of water for towns and cities. They are also transportation routes and important sources of hydroelectric power.

Figure 16.1 shows New York State's nine major drainage basins and the divides between them. If you compare that figure with Figure 11.1B, you can see how the major rivers drain those nine basins.

New York also has some of the finest lakes in the nation. Most of these lakes are the result of Pleistocene glaciation, although some were created artificially by the construction of dams. Ice sheets gouged many lake basins in the bedrock. Some of the basins were scoured below sea level. Lakes were also created when the melting ice left earth dams in valleys or when piles of glacial deposits redirected streams. In addition, the ice sheets left behind many large blocks of ice that were then buried by glacial deposits. When these blocks melted, they left holes that filled with water to form kettle lakes (see Figure 12.20).

All lakes are temporary features of the landscape. The streams flowing into them carry soil and sediments eroded from the surrounding hills. This material may eventually fill in the lakes completely. Lakes can also disappear when erosion opens up a new, lower outlet that drains the lake.

Lake waters reflect the chemical makeup of nearby rock and the sediments through which rainwater soaks on its way to the lake. Normal rainwater is slightly acidic because it dissolves carbon dioxide from the air to form weak carbonic acid (chemical composition H_2CO_3). Industrial plants and automobiles, however, put additional acid-forming gases—sulfur oxides and nitrogen oxides—into the atmosphere. These gases combine with

[1]Adapted from a manuscript by R.J. Dineen.

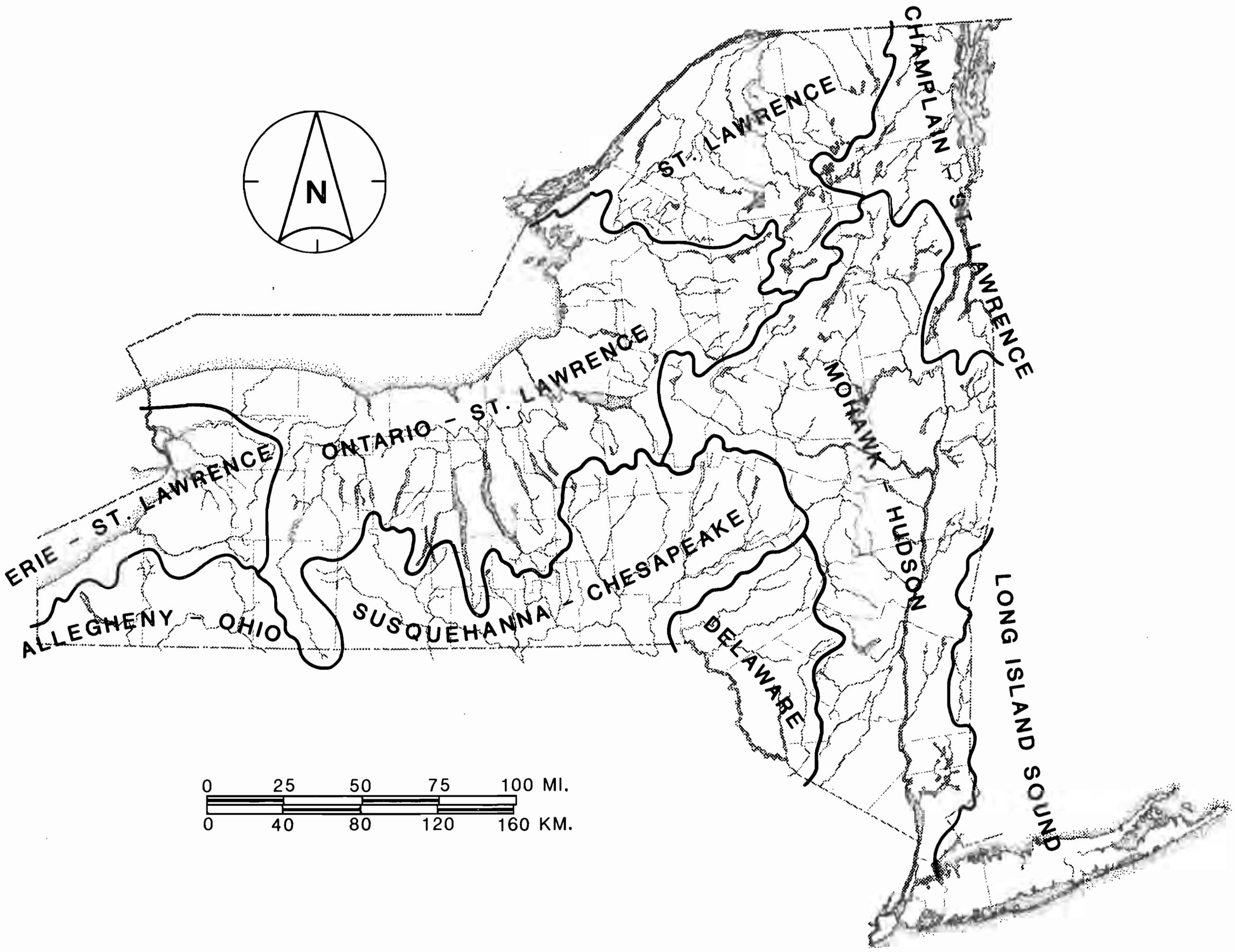


Figure 16.1. This map shows the present drainage divides and drainage basins in New York State. A *drainage basin* is an area in which all of the water that falls as precipitation eventually drains into the main stream of the basin. The borders of a drainage basin are called *drainage divides*. Streams do not flow across drainage divides.

moisture in the air to form damaging acid rain and snow. Carbonate rock (limestone, dolostone, or marble) acts as an "antacid" to neutralize the acid rain. Thus, lakes that are underlain by such rock are less likely to become acidic. Lakes underlain by other rock types, however, succumb to this acid rain and eventually become "dead lakes."

New York State has a moist temperate climate. Rain and snow continually replenish our many lakes and rivers. Most regions of New York receive nearly 100 cm of precipitation each year. However, the annual precipitation varies across the State, as shown in Figure 16.2. In addition, the precipitation is not distributed evenly throughout the year. The greatest precipitation falls in late summer, and the least in winter (Figure 16.3).

Surprisingly, rivers are not always highest at the times of greatest rainfall. By late winter, the ground is usually frozen to a depth of about 1 m. (The depth of freezing is greatest in the Adirondack Mountains and least on Long Island; this fact shows the effects of both latitude *and* elevation.) Therefore, winter precipitation is stored temporarily on the surface as snow or ice. When the spring thaw begins, the frozen ground cannot absorb the meltwater, and the water flows over the surface. The resulting high volume of surface water spills into streams and rivers, causing spring floods.

The volume of water in a river varies in other seasons as well. In the summer, storms can cause temporary flooding when rain falls faster than the soil can absorb it. Between summer storms, streams receive water from near-surface groundwater or from springs. Rainfall is greatest in New York State in the late summer, but even so, stream flow falls significantly at that time. Why?

Figure 16.2. The lines on this map represent the average yearly level of precipitation (in inches) across New York State over a 25-year period. Notice how much the amount of rain varies—from a low of 28 inches per year in northeastern New York to a high of 60 inches per year in southeastern New York. (Hydrogeologists commonly use English units rather than metric units, so the amount of rain is given in inches instead of centimeters.)

Because summer heat dries the soil, enabling it to absorb much more water. In addition, plants remove more and more water from the ground, releasing it as vapor through their leaves.

Floods are a major concern of hydrogeology. They can be controlled, to some extent, by dams. Flood control dams are designed to hold back the initial rush of floodwater from a normal spring melt and then release it gradually. Straightening stream channels is another way to reduce flooding, because a straighter channel allows water to move downstream more quickly. However, such *channelization* may only transfer the flooding downstream to other areas.

Many other human activities make floods more severe. In forested areas, standing trees tend to break up the falling drops and much of the rain flows gradually down the tree trunks. Deforestation, on the other hand, allows rain to fall directly on the ground as large drops. The result is that the large drops both dislodge soil particles and form small streams that flow rapidly downhill without soaking into the ground. Therefore, rivers rise more quickly and higher in deforested areas and carry off the soil. In urban and suburban areas, extensive streets, buildings, and paved areas prevent rainwater from soaking into the soil. Instead, the rainwater flows rapidly over the land surface or into storm sewers as runoff, which can cause nearby streams and rivers to flood.

Natural stream channels are usually cut into a broad flat area called a *floodplain.* A floodplain can have terraces at several levels. The lowest terrace may be flooded several times a year, or at least during spring flood stage. Higher terraces flood less frequently. The lower terraces commonly are used as farmland or park land. Such areas flood too often to be safe sites for permanent homes. Even so, many communities are located in flood-prone areas.

Rivers and lakes are easily affected by pollution and other human activity. If well managed, they are splendid

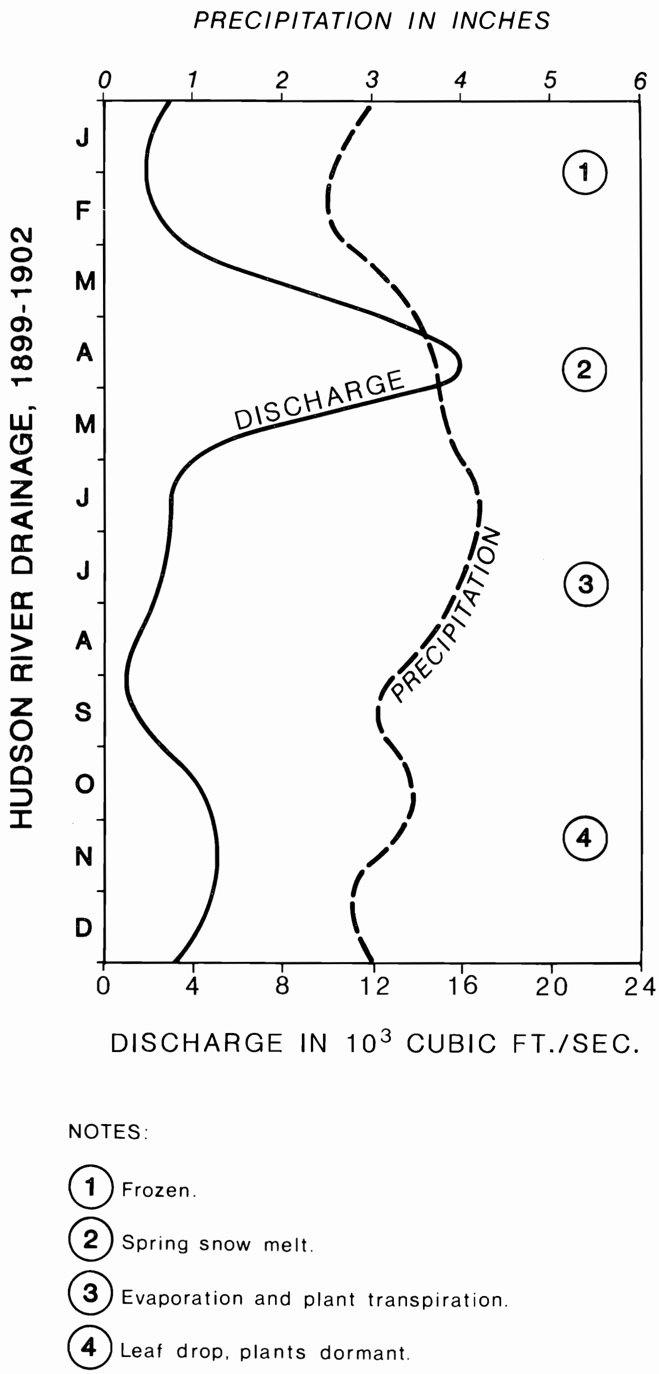


Figure 16.3. The dashed line in this graph shows the average number of inches of precipitation in the Hudson River drainage basin each month. The solid line shows volume of water discharged into the Atlantic Ocean by the Hudson each month. Although the graph covers the years 1899-1902, the pattern is similar to what we see today. (Hydrogeologists commonly use English units rather than metric units, so the volume of water is given in cubic feet instead of cubic meters.)

sources of water for drinking, industry, hydroelectric power, recreation, and transportation. If mismanaged, they can cause many problems. Rivers and lakes must be treated in a responsible manner.

Groundwater

Rainwater soaks into the ground and fills the pore spaces in the soil and the cracks in rock. *Groundwater* is all water present below the land surface. Groundwater provides an important source of our water supplies in New York State. It is used by industry, cities and towns, and individuals. It is a renewable resource: if we use and conserve it properly, we will have a continuous supply. However, if we contaminate the groundwater with toxic substances, it can become undrinkable for decades.

As water soaks through the soil and fills all the pore spaces and cracks, it eventually saturates the earth material below a certain level. This level is called the *water table*.

The level of the water table rises and falls. Abundant rain will cause it to rise. Dry periods and continuous pumping from wells will cause it to fall. The level of the water table roughly follows the surface of the land. Groundwater flows through pore spaces toward the low points of the landscape, where it emerges as surface water in rivers, streams, springs, and lakes (Figure 16.4).

The amount of empty space in the soil and underlying rock (called *porosity*) and the rate that water can flow through those spaces (called *permeability*) vary with the rock material. Permeable underground layers that can supply usable quantities of drinking water are called *aquifers*. Aquifers are not "underground streams," as some people think. Instead, they are porous, permeable rock material that is thoroughly soaked with water.

The best aquifers in New York State are widespread glacial sand and gravel deposits from the Pleistocene Epoch and some loose Coastal Plain deposits from the Cretaceous Period beneath Long Island. The major Pleistocene aquifers of the State are near major rivers, including the Susquehanna, Hudson, Mohawk, Allegheny, and Genesee (Figure 16.5; compare with Figure 11.1B). Bedrock aquifers are less porous, so they tend to carry less water. They are drilled mainly to provide water for local household uses.

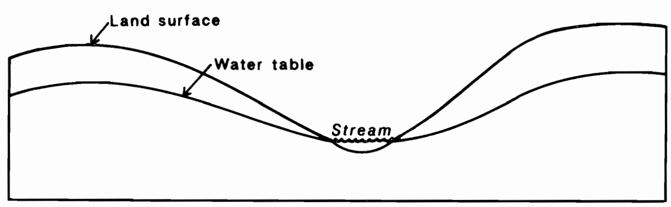


Figure 16.4. This simplified diagram shows how groundwater flows toward the low points of the landscape, where it emerges as surface water (in this illustration, a stream).

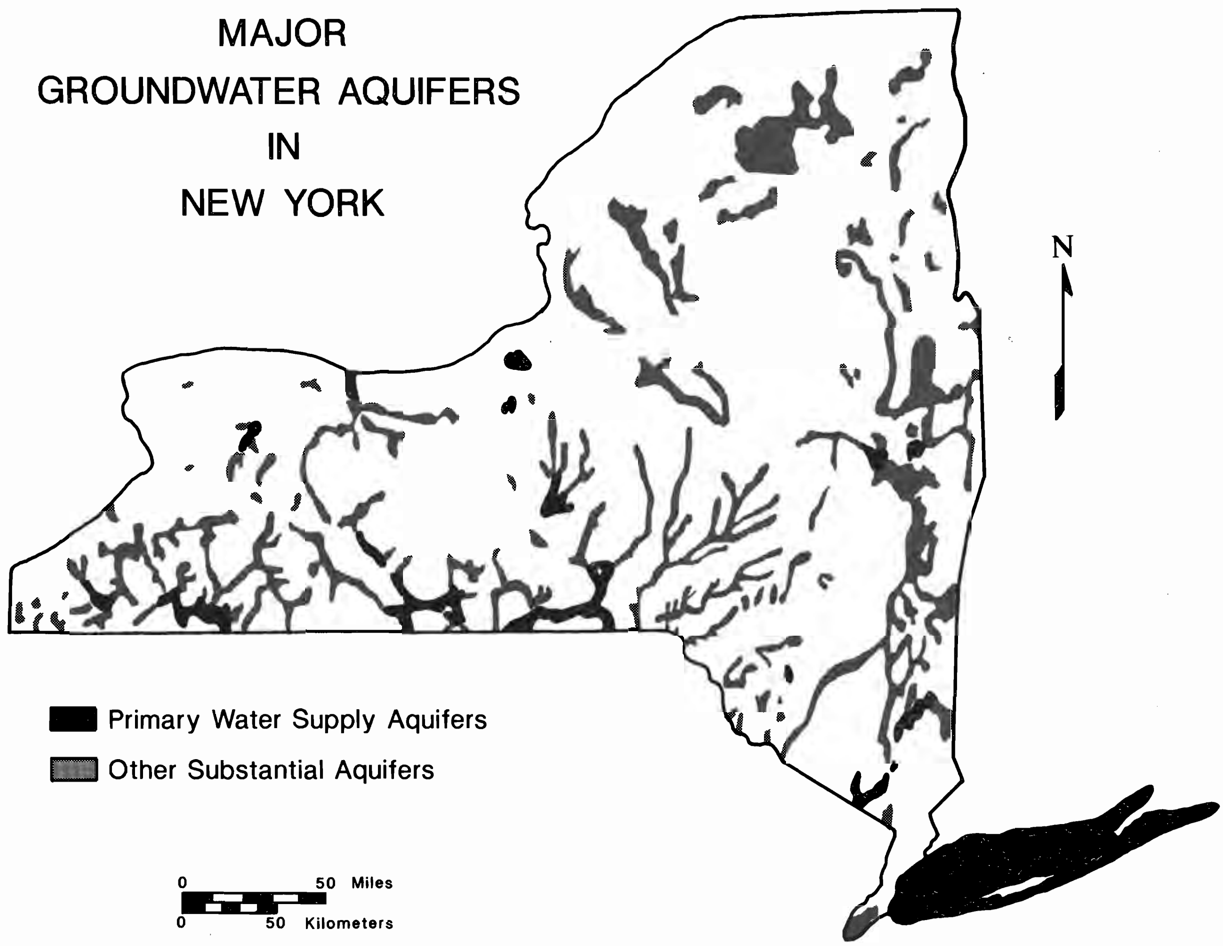


Figure 16.5. This map shows the location of important aquifers in New York State. Compare it with the drainage map in Figure 11.1B. Notice that river valleys, with their loose fill of sand and gravel, are important as aquifers.

The Growing Demand for Water

Cities periodically outgrow their supply of ground and surface water. New York City, for example, originally obtained most of its water from local wells, springs, and streams. By the late 19th century, though, the city had to create major reservoirs in Westchester County to meet increased demand. This reservoir system was much expanded in the 20th century by the construction of large reservoirs in the Catskill Mountains.

As demand for drinking water rises, the danger of biological and chemical pollution rises as well. Perhaps the greatest pollution threat comes from chemical fertilizers and pesticides, because their use is so widespread. The next greatest danger comes from improperly located dumps, landfills, and toxic chemical waste sites. Rain and surface water continually soak through the ground to replenish the groundwater supply. Where this water flows through ground containing such pollutants, it becomes contaminated.

A growing pollution problem is caused by excessive pumping of groundwater in coastal areas such as Long Island. In such areas, the ground is saturated with fresh water near the surface and with salt water beneath that. As fresh groundwater is pumped out, the water table surrounding the source well is lowered. If the water table is not given enough time to recover, the fresh water may be replaced by salty groundwater.

Everyone, not just industries and large cities, must be careful to avoid contributing to the pollution of groundwater and surface water. Individual homeowners can easily contaminate their own well water by having a badly located or designed septic system.

Dealing with Environmental Problems

"Environmental problems" can mean damage caused by natural hazards such as earthquakes, floods, or landslides. However, the major environmental problem facing New York State involves pollution of the water caused by human beings. Significant changes in human activities will be required to eliminate these problems and restore the health of our natural environment.

Industrial and agricultural chemicals, radioactive wastes, sewage, and road salt pollute streams, lakes, reservoirs, and groundwater in many places. Unless proper procedures are used, human activities such as mining and smelting, petroleum production, stream damming and dredging, clear cutting of forests, and disposal of biological and toxic wastes can also cause severe environmental problems. When such operations are planned, hydrogeologists must analyze both the site and the surrounding region. This analysis can make it possible to design and run these operations safely or can provide warning about which operations cannot be made safe and must be cancelled. For example, commercial development of natural areas can severely deplete or contaminate the groundwater. To understand the potential damage to the groundwater, we need to know the size, shape, and physical and chemical properties of the aquifers at the proposed development site and in the surrounding area. A hydrogeologist would be needed to make the required study of the area.

To prevent danger to people from natural hazards, the first step is to find out how great the risk is. Estimates of potential risk are based on the geology of an area and past occurrences of hazardous events. Risk is expressed as a *frequency of recurrence*, that is, how often a particular event will occur. However, the frequency of recurrence cannot tell us for certain whether a dangerous event will happen—only how probable it is. For example, a "100-year flood" is a flood of a size that has a probability of occurring every 100 years. But we all know that a flipped coin can come up heads five consecutive times, even though the probability for each flip is 50/50. In the same way, it is possible to have "100-year floods" two years in a row. Two such floods, for example, happened in western New York in 1972 and 1973.

Review Questions and Exercises

What is the difference between surface water and groundwater? How are they related? How does groundwater move, and why?

What is a *drainage basin*? Describe the major rivers and drainage basins in New York State. Which drainage basin do you live in?

How long have most of New York State's lakes existed? What can you say about their probable future in the natural course of events?

At what time of year does the greatest amount of precipitation fall in New York State? The least? How does the precipitation relate to the amount of water in rivers? Explain.

What is the *water table*? What controls its shape? What are some of the things that cause it to vary?

What is an *aquifer*? What kind of materials can it be made of? What can threaten the usefulness of an aquifer?

What kinds of environmental problems might a hydrogeologist be expected to deal with?

Chapter 17
Earthquake!
What, Where, When, Why[1]

Summary

The study of earthquakes starts with the study of earth vibrations, called seismic waves, which travel at different speeds in different kinds of rock. The two basic types of seismic waves are P waves and S waves. P waves travel faster and can travel through solids, liquids, and gases. S waves can travel only in solids. The most common kind of earthquakes happen when rock suddenly moves along an existing fault or when rock breaks to form a new fault. For most earthquakes, the forces that break the rock come from the motion of the earth's plates. Every year, more than 50,000 earthquakes large enough to be felt by people happen on earth; about 5 to 10 of them occur in New York State. When an earthquake is detected, we use what we know about the speeds of seismic waves to find where it originated. We can describe the size of an earthquake in three ways: magnitude, maximum intensity, and the size of the area in which it was felt. Magnitude scales, for example the Richter scale, are based on amplitude of ground motion and are related to the energy of seismic waves. The greater the energy released by an earthquake, the greater its magnitude. Intensity describes the effects of the ground shaking. We assign intensity values based on people's reports of what they observed at the time of an earthquake. Such reports gathered from a wide area allow us to determine the total area in which an earthquake was felt. For earthquakes that happened before measuring instruments became available (around 1900), we use historical records to estimate the maximum intensity or the total area in which an earthquake was felt. From this value, we can estimate the magnitude of an earthquake. Most earthquakes occur along plate margins. New York State is located far from any plate margins and has few earthquakes. California has about 100 times more earthquakes than New York. Seismographs locate up to several hundred small earthquakes in New York State every year, but usually fewer than 10 are large enough to be felt. Earthquakes have been happening in the same areas of the State since 1730. Earth scientists cannot predict with any accuracy when earthquakes will happen in a given area. The largest known earthquake in New York State had a maximum intensity of VIII; however, it is not known whether a larger earthquake could occur in the State. We need to do much more research before we can better estimate earthquake hazard.

Seismic Waves

The study of earthquakes starts with the study of all earth vibrations, natural and artificial, how they travel, and what they reveal. This study is the science of *seismology*. Vibrations of this type that travel through rock are called *seismic waves*. Once they start, these waves continue through the earth until their energy is used up.

Seismic waves are detected and recorded by an instrument called a *seismograph*. From many such records obtained throughout the world, we can determine how fast seismic waves travel at various depths, from the earth's surface to its core. Seismic waves generally travel faster in denser rock. Using such information, we have developed the idea that the earth is made of a solid iron inner core, a molten iron outer core, a mantle, and an outer crust (Figure 17.1).

There are two basic types of seismic waves, and they travel at different speeds through the earth. The faster *P waves* move by alternately compressing and expanding

[1]Adapted from a manuscript by W. Mitronovas.

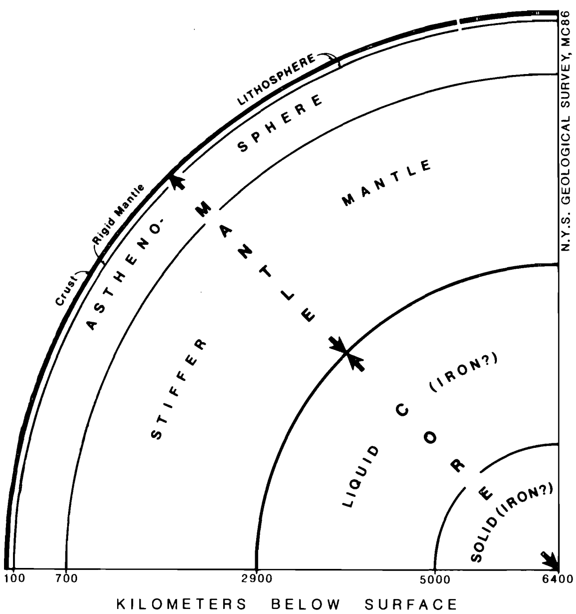


Figure 17.1. This drawing shows a slice to the center of the earth. Notice the structure: a solid inner core surrounded by a liquid outer core, the mantle, and the crust. The study of seismic waves provides the evidence for this structure.

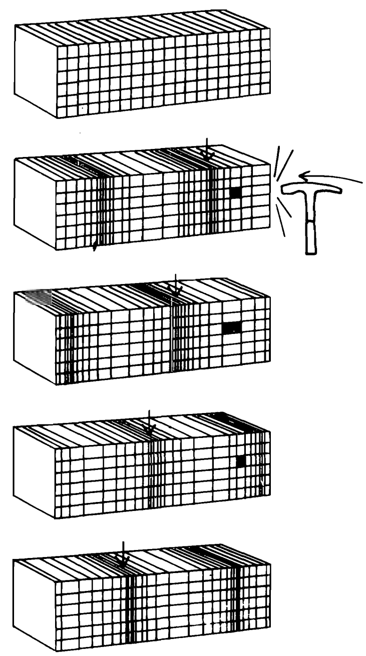


Figure 17.2. These drawings show how a P wave travels by vibrating back and forth. The black box shows how an area of rock deforms as the wave passes.

the rock. The particles move back and forth in the same direction the wave is travelling. You can see this kind of wave action in the coils of a Slinky toy or some other loose spring (Figure 17.2). P waves can travel through solids, liquids, or gases. When P waves travel in air, they are called sound waves. In most rock types, P waves travel between 1.7 and 1.8 times as fast as the second kind of seismic waves, S waves.

The slower *S waves* move like a wave in a rope (Figure 17.3). The particles vibrate at right angles to the direction in which the wave is travelling. S waves can travel only in solids. They do not travel through the earth's outer core; this fact tells us that the outer core is liquid.

With this brief discussion of seismic waves, we can begin to study earthquakes.

Earthquakes

Many events can cause the earth to vibrate. A large meteorite striking the earth, for example, would cause it to "ring" like a bell. Artificial explosions also cause earth vibrations. Indeed, nations monitor each other's underground nuclear bomb tests by detecting such vibrations. The most common cause of earth vibrations, however, is the sudden movement of rock, along either a preexisting break or a fresh break. Such breaks are called *faults*. The motion along the fault produces vibrations of the earth that can be felt (and often heard) as an earthquake.

Strain (rock deformation) can be built up slowly over many years through forces that stretch and deform the crust and rigid mantle. The rock stores this strain like a giant spring being slowly tightened. Eventually, the rock may reach the breaking point. Then suddenly it starts to move at the weakest place—along a new or pre-existing fault.

This break and the accompanying movement along the fault release the accumulated strain in the rock, which can represent an enormous amount of energy. Some of the released energy is used up in cracking and pulverizing the rock as the two blocks of rock separated by the fault grind past each other. Part of the energy, however, speeds through the rock as seismic waves. This energy can cause damage at great distances and is the most interesting and useful to seismologists.

What is the source of forces powerful enough to deform rock to the breaking point? The ultimate source is the heat within the earth. As we know from the study of plate tectonics (see Chapter 3), heat from radioactive decay causes motion in the partly melted rock of the mantle. The mantle moves in convection currents like those in a slowly simmering pot of oatmeal. Floating on top of this moving mantle, plates of the *lithosphere* (made up of the crust and hard outer mantle) are pushed from below. This motion deforms rocks and generates earthquakes.

One million or more earthquakes are detected by sensitive seismographs on earth every year. By analyzing the records of all earthquakes, we learn that small earthquakes are much more frequent than larger ones. How-

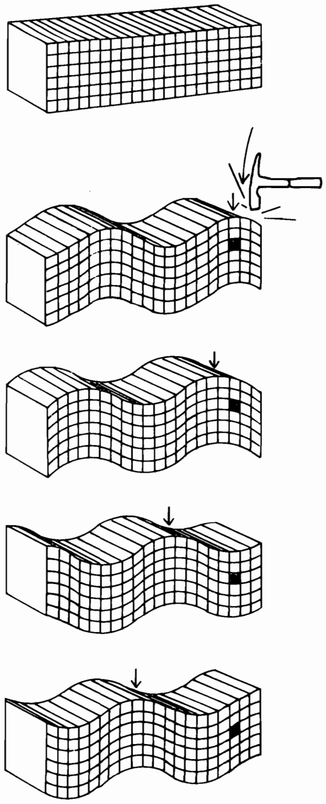


Figure 17.3. This drawing shows how an S wave travels by vibrating up and down. The black box shows how an area of rock deforms as the wave passes.

TABLE 17.1

NUMBER OF EARTHQUAKES PER YEAR	MAGNITUDE
50,000	3.0 - 3.9
6,000	4.0 - 4.9
800	5.0 - 5.9
120	6.0 - 6.9
18	7.0 - 7.9
1	8.0 or larger

ever, over 50,000 of those earthquakes are large enough to be felt by people each year (Table 17.1). About 5 to 10 of these *felt earthquakes* occur annually in New York State, although the actual number varies considerably from year to year.

LOCATING THE SOURCE OF AN EARTHQUAKE

When an earthquake takes place, many people want to know where it occurred and how strong it was. Although the area in which an earthquake is felt can be very large, the place of rock rupture is very localized. The *source* of an earthquake within the earth is the actual place of rock slippage along a fault. The *hypocenter,* the point where the fault starts to move, can be located by using P and S waves. The point at the earth's surface directly above the hypocenter is called the *epicenter.*

Around the world, abrupt motions of the earth are continuously monitored by seismographs. Seismic waves travel outward from the hypocenter of an earthquake in all directions, in the way that sound waves travel through air or water waves in a pond travel outward from a tossed stone. Each seismograph station records the arrival times of the faster P waves and the slower S waves. The closer the station is to the epicenter, the shorter the time between P and S wave arrivals. Therefore, from the difference between the arrival times of these two types of waves, we can calculate the distance to the earthquake; we can then draw a circle with a radius of that length around the station. The epicenter lies somewhere on that circle. Such circles drawn around three or more stations will intersect approximately at the epicenter; this procedure locates the earthquake. We can locate many earthquakes quickly and more accurately by using a computer program to match the calculated arrival times of P and S phases to many recording stations with the observed times at these stations. This method is the only one used by seismologists today.

THE SIZE OF AN EARTHQUAKE

The best way to describe the size of an earthquake would be to state the total amount of energy released when the rock broke. However, we don't have a way of measuring that energy directly. Instead, we use several indirect measures. One indirect measure is *magnitude,* a second is *maximum intensity,* and a third is the *size of the area* over which the earthquake was felt.

Several magnitude scales have been devised. The best-known is the *Richter magnitude scale* (Table 17.2). It is based on the height (called the *amplitude*) of certain seismic waves as recorded by seismographs. It was devised during the 1930s to classify California earthquakes. Other magnitude scales measure the amplitude of different kinds of seismic waves and are adapted to different regions. Magnitude does not tell us directly how much energy is released by an earthquake. However, we know that the greater the energy, the greater the magnitude, although the exact relationship is difficult to determine.

Another way to describe the size of an earthquake is by its *maximum intensity.* Intensity is a description of the effects of the earth movement—on people, buildings, and the landscape. The intensity varies in an earthquake region, depending on how far the observers are from the

Modified Mercalli Intensity Value	Description of Effects	Approximate Equivalent Richter Magnitude
I	Usually detected only by instruments	2
II	Felt by a few persons at rest, especially on upper floors	
III	Hanging objects swing; vibration like passing of truck; noticeable indoors	3
IV	Felt indoors by many, outdoors by few; sensation like heavy truck striking building; parked automobiles rock	4
V	Felt by nearly everyone; sleepers awakened; liquids disturbed; unstable objects overturned; some dishes and windows broken	
VI	Felt by all; many frightened and run outdoors; some heavy furniture moved; glassware broken; books off shelves; damage slight	5
VII	Difficult to stand; noticed in moving automobiles; damage to some masonry; weak chimneys broken at roofline	
VIII	Partial collapse of masonry; chimneys, factory stacks, columns fall; heavy furniture overturned; frame houses moved on foundations	6
IX	General panic; general damage to foundations; partial collapse of substantial buildings; underground pipes broken; conspicuous cracks in ground	7
X	Most structures destroyed; ground badly cracked; large landslides; water thrown over banks of rivers, lakes	
XI	Few, if any, structures remain standing; bridges destroyed; broad fissures in ground; railroad rails greatly bent; underground pipelines out of service	8+
XII	Damage nearly total; practically all works of construction greatly damaged or destroyed; waves seen on ground surface; objects thrown upward into the air	

Table 17.2. Comparison of Modified Mercalli intensity and Richter magnitude. For each intensity value on the Modified Mercalli scale, this table describes the effects on people, buildings, and the landscape. The third column shows the approximate Richter magnitude that is equivalent to each maximum intensity level.

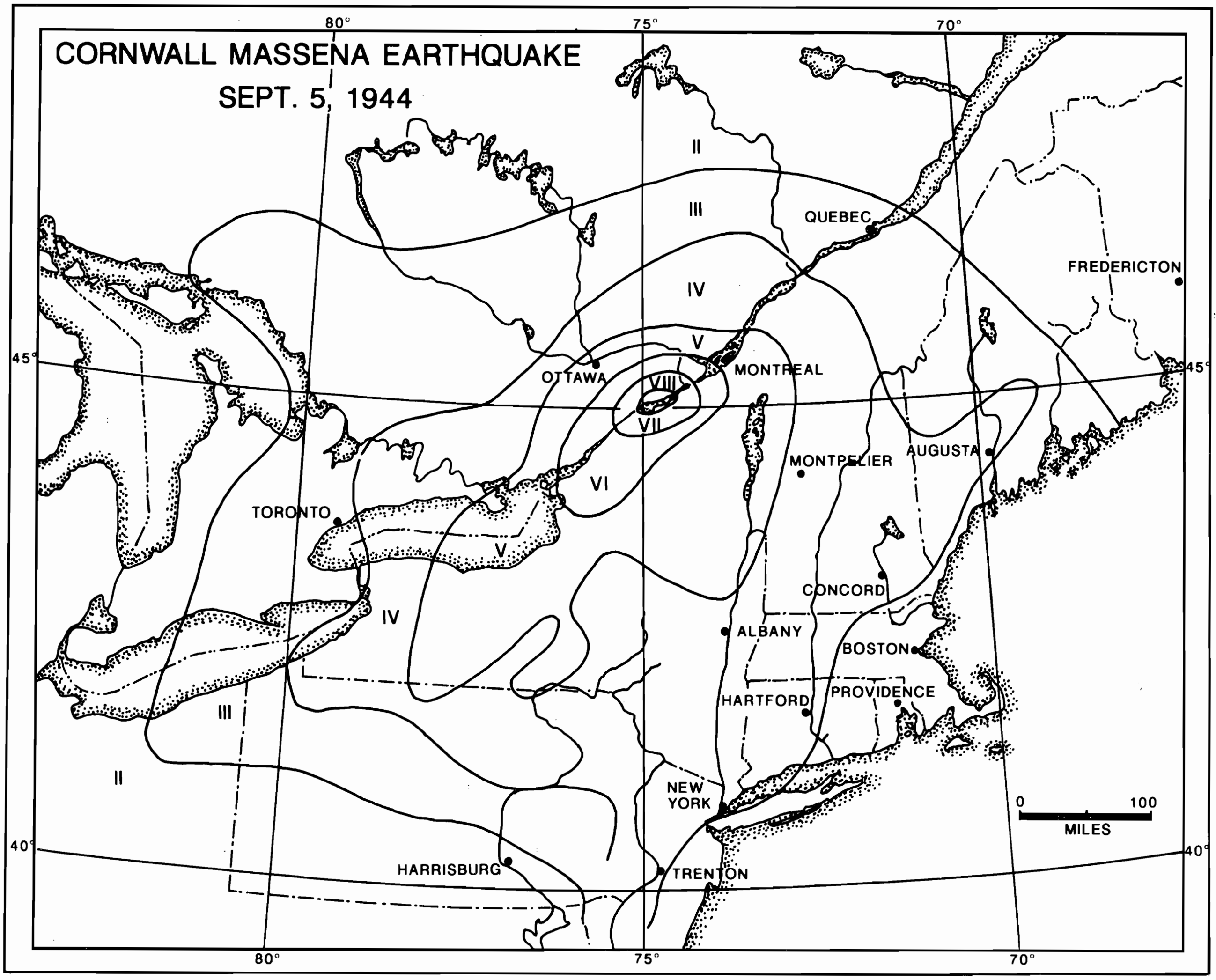


Figure 17.4. An example of an intensity map. This map shows the intensity levels for the largest earthquake ever recorded in New York State. It occurred in the Cornwall-Massena area on September 5, 1944. The maximum intensity, VIII, was noted near the earthquake's epicenter. The intensity levels on this map are based on what people experienced at the time of the earthquake (Table 17.2). Notice that the map also shows us the size of the area in which the earthquake was felt.

epicenter and whether they are standing on soft or hard ground.

An intensity scale includes levels that range from barely perceptible up to total destruction of buildings. The scale we use today in the United States is the *Modified Mercalli scale*—abbreviated *MM* (Table 17.2). The MM scale has 12 levels of intensity. These intensity levels are usually indicated by Roman numerals to distinguish them from magnitude levels, which are shown by Arabic numbers.

Because earthquake intensity depends on people's observations, we use questionnaires to investigate earthquakes. Questionnaires are distributed in an earthquake area to ask people what they heard, saw, and felt at the time of the earthquake. Based on the responses for each location, we assign intensity values and then prepare a map (Figure 17.4). Such a map shows the various intensity values and the total area in which an earthquake was felt.

For earthquakes that happened before seismograph readings became available around 1900, we can obtain an estimate of magnitudes by studying news stories and other descriptions of historical earthquakes. Using this information, we assign intensity values and determine the area over which a particular earthquake was felt. Then, we assign the magnitude that matches the maximum intensity or the size of the area. We determine the relationship between magnitude, maximum intensity, and size of the area through studies of contemporary earthquakes, for which we can determine all three values.

Earthquakes in New York State

According to plate tectonic theory, we would expect to find most earthquakes along divergent margins (where plates separate), along transform margins (where plates grind sideways past each other), and along convergent margins (where two plates collide). The theory of plate tectonics was strengthened when investigators observed that over 95 percent of earthquakes occur in these three kinds of areas.

New York State is far from any plate margins. Therefore, we would not expect much earthquake activity here. Indeed, New York has far fewer earthquakes than parts of the country that are near plate margins. Southern California, which lies along a transform margin (the famous San Andreas Fault system), has a rate of earthquake activity 100 times as great as New York's. The Pacific coast of Alaska is located along a convergent margin and is even more active.

Between 1730 and 1986, more than 400 earthquakes for which location could be determined occurred in New York State. These earthquakes had a magnitude greater than about 2.0. During this period, New York State has had the third highest earthquake activity of states east of the Mississippi River. Only South Carolina and Tennessee have been more seismically active.

But why does New York, located far from plate margins, have any earthquakes at all? We don't really know what causes earthquakes in regions far from plate margins. They probably are caused by plate motions in some way we still don't understand, or by some other process we haven't yet discovered.

It is well known that smaller earthquakes are much more numerous worldwide than larger ones (Table 17.1). Such is also the case in New York State. Of the up to several hundred earthquakes detected by sensitive seismographs in New York every year, generally fewer than 10 are large enough to be felt. An earthquake in the central Adirondacks on October 7, 1983, provides an example. The earthquake had a magnitude of 5.1. During the following three months, more than 50 aftershocks were recorded in that area alone, most of them too small to be felt.

Figure 17.5 shows the size and location of all the earthquakes that were located by seismographs in the northeastern United States and nearby Canada from 1975 to 1987. Table 17.3 lists all the earthquakes larger than magnitude 4 detected in New York State through 1989.

From our study of the historical record, we conclude that earthquakes have been recurring in the same areas of New York since 1730. Will earthquakes continue to occur where they do now, or will they slowly shift them to other parts of the State? In fact, 260 years is a relatively short time in terms of earthquake recurrence. We would need to study a much longer time span to tell whether this pattern is a continuing one or just a temporary state of affairs.

As we mentioned above, California's rate of earthquake occurrence is a hundred times that of New York State. However, there are some similarities between earthquake activity in the two states. The relationship between the magnitude and number of earthquakes, for example, is about the same in both states: for each earthquake of a certain magnitude, there are about 10 earthquakes of one magnitude lower. On the other hand, the crust and upper mantle in New York are older, cooler, and more rigid than in California; as a result, an earthquake here is felt over a much larger area than one of the same size in California.

Earthquake Hazard in New York State

How much danger of earthquakes is there in New York State? There are two ways to look at that question. One way is to estimate the likelihood that a certain size earthquake will occur at a particular place and time. This likelihood is called *earthquake hazard*, and it depends on geologic factors. Earth scientists, using their knowledge of geologic processes and local earthquake histories, try to predict the likelihood of an earthquake in any particular region.

On the other hand, we can look at the likelihood of people getting hurt or killed and property being damaged because of an earthquake. This danger is called *earthquake risk*. Earthquake risk depends in part on the earthquake hazard, but it also depends on additional factors, such as the number of people and population density in a region, how well buildings are designed to resist earthquakes, and how well the public and the authorities are prepared to react to earthquakes.

Earthquake risk is the concern of a great number of people in addition to seismologists and earth scientists—for example, architects, government officials, city planners, the police, the media, educators, and the general public. It would be impossible in this book to cover all of their roles. Therefore, the following discussion will center only on earthquake hazard in New York State.

The largest known New York State earthquake happened in the Cornwall-Massena area along the US-Canadian border on September 5, 1944 (Table 17.3). It had a maximum intensity of VIII on the Modified Mercalli scale (Richter magnitude about 6). It was strong enough to damage even well-constructed buildings. It knocked down chimneys and walls and overturned heavy furniture. Is this earthquake the largest one that could ever happen in New York? We can't answer that question with a definite yes or no.

In regions where many small earthquakes happen, larger ones are more likely as well. We probably know of all the earthquakes with a maximum intensity of V or greater that have occurred in our State during the past 250 years. We estimate that there is only about a 50 percent chance that an earthquake with a maximum intensity of IX or greater should have happened during the past

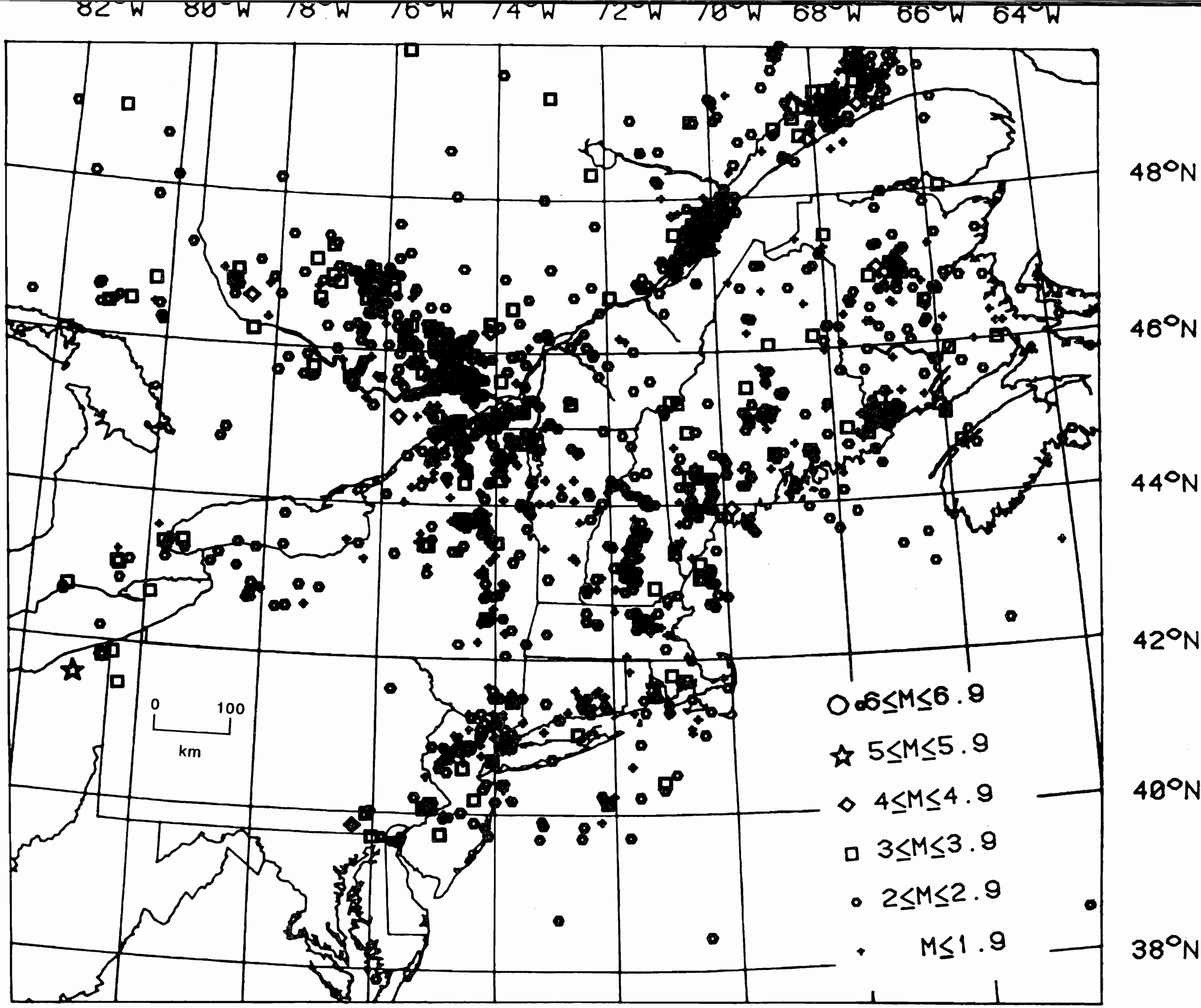


Figure 17.5. This map shows the locations and magnitudes of earthquakes in the northeastern United States and nearby Canada from 1975 through 1987.

TABLE 17.3

DATE	LOCALITY	LOCATION LATITUDE (NORTH)	 LONGITUDE (WEST)	Io	M
Dec. 18, 1737	New York City	40.60	73.80	VI	5.0
Mar. 12, 1853	Lowville	43.70	75.50	VI	4.8
Dec. 18, 1867	Canton	44.05	75.15	VI	4.8
Dec. 11, 1874	Irvington	41.00	73.90	VI	4.8
Aug. 10, 1884	Rockaway Beach	40.59	73.84	VI	5.3
May 28, 1897	Plattsburgh	44.50	73.50	VI	
Mar. 18, 1928	Saranac Lake	44.50	74.30	VI	4.5
Aug. 12, 1929	Attica	42.84	78.24	VII	5.2
Apr. 20, 1931	Warrensburg	43.50	73.80	VII	4.5
Apr. 15, 1934	Dannemora	44.70	73.80	VI	4.5
Sep. 5, 1944	Massena	45.00	74.85	VIII	6.0
Sep. 9, 1944	Massena	45.00	74.85	V	4.0
Jan. 1, 1966	Attica	42.84	79.25	VI	4.6
Jun. 13, 1967	Attica	42.84	78.23	V	4.4
Oct. 7, 1983	Goodnow	43.97	74.25	VI	5.1

Io = Maximum Modified Mercalli Intensity
M = Magnitude

Table 17.3. New York State's largest earthquakes, from 1737 through 1989.

250 years in New York State. Therefore, our 250 years of recorded history may be too short to include a larger earthquake. It is also possible that no earthquakes larger than VIII will ever happen in New York. Larger earthquakes have occurred in nearby regions of Canada and the United States, although they have been rare. We still don't know whether or not the geology of New York excludes such large earthquakes.

In order to better estimate earthquake hazard in New York, we need additional information. We have evidence that the crust is under stress in New York State and throughout the eastern and central United States. We suspect that the stresses are related in some way to tectonic plate motions, although we do not yet understand the details. Future research could tell us more about known faults in New York and how tectonic forces affect them. Such research may eventually enable us to estimate the size of the maximum possible earthquake in our State.

If we could match earthquakes with known faults, it might help us solve this problem. However, even the shallowest earthquakes are at least a few kilometers underground. The deepest known earthquakes in the State occur about 20 km below the surface. Surface faults can be mapped accurately, but the sources of earthquakes can be located only within a radius of a few kilometers. As a result, we've been able to match tentatively only a few very small earthquakes (detected by instruments) in New York State with surface faults. The true relationship of most earthquakes to faults still needs to be determined by more research.

REVIEW QUESTIONS AND EXERCISES

What are three ways of describing how large an earthquake is?

Where on the earth do we find frequent earthquakes? Why? What does that tell us about the likelihood of earthquakes in New York State?

What is the difference between earthquake hazard and earthquake risk? How do scientists go about estimating earthquake hazard in New York State?

Chapter 18
To Build or Not to Build
Engineering Geology[1]

Summary

Engineering geology deals with planning and designing construction projects. It helps develop and safeguard the water supply and protect people from natural geologic hazards. In New York State, there are a number of specific geologic conditions that are important to engineering geology: effects of the Pleistocene glaciers and the nature of glacial deposits, pockets of saprolite, areas of stress in bedrock, shale that expands and breaks down when exposed to air, the stability of slopes and the possibility of landslides, and regions of karst topography. Engineering geology deals with glacial deposits across the State—till that is hard to dig through, sand and gravel that form aquifers that must be protected from pollution, glacial lake clays that can be unstable and cause landslides, and the easily eroded glacial outwash that makes up the southern part of Long Island. Early construction projects, like the Erie Canal, did not benefit from geologic advice. By the end of the 19th century, though, engineers had begun to consult geologists regularly. For example, engineering geology has helped New York City meet its growing demands for water. Other projects using such advice have been the construction of hydroelectric plants, the interstate highway system, and the St. Lawrence Seaway, as well as the location of sites for power plants. Today, engineering geologists are working on New York's environmental problems like protecting drinking water, cleaning up toxic waste sites, finding a place for low-level radioactive waste disposal, and reducing the danger of landslides on the State's highways.

What Is Engineering Geology?

Geology has a great number of practical applications. One good example is using geologic principles to find fossil fuels and mineral deposits. (See Chapter 15 for more information.) In this chapter we discuss how geologic principles are used in engineering. This field is called *engineering geology*. It involves the geologic aspects of planning and designing construction projects of many kinds.

The most vital of such projects involve the world's most valuable and essential resource, fresh water. Engineering geologists, along with hydrogeologists, help develop surface water and groundwater supplies for cities and towns, clean up toxic wastes that contaminate groundwater supplies, and select new, safe sites for the disposal of toxic and nontoxic wastes.

Engineering geologists also study ways to evaluate natural geologic hazards and minimize the danger to people and their property. One such hazard in the northeast United States is coastal erosion, which can be severe during major storms. Another is landslides. We can recognize landslide-prone areas based on kind of material, steepness of slope, and other factors and can show them on maps for the benefit of builders.

Geologic Conditions in New York State

In New York State, several geologic conditions are important to engineering geology:

1. During the Pleistocene, the glaciers wore away almost all of the soft, weathered bedrock in the State, exposing fresh bedrock underneath. The ice also buried this fresh bedrock under a layer of glacial deposits.
2. The glacial deposits vary enormously in thickness and type. It is very important that engineering geologists understand all these types of deposits and their engineering properties, such as strength, *plasticity* (deform-

[1]Adapted from a manuscript by R.H. Fickies and R.H. Fakundiny.

ing under pressure without breaking), *porosity* (the amount of empty space between particles), and drainage characteristics.

3. Near New York City, some areas of soft, weathered bedrock (called *saprolite*) remain. These old Tertiary and interglacial sediments occur in deep pockets in the metamorphic rock surface and present poor foundation conditions. Several saprolite pockets were found during exploratory work done during the planning of the city's water supply tunnels.

4. Areas of stored geologic stress in New York's Paleozoic bedrock can affect large construction projects. One example is in the Niagara Falls-Buffalo area. There, the stored stresses caused the north-south walls of bedrock excavations to close suddenly as much as 45 cm. Similar stress in the gneiss bedrock of New York City has caused problems in tunnel building. In some limestone quarries in western New York, the release of this stored stress when the overlying rock was removed caused quarry floors to pop up.

5. In the Erie-Ontario and Hudson-Mohawk Lowlands, we find shale from the Ordovician and Silurian Periods. This shale is strong and stable as long as it's buried. When it's exposed to the air, though, it expands and breaks down quickly.

6. Limestone in some parts of the State may contain *karst* features. These features are formed when groundwater dissolves parts of the rock. Karst features include fractures enlarged by water, caverns, sinkholes, and sharp pinnacles on the surface of the bedrock.

Specific Problems

Dense glacial till[2] that was compressed by the weight of the ice covers much of the State's bedrock. It is aptly called "hardpan" in this region and is often difficult to dig through with machinery. The thickness and makeup of the till varies greatly.

In other places, there are many kinds of layered glacial deposits that were formed in meltwater streams or glacial lakes. They are usually found in valleys and lowlands. The engineering properties of these sediments can be very important. For example, glacial deposits of sand or gravel often form aquifers[3]. Many communities depend on these aquifers for their water supply. Maintaining a pollution-free water supply from the aquifers is vital to these communities.

Thick layers of clay were deposited in the deeper parts of glacial lakes in the lower and mid-Hudson Valley. These clays can be unstable, especially when they are soaked with water. When soaked, they may cause landslides even on moderate slopes. In the St. Lawrence Valley, we find clays that were deposited in the shallow sea that entered the region after the melting of the Pleistocene ice sheet. These clays can be similarly unstable.

Landslides are a significant problem in New York State. They do approximately $10 million in damage statewide every year. In the past 150 years, landslides in New York have killed 74 people.

The southern part of Long Island is made up of extensive sand plains. This sand is glacial *outwash*, washed out of the end of a glacier by meltwater. It is loose and easily eroded. Thus, waves and currents continually move the sand. Hurricane-driven waves and currents can cause enormous changes in the beaches and barrier islands of the south shore.

Long Island's barrier islands face an uncertain future. Sea level is rising. Human activity, such as the dredging of inlets for harbors and building of piers, stops the movement of sand that would have been washed westward to rebuild the barrier islands. The effects are becoming more and more obvious as the waves and currents eat away at these islands. In 1988 and 1989, the governor declared a state of emergency in Suffolk County. Erosion had moved the shoreline to within 6 m of the South Shore Parkway at several places on Jones Island.

Other hazards to the coastal zone are even more visible: waste disposal and problems with oil spills.

History of Engineering Geology in New York State

We have to understand how earth materials behave in order to plan major construction projects successfully. New York State has a long history of such projects.

Many early projects in the 19th century did not benefit from geologic science. No one studied what geology lay under the surface of the land before beginning excavation or construction. Problems were handled as they occurred. People learned to deal with earth materials by trial and error.

The 363-mile-long Erie Canal was started in 1817. The canal gave naturalists a unique opportunity to study the soil and bedrock across much of the State. Scientists studied the canal extensively, as well as the quarries that provided materials for it. However, we have found no evidence that the engineers consulted geologists during the construction.

[2]*Till* is a miscellaneous mixture of clay, sand, gravel, and boulders deposited by a glacier.
[3]An *aquifer* is an underground layer of rock or sediment that can produce a useable supply of water.

When the canal was rebuilt and enlarged between 1835 and 1856, the canal engineers occasionally asked State Geologist James Hall for advice. By the end of the 19th century, engineers had begun to consult geologists regularly. They had recognized the value of geologic evaluation and of drilling holes to get samples of the materials below the surface. They soon realized that these evaluations should be done even before the projects were designed.

Some of the earliest construction projects in the State were in the rapidly growing city of New York. The city had quickly become a major commercial center in colonial America. The first public water well was dug in Manhattan in 1677. Since that time, trying to plan and build an adequate water supply for New York has been a continuous project.

During the 1830s, New York City's inadequate water supply had become a crisis. Polluted wells spread cholera. Without enough water to put them out, fires burned incessantly, casting a thick pall over the downtown. The problem spurred action: the Old Croton Aqueduct was built to carry water from the Croton River 70 km south to New York City. Although the Assyrians and Romans had built such *aqueducts* (structures that carry water) long ago with much the same technology, it was the first of its kind in the United States.

The Old Croton Dam was built to store the water of the Croton River. From there, there were ridges to pass under and valleys to cross by special aqueducts. Construction began in 1837, and the first water flowed five years later. The water took 22 hours to travel down the gentle slope to New York City. Construction was completed in 1848. The project had been designed to supply New York City's water needs for centuries to come. The city's population growth, however, soon outstripped all expectations. The Old Croton Aqueduct was superseded by the New Croton Aqueduct, three times the length of its predecessor. It was begun in 1885 and delivered water from the Catskill Mountains five years later. It is still supplying the city, but planners are looking at even more distant sources of water for future needs.

The New York City Board of Water Supply may have been the first engineering organization in New York State to routinely seek advice from geologists. In 1905, it appointed Professor James Kemp of Columbia University as its consulting geologist. Ten years earlier, Professor Kemp had participated in the design and construction of the New Croton System. In that activity, he proved the value of engineering geology.

Later, Professor C.P. Berkey of Columbia made a study of the first aqueduct to serve New York City and published a report in 1911.

In the 20th century, engineering geology has played an ever increasing role in major construction projects. Hydroelectric generating plants were built at Niagara Falls and at many other sites across the State between 1920 and 1940. Geologists investigated dam and reservoir sites, as well as routes for the power lines. After 1950, the Federal government provided funds for building an interstate highway system. New York State began to employ engineering geologists in the Department of Public Works (now the Department of Transportation) to help in highway design and construction. Another major project, the St. Lawrence Seaway project, also required extensive geologic studies.

The decade between 1965 and 1975 may have seen the greatest demand for engineering geology studies in New York State. Geologists made detailed investigations of more than 20 possible sites for nuclear power plants. State and Federal laws require a series of thorough geologic studies before a nuclear plant can be licensed or built. These studies become part of a required environmental impact statement. Fewer than one-third of the proposed plants were ever built and licensed. Because earthquake potential is such a vital consideration in nuclear power plant siting, the studies taught geologists a great deal about seismic activity in the State.

Current Problems for Engineering Geology

During the past 20 years, most of the major engineering geology projects in New York have concerned protecting the environment and reducing environmental hazards. Federal and State laws require that toxic waste sites be cleaned up. They also require that sources of drinking water, like aquifers, streams, and rivers, be protected from pollution. Modern sewage treatment facilities have been built across the State. In Rochester, miles of tunnels have been dug through the bedrock beneath the city. These tunnels are designed to control runoff of storm water and reduce pollution in Lake Ontario. Geologists and other scientists have been studying groundwater pollution in the Buffalo-Niagara Falls area for a number of years.

Engineering geology studies at a radioactive waste burial site in Cattaraugus County will help planners select a location for New York's first statewide low-level radioactive waste disposal site. In addition, there are several hundred toxic waste disposal sites throughout the State that are no longer being used. Government and private engineering geologists are studying these sites in an effort to determine the best means of cleaning them up.

In 1989, the State Thruway Authority began a major landslide hazard reduction program, based in part on geologic studies of landslides across the State. This program should make the Thruway's 559 miles of highway safer.

REVIEW QUESTIONS AND EXERCISES

What is engineering geology? What kind of projects does it work on?

What are some of the problems from across the State engineering geology has coped with in the past? What projects in your own community have used engineering geology?

What are some of the problems engineering geology is trying to cope with today in New York State? What engineering geology problems exist in your community?

Oh, By the Way . . .
Appendix

The Appendix contains the following:

Figure A.1. Our Restless Earth.
The first drawing shows earth's continents and ocean basins 40 million years ago. Africa touched Eurasia. Rapid expansion of the Mid-Ocean Ridge raises the sea level, flooding continental margins. India, a separate continent, moves northward towards Asia.

The second drawing shows earth's continents and ocean basins today. The Mediterranean Sea has shrunk, the south Atlantic Ocean has widened, and India has collided with Asia. The northward push of India continues today, causing the lofty Himalayas and the Tibetan Plateau north of it to rise a meter each century. 1 page.

Figure A.2. Physiographic diagram of the continental United States. 1 page.

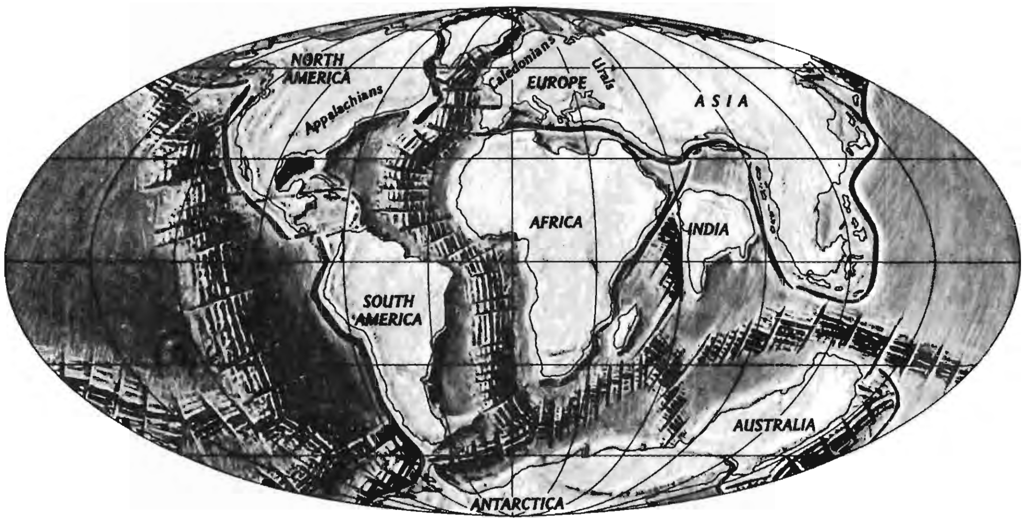
Figure A.3.
Drawings of some typical fossils from Paleozoic rocks of New York. All illustrations are natural size, unless indicated otherwise. (Enlargements and reductions are indicated by X followed by a number. For example, X2 means two times natural size; X1/5 means one-fifth natural size.) 4 pages.

Figure A.4.
A summary of the geologic history of New York in a series of 61 cross-section block diagrams. 12 pages.

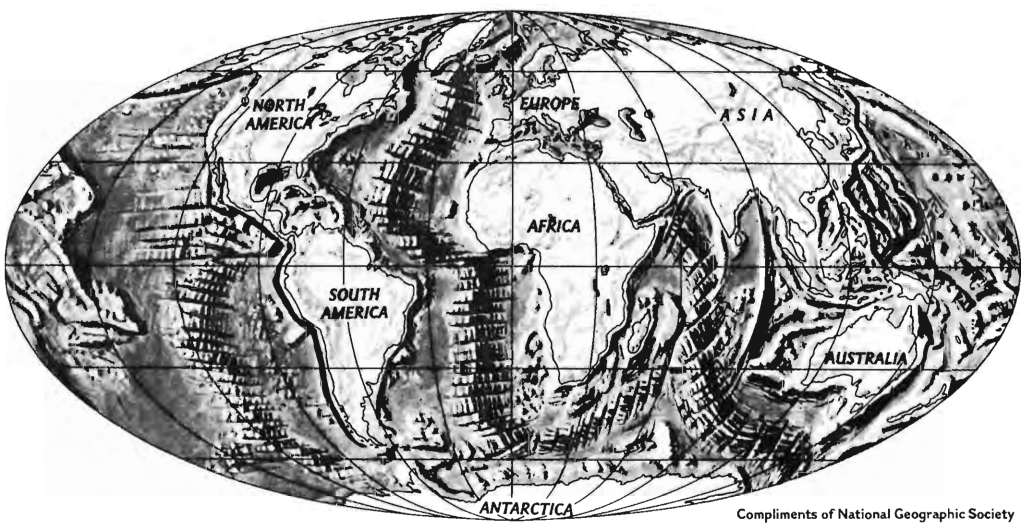
Figure A.5.
Simplified map showing the extent of brittle deformation (faults and fractures) in New York State. In the Adirondacks and Hudson Highlands, the lines represent known faults and fracture zones, as well as straight valleys that we suspect are fracture zones. In the rest of the State, the lines show straight segments of streams; these segments may flow along zones with closely spaced joints or other fractures. 1 page.

Table A.1.
List of maps of New York State available from the New York State Geological Survey. 1 page.

Table A.2.
Common metric measurements used in this book with their equivalents in English units. 1 page.



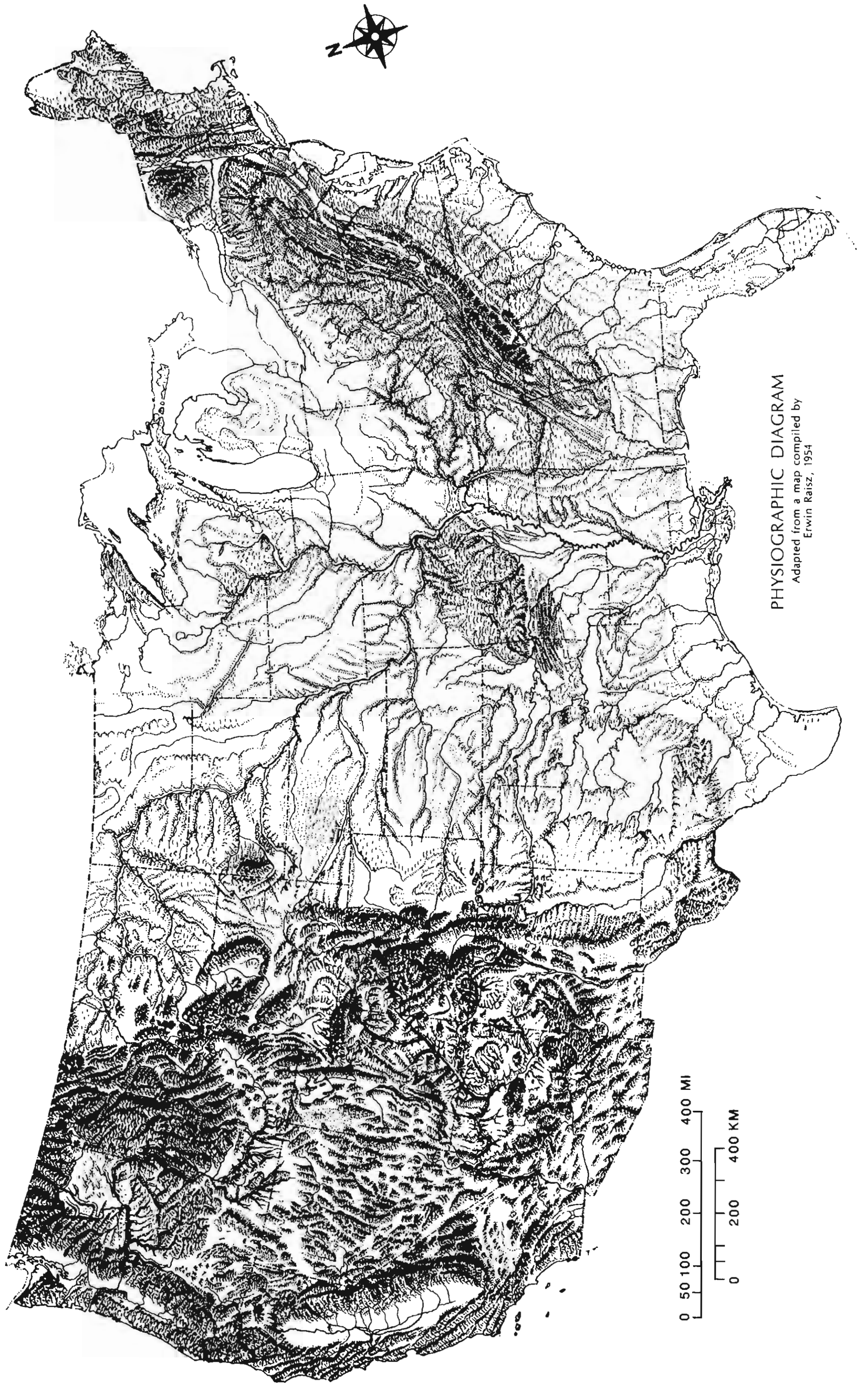
On the six major landmasses, mammals diversify and come to dominate reptiles. Rapid expansion of the Mid-Ocean Ridge raises the sea level, flooding continental margins. India moves northward. Forty million years ago Africa touched Eurasia; northern animals spread south, while the African mastodon and elephant expanded their range, even to the New World.



Compliments of National Geographic Society

The Himalayas and the Tibetan Plateau, produced by the convergence of India and Asia, rise a meter each century. The Mediterranean Sea, the shrinking remnant of Tethys, is the site of a complex plate boundary where Europe and Africa collide. Rifts inch open in East Africa. Coastal California moves northwest and 40 million years from now will be an island.

Figure A.1.


N
PHYSIOGRAPHIC DIAGRAM
Adapted from a map compiled by
Erwin Raisz, 1954
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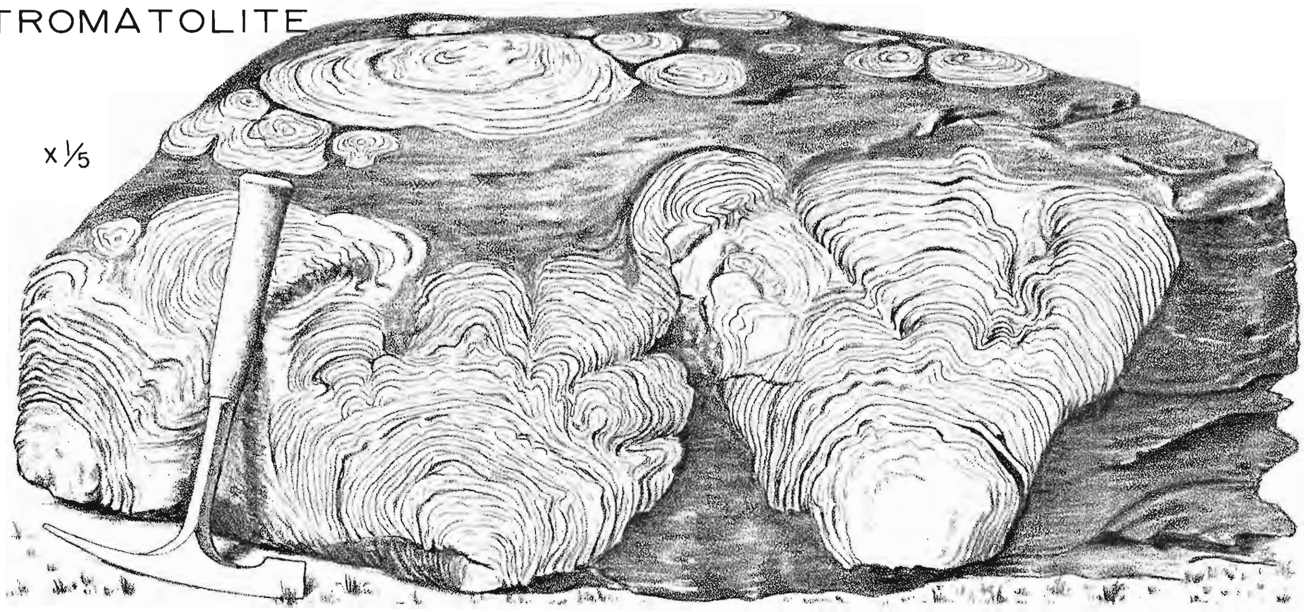
0 200 400 KM

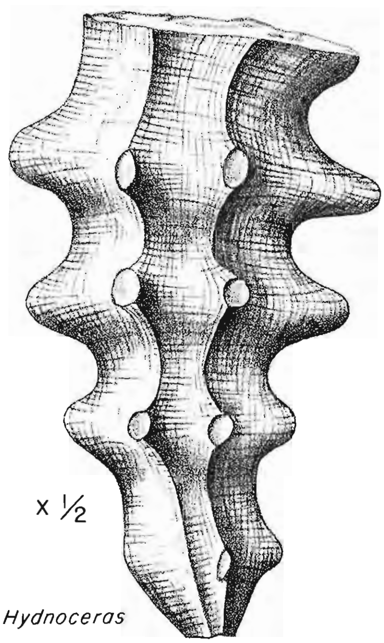
Figure A.2

Figure A.3

STROMATOLITE



SPONGE



Hydnoceras

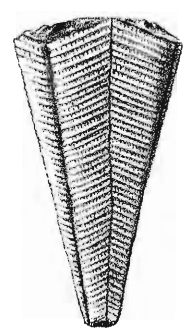
COELENTERATES

CORALS

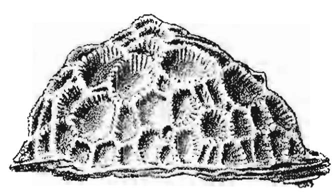
Cystiphyllum

Horn coral

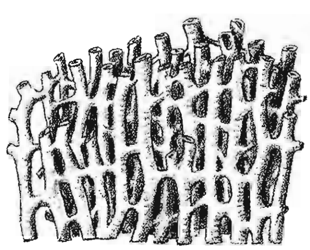
CONULARID



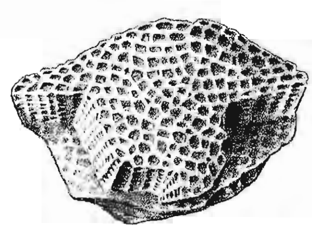
Conularia



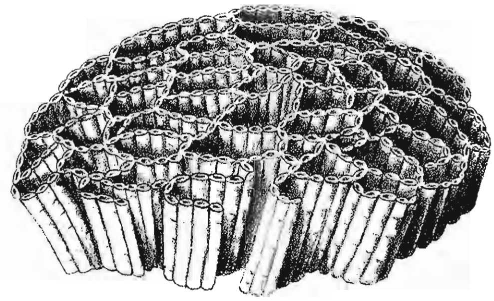
Pleurodictyum



Syringopora Tube coral



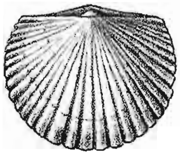
Favosites Honeycomb coral



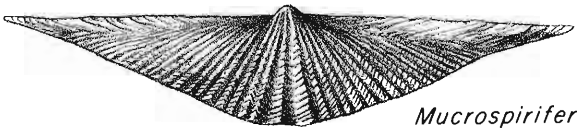
Halysites Chain coral

Figure A.3 continued

BRACHIOPODS



Dinorthis

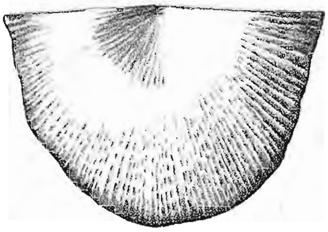


Mucrospirifer

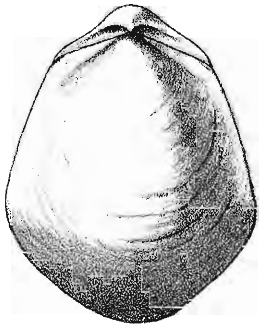
Paucicrura

Athyris

Lingulepis (phosphatic)

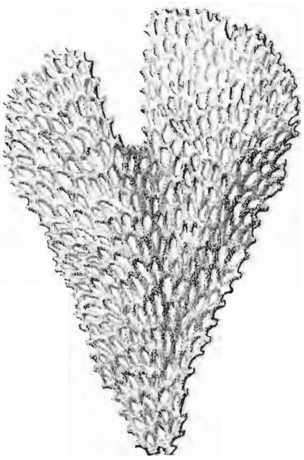


Strophonella

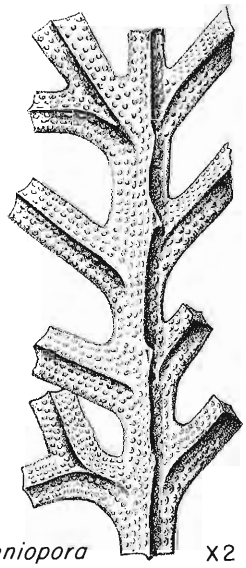


Pentamerus

BRYOZOANS



Phylloporina



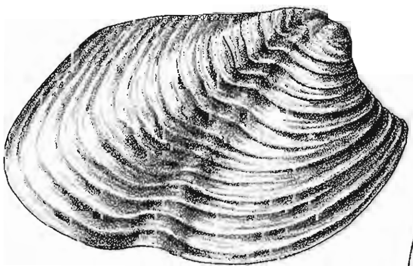
Taeniopora X2

MOLLUSK-LIKE FORMS

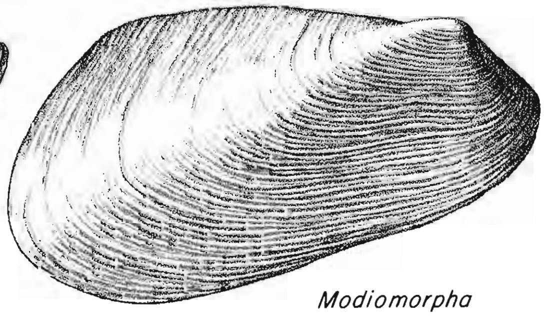
Hyolithes

Tentaculites X4

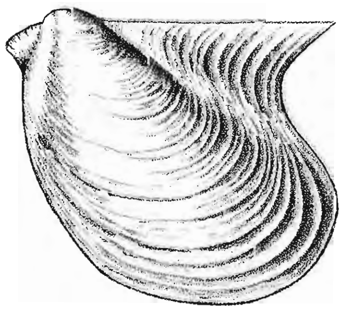
PELECYPODS



Grammysia



Modiomorpha



Leiopteria

Figure A.3 continued

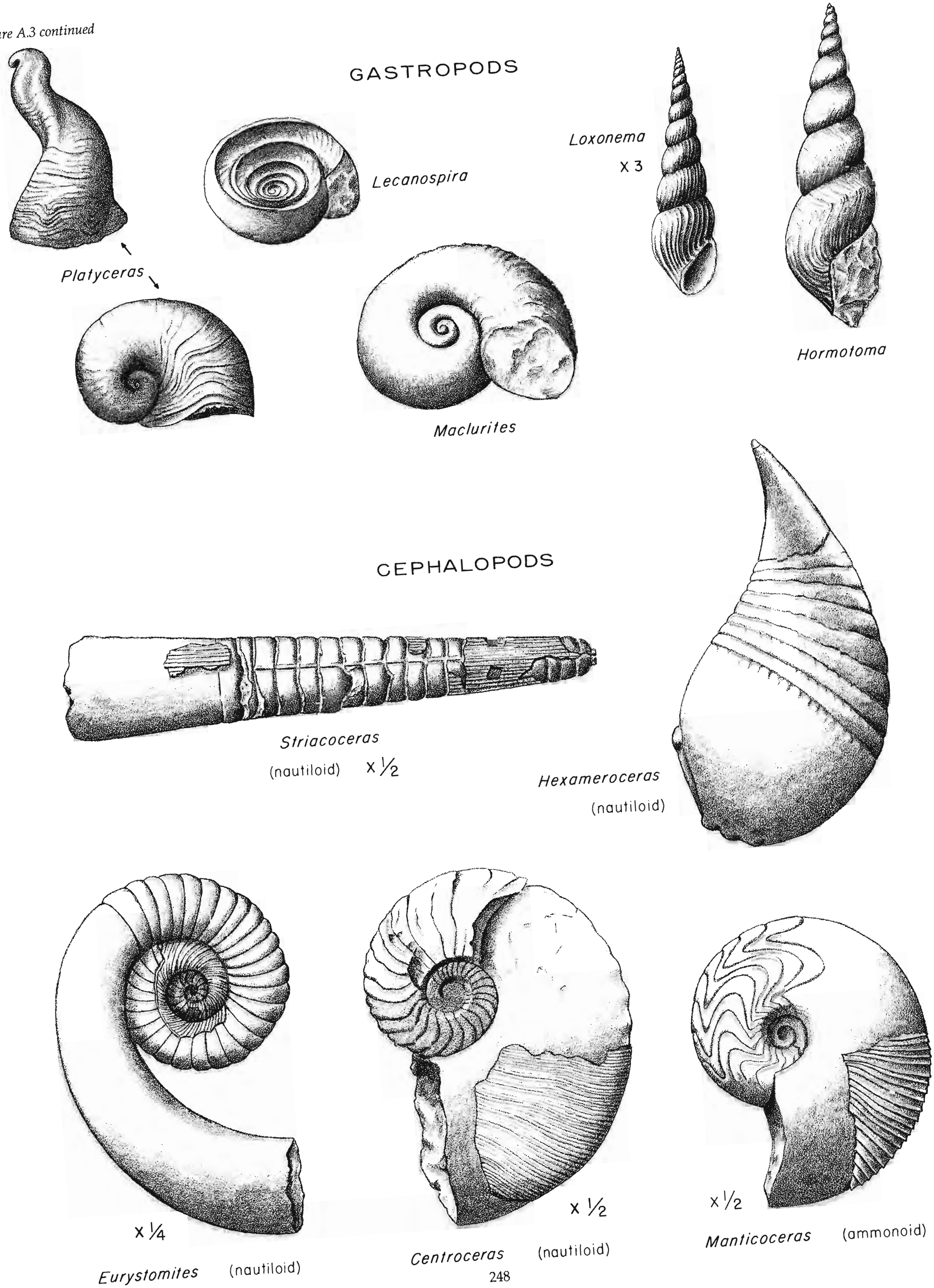


Figure A.3 continued

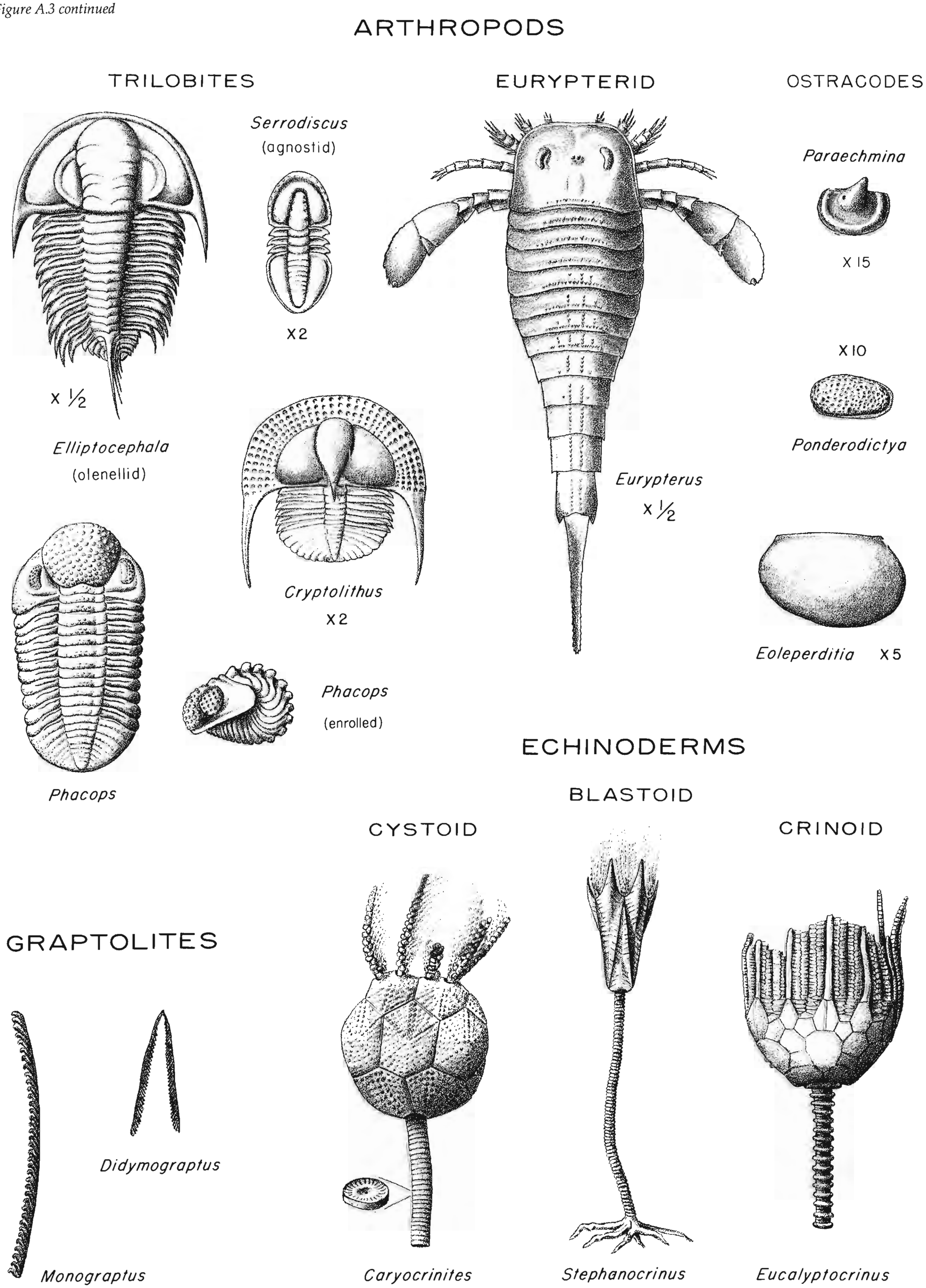
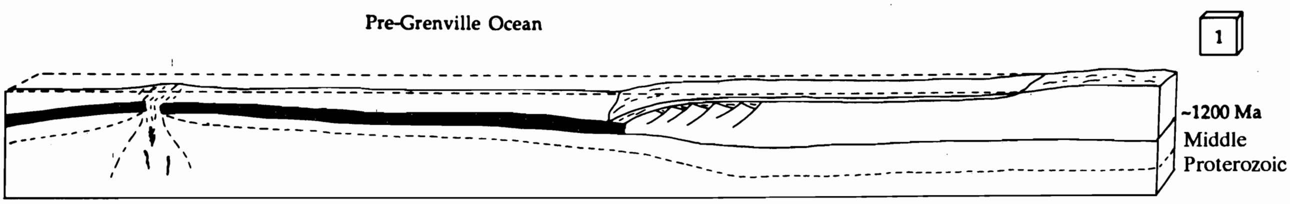


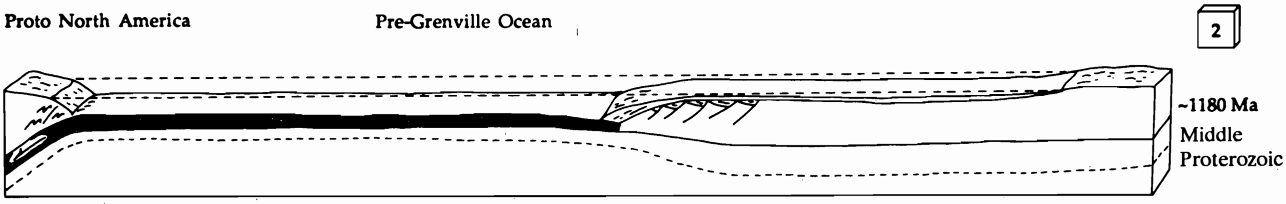
Figure A.4. These 61 three-dimensional diagrams, drawn by Professor Barbara Tewksbury, illustrate, in a very general way, the plate tectonic history of eastern North America. The time covered is from 1.2 billion years ago to the present. See Chapter 3 for more information.

In each drawing, the uppermost dashed line shows sea level. The lower dashed line is within the mantle and marks the base of the lithosphere. Beneath it is the asthenosphere, on which the plates of the lithosphere glide. Black represents oceanic crust. Within the continental crust, curved lines represent folds and straight lines represent faults. Arrows show relative movement along some faults. The "tear drop" shapes that appear in many of the diagrams represent intruding magma.

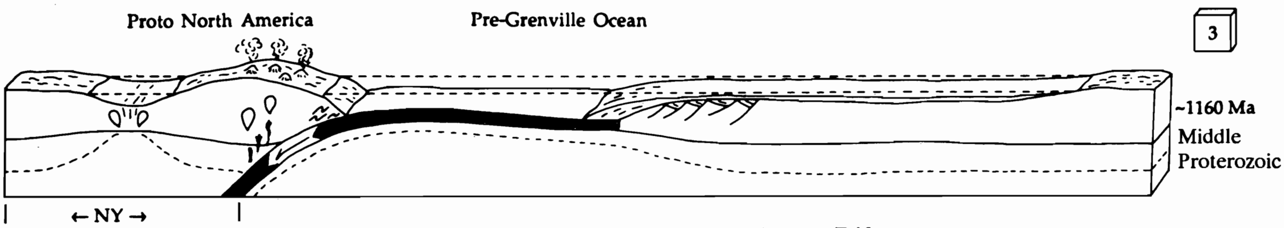
Notice that the New York State area of each diagram is indicated by *NY* beneath it. The abbreviation *Ma* stands for "million years ago." For example, the notation *~1100 Ma* is translated as "approximately 1100 million years ago" or "approximately 1.1 billion years ago."



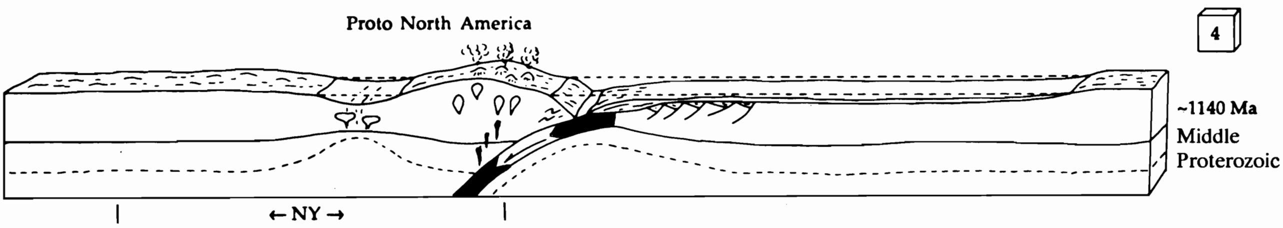
Pre-Grenville Ocean



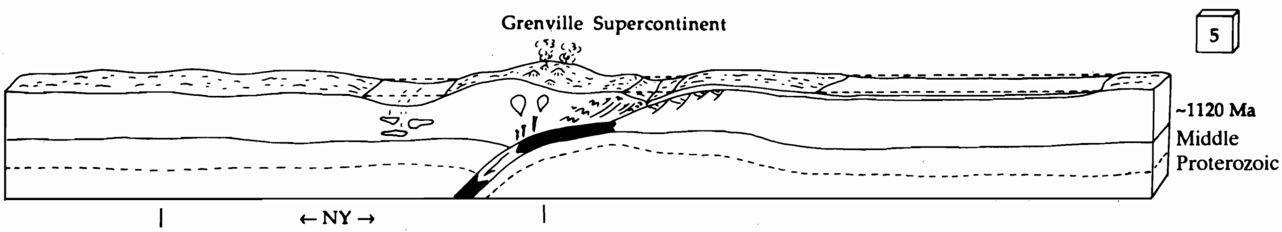
Closing of Pre-Grenville Ocean by Subduction



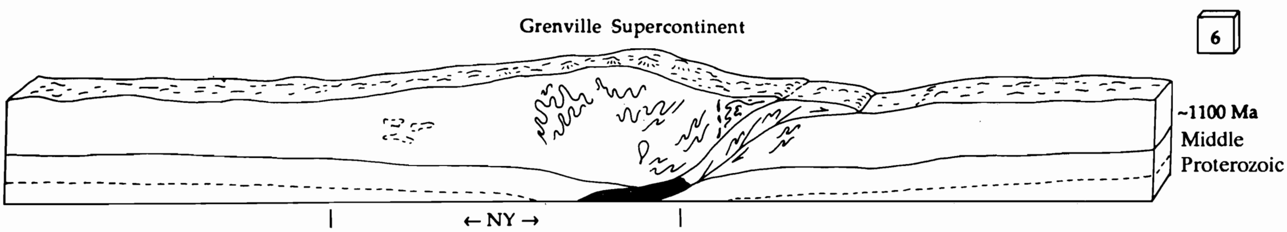
Development of Magmatic Arc and Back Arc Rift



Onset of Grenville Orogeny

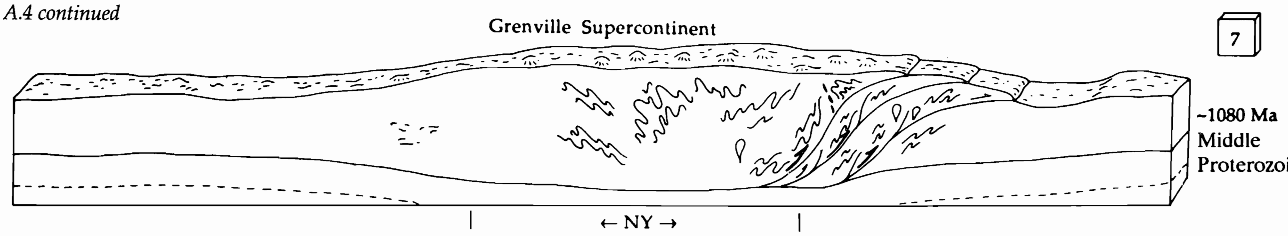


Grenville Orogeny

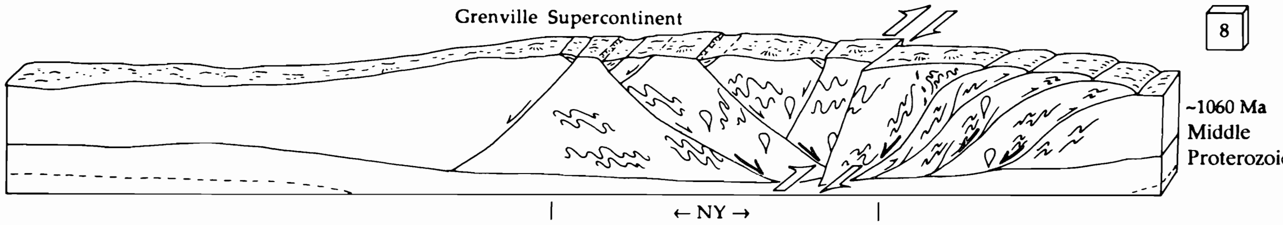


Continued Grenville Orogeny

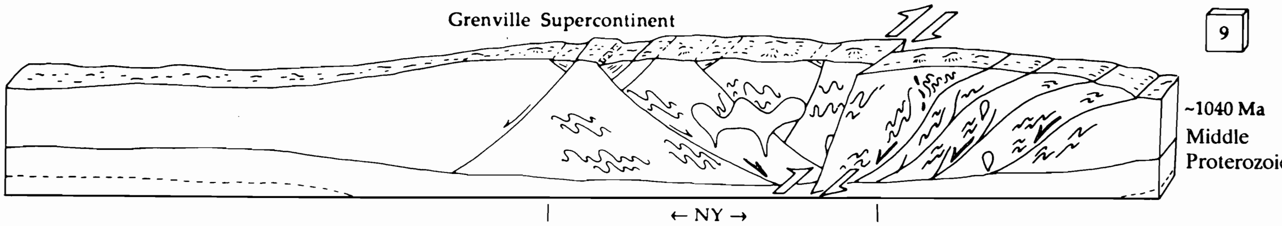
Figure A.4 continued



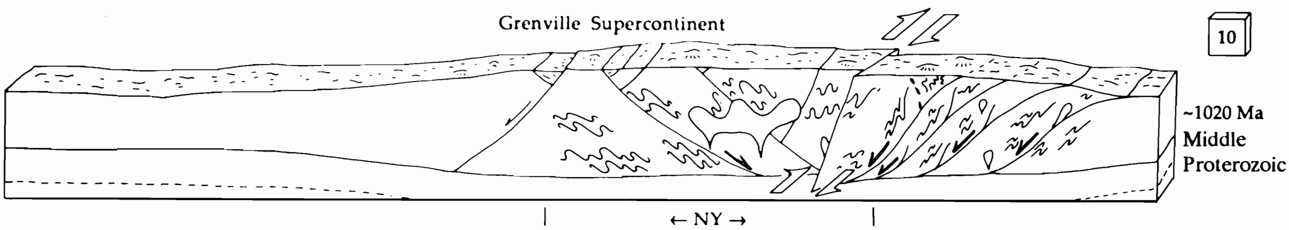
Continued Grenville Orogeny



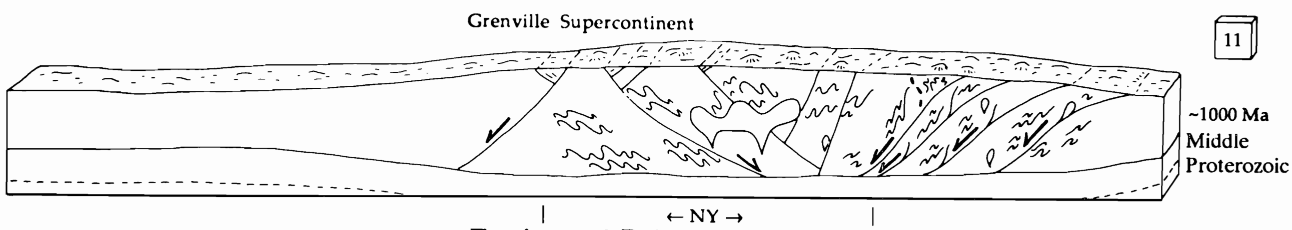
Crustal Relaxation, Strike-Slip Faulting, and Erosion



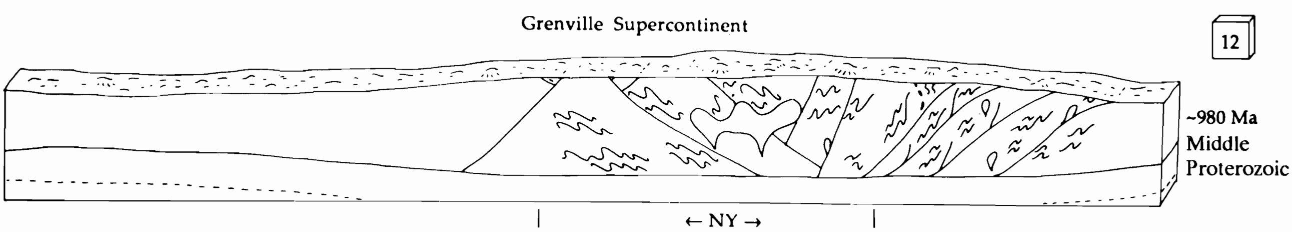
Relaxation, Rifting, Strike-Slip Faulting, and Erosion



Strike-Slip Faulting and Erosion

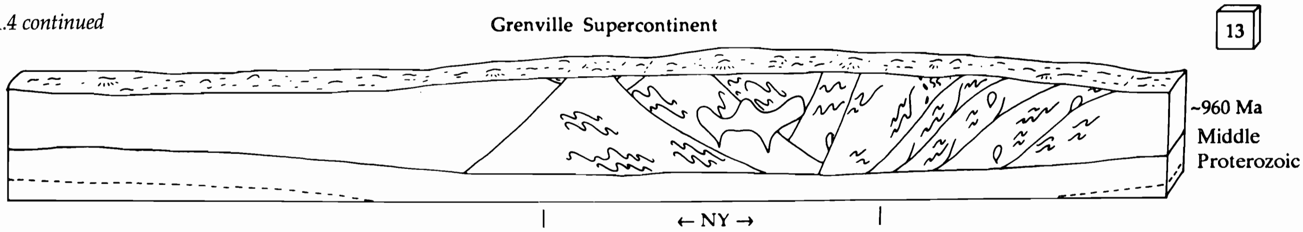


Erosion and Rebound

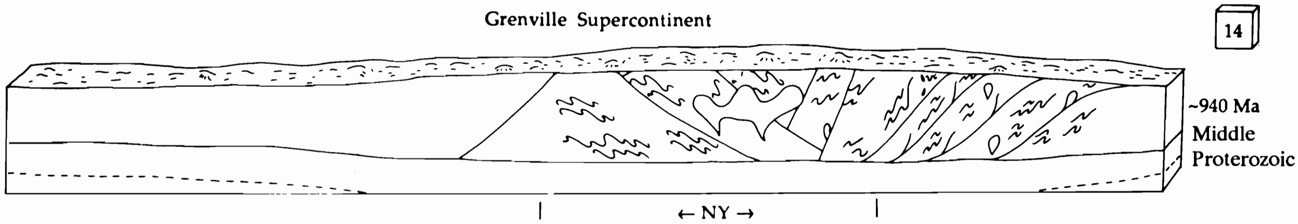


Continued Erosion and Rebound

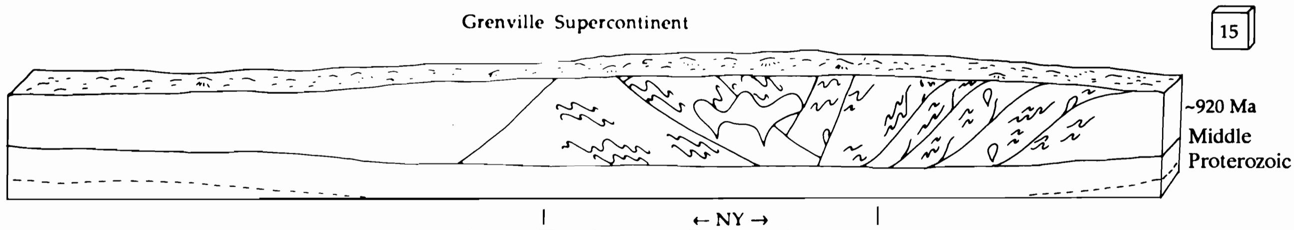
Figure A.4 continued



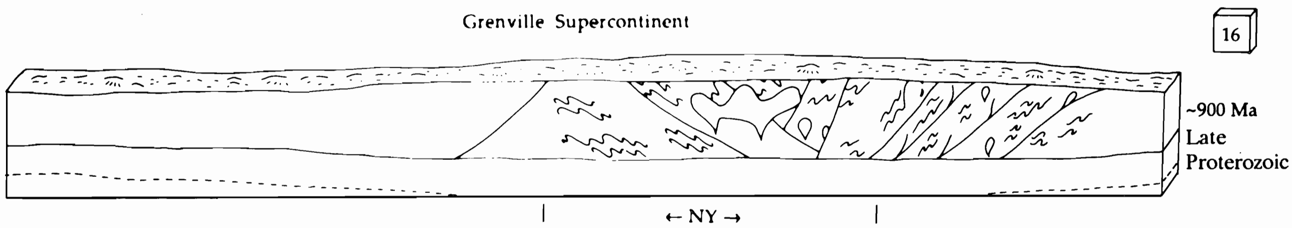
Continued Erosion and Rebound



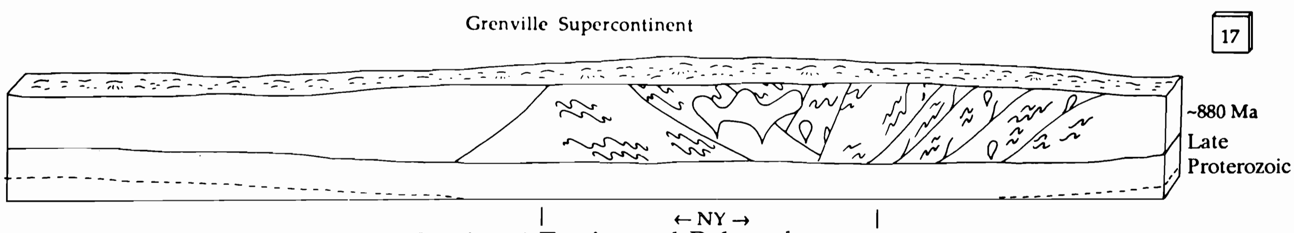
Continued Erosion and Rebound



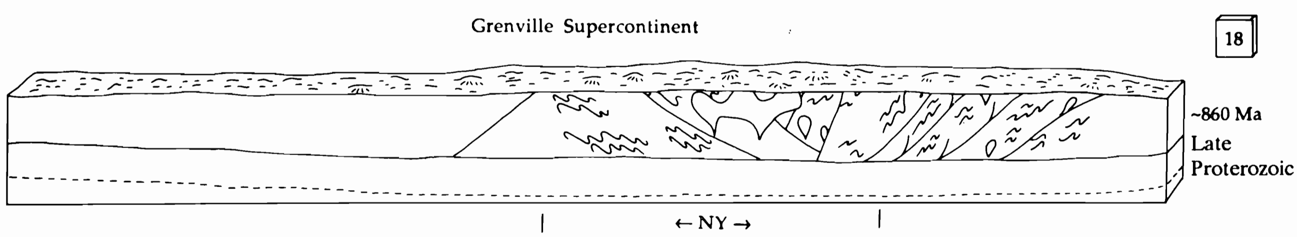
Continued Erosion and Rebound



Continued Erosion and Rebound



Continued Erosion and Rebound

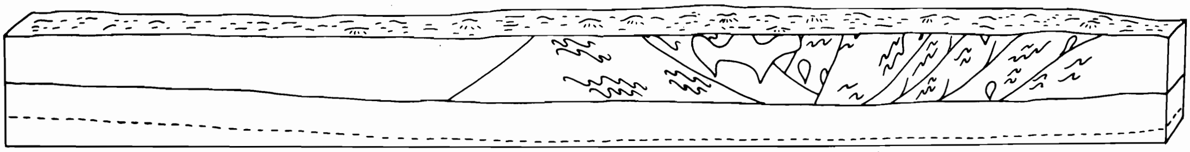


Continued Erosion and Rebound

Figure A.4 continued

Grenville Supercontinent

19



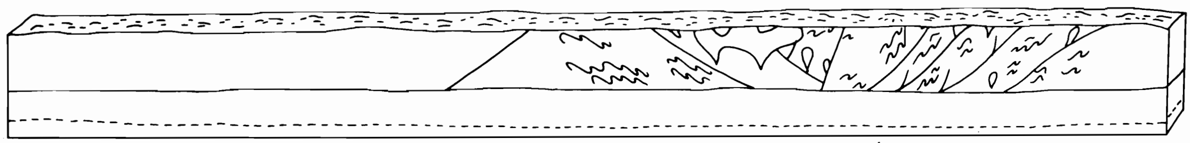
~840 Ma
Late
Proterozoic

← NY →

Continued Erosion and Rebound

Grenville Supercontinent

20



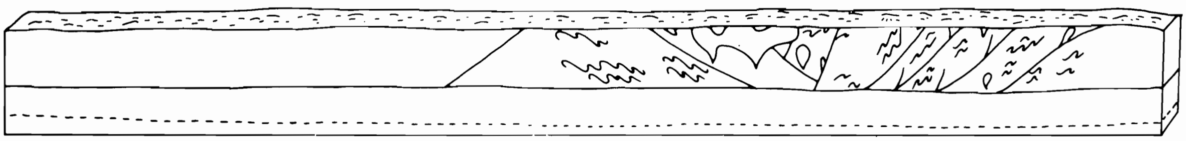
~820 Ma
Late
Proterozoic

← NY →

Continued Erosion and Rebound

Grenville Supercontinent

21



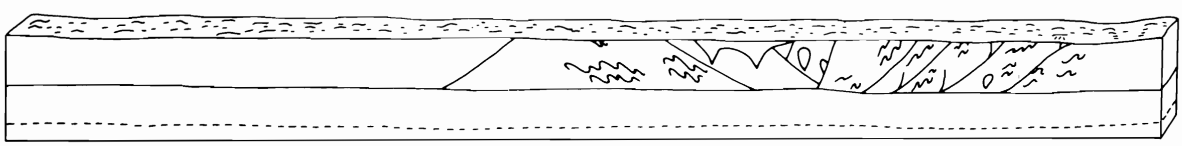
~800 Ma
Late
Proterozoic

← NY →

Continued Erosion and Rebound

Grenville Supercontinent

22



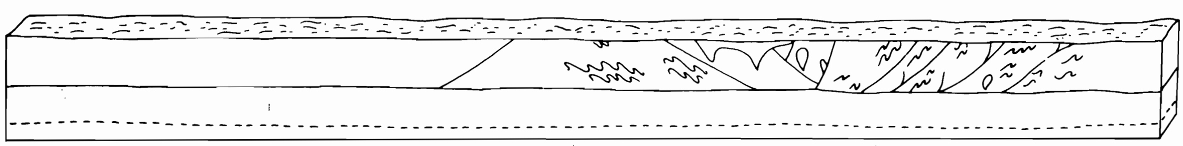
~780 Ma
Late
Proterozoic

← NY →

Continued Erosion and Rebound

Grenville Supercontinent

23



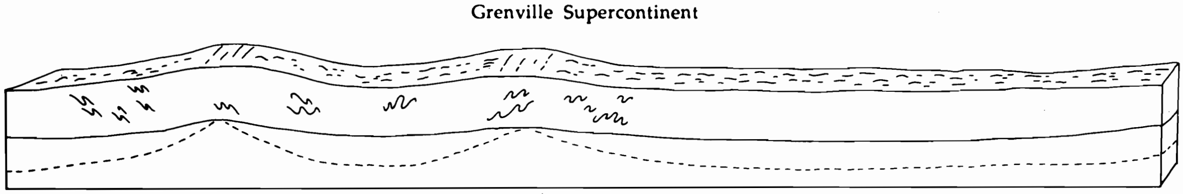
~760 Ma
Late
Proterozoic

← NY →

Continued Erosion and Rebound

Grenville Supercontinent

24

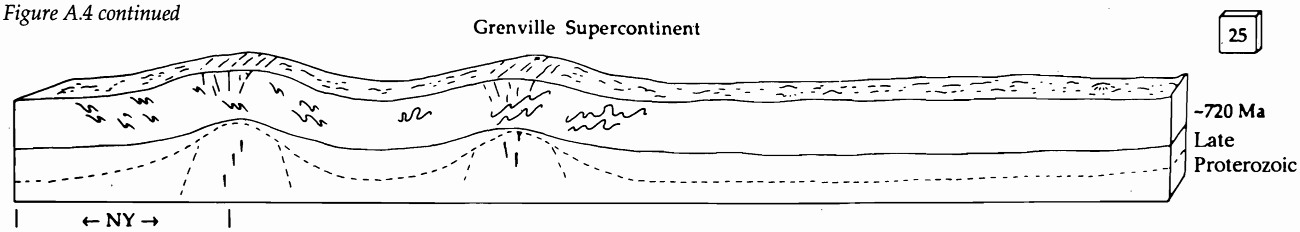


~740 Ma
Late
Proterozoic

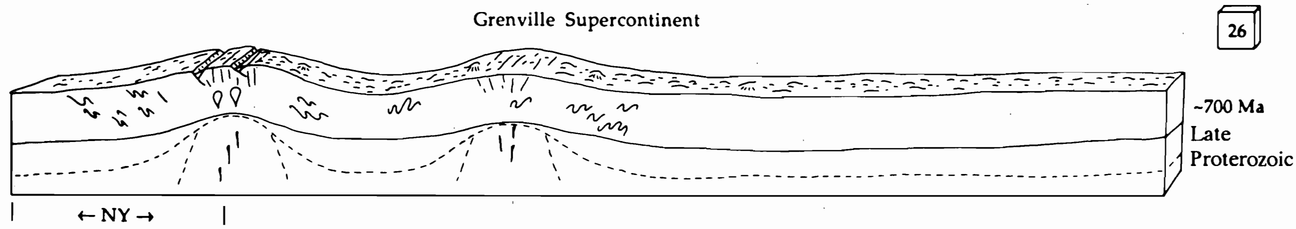
← NY →

Doming and Initial Rifting

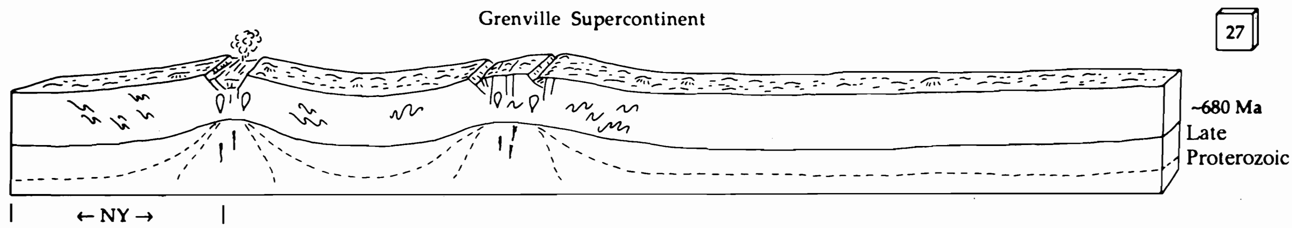
Figure A.4 continued



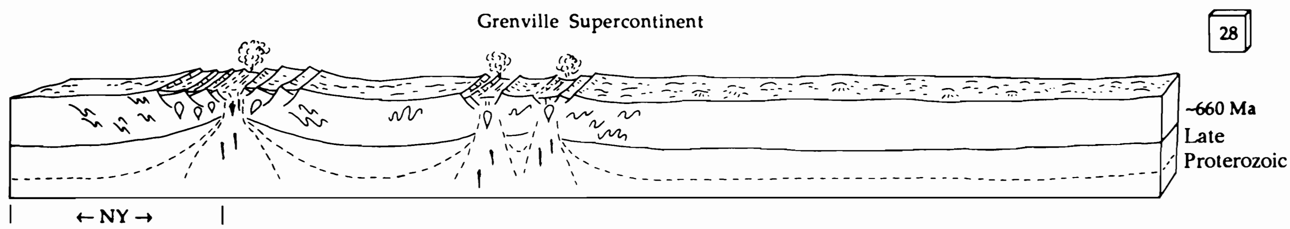
Continued Doming and Initial Rifting



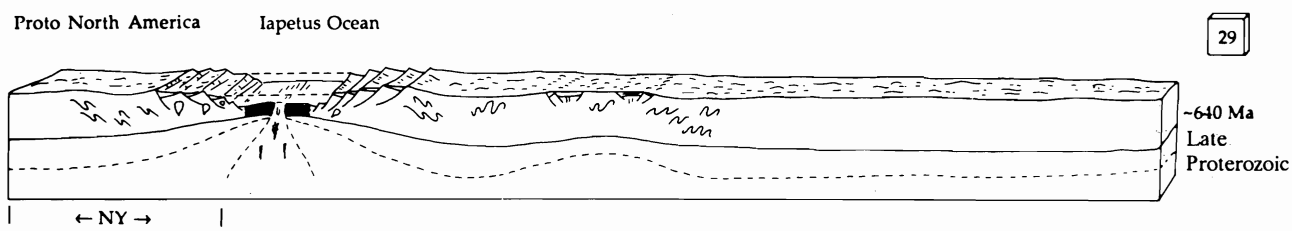
Initial Rifting



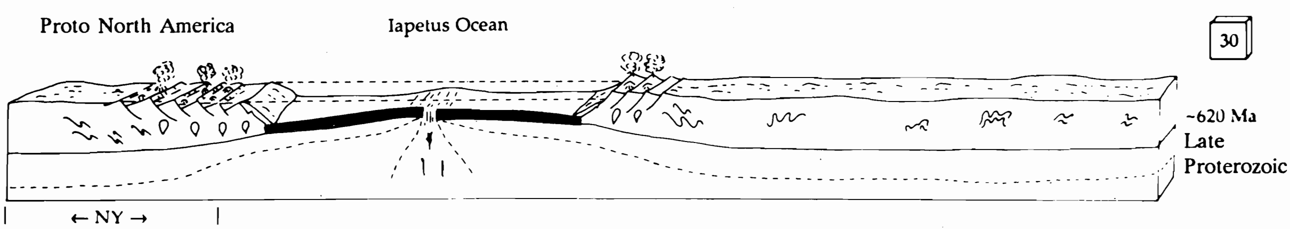
Rifting and Volcanism



Continued Rifting and Volcanism

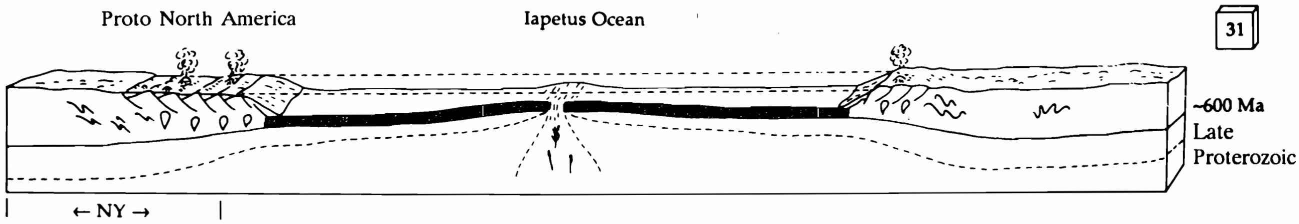


Rifting and Initial Opening of Iapetus Ocean

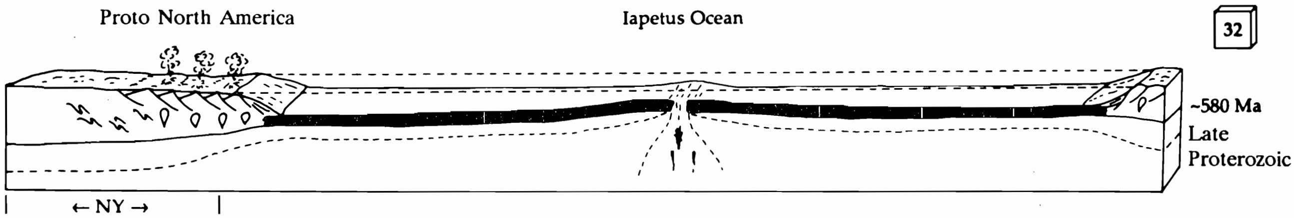


Continued Rifting and Opening of Iapetus Ocean

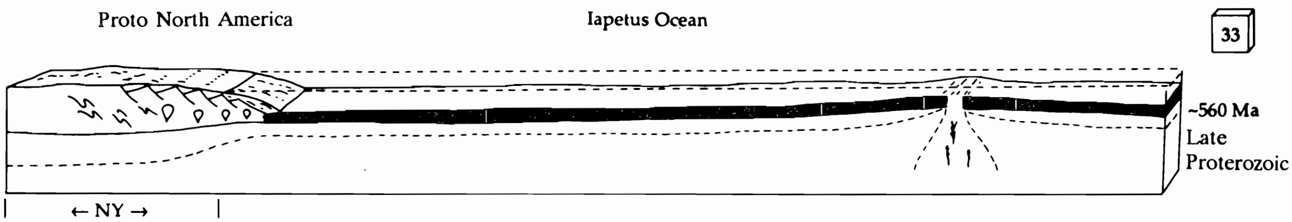
Figure A.4 continued



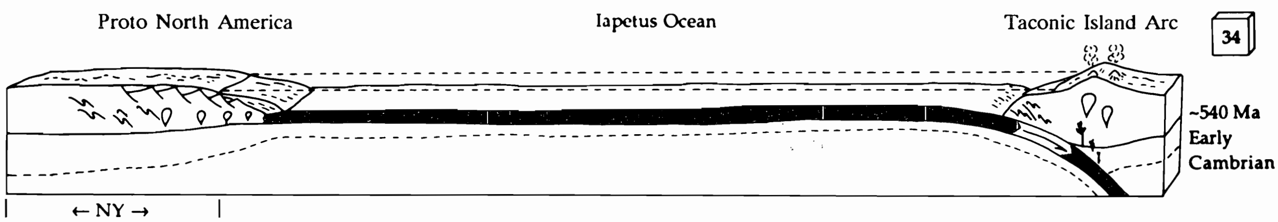
Continued Opening of Iapetus Ocean



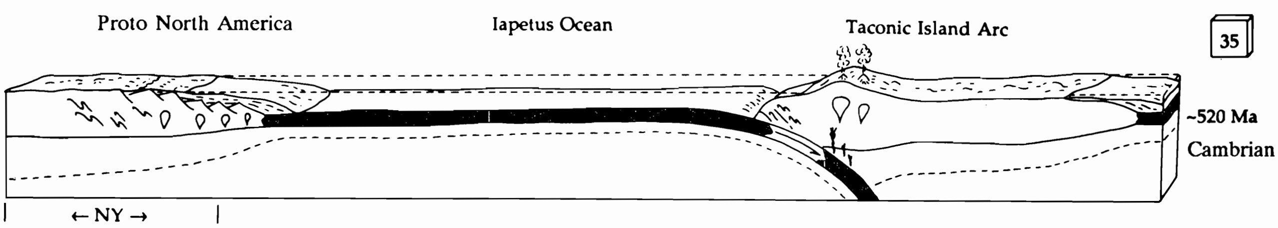
Continued Opening of Iapetus Ocean



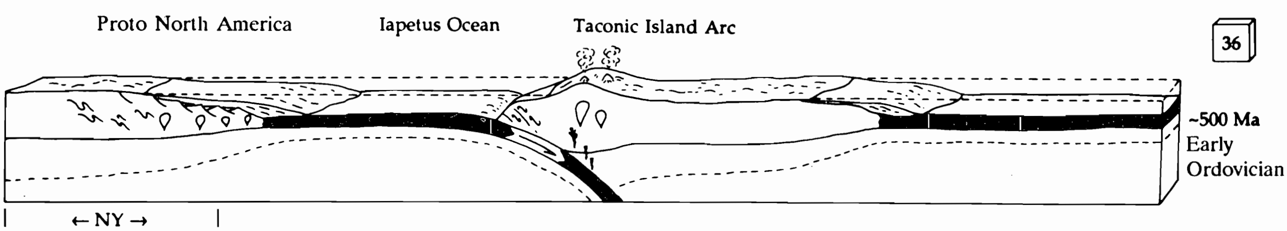
Development of Passive Margin on Proto North America



Initial Subduction of Iapetus Ocean Crust under Taconic Island Arc

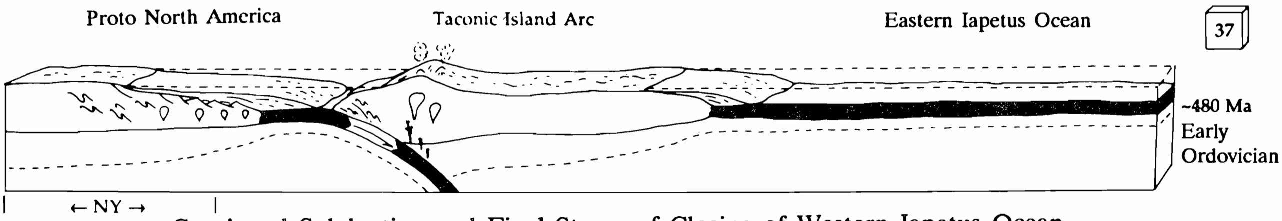


Continued Subduction and Initial Stages of Closing of Iapetus Ocean

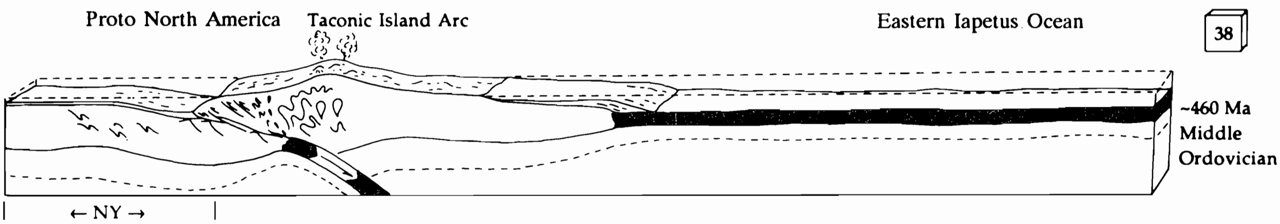


Continued Subduction

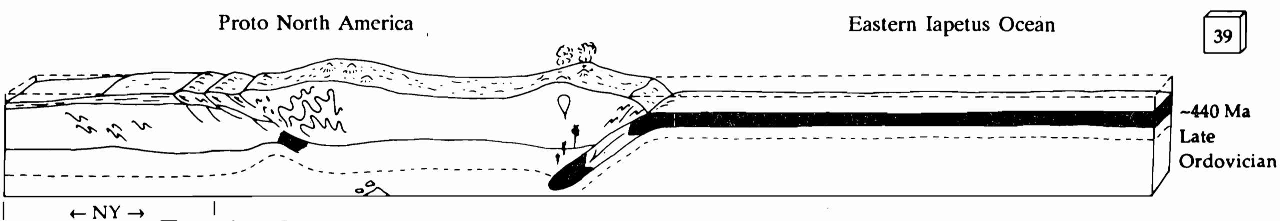
Figure A.4 continued



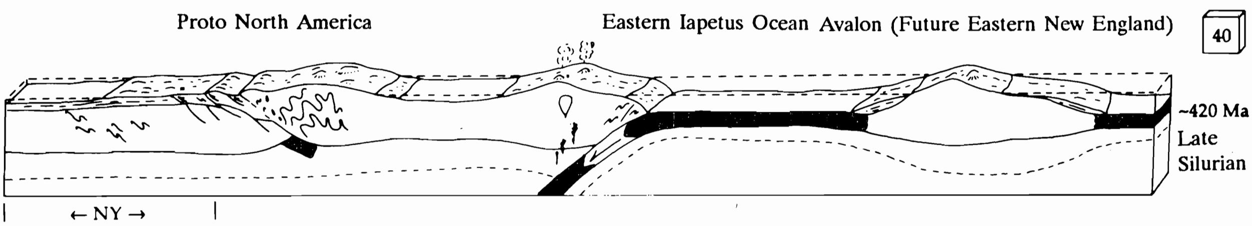
Continued Subduction and Final Stages of Closing of Western Iapetus Ocean



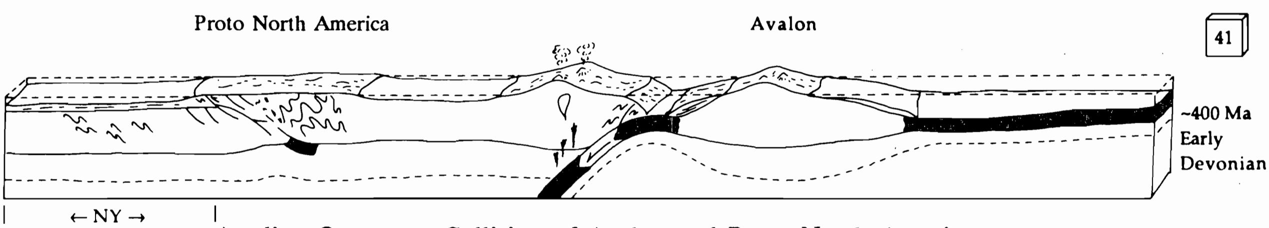
Taconian Orogeny - Collision of Island Arc and Proto North America



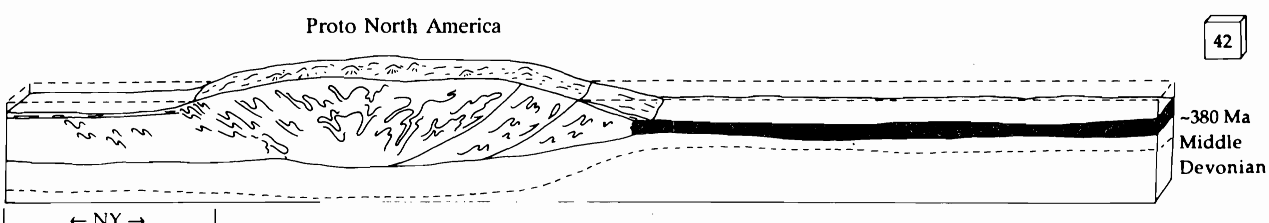
Taconian Orogeny and Renewed Subduction Under Enlarged Proto North America



Erosion of Taconic Mountains and Continued Subduction

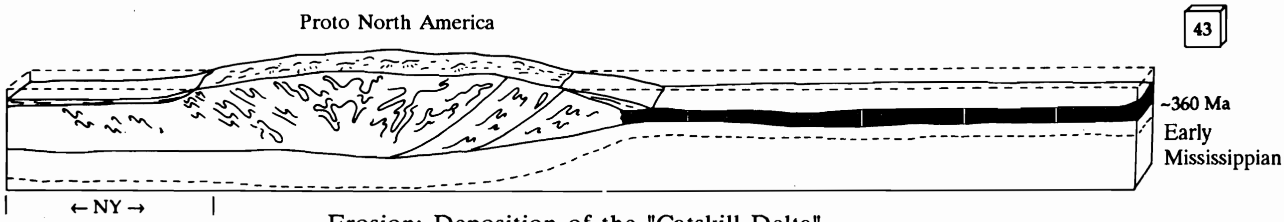


Acadian Orogeny - Collision of Avalon and Proto North America

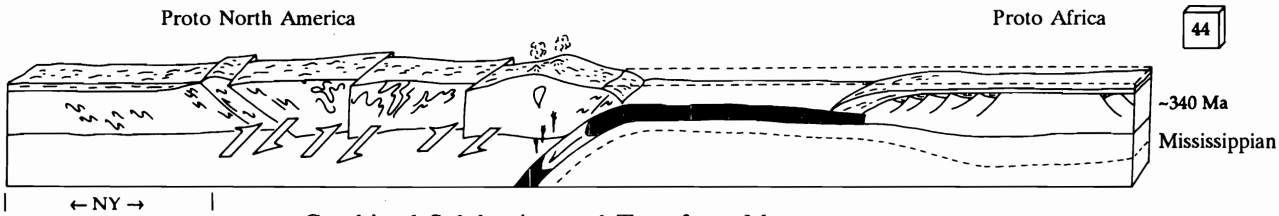


Continuing Acadian Orogeny and Erosion of Acadian Mountains

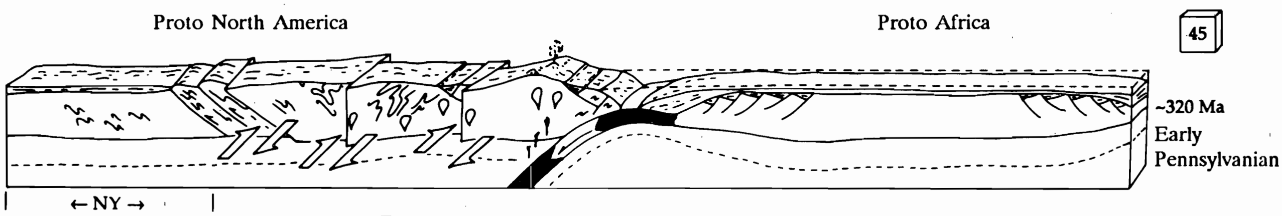
Figure A.4 continued



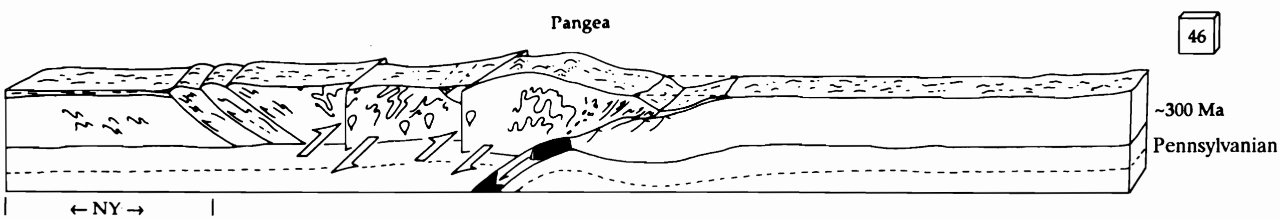
Erosion; Deposition of the "Catskill Delta"



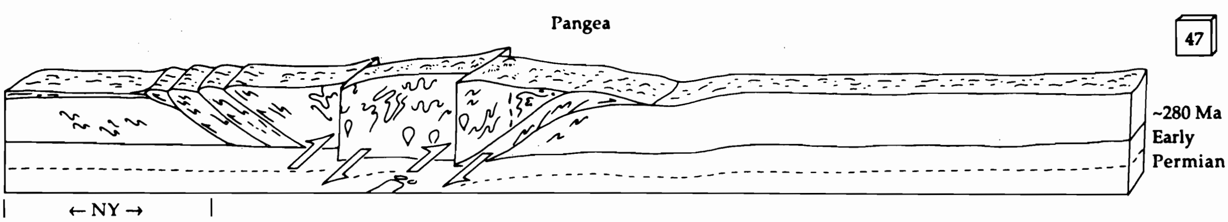
Combined Subduction and Transform Movement



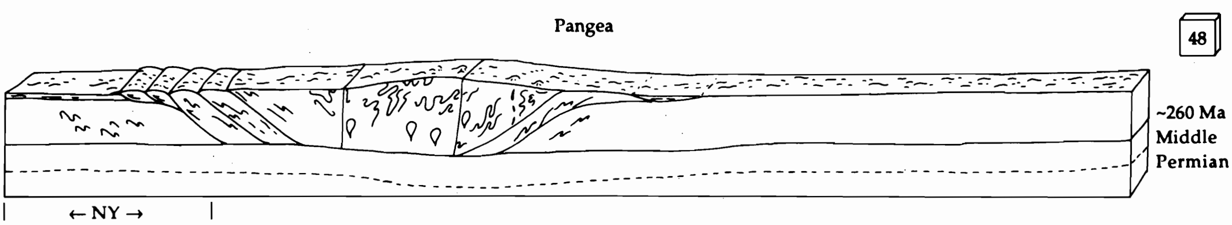
Beginning of Alleghanian Orogeny



Continued Alleghanian Orogeny - Formation of Supercontinent Pangea

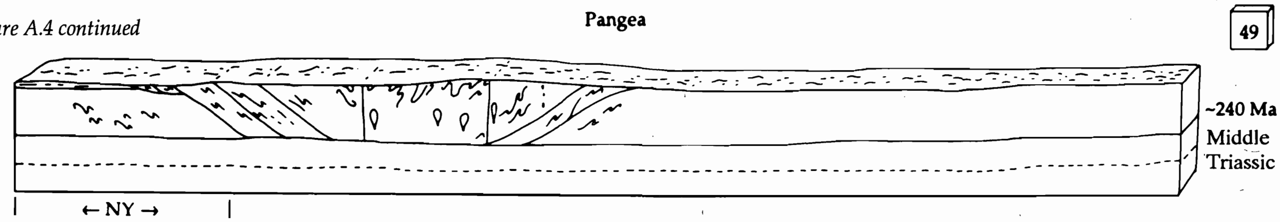


Continued Alleghanian Orogeny

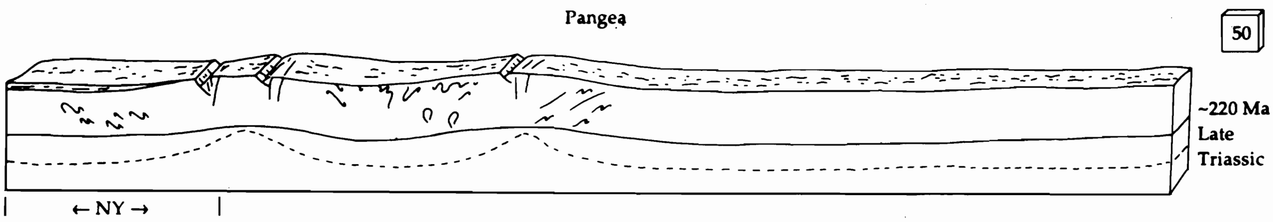


Erosion of Alleghanian Mountains

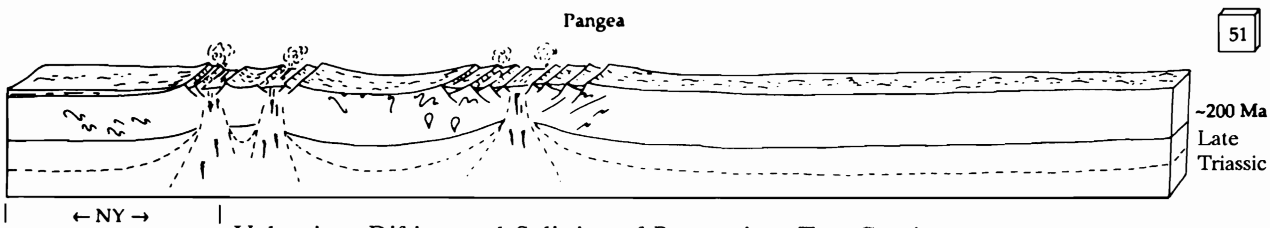
Figure A.4 continued



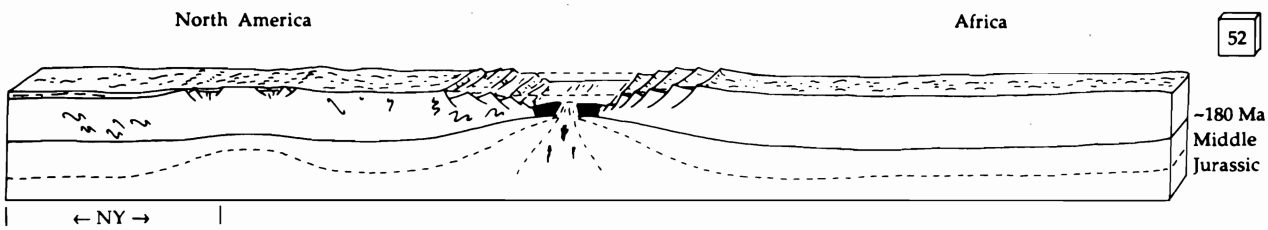
Continued Erosion



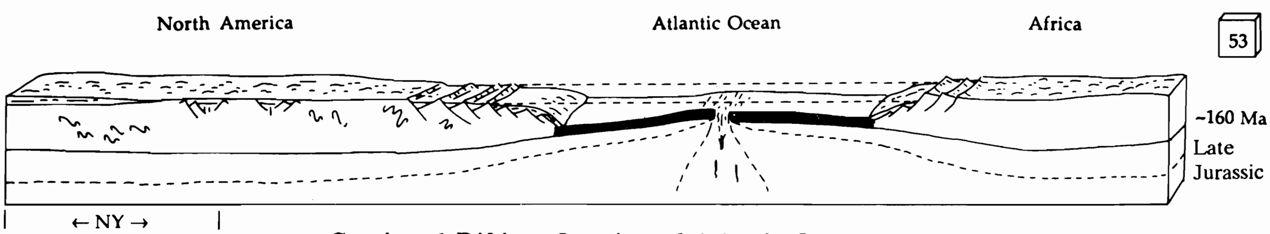
Doming and Initial Rifting



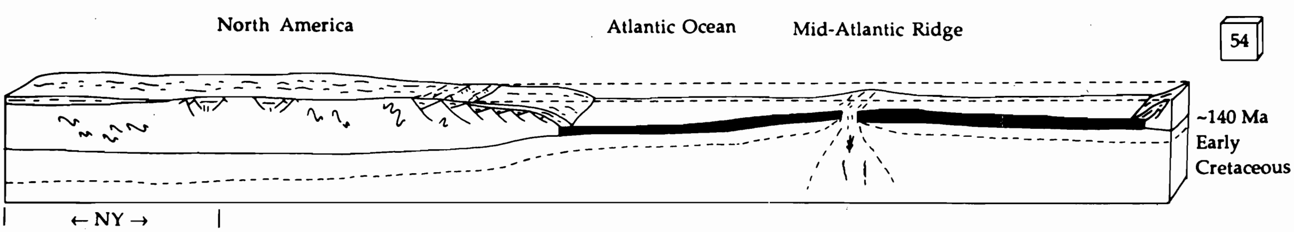
Volcanism, Rifting, and Splitting of Pangea into Two Continents



Continued Rifting

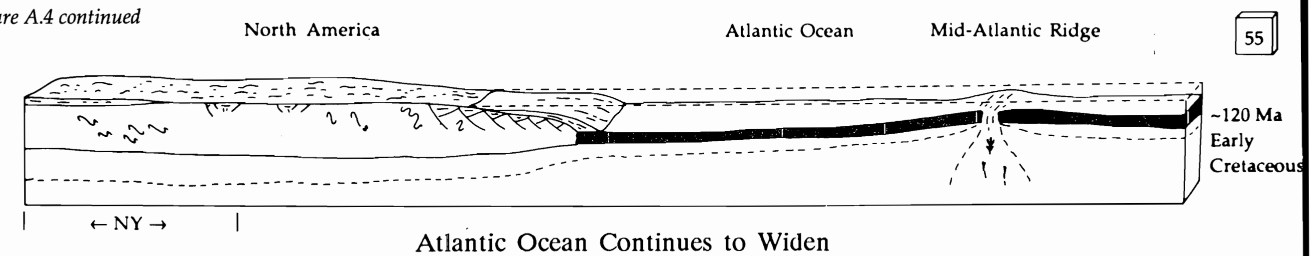


Continued Rifting; Opening of Atlantic Ocean

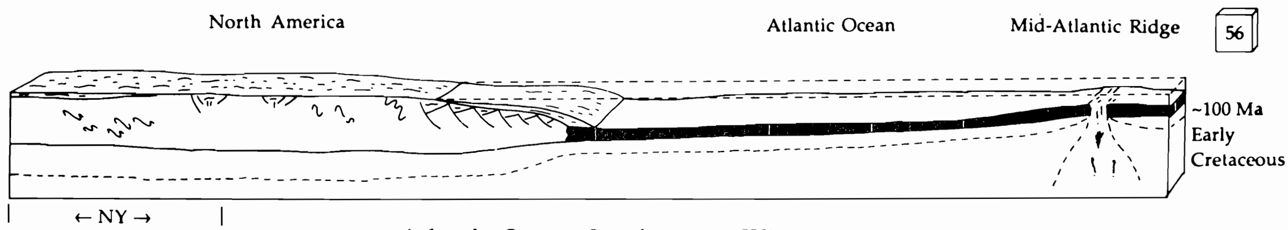


Passive Margin Develops

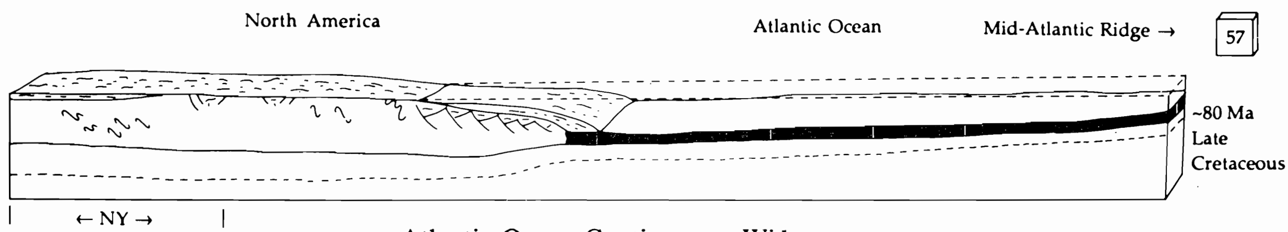
Figure A.4 continued



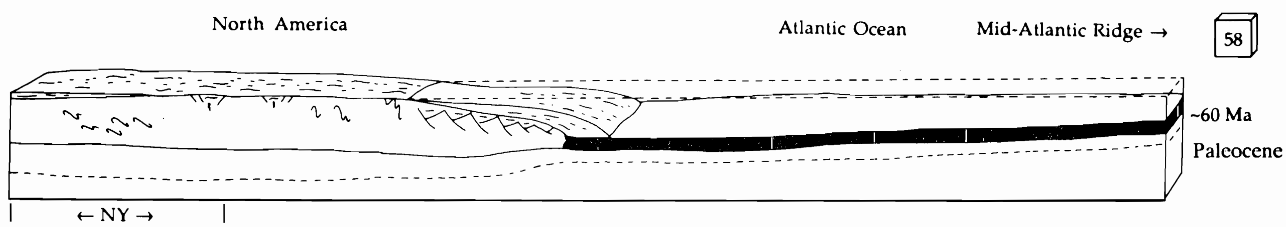
Atlantic Ocean Continues to Widen



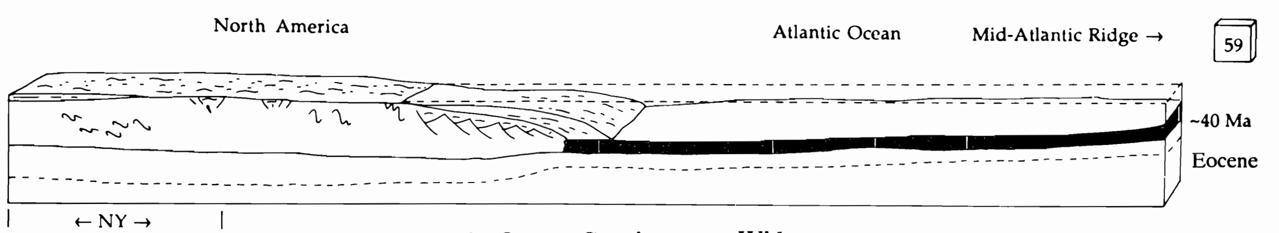
Atlantic Ocean Continues to Widen



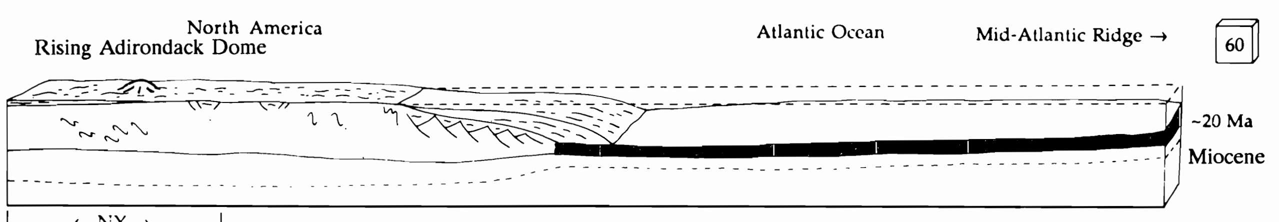
Atlantic Ocean Continues to Widen



Atlantic Ocean Continues to Widen

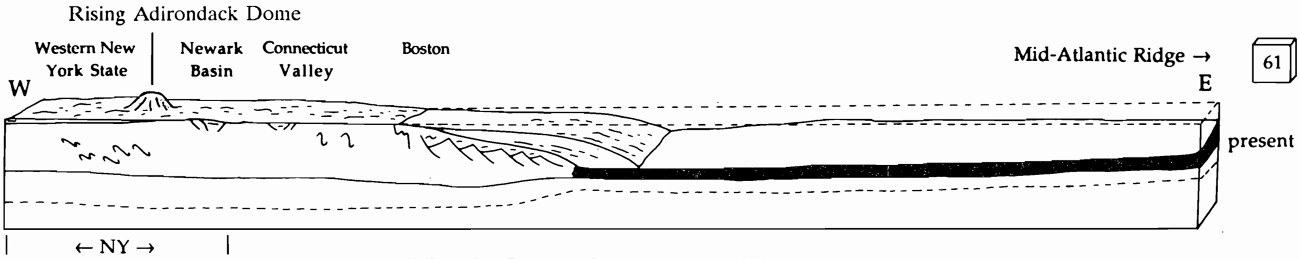


Atlantic Ocean Continues to Widen



Atlantic Ocean Continues to Widen

Figure A.4 continued



Atlantic Ocean Continues to Widen

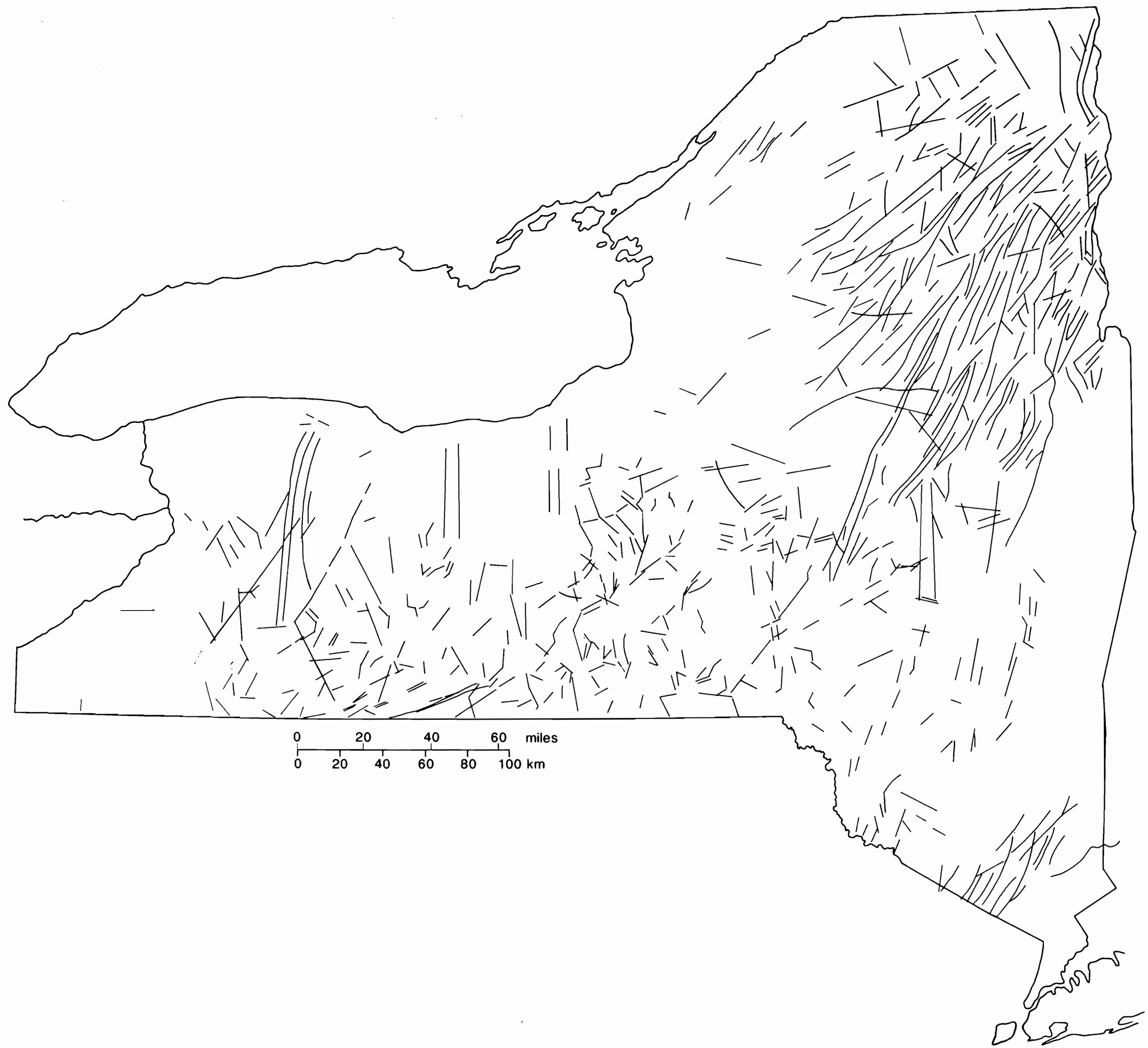


Figure A.5. Simplified map of brittle deformation in New York State.

TABLE A.1

THE FOLLOWING STATEWIDE MAPS ARE AVAILABLE FROM THE NEW YORK STATE GEOLOGICAL SURVEY.

GEOLOGIC MAP OF NEW YORK STATE,
by D.W. Fisher, Y.W. Isachsen, and L.V. Rickard, 1970.

Consists of six sheets in four colors: Niagara, Finger Lakes, Hudson-Mohawk, Adirondack, Lower Hudson, and Master Legend. (Hudson-Mohawk sheet is out of print.) 1:250,000. Master legend sheet contains index to all quadrangle geologic maps, published and unpublished.

BRITTLE STRUCTURES MAP OF NEW YORK, BY Y.W. ISACHSEN AND W. MCKENDREE, 1977.
Preliminary brittle structures map of New York State.

In two colors. Consists of four sheets at 1:250,000 (Niagara-Finger Lakes, Hudson-Mohawk, Adirondack, and Lower Hudson), one sheet at 1:500,000, a sources of information map, and a generalized map of recorded joint systems in New York at 1:1,000,000.

SIMPLE BOUGUER GRAVITY ANOMALY MAPS OF NEW YORK,
by F.A. Ravetta and William Diment.

Consists of four black-and-white maps at 1:250,000, as follows: Western New York (Finger Lakes Sheet)—1971; Northern New York (Adirondack Sheet)—1973; East-Central New York (Hudson-Mohawk Sheet)—1973; Southeastern New York (Lower Hudson Sheet)—1973.

BOUGUER GRAVITY MAP OF NORTHEASTERN UNITED STATES AND SOUTHEASTERN CANADA, ONSHORE AND OFFSHORE,
by C.T. Hildreth, 1979.

Includes two sheets, western and eastern, at 1:1,000,000.

SURFICIAL DEPOSITS MAP OF NEW YORK,
by D.H. Cadwell and others.

Consists of five sheets in four colors, 1:250,000. Four sheets have been published, as follows: Finger Lakes Sheet—1986; Hudson-Mohawk Sheet—1987; Niagara Sheet, 1988; Lower Hudson Sheet—1989. Publication of Adirondack Sheet projected for 1991.

AEROMAGNETIC MAPS.

U.S. Geological Survey Maps 927 and 928. 1:1,000,000. Four colors.
U.S. Geological Survey Map GP-943. Covers the northeastern United States at 1:2,000,000. Black and white.
U.S. Geological Survey Map GP-938. Five sheets at 1:250,000. Black and white.

EPICENTER MAP OF NORTHEASTERN UNITED STATES AND SOUTHEASTERN CANADA, ONSHORE AND OFFSHORE,

G.N. Nottis, editor, 1983.

Table A.2

About Measurements

In this book, we use the metric system. In case you are not familiar with this system of measurement, this chart gives you approximate English system equivalents for common metric units used in this book.

1 centimeter (cm)	=	.39 inches
1 meter (m)	=	1.09 yards
1 kilometer (km)	=	.62 miles
1 square kilometer (km^2)	=	.39 square miles

To convert temperature in degrees Celsius (°C) to degrees Fahrenheit (°F), use this formula:

$$^9/_5(\text{temperature in °C}) + 32 = \text{temperature in °F}$$

Say What?

Glossary of Technical Terms[1]

abrasives Gritty materials used for grinding, polishing, or cutting. They are also used in common household products like sandpaper, fingernail files, and nonslip surfaces for floors and stairs.

Acadian Mountains The mountains built by the Acadian Orogeny.

Acadian Orogeny A mountain-building event that happened about 410 to 380 million years ago, when the eastern part of the Iapetus Ocean closed and the small continent of Avalon was attached to proto-North America.

"Acadian Plateau" The high plateau that formed behind the mountains built by the Acadian Orogeny.

acid rain Rain that is so acidic that it damages the environment; caused by pollution from industry and automobiles.

accretion The addition of new crust to a continent.

accretionary prism A wedge-shaped pile of contorted rocks and sediments that are scraped off the down-going plate and added to the edge of the overriding plate during subduction.

adjacent Next to.

aeromagnetic map A map of the earth's magnetic field made with a special instrument carried in an airplane.

aftershock An earthquake that occurs after a larger earthquake and originates at approximately the same place.

Age of Fishes An informal name for the Devonian Period, when fish thrived in the world's oceans.

aggregate One of the ingredients that, together with cement, makes up concrete. Gravel and crushed stone are both used as concrete aggregate.

agnostid A kind of small trilobite with head and tail almost alike; one group of agnostids lacked eyes.

Alleghanian Orogeny A mountain-building event that happened about 330 to 250 million years ago, when the continents of proto-North America and proto-Africa collided along a transform margin.

alluvial fan A large fan-shaped deposit of coarse sediments made by a stream at the foot of a steep slope.

alluvial plain A flat land surface formed from deposits made by a river.

alluvial sediments Sediments deposited by a stream or flowing water.

alumina Aluminum oxide (chemical composition Al_2O_3). It is found naturally as the mineral corundum.

ammonoid An extinct kind of shelled cephalopod; important in determining the age of sedimentary rocks.

amphibian A cold-blooded vertebrate that is able to live both on the land and in the water.

amphibolite A dark-colored metamorphic rock composed of the minerals amphibole and plagioclase.

amplitude The height of vibration of a wave.

ancestral Adjective describing a feature that existed in the past.

anhydrite A light colored mineral found in evaporite deposits. Its chemical composition is $CaSO_4$.

anorthosite An igneous rock composed almost entirely of the mineral plagioclase.

anthracite grade The metamorphic grade that produces the highest quality of coal.

anthraxolite A black substance similar to hard asphalt found in veins in sedimentary rocks.

[1]By J.M. Lauber and T.D. Mock.

anticlinal trend The map direction of the long axis of an anticline.

anticline A fold in rock that is convex upward.

anticlinorium A large anticline.

Appalachian Basement Rock in eastern New York that lies below younger rock that was deformed during the formation of the Appalachian Mountains.

Appalachian Basin A basin that held a shallow inland sea during most of the Paleozoic Era. Many of the sedimentary rocks exposed in New York State were deposited in the Appalachian Basin.

Appalachian mountain-building episodes The Taconian, Acadian, and Alleghanian Orogenies.

Appalachian Upland An area of high elevation in the Appalachian Mountains.

aqueduct A structure that carries a large quantity of flowing water.

aquifer An underground body of saturated rock or sediment that is both porous and permeable enough to provide useable quantities of water.

archaeocyathans Sponge-like creatures that built reefs in the Early to Middle Cambrian seas. Note: *Archaeocyathans* is the plural of *archaeocyathid.*

Archean Adjective referring to the oldest part of geologic time, from the formation of the earth up to 2.5 billion years ago.

arctic climate A very cold climate found north of the arctic circle.

arête A sharp ridge in rugged mountains, formed by glacial erosion.

arkose A sandstone rich in the mineral feldspar, commonly pink or red in color.

arkosic sandstone A coarse-grained sandstone rich in the mineral feldspar.

arthropod An invertebrate animal with a jointed body and limbs, usually with a hard covering. Insects, spiders, lobsters, crabs, barnacles, and the extinct trilobites are all arthropods.

asthenosphere A soft, flowing layer of the upper mantle; it lies under the lithosphere.

at depth Deep below the earth's surface.

Atlantic Coastal Plain The low, wide plain along the east coast of North America.

attached echinoderms An echinoderm that grows attached to the sea bottom.

Avalon A small continent that was attached to proto-North America during the Acadian Orogeny.

axes The plural of *axis*. An axis is a straight line that divides a shape into two symmetrical halves.

Baltimore Canyon Trough A large buried basin on the continental shelf south of Long Island.

bar A bank made of sand or other sediments, at least partly underwater, along the shore or in a river.

barrier island A long, narrow, sandy island, built by waves near a beach.

barrier shoal An underwater sandbank or sand bar roughly parallel to the shoreline.

basalt A dark-colored, dense rock formed from molten rock. Oceanic crust is made of basalt.

basalt flow Basalt formed from molten rock that flowed out onto the surface of the earth and hardened.

basaltic lava Molten rock that flows out onto the earth's surface, where it cools and hardens to become basalt.

basaltic volcanism Volcanic activity that produces basaltic lava.

Basement Hinge Zone The zone in an offshore sedimentary basin where the depth of the basement increases rapidly.

basement rock The deeply eroded metamorphic bedrock that is usually covered by younger sedimentary rocks.

basin A depression or low area that holds (or once held) a lake, sea, or ocean.

Bass Island Structural Trend A complex anticline found below the earth's surface in western New York. It is a structural trap that contains oil and natural gas.

beach ridge A long sandy mound on a beach, beyond the reach of storm waves or high tide. It was built by waves and currents when the water level was higher.

bed A layer of rock, usually sedimentary rock.

bedding Layers in sedimentary rock.

bedding plane The flat to undulating surface that physically separates layers of sedimentary rock.

bedding surface A surface within a layered sedimentary rock that represents the original surface where sediments were deposited.

bedrock The solid rock that lies under the soil.

bedrock geology The solid rock of the earth's crust exposed at the surface of the earth; also, the study of that rock. It may be covered by surficial geology.

benchmark A mark on a permanent object indicating elevation; used as a reference in topographic mapping.

bentonite A clay-rich rock that is made from volcanic ash.

biotite A dark brown to black mineral found in both igneous and metamorphic rocks.

bioturbation Churning and stirring of sediment by living things.

birdseye A cavity in limestone or dolostone filled with the mineral calcite or dolomite.

bison Buffalo.

bivalve mollusk An invertebrate animal with a soft body and a shell made up of two parts.

black mica A dark-colored mineral of the mica group, usually biotite.

blast furnace The type of furnace used to refine iron ore.

blastoid A kind of stalked echinoderm.

blind thrust Thrust fault in rocks below the surface of the earth, where it can't be seen.

block diagram A diagram that shows three dimensions; for example, geologic cross sections (as in Figure A.4) that also include drawings of the land surface.

bluestone A fine-grained kind of graywacke, bluish gray to olive green in color. It splits easily into thin slabs and is used for building and paving stone.

bluff A high, steep bank or cliff.

body fossil Fossils that represent the mineralized or organic internal or external skeleton of organisms or the impression of the form of the organism. Shells, bones, petrified wood, leaves, and body impressions are types of body fossils.

bog Wet, spongy ground, frequently surrounding a body of open water.

brachiopod An invertebrate sea animal with a two-part shell. Brachiopods have existed from the Cambrian Period to the present and are an important fossil in the correlation of marine sedimentary rocks.

brackish water Water that is somewhat salty.

braided streams Streams that divide into a number of smaller channels that reunite farther downstream.

breccia A rock made of sharp-edged pieces of other rocks that have been cemented together.

brine Water with a high amount of dissolved salts.

brittle deformation The breaking of rock by faulting or fracturing. Brittle deformation takes place in rock at or near the surface of the earth.

brittle structure A break in rock caused by faulting, fracturing, or jointing.

bryozoan An invertebrate sea animal that lives in permanently attached colonies.

buoyant Adjective referring to crust that is lighter than the surrounding crust.

calcareous Composed partly or completely of calcium carbonate. Used to describe sediments, rock, or shells of organisms.

calcareous nodules Lumps of limestone that form within sediments.

calcite A white to colorless mineral (chemical composition $CaCO_3$). One of the two carbonate minerals; the other is dolomite.

calcitic Containing the mineral calcite.

calcium carbonate A substance (chemical composition $CaCO_3$) found in the mineral calcite and in animal bones and shells.

calcsilicate rock A metamorphic rock formed from impure limestone or dolostone.

"Cameron's Line" A major geologic boundary in southeastern New York and New England. It separates rocks formed as part of North America from rocks formed elsewhere.

Canadian Shield The large area of eastern Canada where the oldest rocks in North America are exposed at the surface.

caprock A hard rock layer, usually sandstone or carbonate, that forms the top of a cliff. Also refers to an impermeable rock layer that traps oil or natural gas in the permeable rock layer below it.

carbon-14 A naturally occurring radioactive isotope of the chemical element carbon.

carbonate environment An environment in which carbonate rock is deposited.

carbonate minerals The minerals calcite and dolomite.

carbonate rock Sedimentary rock (like limestone, dolostone, and marble) that was originally formed from sediments rich in carbonate minerals.

carbonate sediments Sediments rich in calcium carbonate.

carbonate sequence Strata of carbonate rock.

carbonate shelf A flat, shallow area where carbonate rock is deposited.

caribou A kind of large deer related to the reindeer.

carnivorous Meat-eating.

Carthage-Colton Mylonite Zone A narrow zone of intensely deformed rocks in the Adirondack region; it separates the Northwest Lowlands from the Central Highlands.

cascade A small waterfall, especially one in a series.

casts of grooves, tracks, trails, and flutes Bulges formed on the bottom of a sedimentary layer when the sediment fills in various kinds of depressions in the underlying layer.

"Catskill Delta" A huge wedge of sedimentary rock formed in eastern proto-North America during Devonian time. The sediments of the "Catskill Delta" were eroded and transported westward from the mountains built during the Acadian Orogeny.

cementation The process by which loose sediments become consolidated into hard rocks.

Central Highlands The largest part of the Adirondack region; includes the High Peaks region.

cephalopod A group of marine animals that have well-defined heads. Includes squid, octopus, ammonoids, and nautiloids.

Champlain Sea The sea that formed when marine water flooded parts of the St. Lawrence and Champlain valleys after the last Pleistocene ice sheet had retreated from the region.

chain coral A kind of coral that grows in a branching, chain-like form.

channelization Straightening of stream channels to reduce flooding upstream.

charnockite An igneous rock that is similar in composition to granite but also contains the mineral pyroxene.

chemical composition A description of the chemical elements that make up a substance. It is usually represented by abbreviations for the elements and numbers that show the number of atoms of each element. For example, water has the chemical composition H_2O; this means that a water molecule is made of two atoms of hydrogen and one of oxygen. The abbreviations for elements used in this book include: Ag=silver, Al=aluminum, C=carbon, Ca=calcium, Cl=chlorine, Fe=iron, H=hydrogen, K=potassium, Mg=magnesium, Na=sodium, Ni=nickel, O=oxygen, Pb=lead, S=sulfur, Si=silicon, Ti=titanium, Zn=zinc.

chemical element A substance that consists of only one kind of atom.

chemical weathering The breakdown of rock by chemical action.

chert A hard, dense sedimentary rock made of microcrystalline quartz. Flint and jasper are varieties of chert.

chlorite A green-colored mineral found in many metamorphic rocks.

"Christmas tree" Informal name for the complex structure of valves, pipes, and gauges on top of an oil or gas well.

chromite An unusual brown-black to black mineral; it is the major ore of chromium.

cirque A large bowl-shaped area dug out of bedrock at the head of a mountain glacier.

Clarendon-Linden structure A prominent structure on the Allegheny Plateau. At the surface, it is a north-south-trending fold. Below the surface, it is a fault zone made up of three or more separate faults.

clast An individual grain or piece of a larger rock mass that has been broken apart by weathering.

cleavage The surface along which a rock or mineral tends to break.

coastal plain A gently sloping plain at the edge of a continent.

cobble A rock fragment bigger than a pebble and smaller than a boulder.

Coelophysis A meat-eating dinosaur. Its footprints have been found in the Newark Lowlands of New York State.

commercial quantity The amount of a mineral resource needed to make it profitable to use or produce the resource.

commodity A product of mining or agriculture that can be sold for profit.

compaction The reduction in volume of a sedimentary rock due to the weight of the overlying sediment.

composition The minerals a rock is made of.

compression Pushing together.

concrete A building material made of an *aggregate* (for example, gravel or crushed stone) and a cement that holds the aggregate together.

concretion General term for a hard, dense mass made of calcite, pyrite, silica, or other minerals that forms within sediments or sedimentary rock.

conglomerate A coarse-grained sedimentary rock with large rounded pebbles or boulders surrounded by finer grained sediments.

conodont An extinct swimming animal known only from small, tooth-shaped fossils. Conodont fossils are important in determining the age of Paleozoic-age sedimentary rocks.

contact The surface between two different types or ages of rock.

continent-continent collision A convergent margin at which continental crust collides with continental crust.

continental crust Thick and relatively light crust that floats high on the asthenosphere and commonly forms land.

continental glacier A thick ice sheet that covers a large area.

continental ice sheet A large glacier that forms on relatively flat land and flows out from its center.

continental rise The relatively smooth, gently sloping offshore area between the continental slope and the deep ocean floor.

continental shelf The gently sloping (less than 1°) edge of a continent that extends into the ocean as a relatively shallow underwater platform.

continental slope The steeper (3° to 6°) underwater area between the continental shelf and the continental rise.

contour Contour line.

contour line A line on a topographic map connecting points of the same elevation.

convection cells A system of convection currents in the earth's mantle where hotter material slowly rises and cooler material sinks.

convection currents The circular motion within a fluid created when warmer, less dense material rises and cooler, more dense material sinks.

convergent margin The boundary between two tectonic plates that are being pushed together.

converging Moving closer together at a convergent margin.

convoluted bedding Very thin crumpled or folded sedimentary layers that occur within a bed that is otherwise undisturbed.

cordierite A blue-colored mineral found in some metamorphic rocks.

core The center part of the earth; it is divided into a solid inner core and a liquid outer core.

corona A ring of minerals that surrounds another mineral or minerals.

correlate To match up two rock units as being of the same age.

correlation chart A diagram that shows the sedimentary rocks that are present in one or more regions, their general arrangement, and their ages. The columns on the chart represent geographic areas; older rocks are shown at the bottom and younger rocks at the top of a column. The legend on Plate 3 of the *Geological Highway Map* is an example of a correlation chart.

Cortlandt Complex A large body of mafic rock found in Westchester County in southeastern New York.

craton The oldest and most stable part of a continent.

crinoid A kind of marine invertebrate that grows fastened by a stem to a firm surface, usually the sea floor. Also called *sea lily*.

crinoid columnals One of many disk-shaped pieces that make up the stem of a crinoid.

crop out To appear at the earth's surface; applies to a geologic formation.

cross-bedding Thin, inclined sedimentary layers deposited by wind or water currents (see Figure 7.1).

cross-lamination Cross-bedding.

cross section A drawing of what something would look like if it were sliced through the middle.

crust The thin, solid shell of rock that forms the outermost layer of the earth.

crustacean A type of arthropod. Most are marine. Some modern examples are lobsters, shrimp, and barnacles.

crustal blocks Blocks of crust.

crustal rupture The breaking of the crust into two or more pieces at a particular place.

crustal shortening The making shorter of sections of the earth's crust by folding, thrust faulting, and layer-parallel shortening.

crustal stretching Stretching of the crust.

crystalline Composed of large individual mineral grains; refers to an igneous or metamorphic rock.

crystallize To form crystals; refers to igneous rock solidifying from magma by the formation of mineral crystals.

cyanobacteria Blue-green algae.

cystoid An extinct marine invertebrate that grew fastened by a stem a firm surface, usually the sea floor.

daughter An isotope that is produced when a radioactive isotope (the parent) decays.

dècollement A horizontal fault along which much movement has occurred.

deforestation Large-scale cutting down or clearing away of forests.

deformation The folding and faulting of rock by geologic forces.

deformed fossils Fossils whose original shape was changed when the rock that contains them was deformed.

delta A fan-shaped low-lying area formed by sediments deposited at the mouth of a river.

density current An underwater current that contains a large amount of sediment in suspension.

deposit Earth material, such as sediment, laid down by water, ice, or wind.

deposition The process of depositing sediments.

depositional environment The place in which sediment was deposited, such as a lake, an ocean, a stream, a beach, or land.

depositional landform A feature of the earth's surface formed by sediments deposited by a glacier, stream, or wind.

depress To press down or cause to sink.

derrick A tower built over an oil or natural gas well.

dew point The temperature at which water vapor in the air begins to condense into a liquid.

dewatering The removal of water.

diabase A kind of intrusive igneous rock primarily made up of the minerals plagioclase and pyroxene.

diabase feeder Source of magma of diabase composition that reached the earth's surface.

digitize To represent something (for example, data) by number values.

dike A mass of igneous rock formed when molten rock is pushed up into overlying rocks, cutting across the preexisting layers.

dip To slope downward; or, the amount of downward slope in degrees.

dire wolf A large wolf that lived in Pleistocene North America.

divergent margin The boundary between two tectonic plates that are being pulled apart; new crust is formed at a divergent margin.

dolomite A light-colored mineral (chemical composition $(Ca,Mg)(CO_3)_2$). One of the two carbonate minerals; the other is calcite.

dolomitic Containing the mineral dolomite.

dolostone A carbonate rock primarily made of the mineral dolomite.

domal Dome-shaped.

down-dropped Said of the side of a fault that has moved downward.

downfaulted Adjective referring to a crustal block that has moved downward along a high-angle fault.

downwarping A slight bending downwards of a large area of the earth's crust.

downwind In the direction that the wind blows.

drainage The rivers, streams, and lakes of a region.

drainage basin An area in which all of the water that falls as precipitation eventually drains into one main stream.

drainage divide The border of a drainage basin. Streams do not flow across drainage divides.

drainage pattern The map pattern made by streams and rivers flowing across a region.

drape folds Long, low, wave-like folds that form in weak rocks such as shale when the underlying rocks are faulted.

drift Glacial drift.

drill hole test The drilling of a hole in the earth's surface to determine what rocks or sediments lie beneath the surface.

drumlin A long, low, cigar-shaped hill made of glacial till.

ductile deformation The deforming of rocks by flowing instead of breaking, for example by folding. Occurs at high temperatures and pressures far below the earth's surface.

ductile normal fault A normal fault where the rock has deformed by flowing rather than by breaking.

ductile shear The deformation caused by two blocks of rock sliding past one another deep below the earth's surface.

ductile shear zone The area of intensely deformed rocks along which ductile shear has taken place.

dune A hill or ridge of sand piled up by the wind.

earthquake hazard The chance that an earthquake of a given size will happen at a particular place within a certain period of time.

earthquake risk The chance that people will be killed or hurt or property will be damaged by an earthquake.

East Coast Boundary Fault The boundary along the east coast of the United States between highly thinned continental crust and crust that is part continental and part oceanic.

echinoderm An invertebrate sea animal. Echinoderms include modern-day crinoids, starfish, and sea urchins and their ancient relatives.

elevation Height above sea level.

elk A kind of large deer.

elliptical Having the shape of a circle that has been stretched in one direction.

emergent Above sea level.

emery A metamorphic rock primarily made of the minerals corundum and magnetite. It is an extremely hard abrasive used for grinding and polishing.

end moraine A moraine that marks the farthest advance of an ice sheet.

engineering geology The study of how rocks and other earth materials are used in and affected by construction.

English system A system of weights and measures based on the foot and the pound.

epicenter The point on the earth's surface directly above the *hypocenter*, or underground source of an earthquake.

erosion The wearing away of rock, sediment, or soil by water, wind, or glacial ice.

erosion surface A land surface shaped by erosion.

erratic A boulder transported from its place of origin by a glacier and left when the ice melts.

escarpment A long, continuous cliff.

esker A long, narrow ridge formed from deposits of a meltwater stream flowing beneath a glacier.

estuary The part of a stream or river affected by ocean tides.

eurypterid A large sea scorpion that lived in the salty seas of the Silurian Period. The eurypterid is the New York State fossil.

evaporite A sedimentary rock that forms in shallow, salty water as the water evaporates. Rock salt, gypsum, and anhydrite are all evaporites.

exotic Adjective referring to a rock or body of rock that has been moved far from its place of origin by one of several possible processes.

exposure A place where rock or sediment can be seen at the earth's surface.

extrusion A volcanic rock.

facies The kinds of rock, sedimentary structures, and fossils found in a particular sedimentary rock unit that indicate what the depositional environment was like.

fall zone A narrow area along the boundary between an upland and a lowland. Rivers flowing from the upland to the lowland form waterfalls at the fall zone.

Fall Zone Peneplain A flat eroded rock surface that had developed in New York and surrounding areas by the mid-Jurassic and was later covered by younger sediments.

false color Photographic technique used to show part of the electromagnetic spectrum outside the range of human vision. For example, infrared energy is shown as red on the Landsat image on Plate 1 of the *Geological Highway Map*.

fault A break or fracture in rock along which movement occurs or occurred in the past.

fault block A large piece of the earth's crust that is partially separated from the rest of the crust by a fault or faults.

fault breccia Breccia that contains fragments shattered by movement on a fault.

fault zone A fault that consists of a narrow area of many small fractures.

feather edge The very thin edge of a rock or bed where it thins to zero thickness.

feldspar An important group of minerals that are found in almost all crystalline rocks. Feldspars are made of two mineral series: plagioclase and potassium feldspar (orthoclase).

felsic Composed of light-colored minerals such as quartz and feldspar.

felt earthquake An earthquake large enough to be felt or noticed by people.

fibrous Made up of long, thin, needle-like crystals.

field An area in which a number of wells produce oil or gas from a single rock formation.

field studies Geologic studies that involve studying a region's rocks, sediments, and geologic features where they naturally occur.

fill Soil or loose rock used to raise the surface of the land.

"five-spot" flood pattern A procedure for producing oil in which four wells on the corners of a square are used to inject water, which forces oil to a fifth well in the center.

fjord A long, narrow bay between cliffs. Formed by glacial erosion.

flagging Flagstone.

flagstone Flat stone used for paving.

floodplain A flat area next to a river that tends to flood when the river rises.

flotation separator A device used to purify titanium ore (ilmenite).

fluorite A transparent or translucent mineral.

flute and groove casts Bulges or ridges on the bottom of a sedimentary layer. They form when currents erode a small trough into sediment and then deposit a blanket of sand or silt that fills the groove.

foliation A layer-like structure that forms when a rock is deformed.

foraminifera Microscopic one-celled animals that live in ocean water.

formation A body of rock, usually sedimentary rock, that formed under relatively uniform conditions. Formations are the basic rock unit used for geologic mapping; they may be combined in groups or subdivided into members.

formation contact The boundary between two formations.

fossil hash A sedimentary layer of jumbled and broken animal remains.

fracture A crack or break in rock.

fracture system A group of fractures that have the same orientation.

fracture zone An area where rock has shattered in place but with no motion along the zone.

frequency of recurrence The amount of time that will probably elapse between two geologic events of a certain size, like floods or earthquakes.

Frontenac Arch A narrow zone of Proterozoic rock that connects the Adirondack region and the Grenville Province of southeastern Canada. Its rocks, which resist erosion strongly, form the Thousand Islands in the St. Lawrence River.

gabbro A dark-colored igneous rock made of the minerals plagioclase and pyroxene.

galena A dark gray, dense mineral with chemical composition PbS that is the most important source of lead ore.

garnet A hard, commonly red metamorphic mineral that is used as an abrasive and as gemstones. Garnet is the official mineral of New York State.

garnet gneiss A layered metamorphic rock that contains the mineral garnet.

gas show Evidence that natural gas is present.

gastropod An animal that has a head with eyes and a broad foot. Most gastropods have a single shell. A snail is one example of a gastropod.

geologic cross section A drawing that shows the arrangement of rock as would be seen in a vertical cut through the earth's crust.

geologic map A map that shows the type, distribution, age, and structure of bedrock or surficial deposits in a region.

geologic province A region that has relatively similar bedrock, structure, and geologic history.

geologic time scale An arrangement of geologic events in the order they happened. If the time scale includes actual ages in years, it is called a *quantitative time scale.* If it does not, it is called a *relative time scale.*

geomorphologist A scientist who studies the processes that shape the land surface.

geophysics The branch of earth science that applies physics to the study of geologic structures and processes.

giant beaver An animal of Pleistocene North America, now extinct. It was similar to the modern beaver, but much larger.

glacial debris Glacial drift.

glacial deposit Glacial drift.

glacial drift All rock material transported by a glacier and deposited by the ice or by meltwater.

glacial erosion The erosion accomplished by the moving ice and rock fragments of a glacier and by its meltwater streams.

glacial feature A feature of the landscape created by the action of glaciers.

glacial lake A lake made of the water melting from a glacier.

glacial sediments Glacial drift.

glaciation Covering with a glacier; subjecting to glacial action.

glacier A large mass of compacted ice that lasts the entire year.

glauconite A dull green mineral found in sediments and sedimentary rocks deposited in the ocean. The presence of glauconite suggests that the sediments were deposited slowly.

gneiss A coarse-grained metamorphic rock with a strong foliation.

Gondwana A large continent that existed during the Paleozoic Era. It included the modern continents of Africa and South America.

graben A large block of the earth's crust that has dropped down along faults.

grade Metamorphic grade.

grade into To gradually change into. For example, conglomerate that gradually becomes finer and finer upward in an outcrop until it is sandstone is said to *grade into* sandstone.

granitic gneiss A layered metamorphic rock having the composition of granite.

graphite A dark gray to black mineral found in metamorphic rocks. It is composed entirely of the element carbon.

graptolite An extinct animal that lived in colonies. Graptolite fossils are important in determining the age of sedimentary rocks deposited during the Paleozoic Era.

gravity anomaly A variation in the strength of gravity at the surface of the earth; it is caused a change in the density of the underlying rock.

graywacke A coarse, usually dark gray, clay-rich sandstone or fine-grained conglomerate.

Grenville Basement The older metamorphic rock that underlies most of New York State.

Grenville Orogeny A mountain-building event that happened about 1.1 billion years ago when another continent collided with proto-North America.

"Grenville Plateau" The high plateau that formed behind the mountains built by the Grenville Orogeny.

Grenville Province A large belt of "basement" rock that was metamorphosed and deformed during the Grenville Orogeny about 1.1 billion years ago.

Grenville supercontinent A supercontinent that began to split apart about 660 million years ago.

ground sloth A large, plant-eating mammal, now extinct, that lived in Pleistocene North America. It was related to today's tree sloth.

groundwater Water that is found below the surface of the ground.

gypsum An evaporite mineral with the chemical composition $CaSO_4 \bullet H_2O$. It was produced by the evaporation of very salty shallow seas.

habitat The environment or place where a plant or animal normally lives and grows.

hachures Short, straight lines.

halite Common salt. It is an evaporite mineral with the chemical composition NaCl.

hanging valley The valley of a tributary stream left hanging high above the valley of the main stream that was carved out by a glacier.

hardpan A dense layer of glacial till.

headwaters The source of a stream.

heath hen A kind of grouse, now extinct.

Helderberg Escarpment A cliff southwest of Albany where limestones of the Helderberg Group, which resist erosion, lie on top of more easily eroded sandstone and shale.

hematite A reddish brown mineral with chemical composition Fe_2O_3. It was mined in New York State in the late 19th century for iron ore and was used as a paint pigment.

hematitic limestone Limestone that contains the mineral hematite.

"Herkimer Diamonds" Relatively large quartz crystals that formed in cavities in the Little Falls Dolostone.

high-angle fault A fault that is steeper than 45° with respect to the earth's surface.

highland Elevated or mountainous land.

hogback A ridge with steep slopes on both sides.

honeycomb coral A kind of coral that grows in honeycomb-shaped colonies.

horn coral A horn-shaped coral that does not grow in colonies.

hornblende A dark green to black mineral found in igneous and metamorphic rocks.

horst A long, narrow block of the earth's crust that has been pushed up along faults.

hydrated lime A dry white powder made by treating lime with water.

hydraulic fracturing Pumping water under high pressure into a rock formation to cause it to crack and increase the flow of oil and natural gas through it.

hydroelectric power Electricity produced by means of falling water.

hydrogen sulfide A foul smelling, poisonous gas.

hydrogeology The study of the effect of geology on water at the surface of the earth and underground.

hypocenter The underground source of an earthquake; the place where the rock actually breaks.

Iapetus Ocean An ocean formed by the rifting of the Grenville supercontinent. The Iapetus Ocean lay of the east coast of proto-North America.

Ice Age An informal name for the glaciation during the Pleistocene Epoch; also refers to any time of widespread glaciation.

ice cap A small ice sheet.

ice dam Floating blocks of ice in a river that pile up and partially block the flow of water.

ice front The leading edge or front of a glacier.

ice margin The edge of a glacier.

ice sheet A continental glacier that covers a large area.

iceberg A large, floating mass of ice that broke from a glacier.

igneous intrusion Igneous rock that was pushed up into cracks in overlying rocks, where it cooled and hardened.

ilmenite A shiny black mineral with the chemical composition $FeTiO_3$. It is a source of the metal titanium and the brilliant white pigment titanium dioxide.

impermeable Not allowing liquid or gas to flow through it.

in suspension Mixed with a liquid but not dissolved in it; refers to sediment being carried by water.

inferred Known or discovered by reasoning, instead of direct observation.

infrared Part of the electromagnetic spectrum; it is too low in frequency to be seen by the human eye.

inland sea A shallow sea that lies on top of continental crust.

inner core The solid innermost layer of the earth. We think that it is made primarily of iron.

insoluble Not able to be dissolved.

intensity A description of the effects of an earthquake observed at a particular place on the earth's surface.

intensity map A map showing the locations of the intensity levels observed for a particular earthquake.

interglacial Of or dating from a time of warmer climate between glacial advances.

interlayered Consisting of alternating layers.

intertidal Between high and low tide.

intrude To push into; refers to magma that is pushed into rock and hardens there as an igneous intrusion.

intrusive Forming an igneous intrusion.

intrusive contact The boundary between an igneous intrusion and the surrounding rock.

invertebrate An animal that does not have a backbone.

island arc A chain of volcanic islands on the overriding plate at the site of an ocean-ocean collision.

isotope One of two or more forms of a chemical element. Each isotope of an element has the same number of protons in its nucleus but differs in the number of neutrons.

J-3 fault scarp The boundary along the east coast of the United States between oceanic crust and crust that is part oceanic and part continental.

joint A crack in rock along which no movement has occurred.

joint system Two groups of joints that intersect.

kame A long, low, steep-sided mound made of layers of sand and gravel deposited by meltwater streams from a glacier.

kame delta A steep, flat-topped hill made of sand and gravel deposited by meltwater streams flowing into a glacial lake.

kame terrace A flat ridge made of layers of sand and gravel deposited by meltwater streams from a glacier.

karst topography A landscape that includes caves, disappearing and reappearing streams, springs, and sinkholes. These features are formed by groundwater dissolving limestone.

kettle A bowl-shaped depression formed in glacial drift when a block of ice buried in the drift melts.

kettle lake A lake in a large, bowl-shaped depression that formed in glacial deposits when blocks of ice mixed in the deposits melted.

kimberlite A dark-colored igneous rock containing the minerals olivine and garnet. Kimberlites are thought to be formed by magma derived from the upper mantle.

Knox Unconformity The unconformity that separates Lower Ordovician rocks from younger Middle Ordovician rocks.

lagoon A large body of salt water near or connected with the ocean.

laminations Very thin layers in sedimentary rock.

landfill A place where solid waste generated by humans is buried.

landform A natural feature of the earth's surface.

landward Toward the land.

latitude Angular distance north or south from the earth's equator.

Laurentide Ice Sheet The ice sheet that invaded New York and the surrounding region during the Pleistocene Epoch.

lava flow Rock that formed when molten rock flowed out onto the surface of the land and hardened there.

layer-parallel shortening Shortening of the earth's crust without folding or faulting.

leucogranite Granite that has a few dark-colored minerals.

leucogranitic gneiss A layered metamorphic rock that has the composition of leucogranite.

lignite Brownish-black coal.

lime A white substance with the chemical composition CaO. It is used to make mortar and plaster and in agriculture.

lime mud Fine-grained carbonate sediments.

lime mudstone A very fine-grained kind of limestone.

limestone A sedimentary rock made primarily of the mineral calcite.

limestone conglomerate Conglomerate that contains large fragments of limestone.

limonite A group of iron oxide minerals; mined as an iron ore.

limy Containing significant amounts of limestone or the mineral calcite.

lineation Streaks of minerals or other line-like features that form when a rock is deformed or metamorphosed.

lithosphere The outer, more rigid layer of the earth, made up of the crust and a layer of rigid mantle.

lobe A large, rounded area of ice projecting from the margin of a continental glacier.

locally Occurring in some places but not in other places.

low-angle fault A fault that makes an angle of less than 45° with a horizontal plane.

lowland Land that is relatively low-lying and level.

mafic Composed of dark-colored minerals, especially those rich in magnesium (Mg) and iron (Fe).

magma Molten rock.

magmatic arc A mountain chain formed on the edge of a continent at the site of an ocean-continent collision.

magnesium calcium carbonate The mineral dolomite (chemical composition $(Ca,Mg)(CO_3)_2$).

magnetic separator A device used to purify ores. It uses magnets to separate magnetic and nonmagnetic minerals.

magnetite A black, strongly magnetic mineral with the chemical composition Fe_3O_4. It is the most common iron ore found in the Adirondacks and the Hudson Highlands.

magnitude A number describing the size of an earthquake; it is calculated from the amplitude of the seismic waves as recorded by seismographs.

mammoth A hairy, very large, elephant-like animal of the Pleistocene Epoch. Mammoths had teeth with broad grinding surfaces identical to those of living elephants. They are now extinct.

mangerite An igneous rock similar in composition to charnockite but containing less quartz.

Manhattan Prong The region underlain by metamorphic rocks in the New York City-Westchester County area.

mantle A thick layer of dense rock that lies above the outer core and below the crust of the earth.

map unit A single rock unit or a group of related rock units shown by a color or pattern on a geologic map.

marble A metamorphic rock composed of the minerals calcite or dolomite. It is formed by the metamorphism of limestone.

margin The edge of a continent, ocean basin, or other feature of the earth's surface.

marine Of or relating to the sea.

marl A soft, loose sediment composed of clay and calcium carbonate.

marshland An area of soft, wet land.

mastodont An extinct, elephant-like, hairy animal of the Pleistocene Epoch. It was very similar to the mammoth, but had teeth with high, cone-like bumps on the upper surface that served to chop twigs and branches. (Formerly spelled *mastodon.)*

matrix In conglomerate rocks, the fine-grained material in which the larger fragments are embedded.

maximum intensity The highest intensity level observed during an earthquake. It is used as an indirect measure of the size of an earthquake.

meandering stream A stream that flows along an intricate winding course.

mechanical weathering The mechanical breakdown of rock into small pieces without chemical change.

megaconglomerate A conglomerate that contains very large boulders.

meltwater Water melting from glacial ice.

metagabbro Gabbro that has been metamorphosed.

metal castings Metal objects produced by pouring hot liquid metal into a mold and allowing it to cool and harden.

metamorphic grade A description of the temperature and pressure conditions during metamorphism. For example, high metamorphic grade refers to rock metamorphosed at high temperatures and pressures.

metanorthosite Metamorphic rock formed from the igneous rock anorthosite.

metaplutonic rock Metamorphic rock that has been formed by metamorphism of *plutonic rock*—igneous rock that hardened underground.

metasedimentary rock Metamorphic rock that has been formed by metamorphism of sedimentary rock.

metatonalite Tonalite that has been metamorphosed.

metavolcanic rock Metamorphic rock that has been formed by metamorphism of *volcanic rock*—igneous rock that hardened at the earth's surface.

metric system A system of weights and measures based on the meter and the kilogram.

microcontinent A small continent.

mid-oceanic ridge A huge underwater mountain chain that forms at the divergent margin in the middle of a widening ocean.

migmatite A layered rock that is part igneous and part metamorphic; formed at high temperatures and pressures deep in the earth's crust.

mineral assemblage The collection of minerals that makes up a specific rock.

mineral fuels Coal, oil, and natural gas. New York State produces oil and natural gas.

mineral resources Mineral deposits that are economically valuable.

Modified Mercalli intensity scale The intensity scale used today in the United States to describe earthquakes.

molding sand Sand that contains clay and can be molded into complex shapes.

mollusk An invertebrate animal with a nonsegmented body and a hard outer shell. Snails and clams are examples of mollusks.

monocline A fold in horizontal or gently inclined rock with one steep limb.

montmorillonite A kind of clay formed from volcanic ash; it expands greatly when wet.

moose-elk A large deer, now extinct, that lived in Pleistocene North America.

moraine A pile of unsorted glacial drift deposited along the margin of a glacier.

mottled Marked with spots or blotches of different colors.

mountain glacier A relatively small glacier that forms in the mountains and frequently flows down a valley there.

mud cracks Cracks that form in clay, silt, or mud as it dries. The cracks form a pattern of irregular polygons on bedding surfaces.

mudstone A sedimentary rock made from mud. It does not have the thin layering found in shale.

mulch A substance spread on the ground to enrich the soil.

multispectral scanner A device used in satellites to take pictures of the earth from space without the use of film.

musk ox A large, shaggy wild ox that lives in cold climates.

mylonite The intensely deformed rock formed in a ductile shear zone.

natural cement A kind of cement that is produced by burning and then grinding a special kind of limestone that contains just the necessary amount of clay materials. The ground rock, mixed with water, will dry into a hard mass.

natural gas A flammable gas found in the earth's crust.

naturalist A scientist who studies natural history.

nautiloid A shelled cephalopod. These squid-like animals existed from the Cambrian Period to the present.

nearshore In shallow water, close to the shoreline.

neutron An uncharged particle that makes up part of the nucleus of an atom.

Newark Basin A rift basin formed during opening of the Atlantic Ocean in which the rocks of the Newark Group were deposited.

Newark Group The sedimentary rocks of Triassic age that make up most of the bedrock of the Newark Lowlands.

normal fault A steep fault along which the block of rock above the fault moves down relative to the other block.

Northwest Lowlands The northwestern part of the

Adirondack region; it is divided from the Central Highlands by the Carthage-Colton Mylonite Zone.

nucleus The central part of an atom; made up of protons and usually neutrons.

ocean basin A low area made from oceanic crust and filled with sea water.

ocean-continent collision A convergent margin at which oceanic crust collides with continental crust. The dense oceanic crust is subducted beneath the lighter continental crust.

ocean-ocean collision A convergent margin at which oceanic crust collides with oceanic crust.

oceanic crust Thin and relatively dense crust that floats low on the asthenosphere and commonly forms ocean basins.

offshore Distant from the shore.

oil A naturally occurring thick liquid found in the earth's crust. It is refined into gasoline and other products.

olenellid A kind of spike-tailed trilobite with many body segments that lived during the Early Cambrian.

olivine A green-colored mineral found in igneous rocks.

ore body A mass of ore that is economical enough to mine.

organic materials Organic matter.

organic matter Carbon-rich material derived from living organisms.

orientation The position of an object in space.

oriented Arranged in space.

orogeny A mountain-building event caused by the collision of two or more tectonic plates.

ostracode A small, bean-shaped crustacean.

outcrop Bedrock that is exposed at the earth's surface.

outcrop band Outcrop belt.

outcrop belt An area in which outcrops of a single rock unit or of a group of related rock units are found.

outer core The layer of molten iron that lies between the mantle and the inner core of the earth.

outlet The place where a stream flows out of a lake.

outwash Layers of sand, gravel, and other debris deposited by glacial meltwater streams.

outwash plain A broad, flat sheet of sediment deposited by meltwater streams.

overlie To lie over or on top of.

overriding plate At a convergent margin, the tectonic plate that remains at the surface while the other plate is subducted beneath it.

overthrust A low-angle fault in which movement of several kilometers of more has taken place.

oxygenated Containing dissolved oxygen.

P wave A seismic wave that moves through rock by alternately compressing and expanding it in the direction of travel. P waves are faster than S waves; they can travel through solids, liquids, and gases.

packer In hydraulic fracturing, a piece of rubber that is expanded against the wall of a drill hole to keep the water pressure high enough to fracture the rock.

paleogeography The physical geography of past geologic ages.

Palisades An escarpment along the west bank of the Hudson River made of diabase that solidified in Early Jurassic time. It got its name from the fact that it resembles a colonial log fence, or *palisade*. The mass of diabase that forms the cliff is called the *Palisades Sill.*

Pangea A supercontinent that formed as a result of many orogenies, including the Taconian, Acadian, and Alleghanian. Pangea broke apart in a worldwide rifting event that began about 220 million years ago.

parent A radioactive isotope that decays into another isotope (the daughter) by emitting particles, or energy, or both.

parent material Weathered rock or sediment that later becomes soil.

passive margin A continental edge that is tectonically quiet.

"pearly layer" A layer of shale that is crowded with broken brachiopod shells.

peat The carbon-rich remains of swamp and bog plants that were submerged and chemically altered.

peat bog A low-lying wet area where peat is formed.

peccary A kind of wild pig.

pegmatite An extremely coarse-grained igneous rock.

pelecypod A bottom-dwelling bivalve mollusk. Clams, oysters, and mussels are examples of pelecypods.

pelmatozoan An echinoderm that lives attached to a solid part of the sea floor.

pencil cleavage A kind of cleavage that causes rock to break, when weathered, into long, narrow pieces that look like pencils.

perforated Having a hole or holes.

permeable Allowing liquid or gas to flow through it.

permeability The ability of water to flow through a particular material.

petroleum Oil and natural gas.

phosphatic Containing or made of phosphate minerals.

phosphors Substances that emit light when excited by radiation.

phyllite A metamorphic rock intermediate in metamorphic grade between a slate and a schist. The foliation gives the rock a silky sheen.

physiographic diagram A drawing of the physical features of part of the earth's surface.

physiographic province A region in which the shape of the land's surface is fairly constant, and is different from that of surrounding regions.

physiographic map A map that shows the shape of the earth's surface.

physiography The physical features of the earth's surface.

piedmont Land at the base of a mountain or mountain range.

pillow lava A lava flow that formed in tubes underwater. The lava tubes look like a pile of pillows.

pinchout The place at which a body of rock thins until it disappears.

pine-barren vegetation Plants that are adapted to grow on well drained sandy soils.

pinnacle reef A column of carbonate rock built by corals and other marine organisms in shallow water.

pitch pine A kind of pine tree.

placoderm An extinct kind of armor-skinned fish; placoderm fossils are found in rocks from Late Silurian and Devonian time.

plagioclase One of the most important rock-forming minerals; part of the feldspar group of minerals.

planar Flat or level; lying in a plane.

plastic Adjective referring to deformation that permanently changes the shape of an object without breaking it.

plasticity How materials deform under pressure without breaking.

plate A rigid segment of the earth's lithosphere. Today, there are about eight large and several smaller plates.

plate tectonics The theory that the outer layer of the earth is divided into rigid plates, which move and interact along their edges. The theory of plate tectonics is very important in modern geology.

platform The part of a continent covered by flat-lying sedimentary rocks.

plunge pool A round depression carved in the rock at the foot of a waterfall by the force of the falling water.

plutonic rock Igneous rock that formed when magma cooled and hardened below the earth's surface.

pollen Tiny spores produced by a plant.

poorly sorted Having sediments of all different sizes deposited together.

pore spaces The small unfilled spaces between grains in rock or sediment.

porosity The percentage of empty space in a certain volume of material.

porous Containing a large amount of pore space between grains.

portland cement A kind of cement manufactured by heating limestone and shale together in a kiln.

postglacial Of or dating from a time after retreat of the glaciers from a region.

potassium feldspar An important rock-forming mineral of the feldspar group.

pothole A circular hole formed in bedrock of a river bed by abrasion of pebbles and cobbles in a strong current.

precipitation Rain, snow, sleet, hail, or mist.

preglacial Of or dating from the time before the glacial advance of the Pleistocene Epoch.

pressure solution A process in which rock is deformed by compression, which raises the pressure of the water in the rock's pore spaces. The water dissolves the silica in the rock and leaves behind seams of insoluble material.

primary recovery Producing oil by drilling a new well.

proto-Africa The continent that was later to become Africa. It collided with proto-North America along a transform margin during the Alleghanian Orogeny.

proto-North America The continent that was later to become North America.

proton A positively charged particle that makes up part of the nucleus of an atom.

ptarmigan A kind of grouse that lives in cold climates.

pterosaur An extinct flying reptile.

pyrite A yellow, metallic-looking iron sulfide mineral (chemical composition FeS_2). Larger pieces are known as "fool's gold."

pyroxene A group of dark-colored minerals common in igneous and metamorphic rocks.

quadrangle A rectangular section of land represented by a topographic map (or by some other kind of systematic mapping).

quantitative time scale A time scale that gives the age in years of events or objects.

quarry A large excavation to obtain stone, usually for building.

quartz A common rock-forming mineral (chemical composition SiO_2).

quartzite A metamorphic rock formed by metamorphism of sandstone or chert.

Queenston Delta A thick wedge of sedimentary rock formed in eastern proto-North America during Late Ordovician time. The sediments of the Queenston Delta were eroded from the mountains built during the Taconian Orogeny.

quicklime Lime.

radial drainage The pattern of streams flowing out in all directions from a central high area like spokes of a wheel.

radioactive decay The process by which an unstable isotope (the parent) changes into another isotope (the daughter) by emitting particles, energy, or both.

radioactivity The instability of some isotopes, so that they can change into other isotopes by radioactive decay.

radiocarbon dating Radiometric dating using carbon-14.

radiometric dating A method for measuring the age of objects in years by using the decay rate of radioactive elements.

Ramapo Fault A fault in southeastern New York and northern New Jersey that separates the western and central areas of the Hudson Highlands.

Reading Prong The geologic province of metamorphic rocks that extends from Pennsylvania to Connecticut.

rebound Upward movement of the earth's crust due to removal of the weight of glacial ice sheets by melting or of overlying rock by erosion.

recrystallize Form new crystals in a rock during metamorphism.

reef carbonates Deposits of carbonate sediments made by reef-building animals, such as corals.

reference section A section of rocks that serve as a time line for a certain part of geologic history. Geologists try to match rock units from other areas to the reference section to determine where those units fit in geologic history.

relative time scale A time scale that ranks events or objects from older to younger, but doesn't give their age in years.

release joints Joints that form in rock that was once deeply buried and under great pressure. As erosion removes the overlying rock, the pressure is decreased on the buried rock and it expands, forming joints.

relief The local difference in elevation between the lowest and the highest points of the landscape.

reservoir An artificial lake where water is collected and kept for use.

residual mountains Mountains that remain after the erosion of a high plateau. The Catskill Mountains are an example.

resistant Not easily eroded; applies to rock or other material.

resolution The ability to tell apart objects that are close together.

reverse fault A steep fault along which one block of rock has moved up and over the lower block.

rhyolite lava A kind of igneous rock that has the same chemical composition as granite but cooled at the earth's surface.

Richter magnitude scale The most commonly used magnitude scale. It was devised in the 1930s to measure California earthquakes.

rift basin A rift valley that has filled with water to become a sea.

rift valley A long, narrow valley that forms at the place where a continent is rifting.

rifting The process of splitting one lithospheric plate into two or more pieces by plate tectonic forces.

rigid mantle The strong outer layer of the mantle that together with the crust makes up the lithosphere.

riprap A layer of large pieces of rock used to prevent erosion by waves or currents.

road cut A place where part of a hillside has been cut away to build a road, exposing the rocks.

rocdrumlin Rock drumlin.

roche moutonnée A small, rounded, streamlined knob carved in bedrock by a glacier.

rock debris Any loose material produced by the weathering of bedrock.

rock drumlin A drumlin with a bedrock core.

rock flour Rock that has been ground into clay and silt-sized particles by a glacier.

rock record The bedrock of a region. It contains clues that allow geologists to reconstruct the geologic history of the area; therefore, we say it "records" that history.

rock unit A body of rock that can be treated as a unit because all the rock in it shares the same characteristics (for example, color, structure, mineral composition, and grain size).

root traces Marks left in sediment by the roots of plants.

runoff Water flowing over the surface of the ground.

rusty The color of rust; caused by the weathering of iron-bearing minerals such as pyrite.

S wave A seismic wave that vibrates the rock at right angles to the direction the wave is travelling. S waves are slower than P waves; they can travel only through solids.

Salamanca Re-entrant A small area in southwestern New York that remained ice-free during the Wisconsinan Stage.

salinity The amount of dissolved salts in sea water.

San Andreas fault A large transform fault system in California that separates the Pacific plate from the North American plate.

sandstone A sedimentary rock made up of round quartz grains cemented together.

saprolite The soft, earthy residue left behind when rocks are chemically weathered.

scavenger An animal that feeds on dead animals.

scour To clear, dig, or remove by a powerful current of water or by glacial ice.

scour and fill Preserved water channels that were later filled in with sediment; commonly shows cross-bedding.

sea ice Frozen sea water.

sea lily Crinoid.

seaward In the direction of the sea.

secondary cleavage The tendency of a deformed or metamorphic rock, such as slate, to split in a direction different from the original sedimentary layers.

secondary recovery Producing the remaining oil from an oil field by waterflooding after most of the oil in the field has been pumped out.

section The series of rock units found in a given region.

sediment Rock material transported and deposited by water, wind, or glaciers.

sedimentary structure Any feature in sediment or sedimentary rock formed at the time of deposition. Sedimentary structures include bedding, cross-bedding, ripple marks, mud cracks, and flute casts.

seep A place where oil naturally leaks out onto the ground surface.

seismic waves Vibrations that travel through the earth, whether generated by natural or artificial means.

seismograph A device for detecting and recording seismic waves.

seismology The study of earthquakes and the interior structure of the earth by means of seismic waves.

septarian nodule A large concretion that is broken into irregular blocks by cracks that are filled or partly filled with mineral crystals.

sequence A series of rock units.

serpentinite Rock made almost entirely of the mineral serpentine. Some serpentinite is thought to be preserved pieces of ancient oceanic crust.

serpentinization The process in which mafic and ultramafic minerals are changed into the mineral serpentine.

shale A fine-grained sedimentary rock composed of silt- and clay-size particles. It breaks easily along the bedding plane.

shale basin A sea basin in which shale is deposited.

shear Deformation caused by two objects moving sideways past one another.

shelf Continental shelf.

shelf valley A channel cut in the continental shelf by a river that flowed across the shelf when sea level was lower.

shingle beach A narrow, steep-sided beach made of very coarse sediments.

shore zone The area along the shoreline affected by waves or tides.

shoreward In the direction of the shore.

short-fiber asbestos Minerals of the asbestos group that readily separate into flexible fibers.

siderite A yellow-brown mineral with the chemical composition $FeCO_3$; used for iron ore.

silica A substance made of silicon and oxygen (chemical composition SiO_2). It is present in many minerals, sediments, and rocks, including quartz and chert.

silicate Any of the minerals built around a structure of one silicon atom and four oxygen atoms. The earth's crust is mostly made up of silicate minerals.

sill A broad, flat sheet of igneous rock that lies parallel to the layers of the surrounding rock.

sillimanite A mineral made up of long, needle-shaped crystals; it is found in some metamorphic rocks that formed at high temperatures.

siltstone A sedimentary rock made up of silt-sized particles.

slope Continental slope.

slump A sudden downward slide of land.

soil Surface layer of the land where plants can grow.

soluble Able to be dissolved.

solution The process of dissolving something.

sorted Deposited with the same size particles together.

spaced cleavage A kind of cleavage in which the cleavage forms at regular intervals in the rock.

spectral band A part of the electromagnetic spectrum.

sphalerite A mineral with chemical composition ZnS that is a source of zinc.

spit A tongue of land that extends from the shore into a body of water.

stalked echinoderm An echinoderm that grows attached to the solid sea bottom by a stalk.

stippled Dotted or speckled.

strain The deformation of rock as the result of stress applied to it.

strata Layers of sedimentary rock or sediment. *Strata* is the plural of *stratum*.

stratified drift Glacial drift deposited in layers by a meltwater stream or in a glacial lake.

stratigraphic trap An underground layer of permeable sedimentary rock surrounded by impermeable rock; it holds oil or natural gas. This kind of trap is formed by the way sediments are deposited.

stratigraphic unit An interval of sedimentary rocks regarded by geologists as a natural, easily recognizable unit; we recognize a stratigraphic unit based on rock types or fossils.

stratigraphically upward In undeformed sedimentary rock, moving from lower, older rock to higher, younger rock.

stratigraphy The description, classification, and interpretation of sedimentary rocks and the environments in which they were deposited.

stress Force applied per unit of area. Rock deformation is caused by stress applied to the body of rock.

striation A scratch left on a rock surface by the passage of a glacier.

stripper well An oil well that produces less than 10 barrels of oil per day.

stromatolite A layered mound-like structure built by blue-green algae living in shallow, well-lit water.

stromatoporoid An extinct kind of colonial coral-like sponge that built reefs.

structural history The folding and faulting that have affected a body of rock and the events that caused them.

structural trap An underground pocket of permeable sedimentary rock that holds oil or natural gas surrounded by impermeable rock. This kind of trap is formed by folding or faulting of the rock.

structural unit A unit of rocks that have undergone a similar deformation history.

structure Large or small feature in a body of deformed rock that tell us something about its history. Examples of structures are folds, faults, cleavage, and foliation.

stylolite An irregular surface that runs through a rock. It is marked by insoluble material left behind when silica is dissolved by pressure solution.

subaerial Exposed to the open air.

subarctic A cold, dry climate found in areas near the arctic circle.

subduction The process of one lithospheric plate sinking beneath another at a convergent margin.

subduction zone A long, narrow belt where subduction is occurring.

submarine sediments Sediments deposited in the ocean.

submergence Flooding or placing of something underwater.

subordinate Adjective referring to a minor amount of something, such as a mineral.

subsurface Below the surface of the earth.

subtropical A hot, humid climate found in areas near the tropics.

suite Collection or arrangement; applies to a group of rock units.

sulfide A mineral that contains the element sulfur, such as pyrite or galena.

sun-synchronous Adjective referring to a satellite orbit in which the sun as the same position with each pass of the satellite.

supercontinent A single continent that contains most or all of the earth's continental crust.

Superior Province Area of very old (2.7 billion years) "basement" rocks; located to the west of the Grenville Province.

superposition The idea that, in an undisturbed sequence of layered rock, the upper layers are younger than the lower ones.

surface water Water found in streams, rivers, and lakes.

surficial deposits Loose sediments lying at the surface of the earth, above the bedrock.

surficial geology The loose deposits, such as soil and glacial deposits, that lie on the surface of the earth; also, the study of such deposits.

suture The line along which two continents have been attached together.

suture zone The area in which a suture is found.

swamp Low-lying, wet land, sometimes partially flooded.

syncline A fold in rock that is concave up.

synclinorium A large syncline.

tabular Adjective referring to shapes that are much longer and wider than they are thick.

tabulate coral A kind of coral.

Taconian Orogeny A mountain-building event that happened about 450 million years ago, when a volcanic island arc collided with proto-North America.

Taconic Mountains Highlands in eastern New York and western New England. The mountains built by the Taconian Orogeny are called *ancient* or *ancestral Taconic Mountains.*

Taconic Sequence The sedimentary rocks in eastern New York State and western New England originally deposited in deep water. They were later stacked together by the collision of an island arc with proto-North America during the Taconian Orogeny.

Taconic Unconformity The unconformity that lies between the Middle Ordovician rocks and the younger Silurian and Devonian rocks on top of them.

talc A very soft, white to light green, flaky mineral. The "talc" mined in New York State actually contains less than 50% of the mineral talc.

tectonic map A map that shows the kinds and ages of deformation of the rocks in a region.

tectonic province A region that has undergone a similar tectonic history.

tectonism Plate tectonic activity or motion.

temperate Moderate or mild; refers to climate.

tentaculitid An extinct marine invertebrate animal characterized by a small, cone-shaped shell.

Terminal Moraine The end moraine left by the Laurentide Ice Sheet during the Wisconsinan Stage.

terrace A relatively flat surface, something like a step, built onto the side of a slope.

terrane A large part of the earth's crust that has undergone a similar tectonic history.

terrain The physical features of an area of land.

terrestrial sedimentary rock Sedimentary rock made up of sediments deposited on land.

tertiary recovery Producing oil from an oil field after pumping and waterflooding have been used.

thrust fault A nearly horizontal fault. The sheet of rock above the fault is pushed up and over the rock underneath.

thrust sheet A body of rock transported as a single mass along a thrust fault.

thrust slice A body of rock bounded above and below by thrust faults.

Tibetan Plateau An extensive high plateau north of the Himalayan Mountains. Both the mountains and the plateau were built by the collision between India and Asia, which started 40 million years ago and is still going on today.

tidal flat The flat-lying area along the seashore that is covered by water at high tide and uncovered at low tide.

tidal zone The area of a shoreline between high and low tide.

tight sands Impermeable sandstone.

till An unsorted mixture of clay, sand, gravel, and boulders deposited directly by a glacier.

time-correlation The matching of rock units of the same age from different areas.

time marker A feature, such as a fossil, in rock that helps show where the rock belongs in geologic time.

titanium A strong, lightweight metal used in the aerospace industry. The mineral ilmenite is the major source of titanium.

titanium dioxide A brilliant white pigment used in paints. It is made from the mineral ilmenite (titanium ore).

tonalite An igneous rock composed primarily of the minerals plagioclase and quartz.

tonalitic gneiss A layered metamorphic rock that has the composition of tonalite.

topographic map A map with contour lines showing the shape and elevation of the land surface.

topographic relief Relief.

topography The shape and height of the earth's surface.

trace fossil A mark, like a burrow or a track, left by an animal or plant root in sediment and preserved when the sediment becomes rock.

transform margin The boundary between two tectonic plates that are moving sideways past each other.

transform movement Sideways movement.

trend The compass direction in which a rock body or other geologic feature runs.

tributary A stream that flows into a larger stream or lake.

trilobite An extinct, Paleozoic, sea-living arthropod.

tropical climate A hot, humid climate found in the tropics.

trough A long, narrow stream channel; a long, shallow depression in the sea floor.

tube coral A kind of coral.

tundra A treeless plain found in arctic and subarctic regions.

tundra climate A very cold climate.

turbidite A sedimentary rock formed from sediments deposited by a turbidity current.

turbidity current An underwater current that carries a large load of sediment in suspension.

ultramafic Adjective referring to a dark-colored igneous rock composed chiefly of mafic minerals.

unconformity A surface in a rock sequence where there is a gap in the geologic record. An unconformity forms when rock is eroded and new rocks are deposited on the eroded surface.

unconsolidated Loose or uncemented.

underground storage The practice of storing natural gas produced elsewhere in underground sedimentary rock layers. These layers once contained natural gas, but the gas has already been pumped out.

underlie To lie under or be located underneath.

undulatory Having a wavy surface or structure.

unit Rock unit.

unsorted Deposited with different size particles together.

upland An area of land relatively high in elevation.

uplift The upward movement of part of the earth's surface. Also refers to a region that has been uplifted.

U-shaped valley A steep-sided valley that has been carved out by a glacier. The cross section of the valley is shaped like the letter *U*.

valley fill Sediments left behind in a valley by a stream or a retreating glacier.

Valley Heads Moraine A moraine built by the Laurentide Ice Sheet across central New York. It dammed the southern ends of the Finger Lakes and formed an east-west drainage divide.

variegated Having varied colors.

veneer stone A thin ornamental surface of cut stone.

vertebrate An animal that has a backbone.

visible spectrum The part of the electromagnetic spectrum that is visible to the human eye.

volcanic rock Rock that is formed when molten rock flows out onto the surface of the earth and hardens there.

volcanism Volcanic activity.

V-shaped valley A valley cut by a stream. The cross section of the valley is shaped like the letter *V*.

water gap A deep, narrow notch cut through a ridge by a river.

water jet A thin stream of high-pressure water used for cutting.

water table The top of the underground layer that is saturated by groundwater.

waterflooding The practice of injecting water into a depleted oil field. The water pressure forces oil that remains in the ground to a selected well.

weathering The physical and/or chemical decomposition of earth materials at or near the earth's surface.

well sorted Having all the sediment particles of approximately the same size deposited together.

wildcat well An oil or gas well drilled in a region that had not previously produced oil or natural gas.

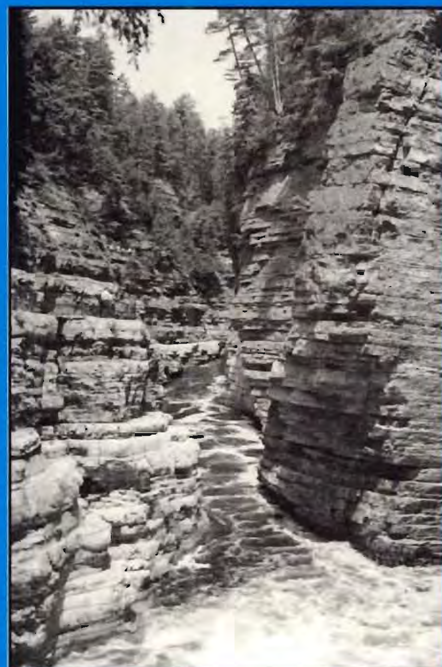
winnowing Washing away of fine particles of sediment, leaving the coarser grains behind.

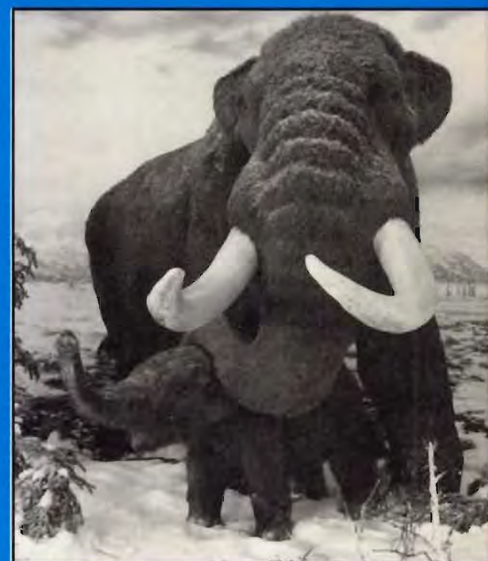
Wisconsinan Stage The last part of the Pleistocene Epoch, during which New York's last episode of glaciation occurred.

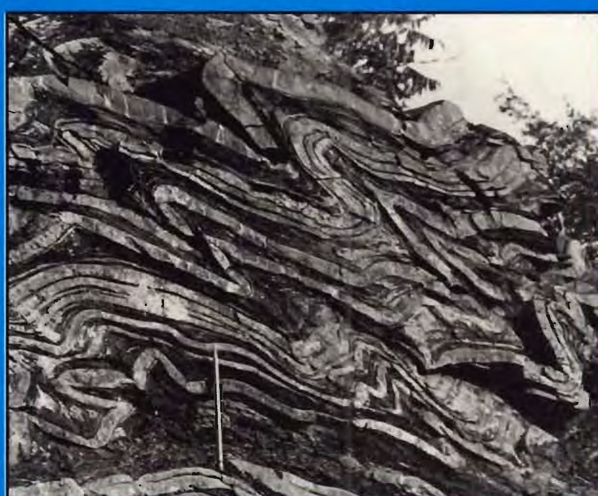
wollastonite A white, fibrous mineral with the chemical composition $CaSiO_3$. It is used in ceramics and in paints.

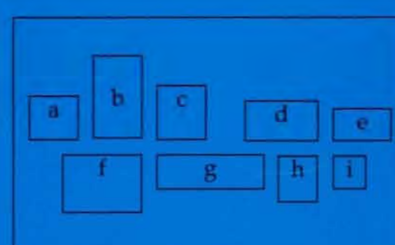
Woodfordian Substage The last part of the Wisconsinan Stage.

wooly mammoth A hairy, very large, elephant-like animal of the Pleistocene Epoch. It is now extinct.









KEY TO ILLUSTRATIONS:

a Mount Whiteface
b Ausable Chasm
c Mastodont
d Taughannock Falls
e The Palisades
f Deformed Taconic rock layers
g Helderberg Escarpment
h Devonian armored fish (on right)
i Devonian sea life: cephalopod attacking a trilobite