GEOLOGY OF NEW YORK
A Simplified Account

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Second Edition

New York State Museum Educational Leaflet 28

New York State Museum/Geological Survey
The State Education Department
The University of the State of New York
Albany, NY 12230
2000

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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.

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

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

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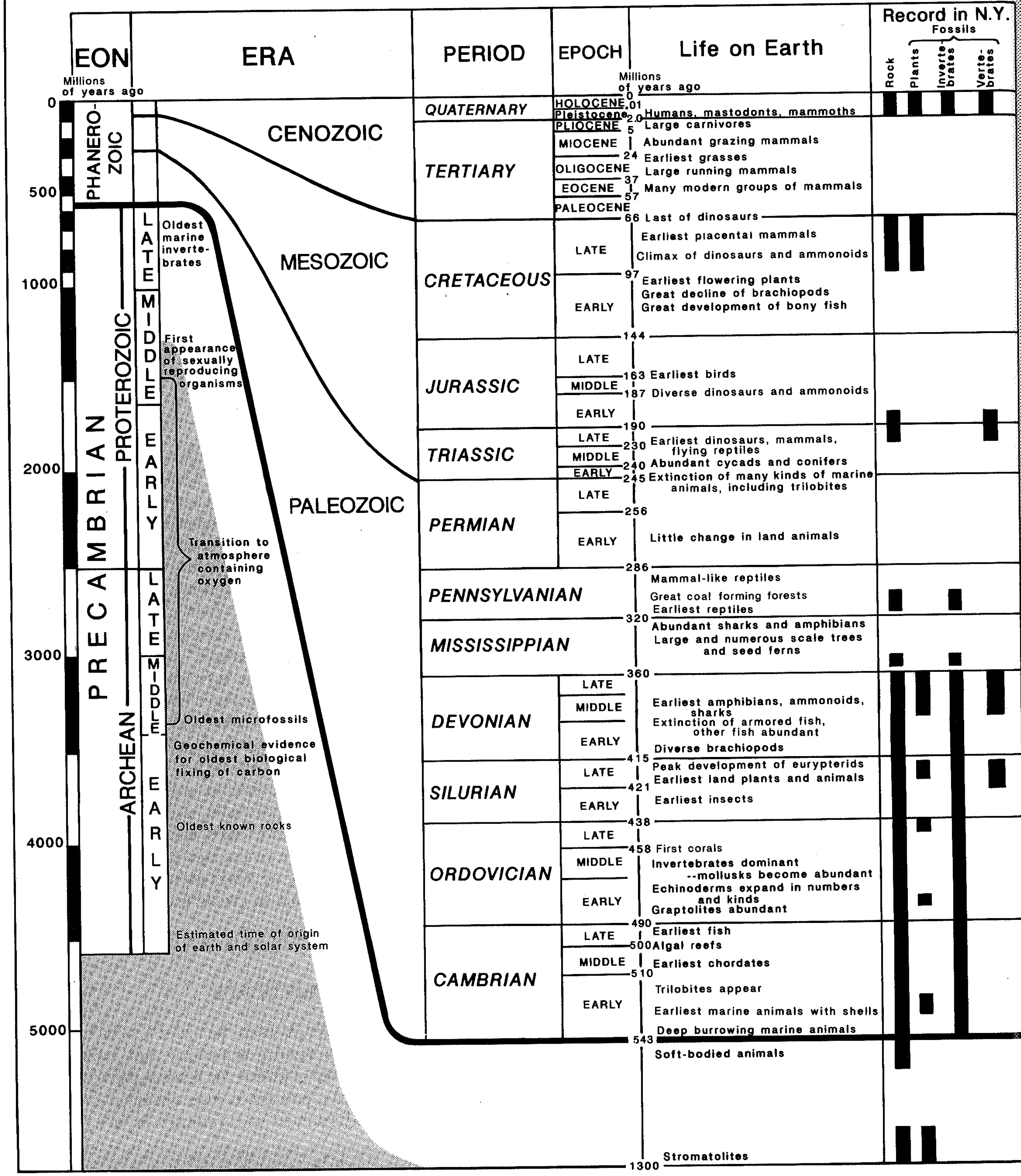
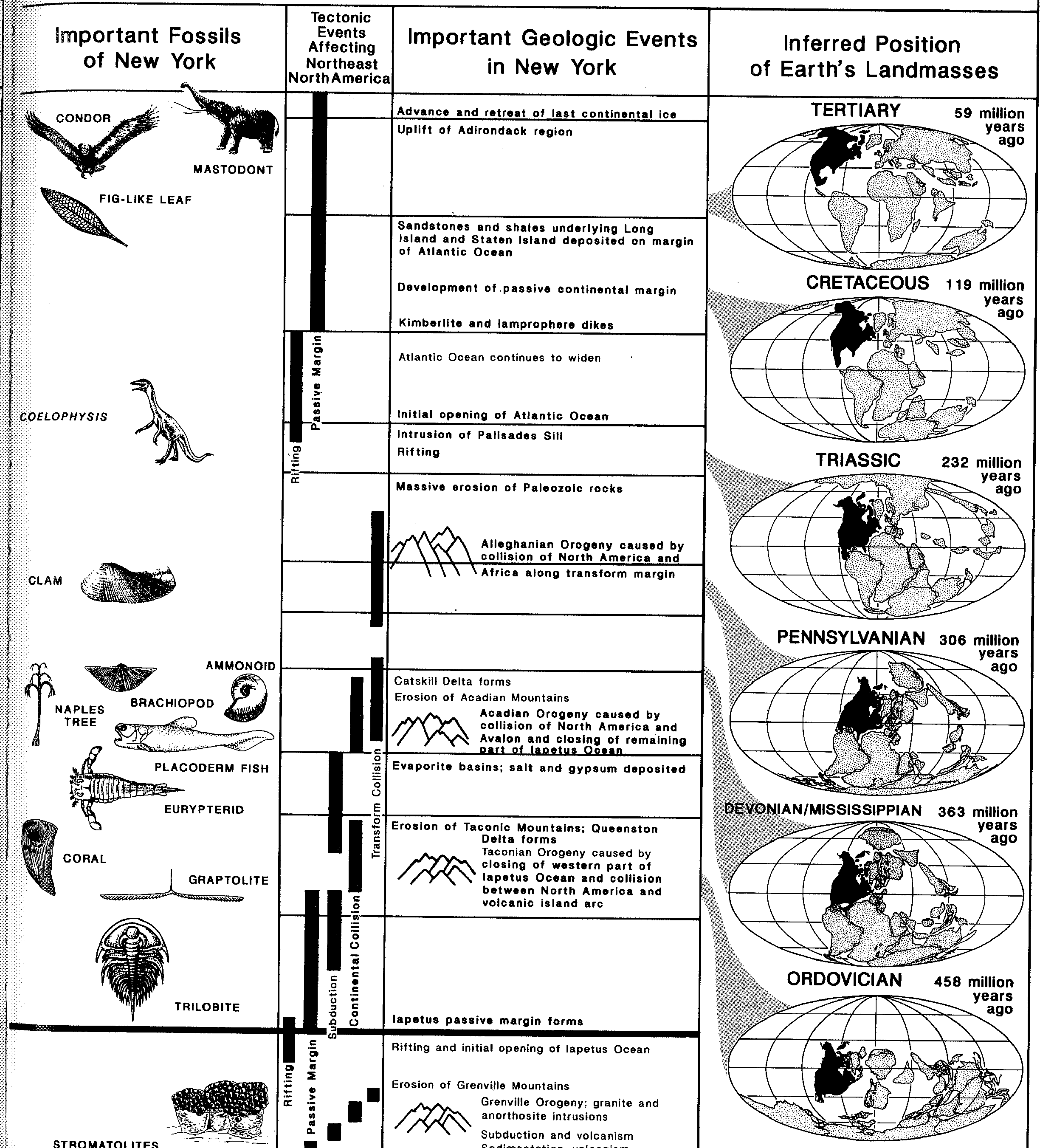


Figure 2.1. This figure includes the geologic time scale. In the left-hand part of the chart, the columns headed "EON," "ERA," "PERIOD," and "EPOCH" make up the relative time scale. The two columns headed "Millions of years ago" convert it to the quantitative time scale. The rest of the figure summarizes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

YORK STATE AT A GLANCE



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.

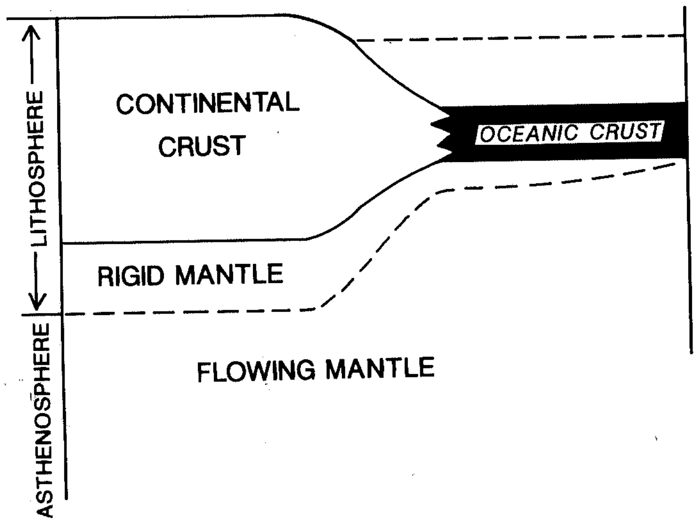


Figure 3.1. This diagram shows the general structure of the outer part of the earth. The outermost shell, the lithosphere, is made up of crust and rigid mantle. The asthenosphere below it is made up of flowing mantle. Notice that the light continental crust is much thicker and floats higher than the 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.

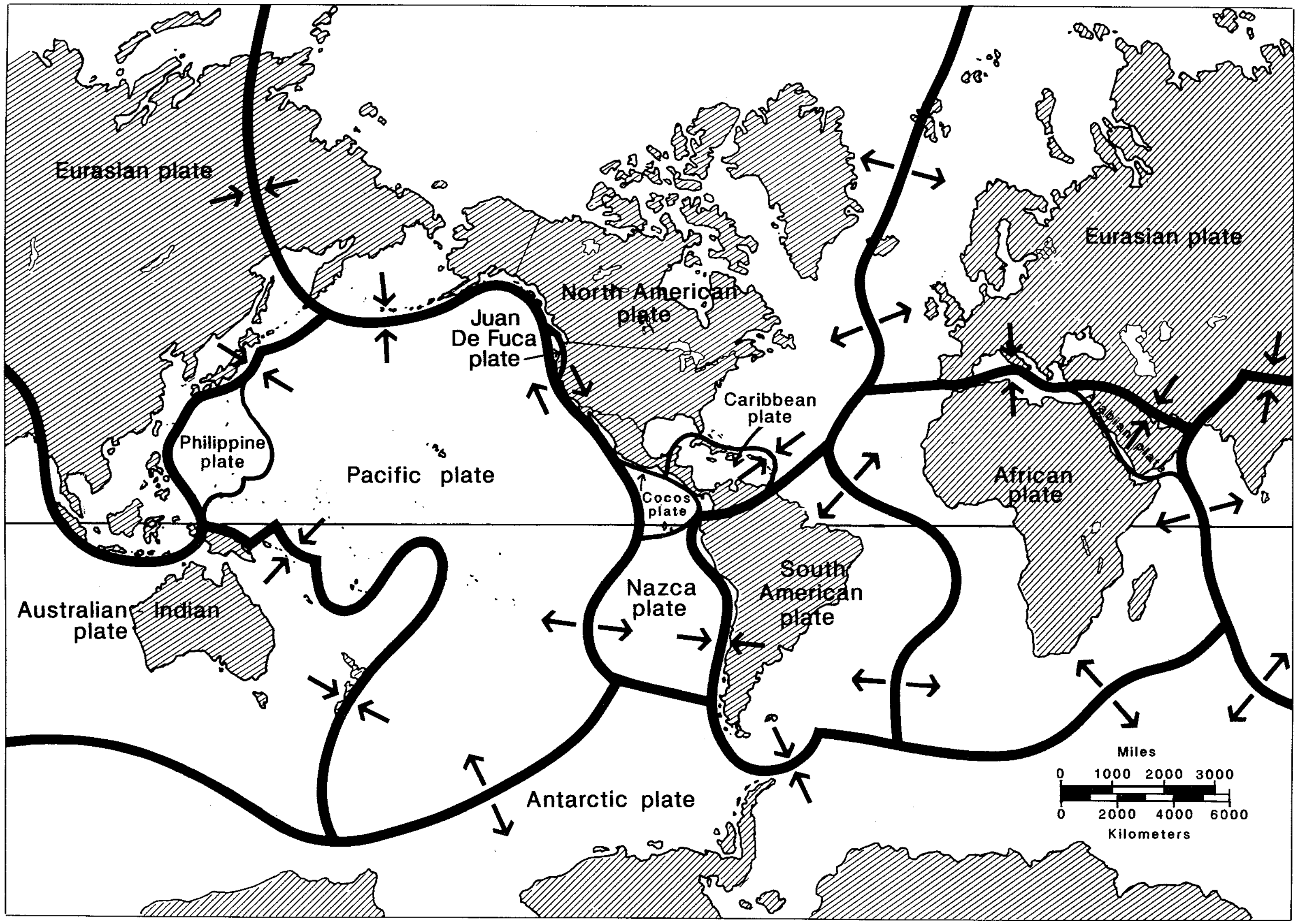


Figure 3.2. A simplified map showing how the lithosphere is broken into plates. The arrows indicate the relative movements between plates. The Juan De Fuca plate is moving toward North America.

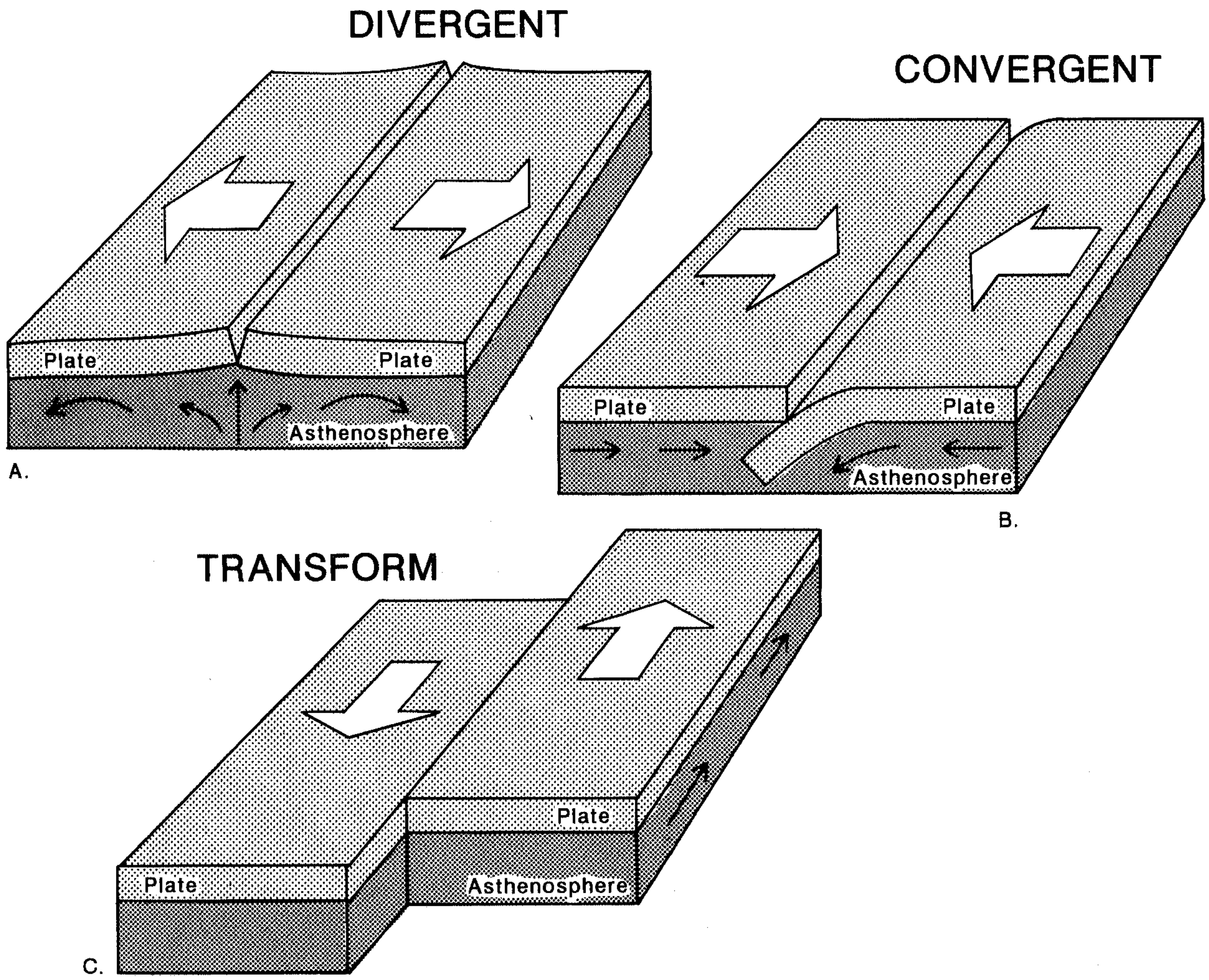


Figure 3.3. The three types of plate margins: (A) divergent; (B) convergent; (C) transform. The black arrows show the motion of convection currents in the asthenosphere.

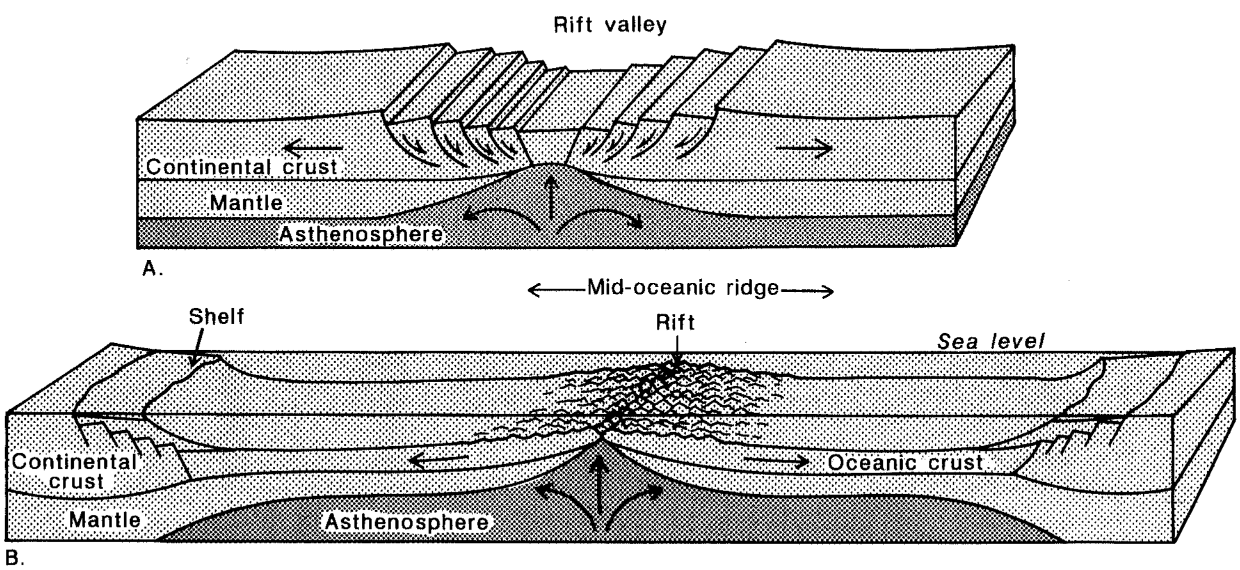


Figure 3.4. Two stages of rifting. In (A), the plate has begun to separate and a rift valley has formed. In (B), the rift has widened and become a new ocean basin between two new continents. Notice the mid-oceanic ridge in the basin.

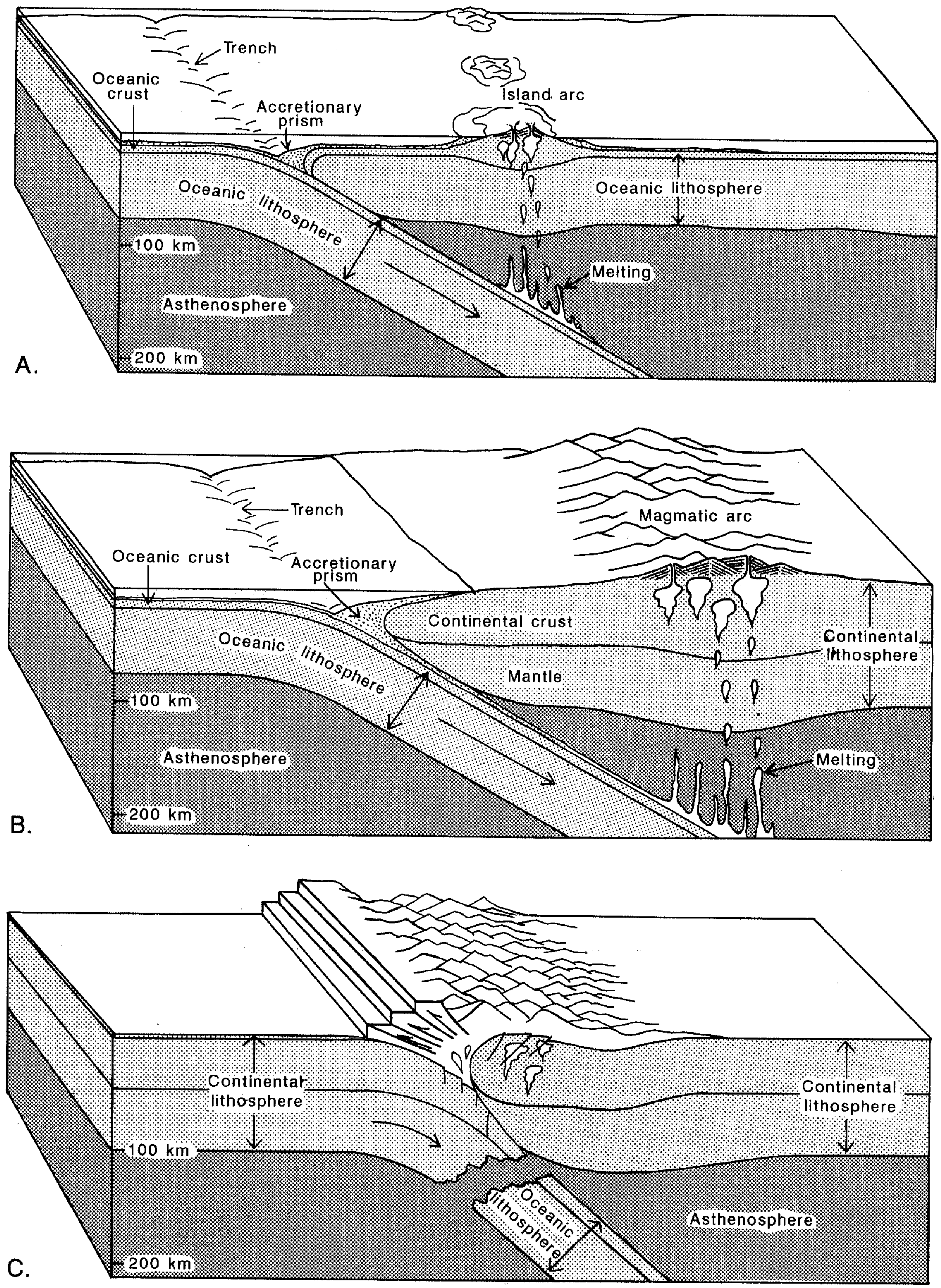


Figure 3.5. The three types of convergent margins: (A) ocean-ocean collision; (B) ocean-continent collision; (C) continent-continent collision. Notice that as the plates converge, the oceanic lithosphere is bent downward and is consumed in the asthenosphere.

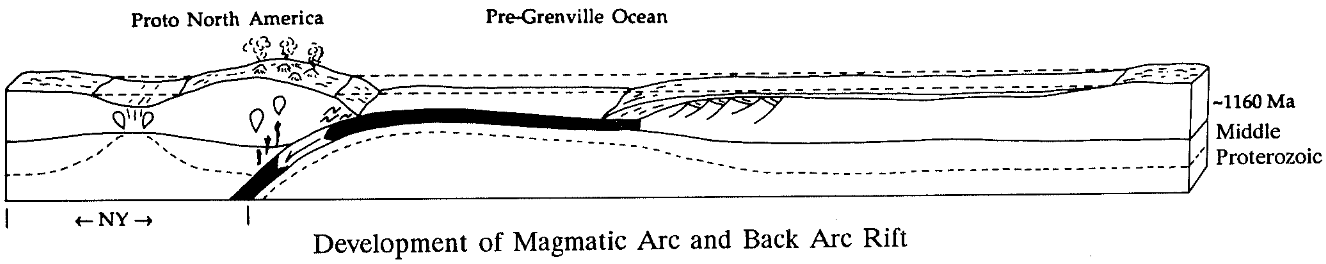


Figure 3.6. Block diagram showing subduction beneath proto-North America between 1.2 and 1.1 billion years ago. Notice the volcanoes in the magmatic arc and the rift beginning behind it. (Compare with Figure 3.1 to recognize continental and oceanic crust and the boundaries of the crust, lithosphere,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

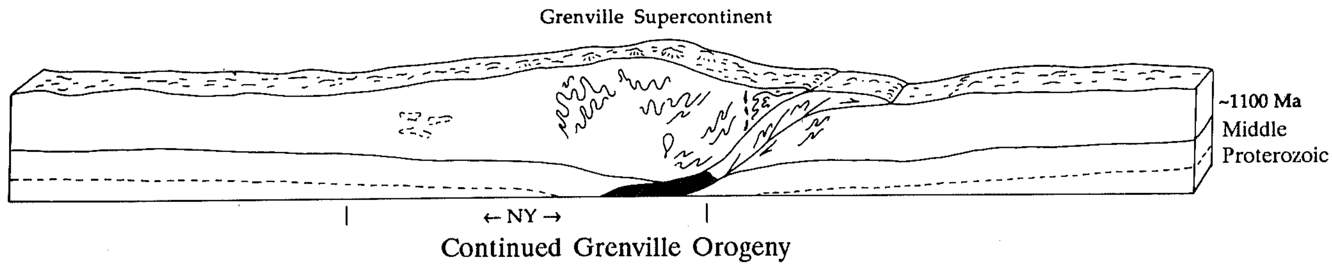


Figure 3.7. Block diagram section showing the results of the Grenville Orogeny. Notice the double-thick continental crust where the continent-continent collision built mountains and a high plateau.

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-

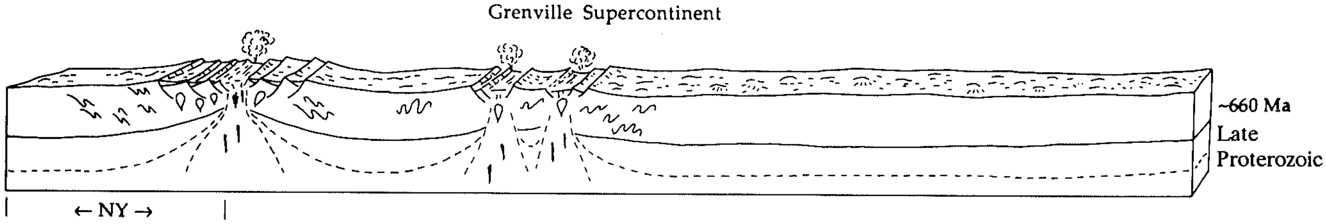


Figure 3.8. Block diagram showing the rifting of the Grenville supercontinent along the east coast of proto-North America.

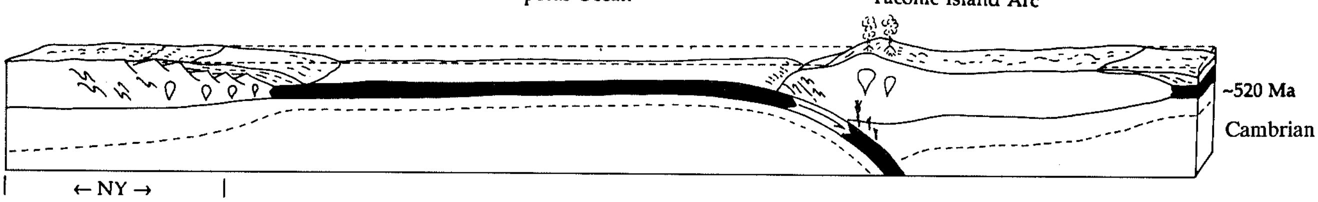


Figure 3.9. Block diagram showing the Taconic island arc approaching proto-North America as the western part of the Iapetus Ocean closes.

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

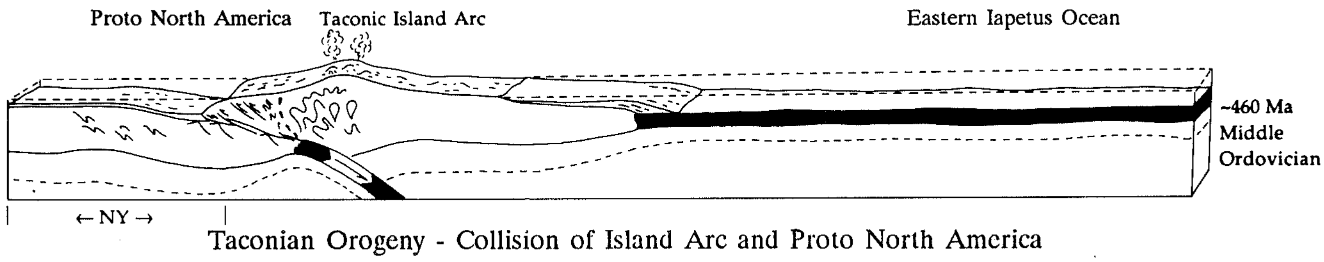


Figure 3.10. Block diagram showing the collision between the island arc and proto-North America. This collision is the Taconian Orogeny. Sediments eroded from the mountains built the Queenston Delta in western New York.

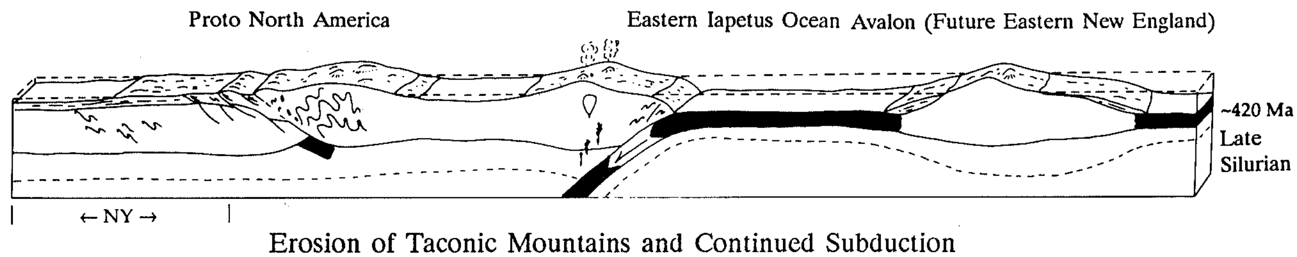


Figure 3.11. Block diagram showing the small continent of Avalon approaching proto-North America as the eastern half of the Iapetus Ocean closes.

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

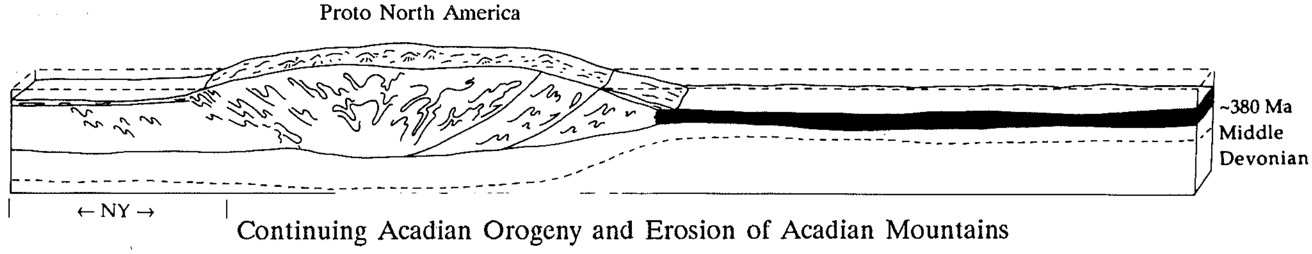


Figure 3.12. Block diagram showing the mountains built by the Acadian Orogeny—the collision between Avalon and proto-North America. Sediments eroded from the mountains built the "Catskill Delta" to the west of the mountains.

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

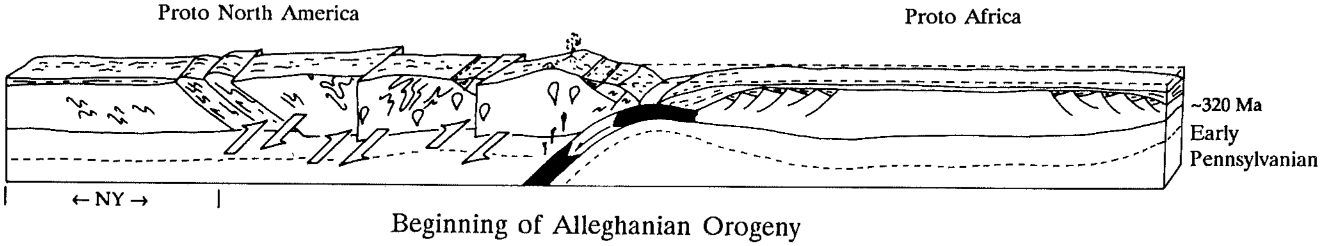


Figure 3.13. Block diagram showing proto-North America and proto-Africa colliding along a transform margin. This collision, the Alleghanian Orogeny, built the Appalachian Mountains.

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

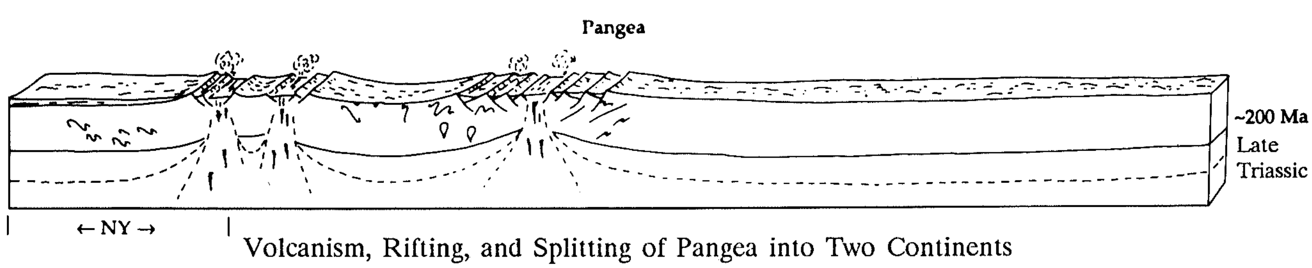
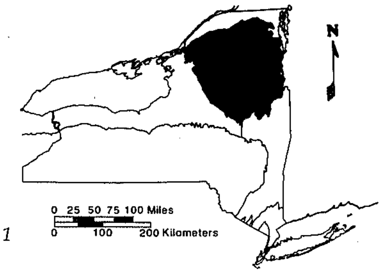


Figure 3.14. Block diagram showing the rifting of the supercontinent of Pangea. The Newark Basin is a rift formed at this time.

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.

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[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).

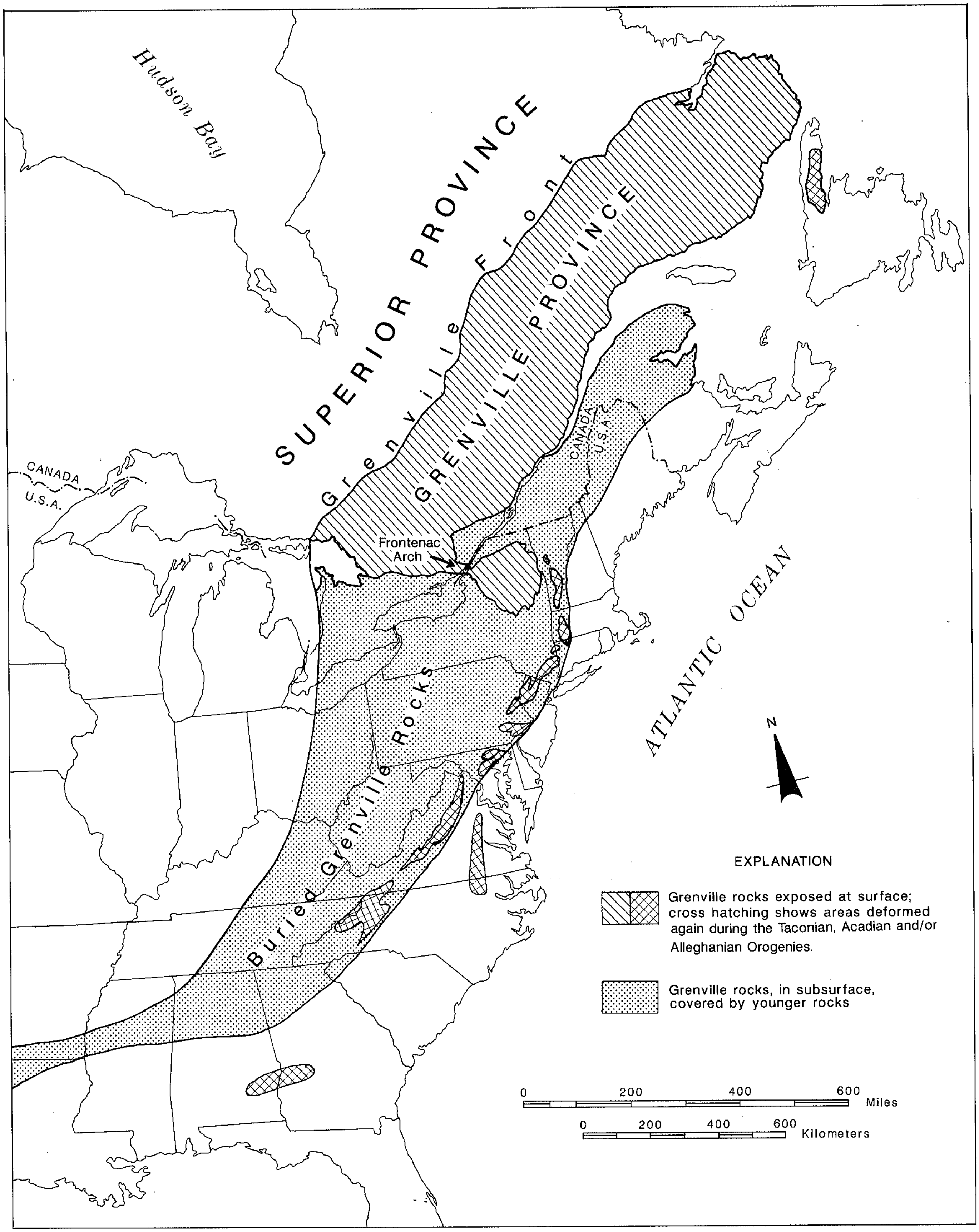
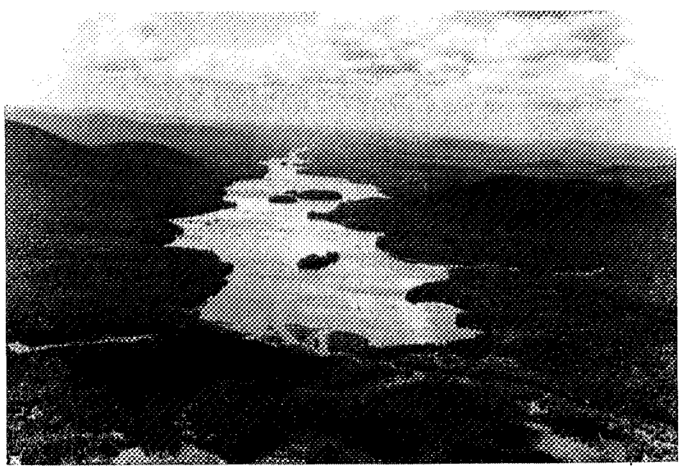


Figure 4.2. This map shows how far the Grenville Province extends in eastern North America. These rocks were all metamorphosed during the Grenville Orogeny approximately 1.1 billion years ago. Slanted lines show where Grenville rocks appear at the surface. The cross-hatch pattern shows locations of Grenville 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-north-east. 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.



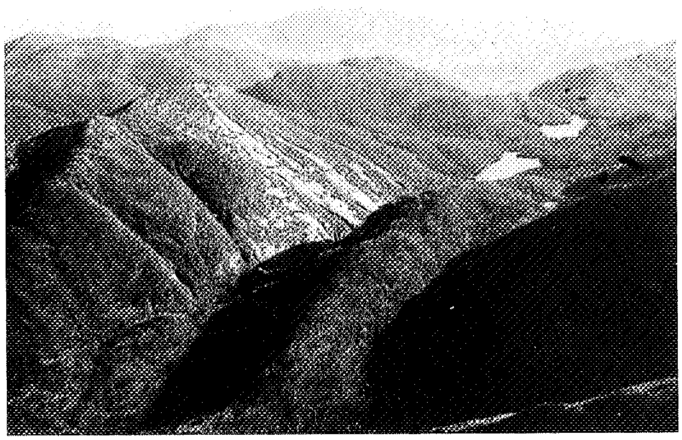


Figure 4.4. (A) This photo looks south-southwest along a long, straight valley in the Adirondacks. The entire valley is 115 km long. You can see about 30 km of that length in this picture. The lake in the valley is the longest lake in the central Adirondacks, appropriately named Long Lake. (B) This aerial 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.

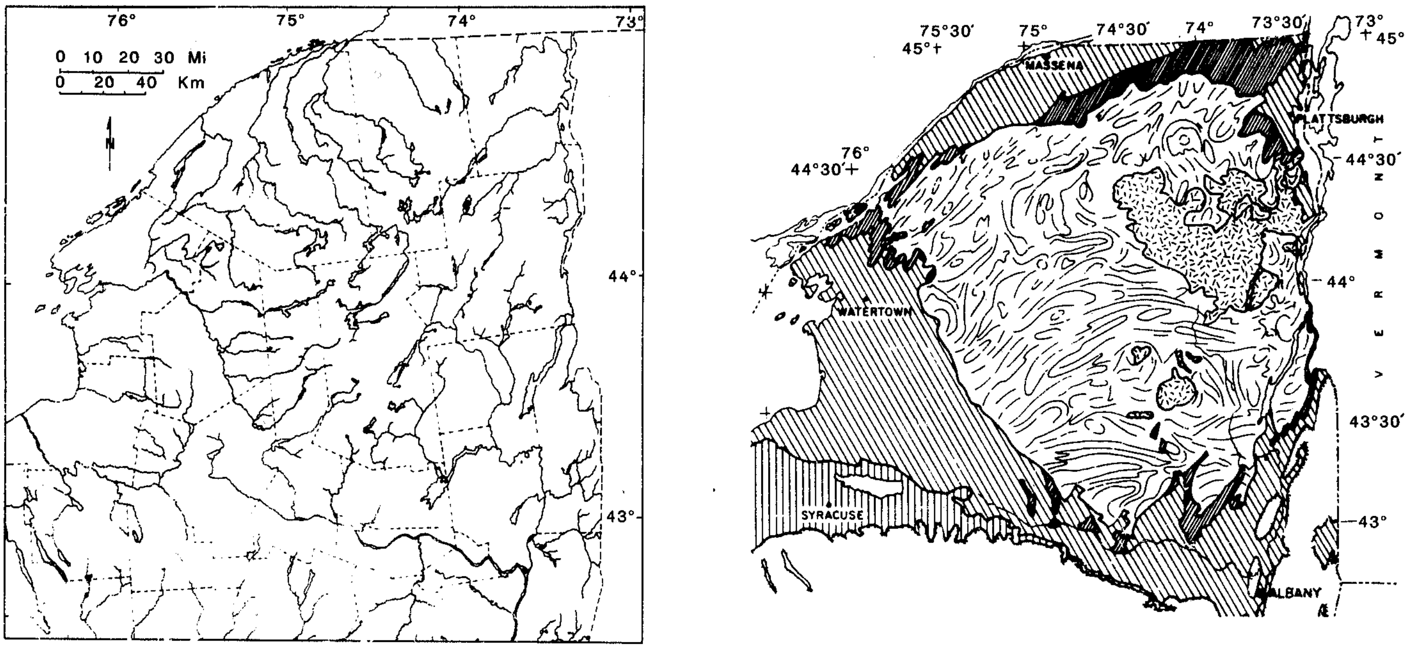


Figure 4.5. (A) Map showing the radial drainage pattern within the Adirondack dome. B) Simplified map of Adirondack bedrock. (See Plate 2 for detailed bedrock map.) The curved lines represent boundaries between strong rocks that resist erosion well and weaker rocks. Notice that the stream pattern ignores 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-

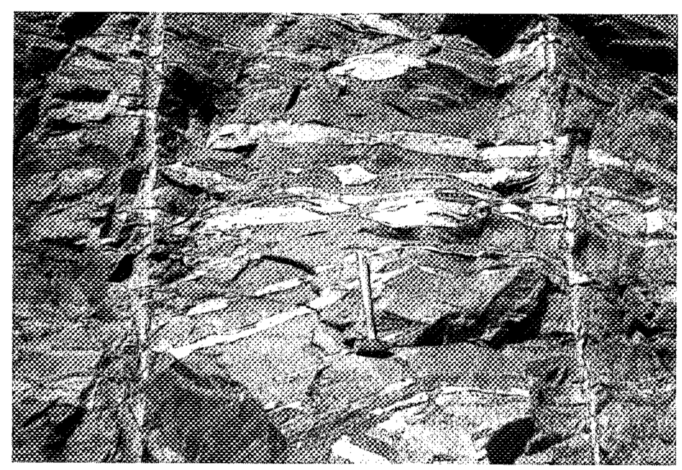


Figure 4.6. This migmatite is a mixed rock—part igneous and part metamorphic. The light layers are composed largely of quartz and alkali feldspar. The dark layers are composed of plagioclase feldspar, biotite, and quartz. The migmatite may have been formed when the rock was metamorphosed at such high 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.

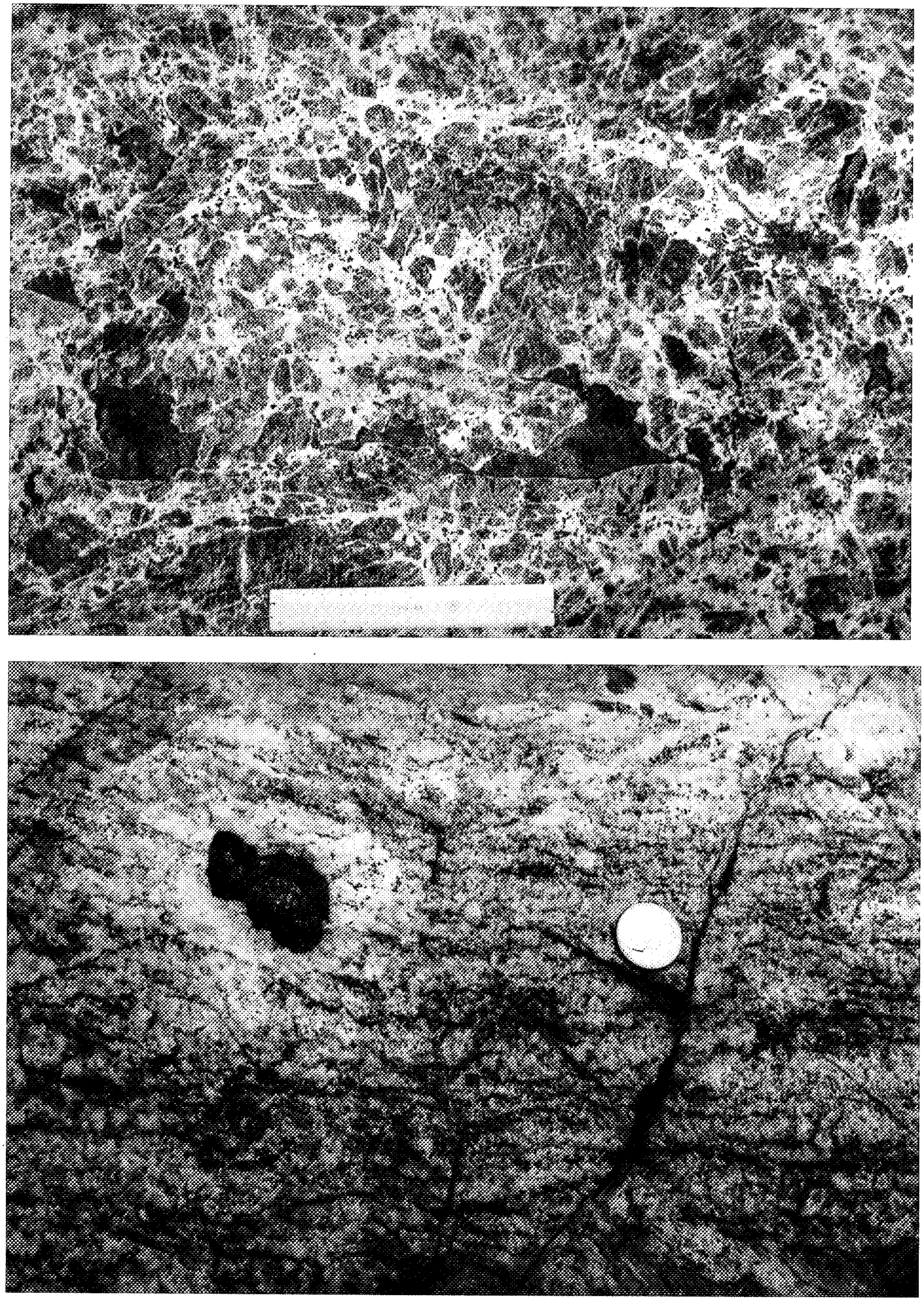
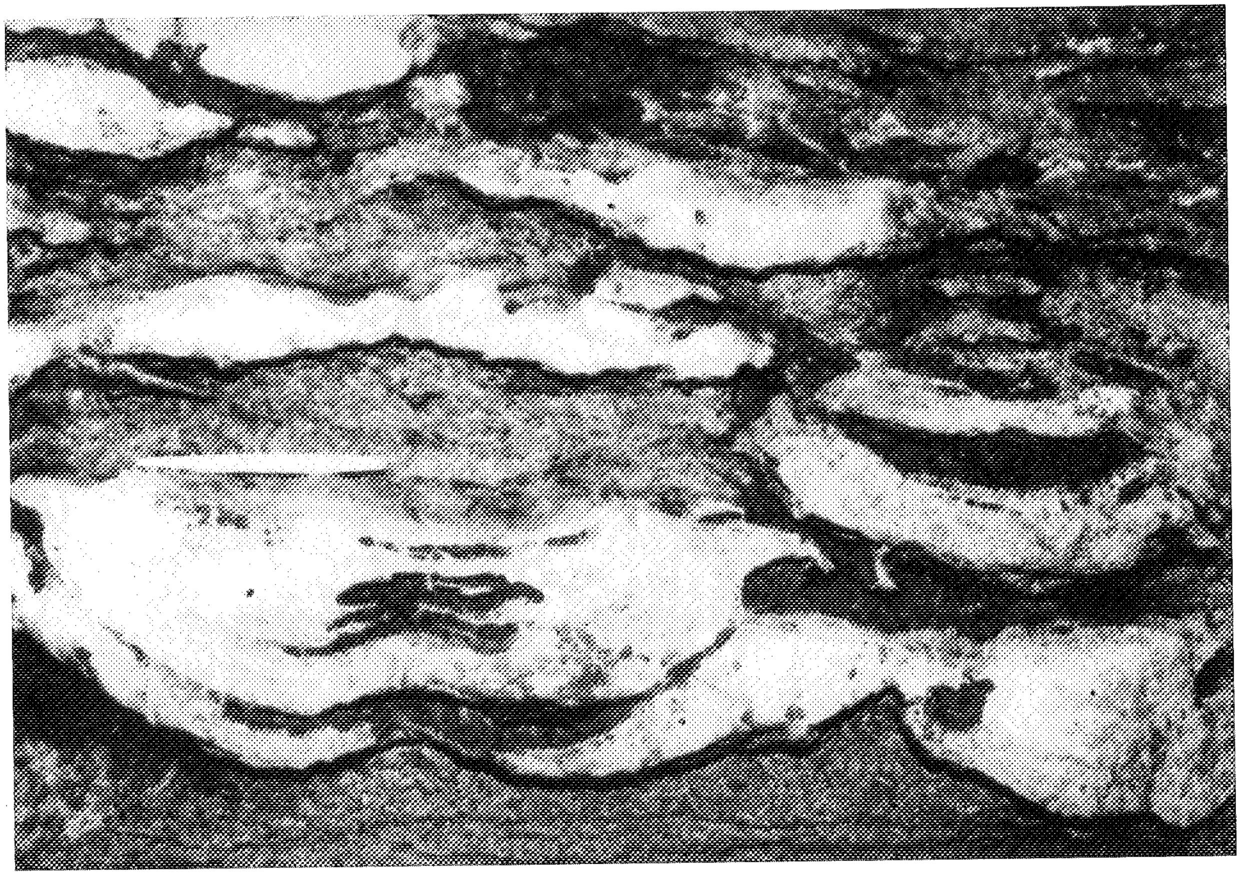


Figure 4.8. These two photos show Adirondack metanorthosite. The metanorthosite in (A) contains large crystals of plagioclase (medium gray), fine-grained plagioclase (white), and green pyroxene (dark gray). (The ruler is 15 cm long.) (B) shows strongly deformed metanorthosite. The layering is called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

A.



B.

C.

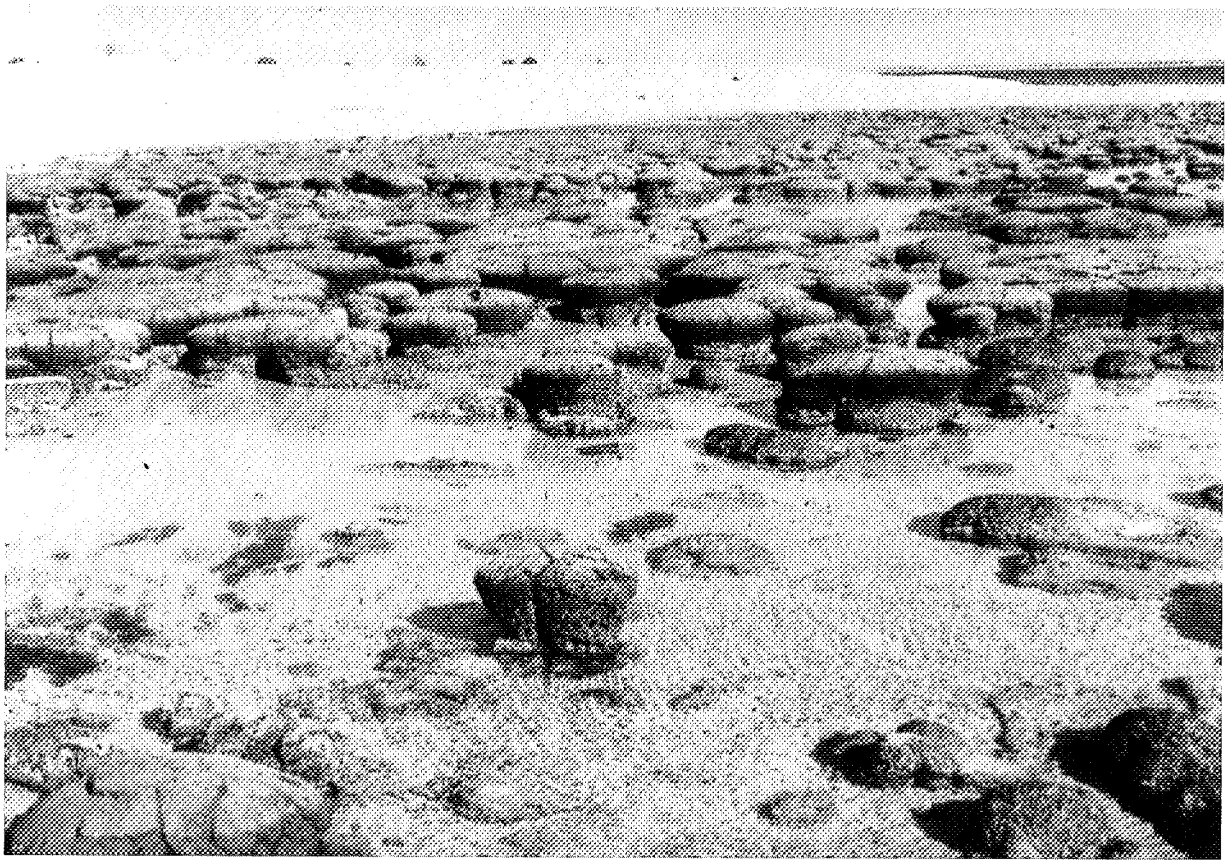


Figure 4.9. These photos show a side view (A) and an eroded bottom view (B) of fossil stromatolites found in marble in the Northwest Adirondacks. (C) shows modern stromatolites at Shark Bay, Australia. This picture was taken at low tide. When we compare the fossils in (A) with the modern stromatolites 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.

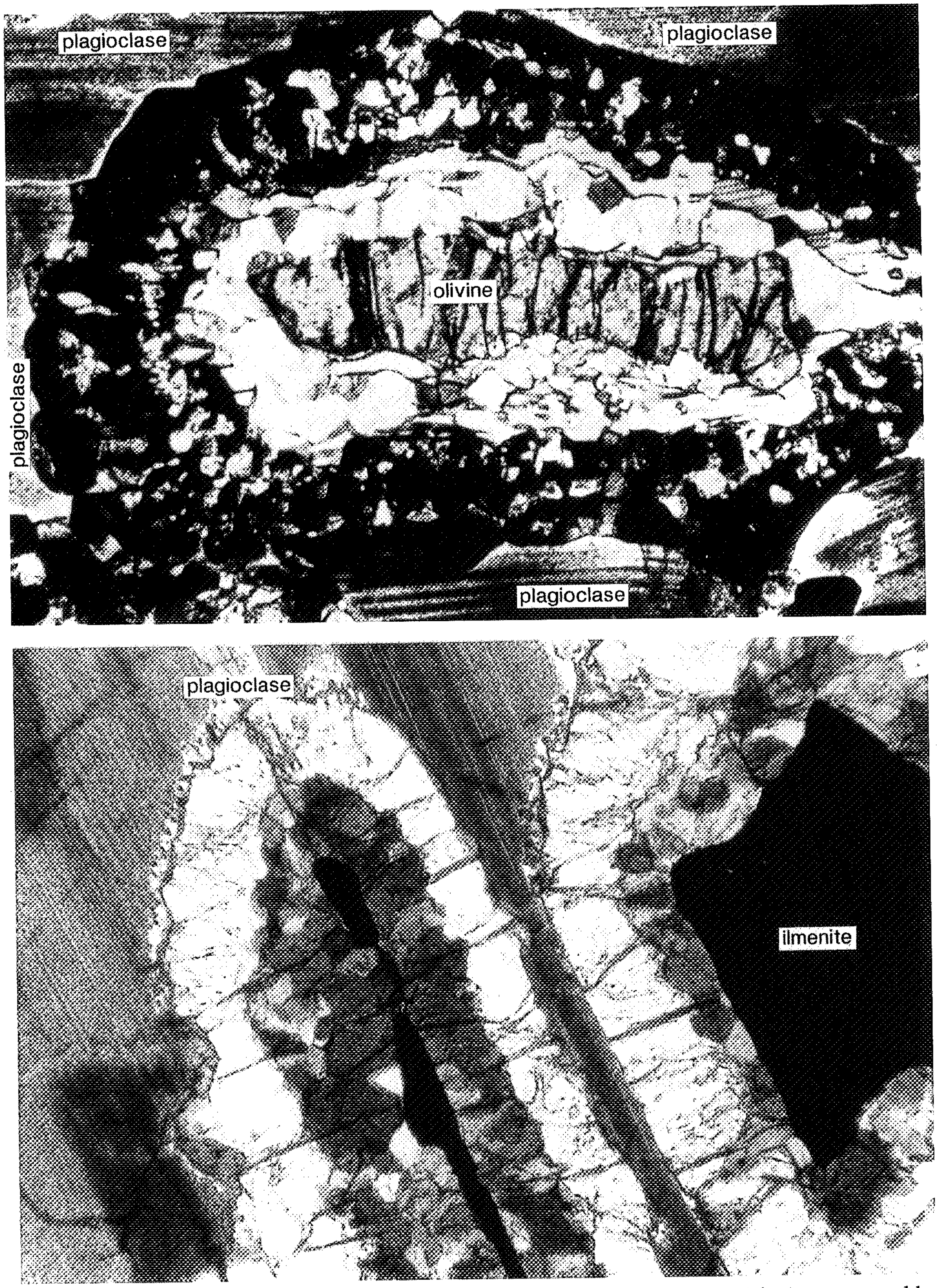
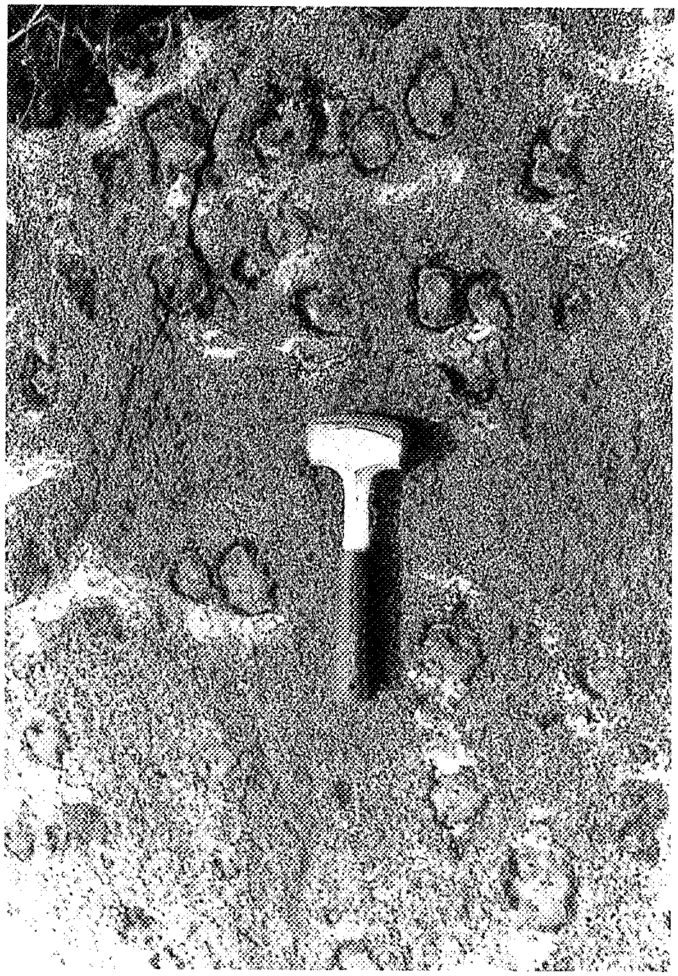


Figure 4.10. These two photographs are of paper-thin rock slices as seen under a special microscope used by geologists. The photos show rings of minerals (called *coronas*) that formed when the rocks were metamorphosed at very high temperatures and pressures. In (A), the original minerals in the rocks 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.

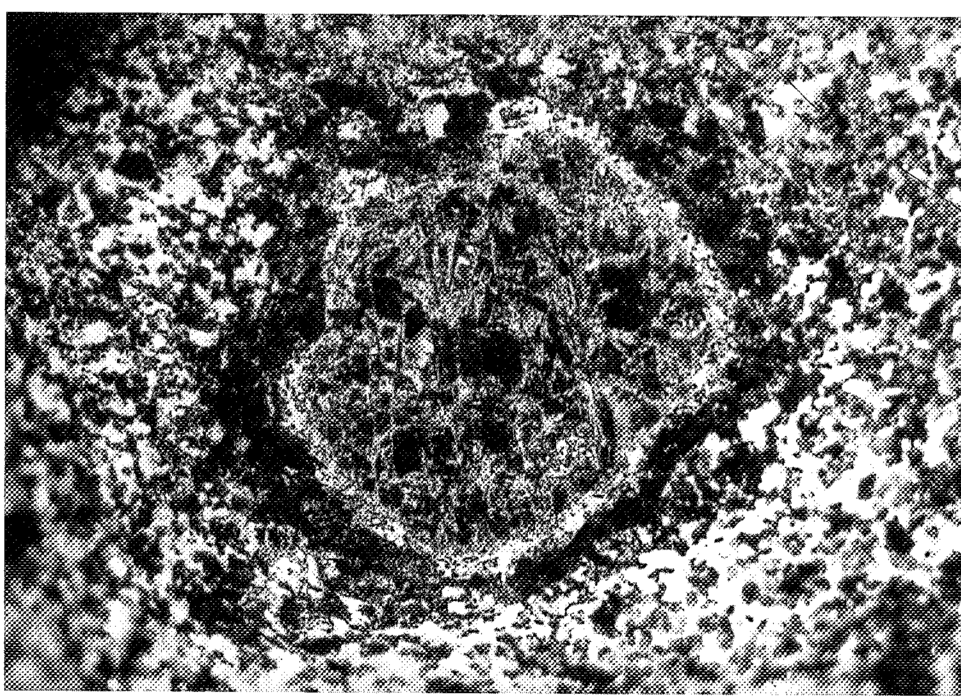


Figure 4.11. These photos are two views of unusually large Adirondack garnets. (A) shows garnets surrounded by rims of the mineral hornblende. The rock is olivine metagabbro. These garnets are found along Wall Street, near I-87, east of Chestertown, Warren County. (B) is a closeup of a single garnet 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. (B) is a close-up 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).

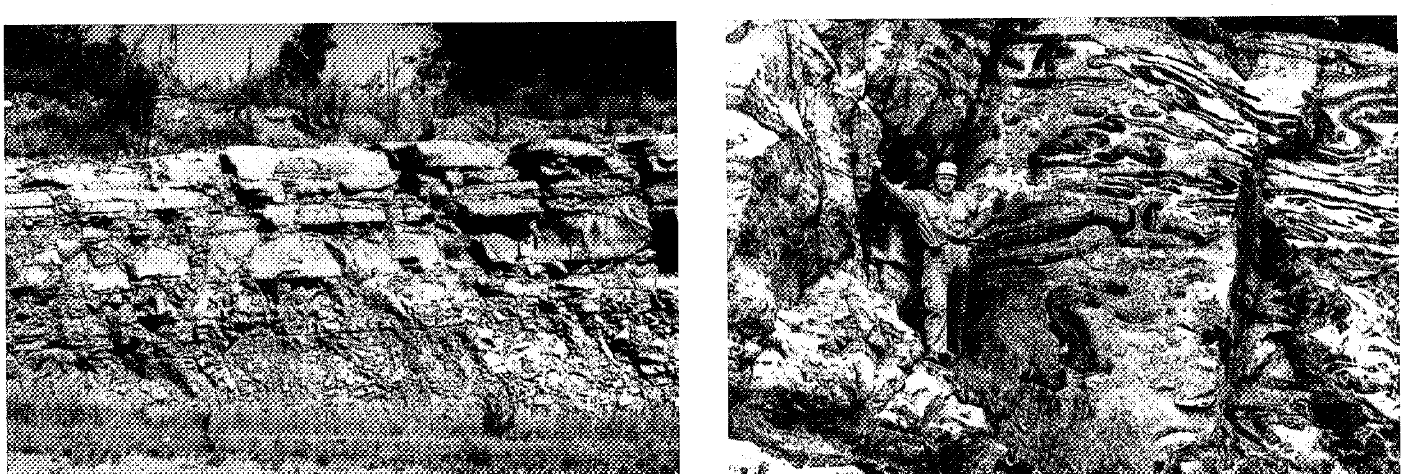


Figure 4.12. These two photos illustrate the kinds of dramatic effects of deformation and metamorphism that occurred during the Grenville Orogeny. The contorted layers in (B), found in the Adirondacks, once looked like the flat layers shown in (A), younger limestone beds of Ordovician age. The limestone 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.

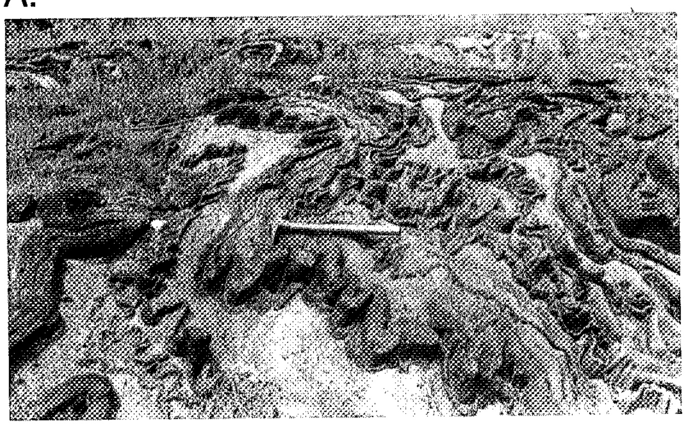
cult to say when the orogeny began. It was under way at least 1.1 billion years ago. The deformation and metamorphism appear to have peaked between 1.1 and 1.05 billion years ago. Some additional plutonic rocks may have been formed at the time, either by partial melting of the crust or by injection of 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

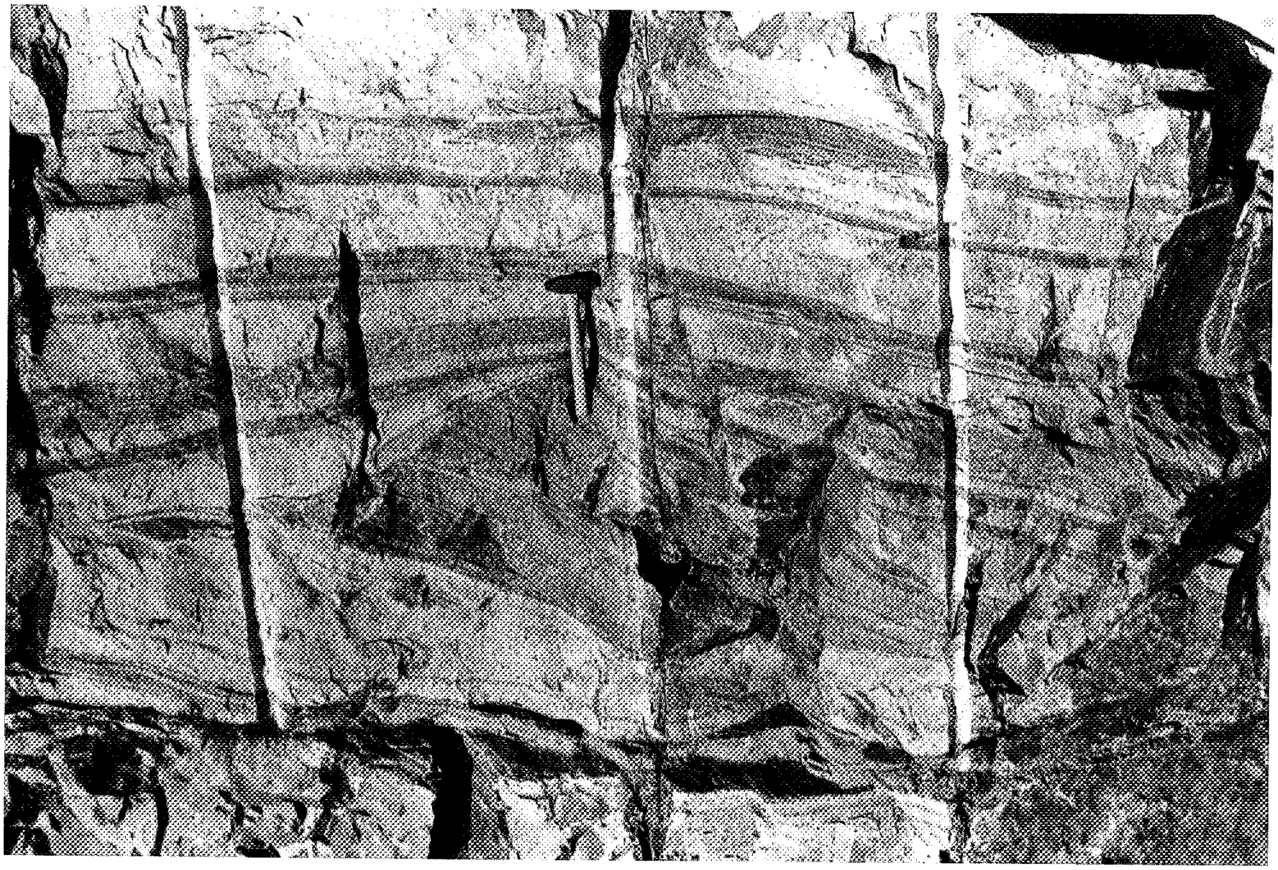
A.



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.

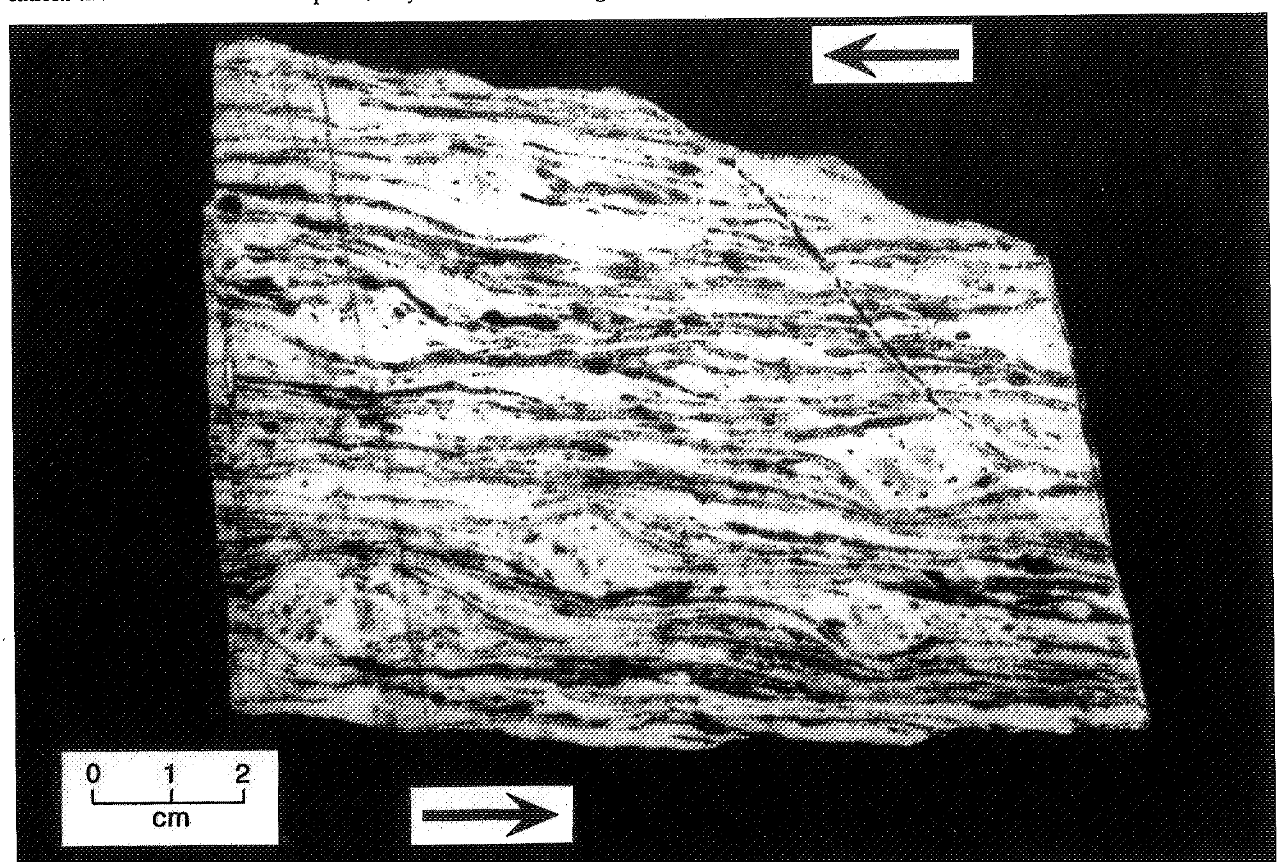


Figure 4.17. This photo shows an Adirondack mylonite. Mylonites are formed as minerals recrystallize in a ductile shear zone. This process makes the mineral grains in the rock much smaller. The large grains are made of the mineral feldspar. Their shapes tell us the directions of the deforming forces. 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.

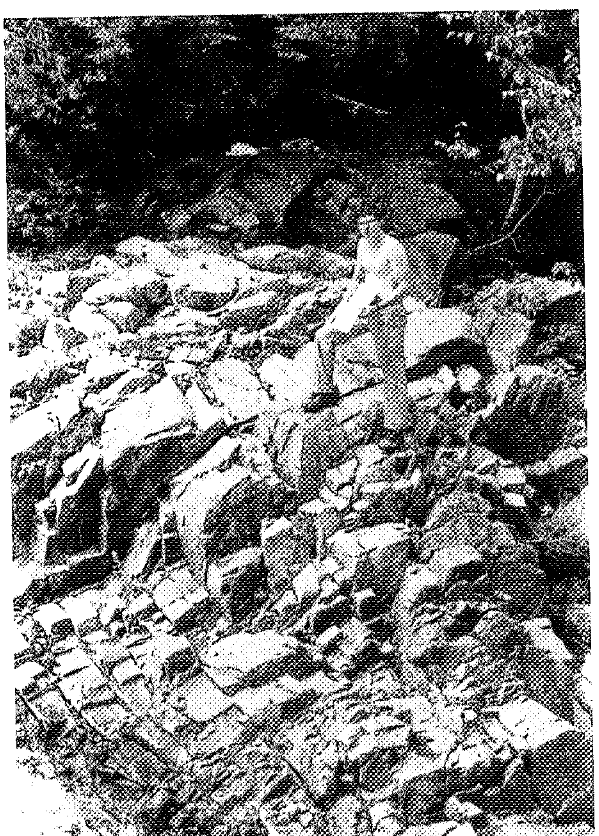
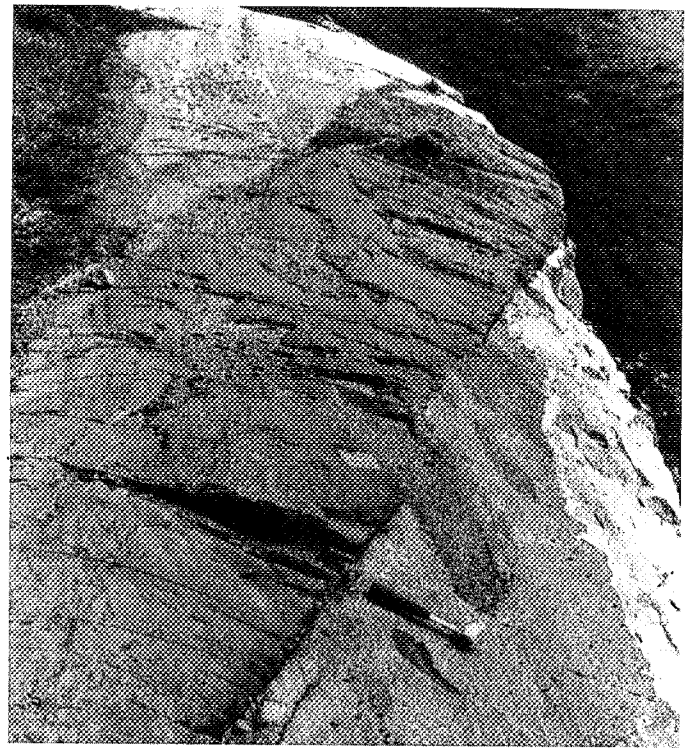


Figure 4.19. This photo shows a well exposed fracture zone at Split Rock Fall near Elizabethtown. Although the rock has shattered in place, it did not move along the zone. This fact makes a fracture zone different from a fault.

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.

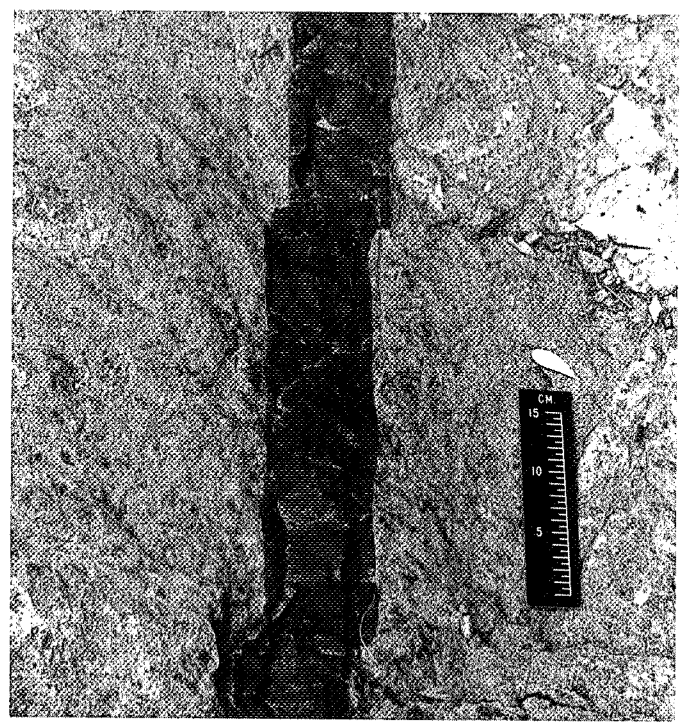


Figure 4.21. These three photos show *dikes* in the Adirondack region. These dikes formed when magma was pushed up from below and hardened. The dike in (A) is made of *pegmatite*, a very coarse-grained igneous rock, cutting across olivine metagabbro. The dike in (B) is the igneous rock *diabase* cutting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