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),

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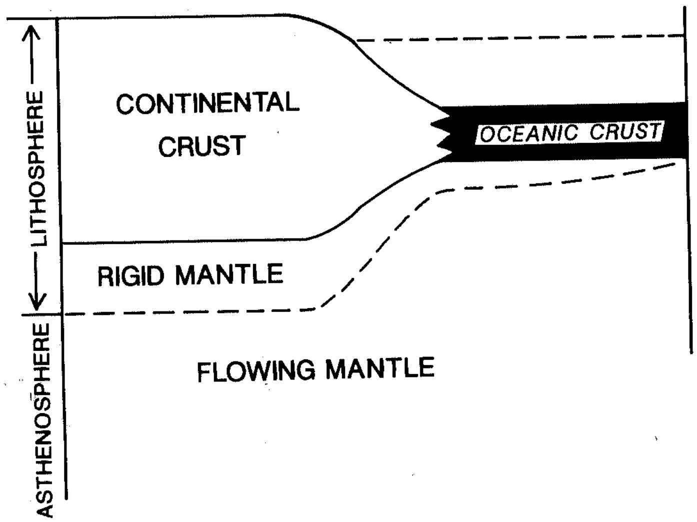


Figure 3.1. This diagram shows the general structure of the outer part of the earth. The outermost shell, the lithosphere, is made up of crust and rigid mantle. The asthenosphere below it is made up of flowing mantle. Notice that the light continental crust is much thicker and floats higher than the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

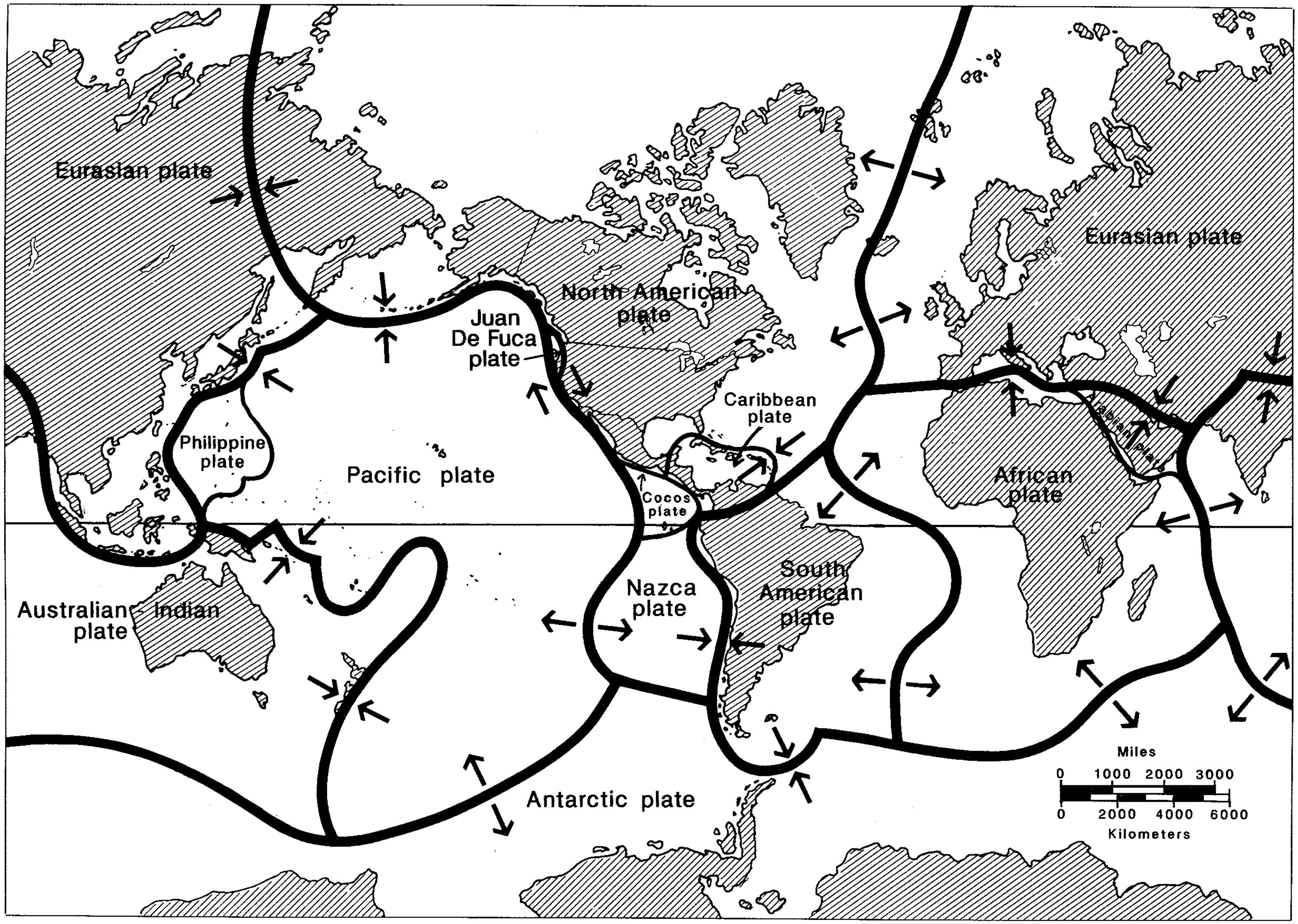


Figure 3.2. A simplified map showing how the lithosphere is broken into plates. The arrows indicate the relative movements between plates. The Juan De Fuca plate is moving toward North America.

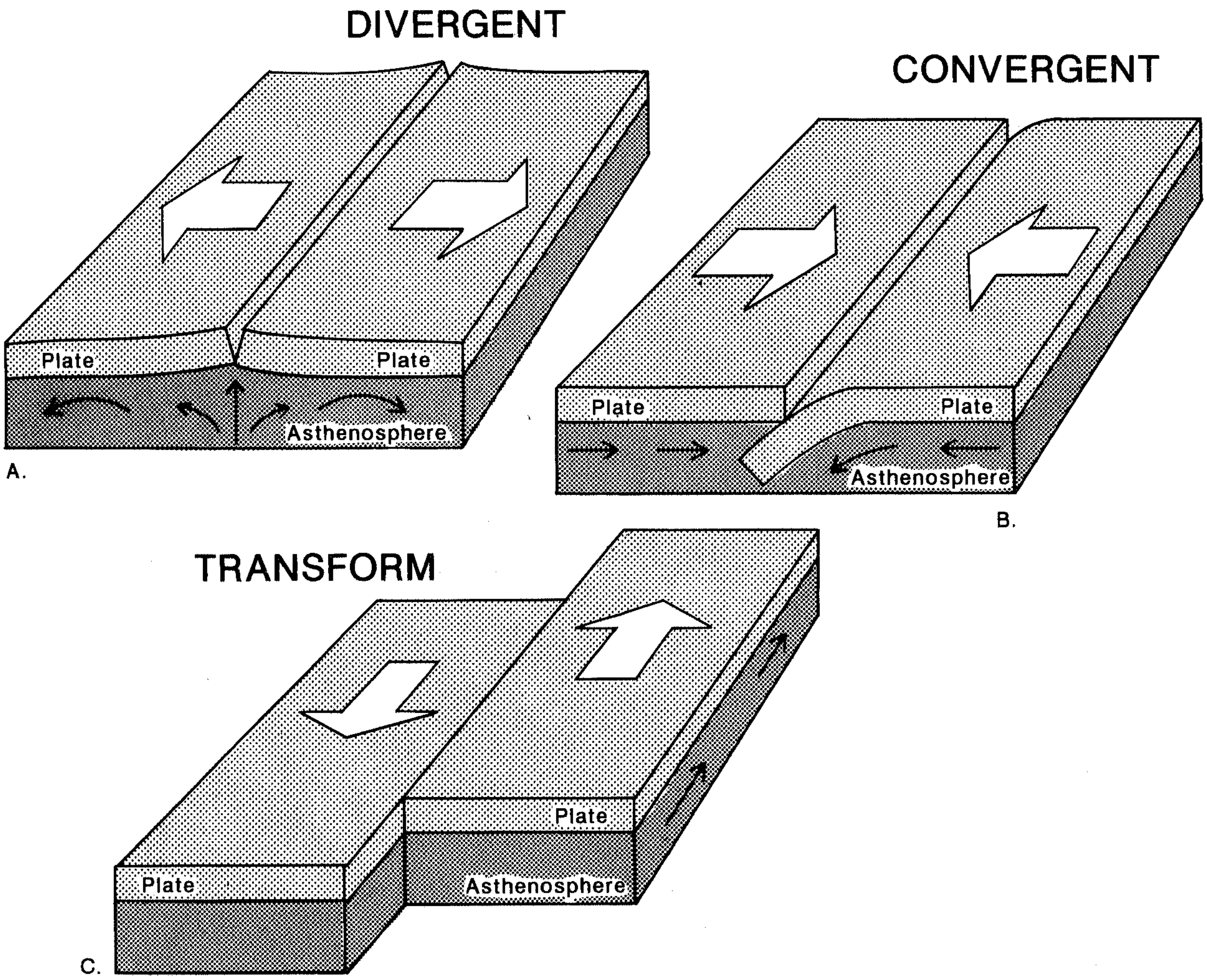


Figure 3.3. The three types of plate margins: (A) divergent; (B) convergent; (C) transform. The black arrows show the motion of convection currents in the asthenosphere.

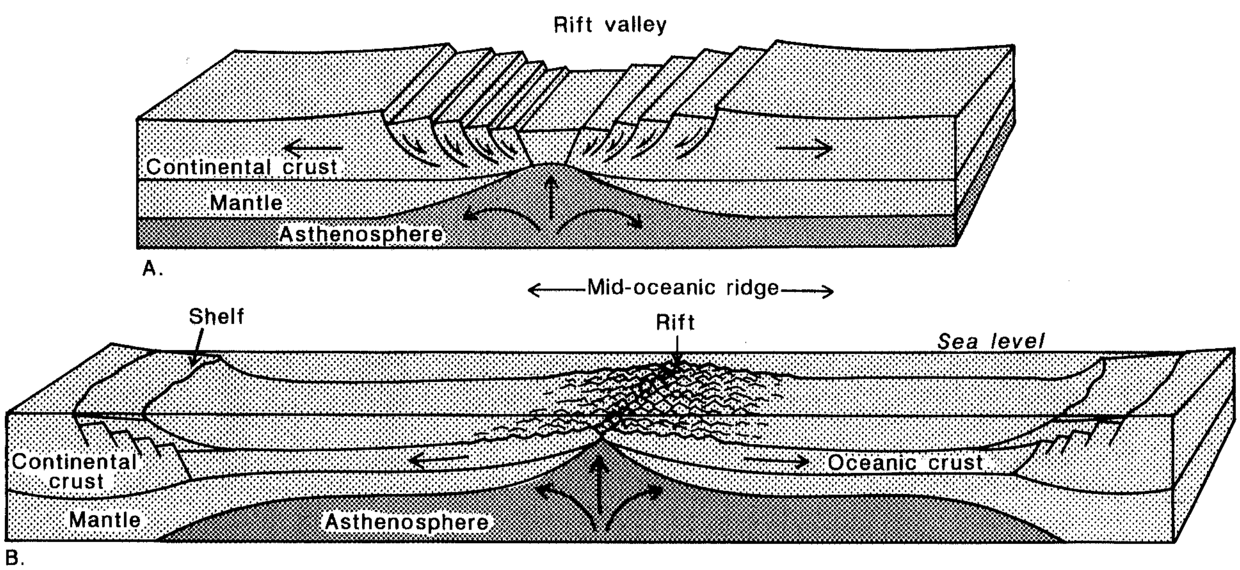


Figure 3.4. Two stages of rifting. In (A), the plate has begun to separate and a rift valley has formed. In (B), the rift has widened and become a new ocean basin between two new continents. Notice the mid-oceanic ridge in the basin.

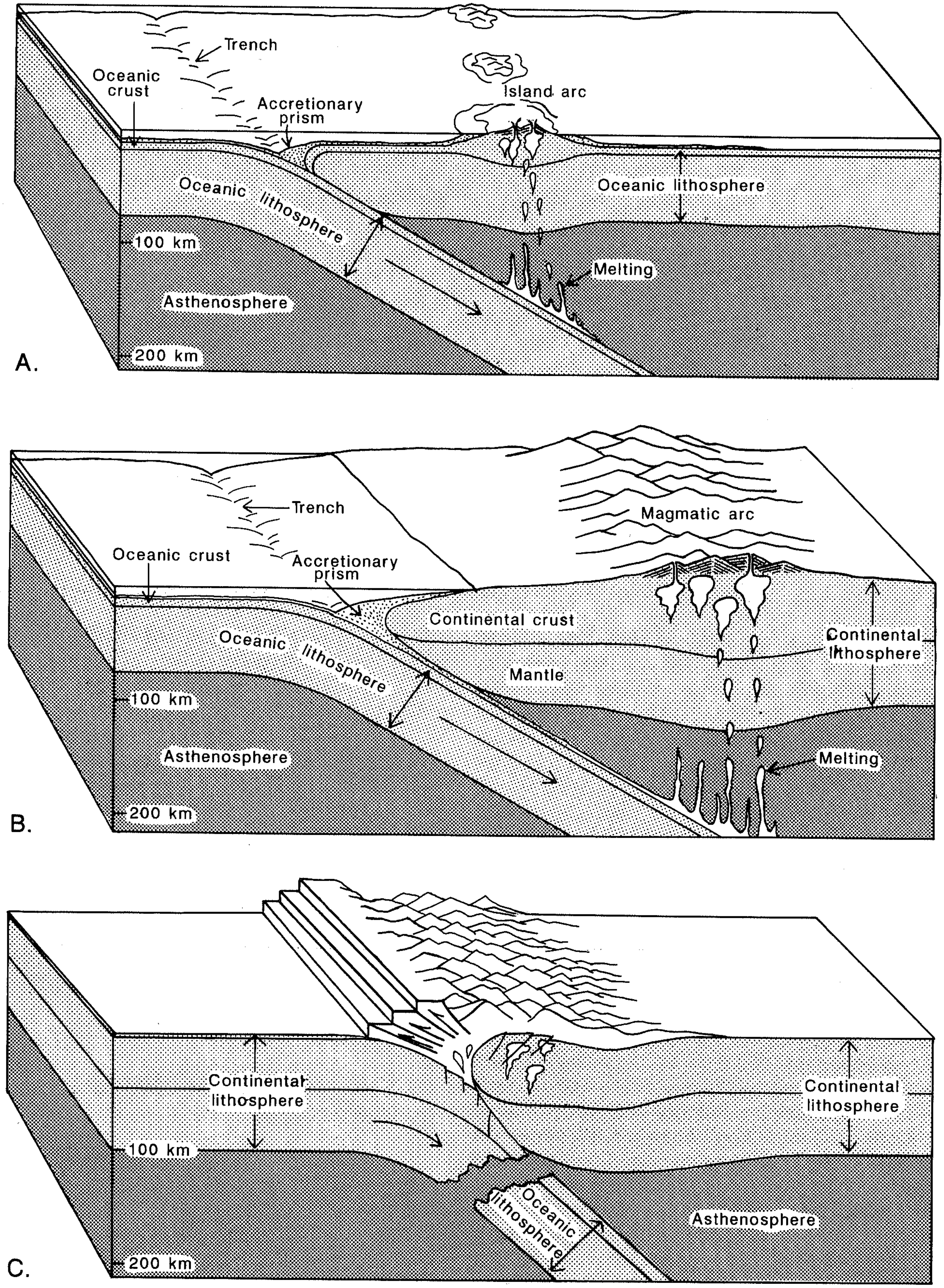
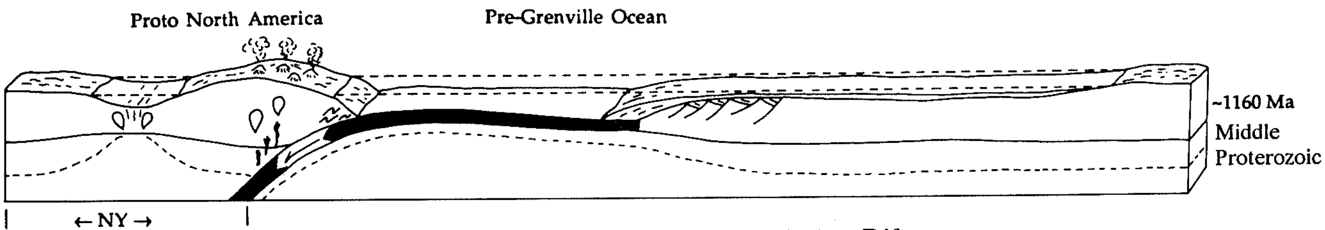
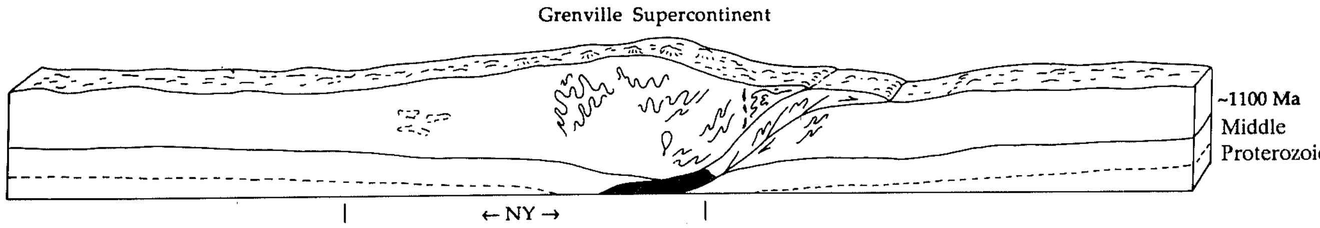


Figure 3.5. The three types of convergent margins: (A) ocean-ocean collision; (B) ocean-continent collision; (C) continent-continent collision. Notice that as the plates converge, the oceanic lithosphere is bent downward and is consumed in the asthenosphere.



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-

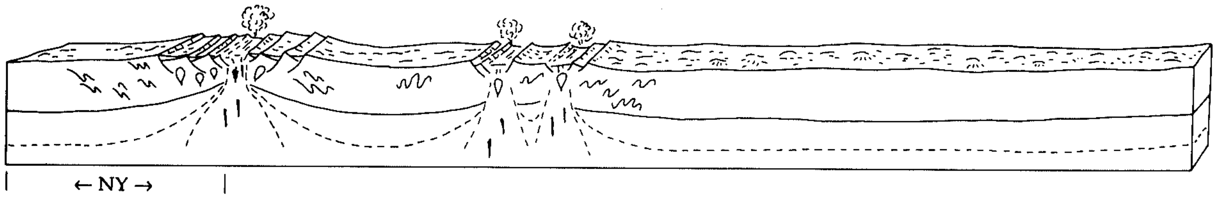


Figure 3.8. Block diagram showing the rifting of the Grenville supercontinent along the east coast of proto-North America.

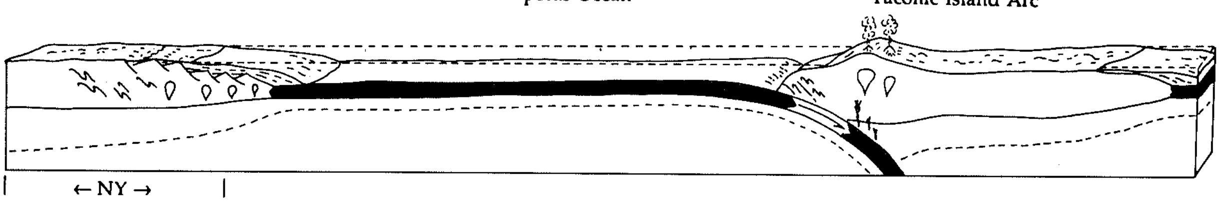


Figure 3.9. Block diagram showing the Taconic island arc approaching proto-North America as the western part of the Iapetus Ocean closes.

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

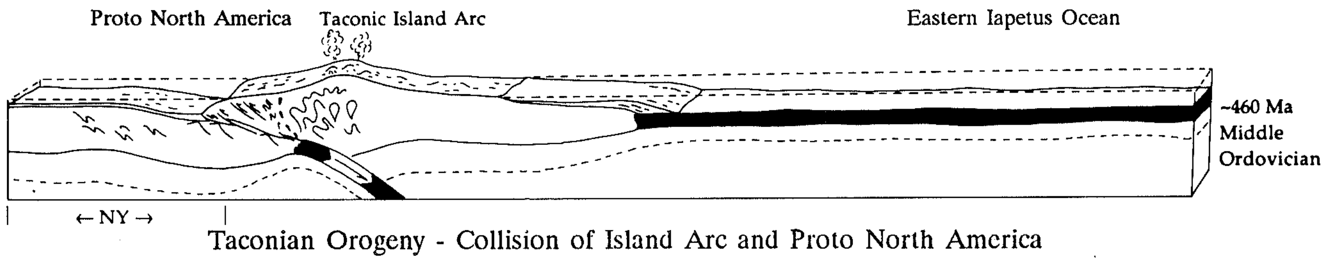


Figure 3.10. Block diagram showing the collision between the island arc and proto-North America. This collision is the Taconian Orogeny. Sediments eroded from the mountains built the Queenston Delta in western New York.

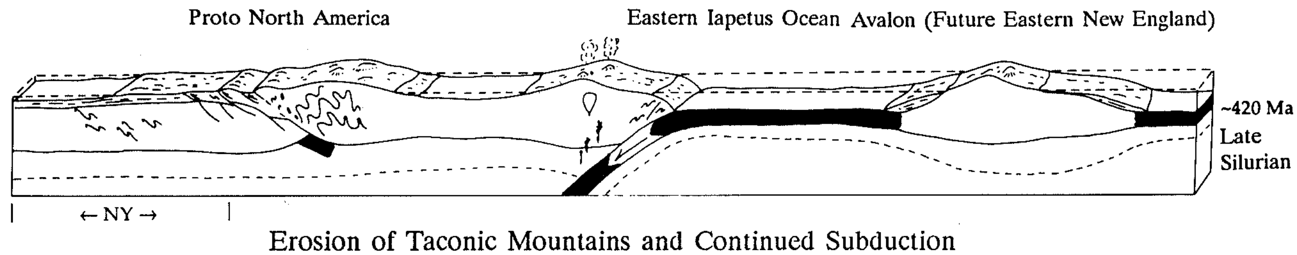


Figure 3.11. Block diagram showing the small continent of Avalon approaching proto-North America as the eastern half of the Iapetus Ocean closes.

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

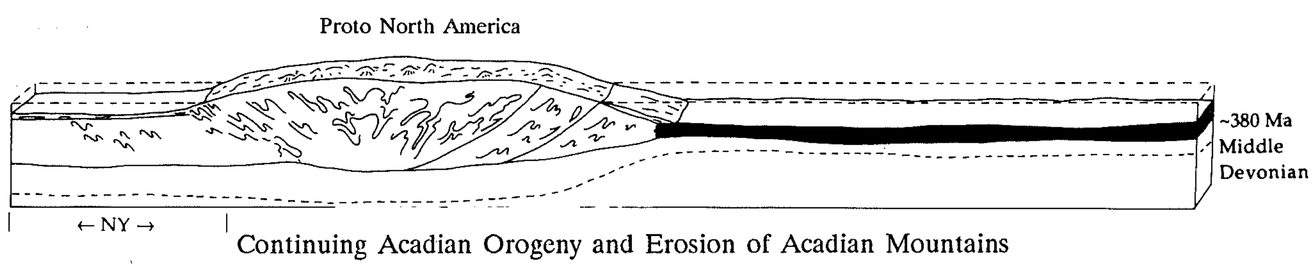


Figure 3.12. Block diagram showing the mountains built by the Acadian Orogeny—the collision between Avalon and proto-North America. Sediments eroded from the mountains built the "Catskill Delta" to the west of the mountains.

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

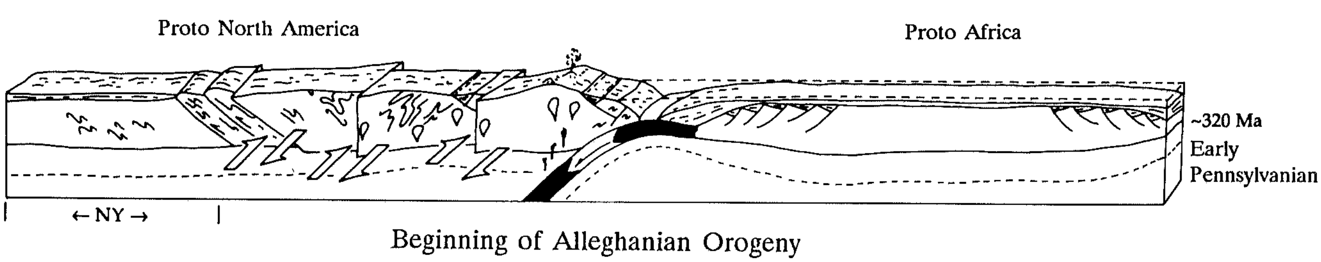


Figure 3.13. Block diagram showing proto-North America and proto-Africa colliding along a transform margin. This collision, the Alleghanian Orogeny, built the Appalachian Mountains.

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

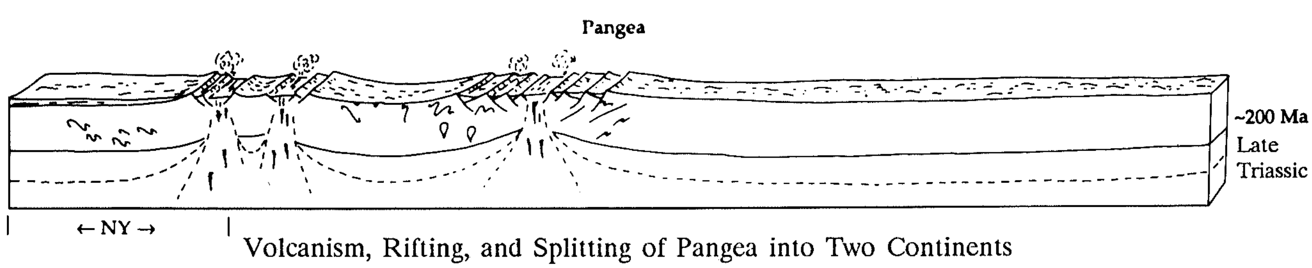


Figure 3.14. Block diagram showing the rifting of the supercontinent of Pangea. The Newark Basin is a rift formed at this time.