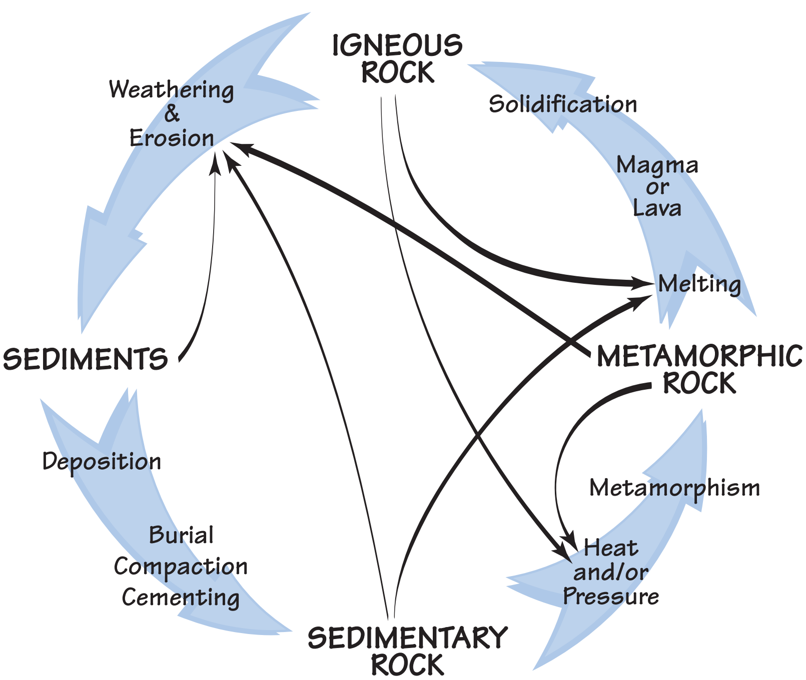
Rocks of the Northeastern US:
a brief review

There is an amazing diversity of rocks exposed at the surface in the Northeast. The rocks record a 1 billion year history of colliding plates, inland oceans, deposition, erosion, uplift, igneous intrusions and extrusions and glacial activity. The different rock types of the region influence the topography and tell us where to look for certain fossils and natural resources. The rocks exposed on the surface in the Northeast are there because of the unique geologic story of the region. Each type of sedimentary, igneous and metamorphic rock forms in a particular environment under particular conditions *(Figure 2.1)*.

Igneous Rocks of the Northeast

granite, *anorthosite*, *basalt*, *pegmatite*, *diorite*, *diabase*, *gabbro*



Sediments of the Northeast (not consolidated into rocks)

gravel, *sand*, *silt*, *clay*

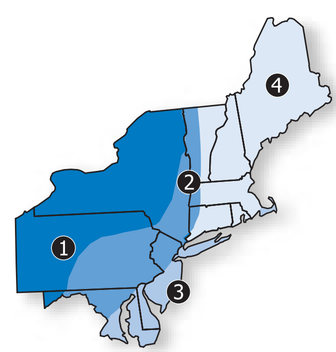
Metamorphic Rocks of the Northeast

slate, *schist*, *marble*, *serpentinite*, *phyllite*, *gneiss*, *quartzite*

Sedimentary Rocks of the Northeast

limestone, *sandstone*, *shale*, *coal*, *dolomite*, *siltstone*, *conglomerate*

Figure 2.1: The rock cycle.

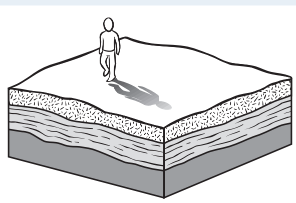


Sedimentary rocks form from the breakup of pre-existing rocks. Weathering and erosion by wind, water or chemical action breaks up sedimentary, igneous and metamorphic rocks to form loose sediments. Sediments are transported downstream by rivers and dumped into the ocean or are deposited somewhere along the way. Compaction of the sediments usually happens through burial by more sediments. As fluids work their way through the spaces between the sediments, cementing-minerals are left behind to form hardened sedimentary rocks: sandstones, siltstones and shales. Sedimentary rocks may also form by evaporation of water, leaving behind deposits of evaporites such as halite and gypsum. Deposits of calcium carbonate, usually formed through the accumulation of calcium carbonate skeletal material (such as clams and corals), create the sedimentary rocks limestone and dolostone.

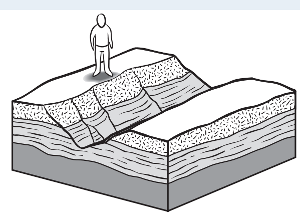
Sediments		**Sedimentary Rocks**	
gravel	→	*conglomerate*	Finer Grain Size ↓
sand	→	*sandstone*	
silt	→	*siltstone*	
clay	→	*shale*	
calcium carbonate	→	*limestone*	
calcium magnesium carb	→	*dolostone*	

Why do we see different kinds of rocks at the surface?

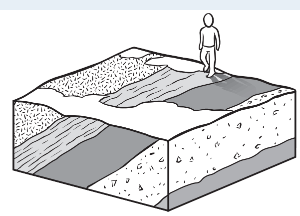
As you walk across the surface of the Earth, you will observe an amazing variety of rock types. If all rocks were flat-lying layers and there was no erosion, then we would only see one type of rock exposed on the surface. Often, though, rocks have been worn away (eroded) and now underlying layers are exposed at the surface. Layers of rock may also be tilted, folded or faulted to reveal underlying rocks at the surface. Figures by J. Houghton.



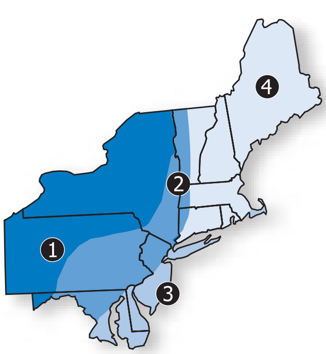
When rocks are flat-lying layers and there is no erosion, folding or faulting, the person walking across the surface sees only one rock type.



When rocks are worn away (often by streams), the person walking across the surface sees the underlying layers of rock exposed.



When rocks are folded or tilted, the person walking across the surface sees several layers of rock exposed.



Igneous rocks form from the cooling of hot molten rock. If the molten rock is below the surface, it is called magma. Rocks with large crystals indicate there was plenty of time for the crystals

Igneous Rocks

Magma *(large crystals)*		**Lava** *(fine crystals)*	
granite		*rhyolite*	*more iron & magnesium* ↓
diorite	*diabase*	*andesite*	
gabbro		*basalt*	
anorthosite			

to grow as the magma cooled slowly below the Earth's surface. Molten rock that breaks through the crust to the surface (usually through a volcano) is lava. Lava cools quickly as the heat escapes to the atmosphere, producing igneous volcanic rocks with very tiny crystals or no crystals at all.

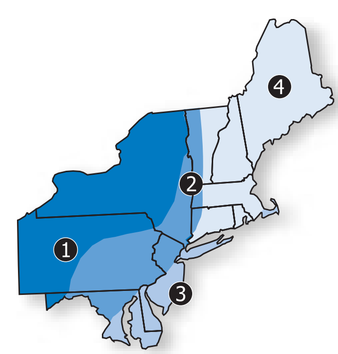
Metamorphic rocks form from pre-existing sedimentary, igneous and metamorphic rocks that are exposed to increases in temperature and pressure. This can occur from plate movements, very deep burial, or contact with molten rock. The minerals within the rock recrystallize and realign, forming a much harder rock. Some examples of metamorphic rocks are given below:

Parent Rocks		Metamorphic Rocks
shale	→	*slate*
slate	→	*phyllite*
phyllite	→	*schist*
peridotite	→	*serpentinite*
sandstone	→	*quartzite*
limestone	→	*marble*
anorthosite	→	*metanorthosite*
gabbro	→	*metagabbro*
granite	→	*gneiss*
shale/sandstone	→	*gneiss*

As you read through this chapter, keep in mind that you should be able to predict the type of rocks in any given region by understanding the events in geologic history that have affected the area. When the plates collided, the compression and friction melted the crust. The rising magma formed igneous intrusions that crystallized below the surface, producing igneous rocks with large crystals such as granite. The rising magma may have broken through the surface as volcanoes, creating volcanic rocks such as basalt. The colliding plates buckled the crust (creating metamorphic rocks), forming an ocean basin to the west of the mountains. The basin filled with shedding sediment from the newly-formed mountains, producing thick sequences of sedimentary rock. Where the plates diverged, as in the Triassic period when Pangea separated, the crust rifted in many places, creating basins filled with sediment that became sedimentary rock. The rifting gave rise to volcanic activity, creating volcanic rocks.

Bedrock vs. Surficial Sediments

The bedrock of the Northeast is covered with a thin layer of recently deposited sediments and soil. This chapter deals mainly with the older bedrock, formed over the last billion years. The bedrock links more closely with the events in geologic history discussed in the preceding chapter. Surficial deposits are discussed in more detail in the next chapter (Glaciers).



Rocks of the Inland Basin

Region 1

see Geologic History, p. 7 and 12 for **Taconic** *and* **Acadian** *events.*

Sedimentary rocks dominate the Inland Basin because the area was covered by the ocean for tens of millions of years: first in the Cambrian when global sea level was high and the ocean stretched far inland over most of the Northeast, and later during the ***Taconic*** and **Acadian** mountain-building periods (Ordovician through Devonian) when an inland ocean existed west of the new mountain ranges. The basin of the inland sea formed by the buckling of the crust from the compression of plates during the mountain-building events. Conglomerates, sandstones, siltstones, shales, limestones and dolostones are common rocks formed in these oceans and the bordering environments such as deltas, swamps, mud flats and tidal areas.

Why are there different sedimentary rocks in different environments?

As mountainous highlands erode, sediments are transported down the mountain by gravity and streams. The sediments that have only been transported a short distance and have not undergone considerable weathering, form conglomerates when compacted and cemented. Conglomerates are made of poorly sorted sediments, containing large pebbles of rock as well as finer sediments in between, typical for a deposit that occurs close to the source of erosion. If the sediments are transported a bit farther before being deposited and undergo more wearing down along the way, the sediments become rounded, smaller, and better sorted, as all of the larger grains drop out of the slowing water. If you examine sediments from the beach out to deep ocean, you will notice that beach deposits (and river deposits) are mainly sandy, followed by finer grained silts in deeper water, and very fine-grained clay in the deepest water above which currents may be slow enough to permit such small particles to settle. Limestones tend to accumulate where the rate of sediment being eroded from the highlands is low enough not to dilute accumulation of the calcium carbonate shell material that forms limestone. Many organisms that secrete calcium carbonate shells thrive ecologically in the clear water. In a shallow continental sea, low rates of sedimentation and clear water may be reached further from shore where sediment derived from land has settled out. Thus, the typical sequence of rocks formed across a shallow continental basin at any given time begins with conglomerate near the source, and sandstone, siltstone, shale and reefy limestone forming farther out.

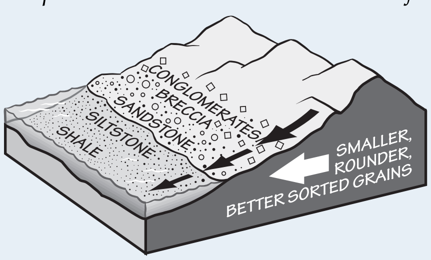
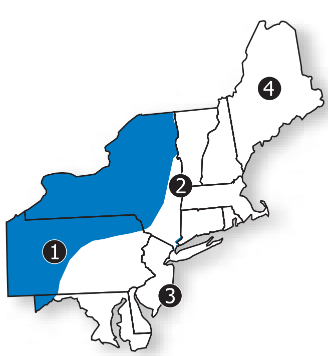
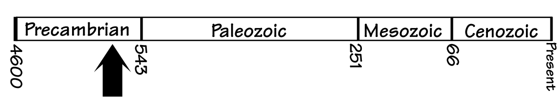


Figure by J. Houghton.



Precambrian Adirondack Rocks:



The Adirondack region of New York is composed of many types of billion-year-old rocks, all of which were metamorphosed as a result of the Grenville Orogeny. These ancient metamorphosed rocks are an anomaly in the basin region, which is dominated by sedimentary rocks. Grenville-aged rocks that were originally sandstones, limestones and shales deposited in a warm, shallow ocean at the eastern margin of proto-North America, make up the bulk of the resistant rocks of the Adirondacks *(Figure 2.2)*. These are the oldest rocks found at the surface in the Northeast. As Baltica approached North America for the first time (in the Late Precambrian), the Grenville belt of sedimentary rocks was squeezed and pushed up onto the margin of proto-North America, forming the Grenville Mountains. During the intensity of the squeeze, the sedimentary rocks were metamorphosed. Sandstone became quartzite, gneiss or schist; limestone became marble; and shale became gneiss and schist.

There are other types of rocks exposed in the Adirondack region as well. During the Grenville mountain-building event, magma created by the friction between the converging plates was rising up into the overlying crust. The blobs of magma rose higher, pushing through overlying sedimentary rocks. The blobs eventually cooled and crystallized, forming igneous rocks such as granite, ***anorthosite*** and, less commonly, gabbro. As the Grenville Orogeny continued, the cooled igneous blobs and the sedimentary rocks of the Grenville Belt were buried under as much as 30 kilometers of crust! With that much crust overhead, the pressure and temperature on the buried rocks was extremely high, causing further **metamorphism**. The granites became gneiss; gabbros became metagabbro; and the anorthosite became metanorthosite. The intensity of the Grenville mountain-building event also sheared the rock as blocks of crust slid past each other in opposite directions. This is most evident in a band of rocks called mylonites in which minerals were compressed and recrystallized upon shearing.

For millions of years following the Grenville mountain-building event, the Grenville Rocks that stretch from Canada to Mexico were worn down and buried by layers of sedimentary rock. Grenville-age rocks are present in many other parts of the Northeast, but are generally deeply buried by younger overlying sedimentary rocks. In the Adirondack region, the Grenville rocks are exposed because of an uplift of the crust that occurred only 10-20 million years ago during the Tertiary period.

The Adirondacks, though composed of billion-year-old rocks, are actually relatively young as mountains. Their exact mode of formation is still debated. Some geologists think that the crust was uplifted because of a hot spot beneath the crust caused by plumes of magma rising from the asthenosphere. As the magma rose, the crust was pushed upwards, forming a dome. The softer

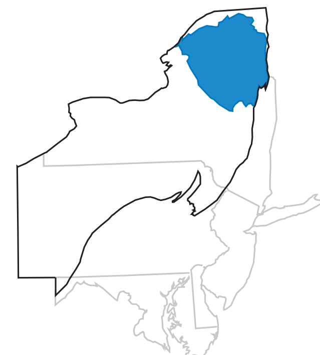
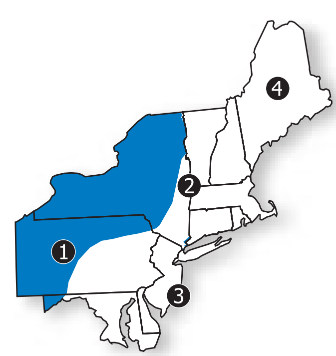


Figure 2.2: Precambrian Adirondack rocks exposed in the Inland Basin.

Anorthosite *is an igneous rock made almost entirely of the mineral feldspar.*

What happens to a rock when it is metamorphosed?

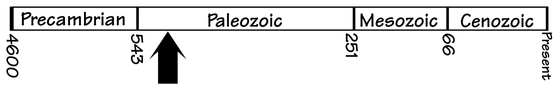
When sedimentary or igneous rocks are subjected to increased temperatures and pressures, they are altered to become metamorphic rocks and exhibit characteristic metamorphic textures such as foliation and recrystallization. As pressure increases, usually by the weight of overlying layers or the compression of colliding plates, foliation occurs whereby minerals in the rock align themselves to the pressure, creating parallel layering. Foliation is obvious in rocks such as gneiss and schist. Recrystallization of rocks is seen in marble and quartzite, as the rock is heated to high temperatures. Individual grains of sediment making up the original rock recrystallize to form a more solid rock with interlocking crystals.



Many of the Grenville igneous and metamorphic rocks are resistant and are being eroded very slowly. In fact, the Adirondack region is still being uplifted today about 2 mm/yr, a rate faster than the mountains can erode in some places.

sedimentary rocks on top of the dome were uplifted, fractured, and eroded away quickly, exposing the underlying Grenville rocks.

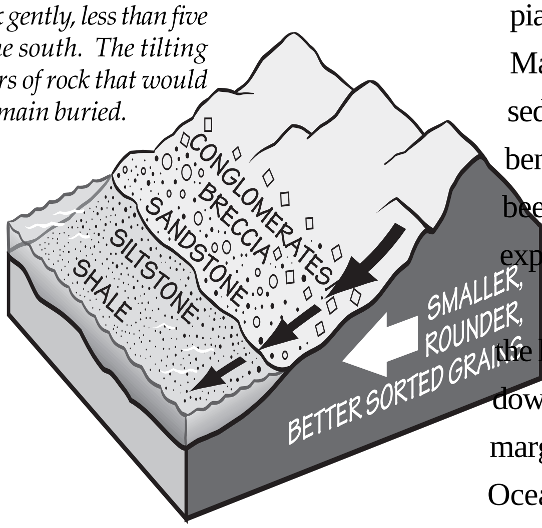
Cambrian-Ordovician Rocks



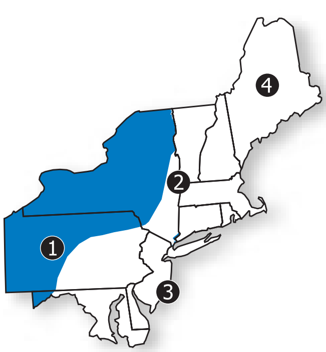
The remaining rocks exposed in the Inland Basin are sedimentary rocks. As you move from north to south on the geologic map of the basin, you will notice that the exposed surface rocks become younger *(Figure 2.3)*.

Cambrian and Ordovician rocks are exposed in northernmost New York and in patches around the Adirondack dome, followed by a thin stripe of Silurian rocks to the south. Most of the southern tier of New York and northern Pennsylvania exposes Devonian sedimentary rocks, followed by exposures of Mississippian, Pennsylvanian and Permian rocks continuing south into Maryland. These rocks were at one time flat-lying layers of sedimentary rock, with the Cambrian rocks lying unseen beneath overlying younger rocks. The layers, however, have been tilted very gently a few degrees to the south and eroded, exposing the underlying older rocks.

Figure 2.3: The east-west stripes of rocks in the Inland Basin occur because of the shallow angle of the rock layers. Regional compressional stress from mountain building tilted the layers of sedimentary rock gently, less than five degrees to the south. The tilting exposes layers of rock that would otherwise remain buried.



When the Grenville mountain building finally subsided in the late Precambrian, a period of erosion followed that wore down the ancient Grenville Mountains, which stretched up the margin of North America. During this period, the Iapetus Ocean opened and widened as Baltica separated once again from North America. Rifts developed in the crust during this separation, creating small basins of down-dropped blocks of crust. Cambrian sedimentary rocks from the eroding Grenville highlands are preserved in the rift basins. The rift basins appear in patchy areas around the Adirondack dome. Globally, sea level rose during the late Cambrian, covering most of the Northeast with a shallow ocean *(Figure 2.4)*. Sedimentary rocks



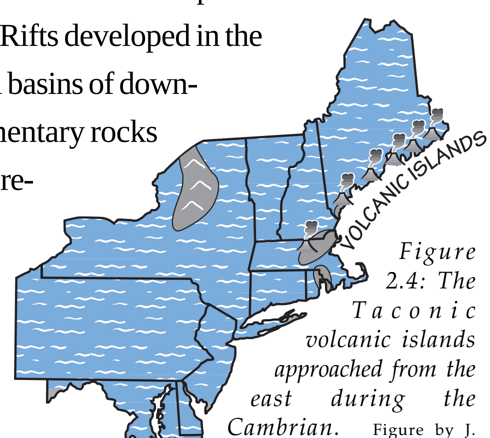


Figure 2.4: The Taconic volcanic islands approached from the east during the Cambrian. Figure by J. Houghton, after *Geological Highway Map of the Northeastern Region, no. 10*, American Association of Petroleum Geologists, 1995.

formed from the sediments eroded from land to the west.

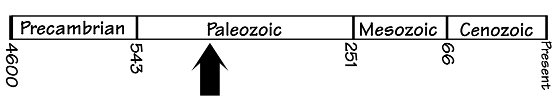
Most of the early Ordovician produced similar deposits to the Cambrian *(Figure 2.5)*. Sea level remained high and the rocks formed were predominantly limestone and dolostone, common in warm, shallow, sediment-starved seas. As sea level dropped later in the Ordovician, these sedimentary rocks were subjected to intense erosion.

Figure 2.6: The Taconic volcanic islands collided with the margin of North America, forming an inland ocean. Figure by J. Houghton, after *Geological Highway Map of the Northeastern Region, no. 10*, 1995.

Towards the end of the Ordovician, volcanic islands that had formed along the subduction zone between North America and Baltica, moved towards the margin of North America. Layers of ash resulting from the volcanic activity to the east were deposited in the basin and can be seen today preserved within the rocks of the Inland Basin. The volcanic islands collided with North America to form the Taconic Mountains and buckled the crust to the west of the mountains, forming an ***inland*** ocean.

Sediment tumbled down the mountain flanks carried by streams westward into the inland ocean, forming the Queenston Delta *(Figure 2.6)*. Close to the highlands, conglomerates formed. Deltaic streams brought sandy, muddy sediments downstream towards the inland ocean basin to form sandstone, siltstone and shale. Settling within the inland ocean, sediments were compacted and cemented to become sedimentary rocks that stretch across to the western border of New York and Pennsylvania.

Silurian Rocks

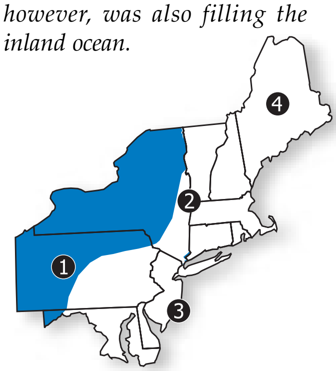


The Silurian rocks exposed east to west across the middle of New York record the continuing story of the inland ocean. Sedimentary rocks were still forming with the rise and fall of ***sea level*** in the inland ocean. During the late Silurian, the ocean became extremely shallow in the Northeast. Sediments in the ocean were exposed as mudflats and rapid evaporation of the shallow seas led to

Figure 2.5: Cambrian and Ordovician rocks exposed in the Inland Basin.

For millions of years during the Paleozoic, an **inland ocean** *existed on the eastern half of North America as an extension of the Iapetus Ocean, filling the basin formed by the mountain-building events with sea water. The inland ocean was separated from the Iapetus Ocean by the Taconic and Acadian Mountains.*

Sea level *rose and fell in the inland ocean during the Paleozoic, in part because the convergence of the plates carrying North America and Baltica continued to buckle the inland basin, deepening the ocean. Sediment eroded from the mountains, however, was also filling the inland ocean.*



the formation of evaporites *(Figure 2.7)*.

Much of the sediments deposited in the earlier Silurian were quickly eroded away when exposed above sea level. The rate of deposition of sediments was also slower during the Silurian because the majority of the Taconic Mountains had already been worn down by this time. As a result, relatively little sediment was preserved as rock in the Silurian, and they are therefore represented by only a thin stripe on the geologic map *(Figure 2.8)*.

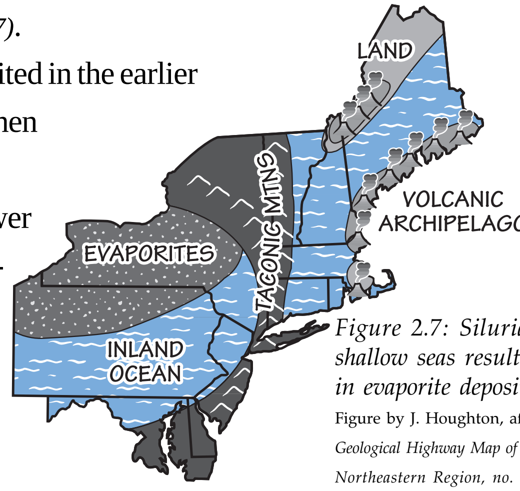
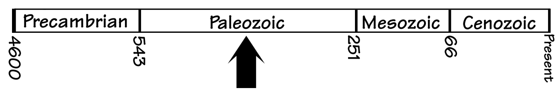


Figure 2.7: Silurian shallow seas resulted in evaporite deposits. Figure by J. Houghton, after *Geological Highway Map of the Northeastern Region, no. 10*, 1995.

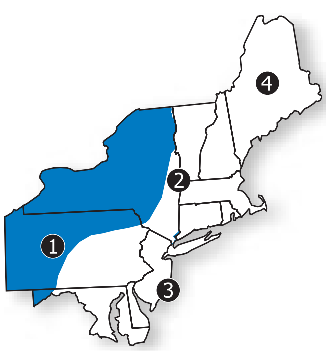
Figure 2.8: Silurian rocks exposed in the Inland Basin.

Devonian Rocks



Devonian-aged rocks are exposed across southern New York and northern Pennsylvania *(Figure 2.9)*. These sedimentary rocks record the Acadian mountain-building event as North America collided with Baltica. The formation of the Acadian Mountains was similar to the formation of the Taconic Mountains. Just as the Taconic mountain building during the Ordovician had formed an inland ocean and the westward spreading Queenston Delta, Acadian mountain building renewed the inland ocean by buckling the crust downward and forming a westward spreading Catskill Delta *(Figure 2.10)*. As one would expect, the rocks of the Devonian period produced during the Acadian orogeny are similar to the rocks of the earlier Ordovician period produced during the Taconic orogeny. Conglomerates were formed close to the Acadian highlands, and finer grained sediments spread westward to form sandstone, siltstone and shale. At times, when the amount of sediment being deposited from

Figure 2.9: Devonian rocks exposed in the Inland Basin.



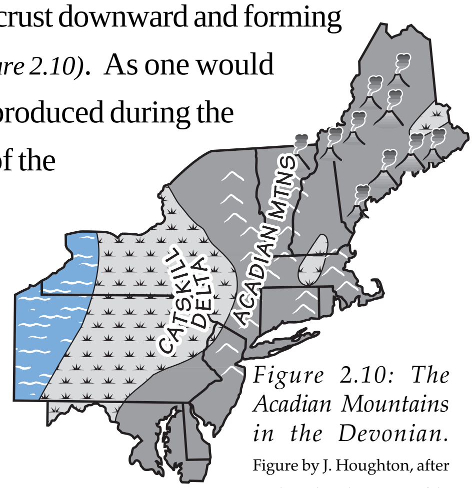
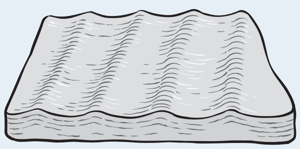


Figure 2.10: The Acadian Mountains in the Devonian. Figure by J. Houghton, after *Geological Highway Map of the Northeastern Region, no. 10*, 1995.

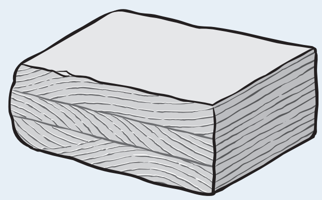
the highlands decreased, limestone and dolostone formed as well. The Acadian highlands eroded rapidly, providing huge amounts of sediments to be deposited on the Catskill delta and into the inland ocean that were preserved as a thick sequence of Devonian-age sedimentary rocks.

Sedimentary Structures

Upon close examination, the Devonian rocks of the Inland Basin often reveal the type of environment in which they formed by the presence of sedimentary structures within the rock. Sedimentary structures include ripple marks, cross-beds, mud cracks, and even rain drop impressions. Consider the type of environment in which you see these sedimentary structures today in the world around you. Figures by J. Houghton.

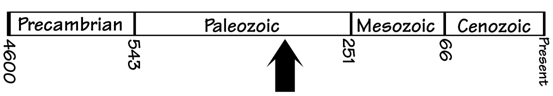


Ripple marks suggest the presence of moving water (though wind can also create ripples and even dunes). Mudcracks indicate that the sediment was wet but exposed to the air to dry and crack.



Cross-beds form as flowing water pushes sediment downstream, creating thin beds that slope gently in the direction of the current as migrating ripples. The downstream slope of the ripple may be preserved as a thin layer dipping in the direction of the current, across the natural flat-lying repose of the beds. Another migrating ripple will form another layer on top of the previous.

Mississippian Rocks



During the Mississippian and Pennsylvanian period, the Inland Basin region was still an inland sea environment, with sediment being shed into the basin from the Acadian highlands in the east *(Figure 2.11)*. Gradually, the amount of incoming sediment into the basin declined. The shoreline of the inland sea moved back and forth across the basin as sea level rose and fell during this period. The fluctuating water levels created alternating sequences of marine and non-marine sedimentary rocks, characterized by red and gray colors *(Figure 2.12)*. Limestones were also forming in the inland sea in areas receiving very little sediment. The Northeast was still located along the equator at this time, so the warm climate created lush vegetation. Large swamps covered the shoreline areas of the inland sea. Plant material in the swamps died and accumulated as thick piles of peat.

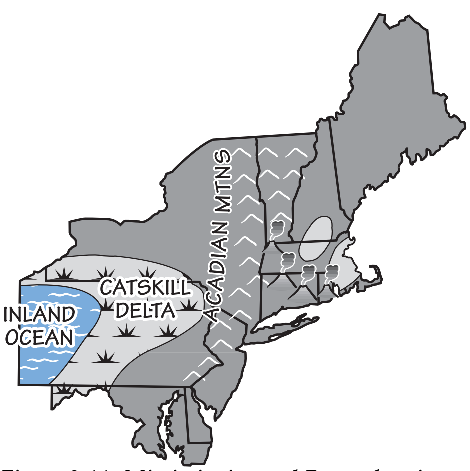


Figure 2.11: Mississippian and Pennsylvanian Northeast landscape. Figure by J. Houghton, after *Geological Highway Map of the Northeastern Region, no. 10,* 1995.

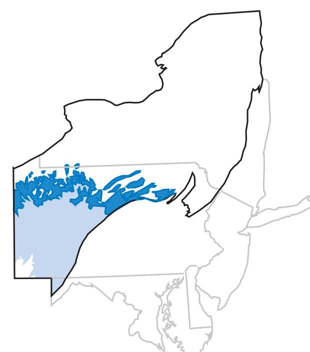
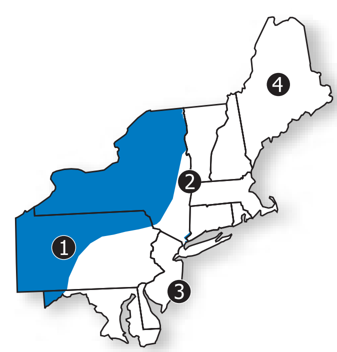


Figure 2.12: Mississippian (dark) and Pennsylvanian (light) rocks exposed in the Inland Basin.



Rocks

Mississippian rocks *are also exposed in small patches at the surface in the Inland Basin in southwestern New York.*

see Non-Mineral Resources, p.154 for more on the formation of **coal.**

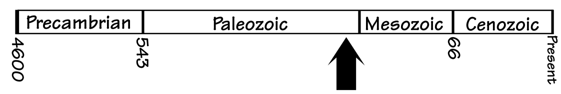
see Fossils, p.90 for more on the composition of **coal.**

Figure 2.13: Permian rocks exposed in the Inland Basin.

> *Though Permian-age rocks have some thin bands of coal, they have nowhere near the abundance of coal seen in the Mississippian and Pennsylvanian rocks.*

Buried by waves of sediment and more vegetation, the peat was compressed. Over time and continued burial, the peat was transformed to layers of coal. Thus, the Pennsylvanian and ***Mississippian rocks*** of the Inland Basin region, found primarily in Pennsylvania, are repeating sequences of alternating sedimentary rock and bands of ***coal*** formed because shifts in sea levels allowed lush vegetation to develop in swampy areas.

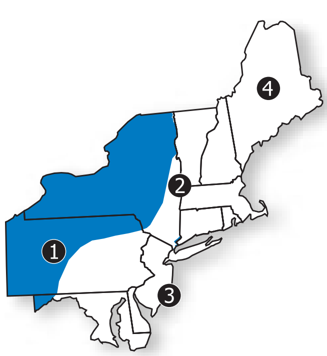
Permian Rocks



Exposed at the surface in the Pennsylvania and Maryland Inland Basin region are Permian-age sedimentary rocks *(Figure 2.13)*. At this time in geologic history, the continents had united to form one giant landmass known as Pangea. North America was sutured to Pangea by the collision of Africa with the east coast of North America during the Alleghanian mountain-building event, forming the Appalachian Mountains. The unification of Pangea signaled the closing of the Iapetus Ocean as well as the last time the inland sea invaded eastern North America. Though sea level fluctuated for a time, the inland ocean gradually retreated, leaving behind river sediment deposits rather than marine deposits. River sediments generally form coarser grained and more poorly sorted sedimentary rocks. With the closing of the Iapetus, the climate in the Northeast became significantly drier as the Northeast was near the center of Pangea. The lush coal swamps of the Mississippian and Pennsylvanian periods gradually disappeared as more arid conditions developed in the area. With the absence of organic-rich swampy areas, very little coal could be formed, accounting for the much smaller amounts of coal in the Permian rock record.

Missing time in the Inland Basin

Where are the rocks representing the Triassic, Jurassic, Cretaceous and Tertiary periods in the Inland Basin? The absence of rocks deposited during certain time periods in regions of a geologic map does not mean that there were no rocks forming during that time. It may mean, however, that very little sediment was deposited, that the sediment was eroded away, or that the rocks are buried beneath the surface. There is no single place on Earth that has a complete sequence of rocks from the Precambrian to the Quaternary. Erosion and weathering over time have removed many meters (and in some cases kilometers) of rock from the surface of the Northeast.



Rocks of the Appalachian/Piedmont
Region 2

The folded, deformed rocks of the Appalachian/Piedmont region record the successive mountain-building events that folded the land into narrow ridges in this area. The rocks of this region were originally sandstone, siltstone, shale and limestone, formed as sediments eroded from the Taconic and Acadian Mountains into the inland ocean basin. Much of the Appalachian/Piedmont rocks are similar to those of the Inland Basin region because they were deposited in the same inland basin, though much closer to the mountains. Many of the sedimentary rocks, however, from the Appalachian/Piedmont Region are no longer sedimentary rocks. They have been squeezed, pushed, faulted and severely deformed in many places because this region was, at various times through geologic history, either the suture area for converging plates or directly adjacent to the uplifting mountains. The Appalachian/Piedmont Rocks were closer to the mountain building than rocks further west, and so felt the effects of the immense pressures of colliding plates much more severely. The northeast-southwest trending narrow ridges and valleys, and the rolling hills of the Piedmont are a result of the stress caused by the intense compression of plates of crust *(Figure 2.14)*.

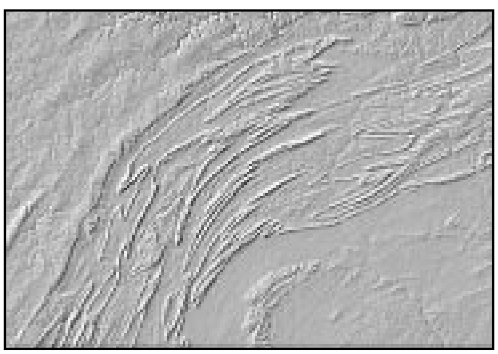
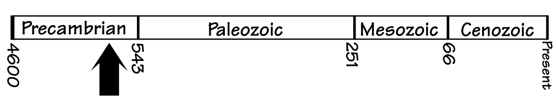


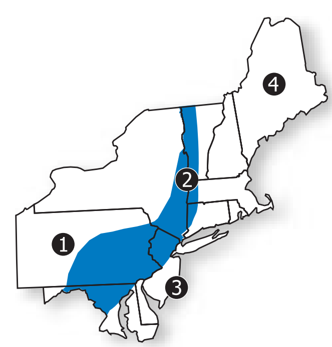
Figure 2.14: Shaded-relief map of the Appalachian-Piedmont Valley and Ridge in Pennsylvania. Image provided by Ray Sterner, Johns Hopkins University.

The rocks of both the Appalachian/Piedmont Region and the Inland Basin got their final squeeze during the Alleghanian mountain-building event. The rocks at the surface today were once buried under kilometers of sediment. They have been exposed over time by erosion and weathering.

Precambrian Rocks



The oldest rocks of the Appalachian/Piedmont region record the deposition of sediments on the ancient North American coastline more than one billion years ago as sediments eroded from the Grenville Mountains. There are several areas in which Precambrian rock is exposed within the Appalachian/Piedmont Region: the Green Mountains of Vermont; the Berkshire Mountains of Massachusetts stretching south into northern Connecticut; the Hudson Highlands and

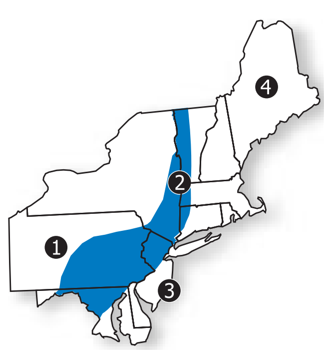


The Manhattan, Reading and Trenton exposures of Precambrian rock are called **prongs** *because of their elongated, narrow outcrops that resemble a prong. In New York City, the Manhattan Prong is actually Precambrian Grenville Fordham gneiss, and the Cambrian Inwood Marble and Manhattan Schist.*

see Geologic History, p. 3, for more on the **Grenville** *rocks.*

Recrystallization of rocks

As temperature and pressure increases during metamorphism, individual grains of sediment making up the original rock are melted slightly and recrystallize. The crystals are more tightly interlocked than an unmetamorphosed rock. The spaces between grains (pore space) in a sedimentary rock are easy paths for fractures and splitting. Elimination of pore space through recrystallization during metamorphism strengthens the overall structure of the rock. Thus, sedimentary rocks in general are an easier target for erosion and weathering than the more resistant interlocking crystals of metamorphic rocks.



Manhattan ***Prong*** of New York; the Reading Prong; the Trenton Prong; the Baltimore Gneiss; South Mountain and the Catoctin Mountains *(Figure 2.15)*. At each exposure, metamorphosed sedimentary rocks are visible, including gneiss, quartzite, schist and marble. Remember, though, that these metamorphic rocks were once sands, silts, muds and limestone deposited in the warm, tropical Iapetus Ocean from the Grenville Mountains. They were repeatedly subjected to enormous pressures and high temperatures from the colliding continents, ***recrystallizing*** to become metamorphic rocks. The Precambrian rock is visible at the surface only because of intense folding of the Appalachian/Piedmont region, which has uplifted layers of rock that were once buried beneath kilometers of crust, and erosion.

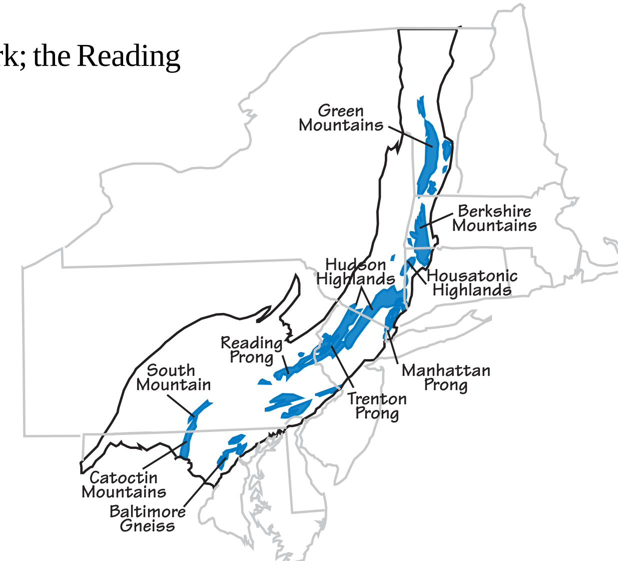


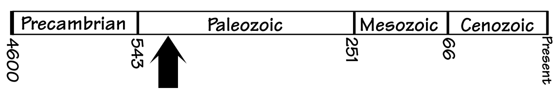
Figure 2.15: The Precambrian rocks of the Appalachian/Piedmont occur in a nearly north-south line, forming the many ridges of the Appalachian Mountains and revealing the location of the ancient Grenville Mountains (though in some places the Precambrian rock has been thrust westward from its original position).

Indeed, the erosion-resistant Precambrian rocks have become the 'backbone' of the range, helping the mountains resist being worn completely flat. The Precambrian rock and overlying younger sedimentary rocks have been compressed by the collisions of the continents into a giant upward fold. The softer sedimentary rocks were eroded away at the peak of the fold, exposing the resistant Precambrian rocks at the center. The Green Mountains of Vermont clearly expose this backbone of Precambrian gneiss and quartzite. The Hudson Highlands, extending into Pennsylvania as part of the Reading Prong, the Berkshire Mountains, Manhattan Prong and the Trenton Prong, follow the same line of resistant ridges of Precambrian rock.

The Precambrian Baltimore Gneiss, near Baltimore, Maryland, is actually a series of domes. The domes have Precambrian gneiss in the middle, surrounded by rings of quartzite and marble. These domes are not simple upwarps of the crust. The rocks of this region have been squeezed so tightly and have been so complexly deformed, that the folds have overturned, folded again, and later eroded to expose the Precambrian gneiss. The ***gneiss*** is a hard, resistant metamorphic rock that has remained a highland, while surrounding softer rocks have worn away.

Basalts, rhyolites and other Precambrian volcanic rocks, as well as Precambrian gneiss and quartzite, are found stretching across the Pennsylvania-Maryland border along the north-south line of Precambrian rock. South Mountain of Pennsylvania and Maryland's Catoctin Mountains record the rifting of North America and Baltica in the Cambrian. As North America moved away from Baltica and the Iapetus Ocean opened up, cracks in the crust occurred that were similar to the younger Triassic rifts from Pangea. The ***rifts*** and fractures in the crust made pathways for emerging lava to pour out across the surface, forming the volcanic rocks seen today.

Cambrian-Ordovician Rocks



The Cambrian and early Ordovician sediments record the ancient North American shelf and slope ***sediments***. Sandstone and shale were the dominant rocks formed from the eroding sediments of the continental highlands and limestone was formed from the abundant shelled organisms in the inland ocean. With the collision of the Taconic volcanic islands, the original limestone, sandstone and shale were metamorphosed in many areas, forming the marble, quartzite and slate that make up the bulk of the Appalachian/Piedmont region. The Cambrian and Ordovician rocks underlie the Champlain Valley of Vermont, the Taconic Mountains and highlands of western New England and eastern New York, and the prominent ridges and valleys further south in Pennsylvania, New Jersey and Maryland. In some areas, particularly the Marble Valley of western Massachusetts, Connecticut and southern Vermont, the less resistant ***marble*** is extensively exposed at the surface, forming a wide valley of fine marble that was once vigorously quarried for buildings and monuments.

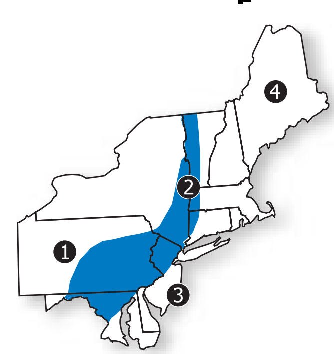
The Taconic Mountain rocks are unusual because older Cambrian rocks (which should be *beneath* younger rocks) are overlying younger Ordovician rocks. This unusual situation occurs because the sediments deposited on the

***Gneiss** is a metamorphic rock that forms by subjecting rocks to high degrees of metamorphism. Gneiss can either form from granite or layered sedimentary rock such as sandstone or siltstone. The result is very similar: parallel bands of light and dark minerals give gneiss its foliated texture.*

*see Geologic History, p. 7 and 16, for more on the **rifts**.*

*These **sediments** were part of a wide bank of carbonate rocks that formed along the margin of the continent while the eroding sediment supply dwindled from the nearly worn-down Grenville Mountains. As the Taconic volcanic islands approached North America during the later Ordovician, sediments were also eroded from the uplifted crust into the inland ocean to the west.*

*see Non-Mineral Resources, p.161, for more on **marble**.*



Unless rock layers are overturned, older rocks are found at the bottom and younger rocks are found at the top of a sedimentary sequence. This is known as the Law of Superposition.

continental shelf and slope of ancient North America were shoved and stacked up onto the coast. Older rocks from the continental shelf and slope were thrust on top of younger rocks from the Inland Basin, causing no small amount of confusion when geologists first tried to unravel the history of the area. The older Cambrian rocks are a resistant cap atop the less resistant Ordovician sedimentary rocks, forming the ridge of the Taconic Mountains *(Figures 2.16 and 2.17)*.

Figure 2.16: Cambrian rocks exposed in the Appalachian/ Piedmont.

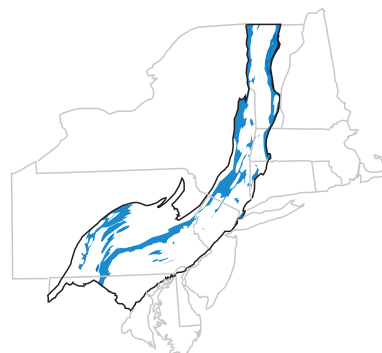
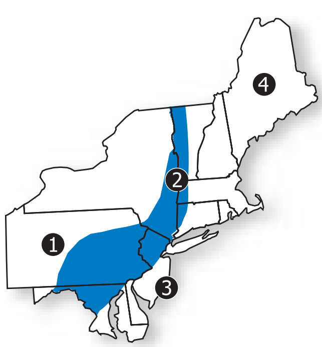


Figure 2.17: Ordovician rocks exposed in the Appalachian/Piedmont.

Figure 2.18: The Serpentine Belt exposed in the Appalachian/ Piedmont.

Along a line from the middle of Vermont through western Massachusetts and Connecticut, southeastern New York, Pennsylvania and Maryland are small exposures of very unusual dark rocks that are part of ophiolite sequences *(Figure 2.18)*. Ophiolites are made of deep-sea sediments, oceanic crust and upper mantle material that are rarely seen at the Earth's surface. The line of ophiolite exposures is located along the ancient suture line between North America and the volcanic island terranes of the Taconic mountain building in the Ordovician period. These igneous rocks, known as the Ultramafic Belt, are very rich in magnesium and iron, but very low in silica, typically forming basalts, gabbros and peridotite. The peridotite, derived from the upper mantle, is often altered slightly through metamorphism to a greenish rock called serpentinite.

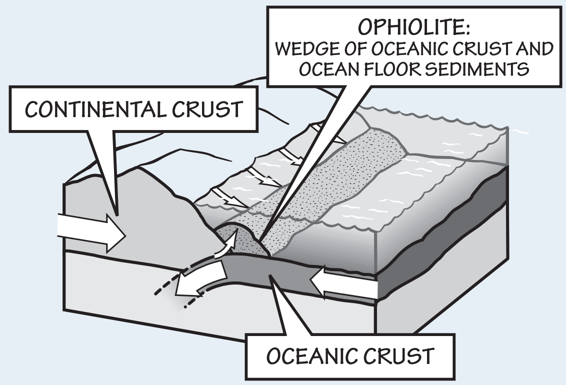
Ophiolites are recognized by their particular sequence of rocks that are not usually found at the surface. The sequence includes sedimentary rock from the ocean floor underlain by flows of pillow basalt. The pillow basalts form as lava pours out of cracks in the oceanic crust and cools very quickly in the seawater, creating a pillow-shaped mass of lava. Beneath the pillow lavas are sills of gabbro, a dark igneous rock formed from cooling magma beneath the



surface. The lowest layer in the ophiolite sequence is composed of peridotite, a rock formed from the upper mantle layer of the Earth that is rarely seen at the surface. The subduction of the oceanic plate also caused igneous intrusions beneath the volcanic islands.

During and after the Taconic mountain-building event, sediments were deposited into the Iapetus Ocean basin and the inland ocean basin east and west of the mountains, mixing with and then covering the limestones that had been building up along the margin of North America prior to mountain building. Volcanic ash within these rock layers indicates volcanic activity occurring as the volcanic islands collided with the continent. The sediments of the Queenston Delta record the deposition of eroding sediment from the Taconic Highlands as well as the changing shoreline as the basin filled.

Ophiolites



When North America was on its collision course with Baltica, the oceanic crust in between the continents was being pushed beneath the continental crust of the approaching North America. As the oceanic crust was subducted, some of the deep-sea sediments overlying the crust, the oceanic crust itself, and perhaps rock from the upper mantle, were scraped off the descending plate and did not get shoved back down into the mantle. Instead, the scraped off ophiolite was left stuck on the continental crust. Subsequent erosion exposed this odd group of rocks that is so unlike the surrounding rock of the continental crust. The ophiolites are significant in the geology of the Northeast because they record the subduction of the oceanic plate beneath the Taconic volcanic islands as they collided with North America. Figure by J. Houghton.

Light-colored vs. dark-colored igneous rocks

Dark-colored igneous rocks generally come from either mantle magma or melting oceanic crust at a subduction zone. Oceanic crust is already dark, dense and rich in iron and magnesium. The dark color originates from the iron and magnesium as well as a relatively low percentage of silica, and characterizes rocks such as basalt and gabbro. Light-colored rocks are formed from continental crust that is melted from the pressure of overlying rock or friction from colliding plates. Continental crust-derived sediments may also form light-colored rocks. Light-colored igneous rocks are very rich in silica and lack significant amounts of iron and magnesium, and include rocks such as granite. The abundance of silica also makes light-colored igneous rocks less dense than oceanic crust.Thus, continental crust, with a density of 2.7 g/cm^3*, is rarely subducted when plates collide because it is too buoyant to be pulled under another plate. Oceanic crust on the other hand, with a density of 3.2 g/cm*^{3}*, is very dense and more easily pulled under an approaching plate.*

Silurian-Devonian Rocks

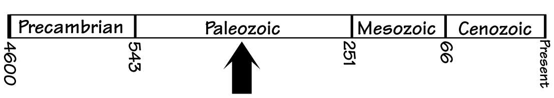
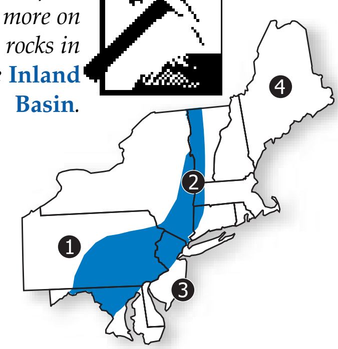


Figure 2.19: Silurian and Devonian rocks exposed in the Appalachian/ Piedmont.

Silurian and Devonian rocks are found primarily in the southwestern-most part of the Appalachian-Piedmont region *(Figure 2.19)*. These rocks are very similar to the Silurian and Devonian rocks of the adjacent ***Inland Basin***. They record deposition in the inland ocean and the collision of Baltica with North America, which formed the Acadian

see Rocks, p.35 for more on similar rocks in the **Inland Basin**.



Mountains and renewed deposition in the inland ocean. The main distinction between the Silurian and Devonian rocks of the Appalachian/Piedmont region and the Inland Basin region is the compression and metamorphism of the Appalachian Piedmont rocks.

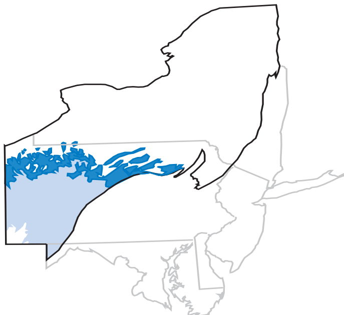
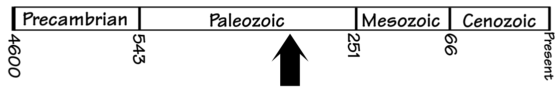


Figure 2.20: Mississippian, Pennsylvanian and Permian rocks exposed in the Appalachian/ Piedmont.

see Rocks, p.37.

see Non-Mineral Resources, p.162, for more on the formation of **coal**.

Mississippian-Pennsylvanian-Permian Rocks

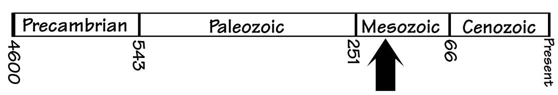


The rocks of the Mississippian, Pennsylvanian and Permian periods of the Appalachian/Piedmont are also only found in the southwestern area of the region *(Figure 2.20)*. Again, these ***rocks*** are very similar to exposures of the same age in the adjoining Inland Basin, recording the lush vegetation and swampy deposits of the receding inland ocean shoreline and deeper-water sediments. However, the rocks of the Appalachian/Piedmont were metamorphosed in many places. The soft coal seen in the Inland Basin is present as very hard anthracite ***coal*** in the Appalachian/Piedmont region.

see Rocks, p.52, for more on rift basin rocks.

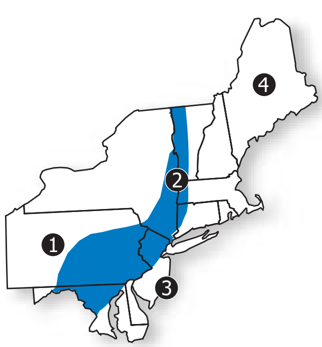
see Geologic History, p. 16, for more on the formation of **rift basins.**

Triassic-Jurassic Rocks



Dissecting the southeastern tip of New York, northern New Jersey, eastern Pennsylvania and Maryland, are two connecting basins filled with rocks dating back to the Triassic and Jurassic *(Figure 2.21)*. The northernmost of the two is called the Newark Basin, and the southern is called the Gettysburg Basin. In the adjoining Exotic Terrane region, a similar basin occurs in Massachusetts and Connecticut known as the Connecticut Valley ***rift basin***. In Connecticut, there are a few other mini-versions of the large rift basins, where smaller faults formed tiny basins that preserved Triassic- and Jurassic-aged sediments.

The basins formed as blocks of crust slid down the fault planes (rifts) during the late Triassic and early Jurassic when Pangea was breaking apart. The basins that formed expose characteristic reddish-brown sedimentary rocks and ridge-forming basalt, an igneous volcanic rock also known locally as 'traprock'. Periodically the basins were filled with water, forming shallow lakes and depositing thin, dark layers of sediment typical of lake deposits.



The rift valley igneous rocks were formed when magma pushed up through fractures in the crust and either poured out on the surface of the basin as flows of lava, or cooled and crystallized as igneous intrusions before reaching the surface *(Figure 2.22)*. The igneous intrusions, typical within the rift basins, formed rather shallow within the crust. The relatively cold temperatures of the upper crust forced the ***magma*** to cool quickly.

The same magma that formed the **Palisades Sill** continued to rise towards the surface. The rising magma cut through the overlying layers and burst out onto the surface, spreading basaltic lava over the basin. These lava flows are recorded by the Wachtung Mountains of New Jersey, left standing because of the resistance of the tilted lava beds in comparison to the weaker sedimentary rocks above and below.

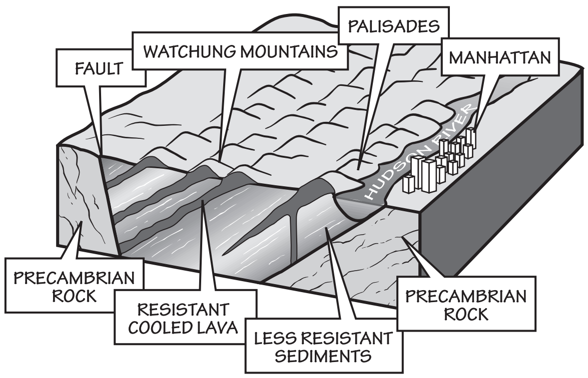


Figure 2.22: The Palisades Sill is an igneous intrusion; the Wachtung Mountains are a volcanic extrusion of lava. Figure by J. Houghton.

Colors of sedimentary rocks:
what do they tell us about the environment?

Color in rocks may be an important indicator of the type of environment in which the rocks were formed. The red-brown color so common in the rift basins of the northeast is present because of iron within the rock that has been oxidized (rusted!), which tells us that the rock formed in a seasonally hot and dry climate on land, where the iron could be exposed to the air and oxidized. Red sedimentary rock is also found in the Silurian rocks of the Inland Basin, reflecting a time of shallow seas in which the ocean floor sediments were often exposed above water and allowed to oxidize. In some marine environments, where iron is reduced rather than oxidized, rocks may take on a greenish hue. However, in well-oxygenated, deep marine conditions, red clays may form.

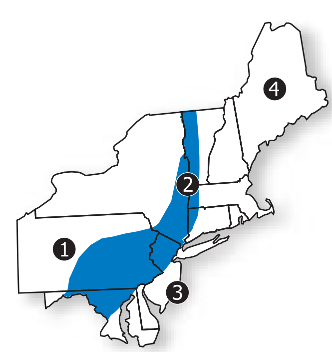
In contrast, most shales are gray or black in color, reflecting the abundance of organic material that can accumulate in quiet-water settings and preserve in fine-grained rocks that are relatively impermeable to oxygen-rich pore water. Shales are most commonly formed in quiet waters where tiny particles have time to settle out to the sea or lake floor, where there is very little oxygen to aid in the decomposition of the organisms, so the sediments retain a black color from the carbon of organic material. The darker the shale, the more organic material that is preserved within! The presence of certain minerals may also affect the color and aid in the interpretation of the environment of deposition. Green sedimentary rocks may indicate the presence of the mineral glauconite, found only in marine environments.

Figure 2.21: Triassic-Jurassic rift basins exposed in the Appalachian/Piedmont.

Magma *cooled quickly has little time to crystallize, and therefore microscopically fine-grained igneous rocks such as basalts are often produced in rifts.*

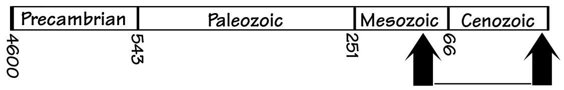
What is a sill?

A sill occurs when rising magma forces its way between layers of rock, spreading out parallel to the layers and creating a flat intrusion like the Palisades along the Hudson River in New York. The **Palisade Sill** *is composed of an igneous rock called diabase. The texture of diabase is a medium-size crystalline texture, between that of a basalt (finely crystalline) and a gabbro (coarsely crystalline). Diabase cools more slowly than basalt because it is not above the surface, yet it cools more quickly than gabbro because it is closer to the surface.*



Rocks of the Coastal Plain

Region 3

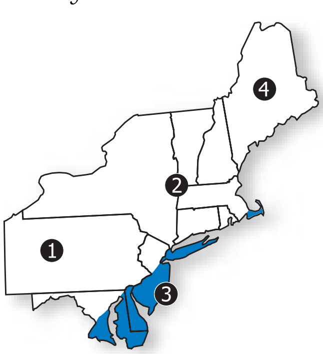


The Coastal Plain region has fairly straightforward geology. The rocks here are actually not yet rocks! Instead, there are usually unconsolidated sediments that have not been cemented or compacted. The sediments are geologically very young, ranging in age from the Cretaceous to the Quaternary. The sediments include gravel, sand, and silt; it may take tens or hundreds of millions of years before these sediments are turned to rock. Overlying the Paleozoic rocks, the Coastal Plain sediments form a wedge of nearly flat-lying layers of sediment that thicken eastward onto the continental shelf and slope and then thin again further to the east.

Figure 2.23: Cretaceous sediments exposed in the Coastal Plain.

Consider the geologic events between the Cretaceous and the Quaternary: the Northeast was experiencing a relatively quiet time tectonically and the east coast of North America had become a passive margin (there were no longer converging or diverging plates right at the margin of the continent). In this time of tectonic quiet, significant erosion of the Appalachian highlands occurred. The sediment deposits were similar to the formation of the ***Queenston*** and ***Catskill Deltas*** of the Taconic and Acadian mountain building millions of years before. Rivers draining from the mountains brought sediment down to the coast. The oldest deposits seen on the Coastal Plain (Cretaceous) record the story of eroded sediments transported by rivers to the coast and are found along the inner edge of the region *(Figure 2.23)*. Cretaceous sediments are also found on Martha's Vineyard at Gay Head Cliff, uplifted and pushed forward by the ice sheet during the Quaternary .

Unlike the Queenston and Catskill Deltas, which have been cemented and compacted to become thick sequences of sedimentary rock, the sediments being transported from the Appalachians have not yet become sedimentary rocks.



Throughout the Tertiary and Quaternary periods, the Northeast repeatedly experienced rise and fall of sea level, in part due to the build-up and melting of glaciers. Overlying the older river deposits of the Cretaceous, Tertiary marine sediments record the rise and fall of sea level over greater than sixty million years *(Figure 2.24)*. 'Greensand' is common in marine Tertiary sediments because marine deposits often contain the green mineral, glauconite, lending the sediment a greenish tinge.

The Quaternary is recorded in the youngest sediments of the Coastal Plain *(Figure 2.25)*. Long Island, Cape Cod and the several smaller islands off the coast of New England (Block Island, Nantucket, Martha's Vineyard) are testaments to the advance and retreat of an enormous ice sheet over the continent. The islands are actually formed from glacial outwash: gravel, sand and silt that piled up in front of the glacier as it melted. The islands represent the maximum extent of the most recent glacial advance over 20,000 years ago. The glaciers never advanced further south than Long Island and northern Pennsylvania. Where the glacier stood still (neither advancing nor retreating for some time) huge ***deposits*** of outwash built up in front of the glacier. This feature is known as a terminal moraine. There are a series of terminal moraines in the Northeast that represent the retreat of the glacier toward the north.

While the continental ice sheet never made it as far south as New Jersey, Delaware, Maryland, or southern Pennsylvania, the glaciers still left their mark on the area. Melt water streaming off the retreating glaciers brought gravel, sand, silt and clay that had been carried along by the glacier downstream to the Coastal Plain. Quaternary deposits make up most of the sediments you see immediately adjacent to modern estuaries and streams because they are relatively recent deposits.

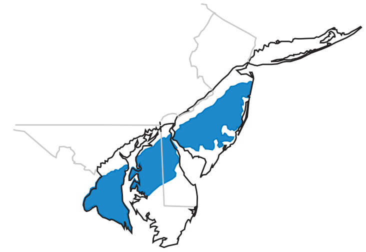


Figure 2.24: Tertiary sediments exposed in the Coastal Plain.

see Glaciers, p. 61, for more on glacial **deposits**.

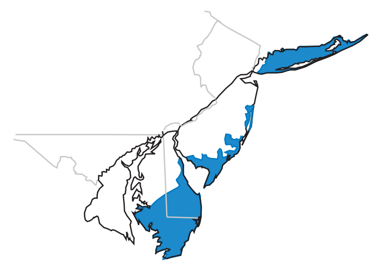
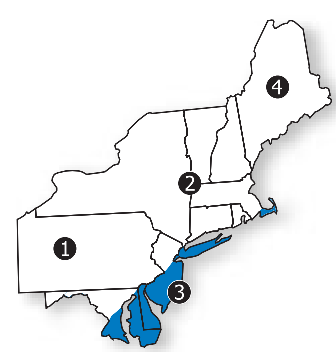


Figure 2.25: Quaternary sediments exposed in the Coastal Plain.



Rocks of the Exotic Terrane
Region 4

There are two basic divisions of the Exotic Terrane region of New England: the Iapetus Rocks, recording the sediments deposited in the ancient Iapetus Ocean, and the Avalonia Rocks, recording the distinctive rocks of the Avalonia microcontinent, which were caught in the middle of the collision between North America and Baltica. The Iapetus and Avalonia Rocks were not originally part of North America. Indeed, the rocks have distinctly different geologic characteristics than the bulk of North America. The Exotic Terrane region is dominated by igneous and metamorphic rocks. Both the Iapetus ***Terrane*** rocks and the Avalonia ***Terrane*** rocks are cut through with igneous intrusions that formed as magma cooled within the compressed crust, and volcanic rocks that formed from volcanoes as lava broke out of the crust. The remaining rocks of the Exotic Terrane region are metamorphosed sedimentary rocks that originated as sediments on the continental shelf of North America, the floor of the closing Iapetus Ocean basin, and shed off of the approaching volcanic islands. In some places, especially northern Maine, the sedimentary rocks were only weakly metamorphosed and still retain much of their original character.

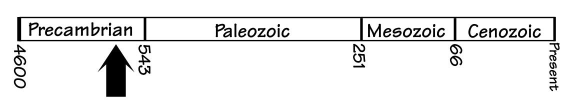
see Geologic History, p. 10, for more on exotic **terranes.**

The origins of metamorphic rocks

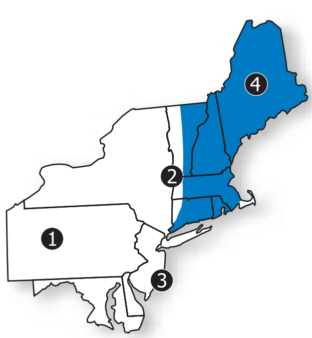
The type of rock produced during metamorphism depends on the composition of the original rock as well as the degree of higher temperatures and pressure. For example, when the sedimentary rock shale is weakly metamorphosed, it becomes slate. Though slate retains much of the original character of the shale, the minerals within the slate have become aligned as the original clays are changed to micas through the pressure of metamorphism. Increased metamorphism produces a phyllite. Finally, with the highest degree of metamorphism, schist is formed as the micas become large, easily observed crystals. Thus, the type of rock in a given area can indicate the degree of metamorphism.

original rock	*weakly metamorphosed*	→	*strongly metamorphosed*	
shale	*slate*	*phyllite*	*schist*	*gneiss*

Precambrian Rocks



Precambrian rock in the Exotic Terrane region is found in eastern Massachusetts, Rhode Island, and Connecticut, and northwestern Maine *(Figure 2.26)*. Eastern Massachusetts, Rhode Island and Connecticut were the Avalonia rocks that collided with North America during the Acadian mountain-building event. Though it is gneiss, the Avalonia gneiss is not the same as the Precambrian Grenville gneiss. The Avalonia rocks were far to the southeast of



North America during the Precambrian.

In northwestern Maine, the mountainous Chain Lakes Massif gneiss stands out as distinctly different from the surrounding rocks. Geologists continue to debate the origin of the Chain Lakes Massif, which is puzzling because of the intensely metamorphosed rocks. It is possible that this mass of gneiss was part of the Grenville belt of sediments.

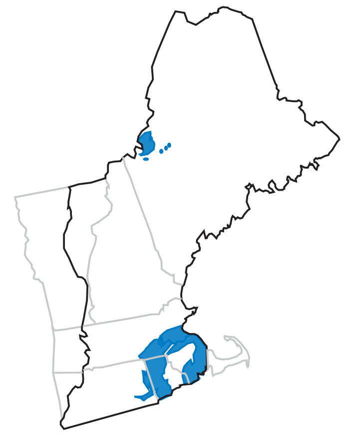


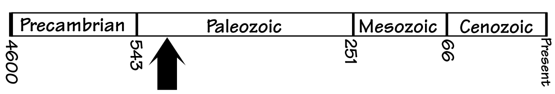
Figure 2.26: Precambrian rocks exposed in the Exotic Terrane.

The Boston Basin

Near the close of the Precambrian, Avalonia was breaking away from Africa, and on a collision course with North America. A rift within the Avalonia rocks created a basin, similar to the rift basins that formed in the Triassic when Pangea began to break apart. The basin filled with Precambrian-and Cambrian-age volcanic and sedimentary rocks. In the Devonian, millions of years later, Avalonia collided with North America to form eastern Massachusetts, Rhode Island, Connecticut and Maine. The rift basin created in the Avalonia rocks during the Precambrian, known as the Boston Basin, is still visible today as the foundation of eastern Massachusetts. The basin may actually extend several kilometers farther east under the Atlantic Ocean. Within the basin is the Braintree Slate, famous for its preservation of an unusually large species of trilobite, Paradoxites.

see *Fossils*, p.96, for more on the **Boston Basin.**

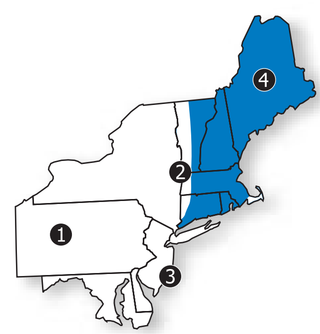
Cambrian-Ordovician Rocks



Close to the Chain Lakes Massif of Maine are several occurrences of ophiolites. Geologists believe that the ophiolites were scraped off a subducting oceanic plate and welded onto the Chain Lakes Massif sometime during the Ordovician.

see *Geologic History*, p. 7, for more on the **Taconic events.**

During the late Ordovician, as the ***Taconic*** volcanic islands approached North America, slices of crust were stacked and squeezed like a collapsing telescope across the Exotic Terrane and Appalachian/Piedmont regions. In the Exotic Terrane region, we see the remains of the volcanic island chain that caused the stacking. Though it is difficult to distinguish individual volcanic islands and slices of crust, there is evidence of the volcanic islands and sediments associated with the volcanic activity of the Taconic mountain building period. Ordovician-age metamorphosed sedimentary ***rock*** that originated



from the Taconic volcanic islands are interwoven with volcanic rocks, including basalt and rhyolite, which form many of the ridges up and down the central New England area *(Figure 2.27)*.

Ordovician-age igneous ***intrusions***, generally granites, are located up and down the volcanic island suture area in and around the sedimentary and volcanic rocks *(Figure 2.28)*. These intrusions are the cooled remains of the magma chambers that formed the Taconic volcanic islands as well as magma formed as the crust compressed during the collision.

Figure 2.27: Cambrian and Ordovician rocks exposed in the Exotic Terrane.

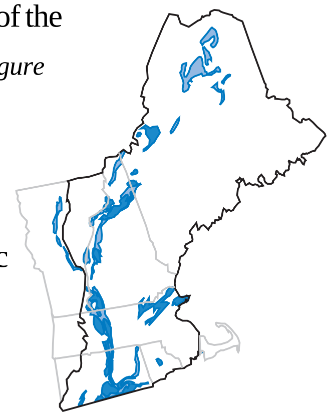


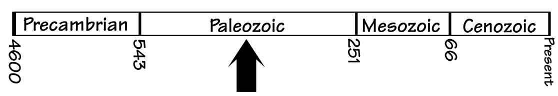
Figure 2.28: Ordovician-age igneous intrusions exposed in the Exotic Terrane.

Volcanic vs. intrusive rocks

What is the difference between volcanic igneous rocks and intrusive igneous rocks? Hot, molten rock beneath the Earth's crust is called magma. As magma rises, pushing through overlying layers of rock, it will begin to cool. The cooling magma may crystallize and harden to become an intrusive *igneous rock. If, however, the magma rises to the surface without cooling enough to crystallize, the magma may be able to break through the crust at the surface forming a volcano or basalt flow. Geologists call volcanic magma 'lava'. Lava cools much more quickly than magma because it is at the surface and exposed to the atmosphere or ocean water where temperatures are much cooler. Lava thus has less time to crystallize than magma. Though the composition of a magma may be the same as a lava, the texture (mineral crystal size) of the rocks will be quite different. It is because of this difference in genesis that geologists are able to make the distinction between volcanic and intrusive igneous rocks when encountered at an outcrop at the Earth's surface.*

	high iron & magnesium	*low* iron & magnesium
Volcanic:	*basalt*	*rhyolite*
Intrusive:	*gabbro*	*granite*

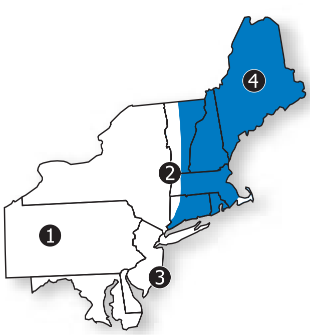
Silurian-Devonian Rocks



Central New England is predominantly composed of the remnants of the sediments deposited during the Silurian and Devonian in the Iapetus Ocean *(Figure 2.29)*. These rocks were originally sand, silt and mud deposited on the floor of the Iapetus Ocean following the Taconic mountain-building event. The sedimentary rocks were later squeezed tight, folded and metamorphosed during the Acadian and Alleghanian mountain-building events. The metamorphosed sedimentary rocks are now the schists and gneiss of central Vermont, New Hampshire and southern Maine, the region where the temperature and pressure were highest.

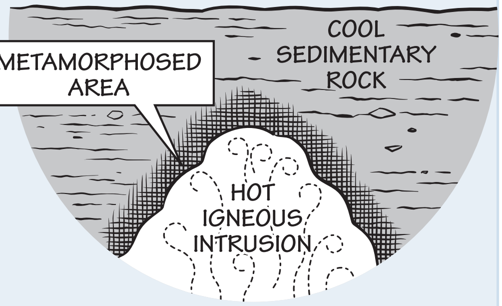
Though the degree of metamorphism varies throughout New England, in general the rocks in the west experienced lower degrees of metamorphism than rocks in the east. Likewise, rocks in Northern Maine experienced far less metamorphism because they were not directly affected by the later Alleghanian mountain-building event. Mild metamorphism in the less-stressed areas formed

These rocks are all part of the Iapetus Terrane.



slates and phyllites. Central Maine is known as the Slate Belt because of the weak metamorphism that affected the Silurian and Devonian sedimentary rocks of the area, which were mainly shales. Intrusions of magma pushing up through the crust during the Acadian mountain-building event also played a role in metamorphosing rocks.

Regional and contact metamorphism



The intense heat of intruding magmas often metamorphoses the rocks into which they are intruded. This is known as contact metamorphism. Shale, rather than becoming slate or phyllite or schist (in which the minerals become aligned through pressure), is often simply baked by an intrusion to become hardened shale known as hornfels. Regional metamorphism, on the other hand, refers to metamorphism induced through increased pressure as the crust is squeezed together and folded when plates collide. The Taconic, Acadian and Alleghanian mountain-building events all produced regional stress on the rocks surrounding the collision zones. In this way, the sedimentary rocks of the Exotic Terrane region and parts of the Appalachian/Piedmont region have been regionally metamorphosed. Figure by J. Houghton.

The eastern section of the Exotic Terrane Region consists of the rocks of the Avalonia microcontinent. They include most of coastal Maine as well as Rhode Island, eastern Massachusetts and Connecticut *(Figure 2.30)*. In the late Devonian, when the microcontinent Avalonia was caught in the middle of the collision between North America and Baltica, numerous igneous intrusions occurred throughout Vermont, New Hampshire, Maine, Massachusetts and the Avalonia Rocks themselves *(Figure 2.31)*. These intrusions are known as the New Hampshire ***Plutonic*** Series.

Intrusions related to this series occur throughout New England and are responsible for several high peaks as the hard granite generally resists erosion better than sedimentary rocks. The famed ***Barre Granite*** of Vermont, commercially valuable for building and monument stone, is also part of the New Hampshire Plutonic Series.

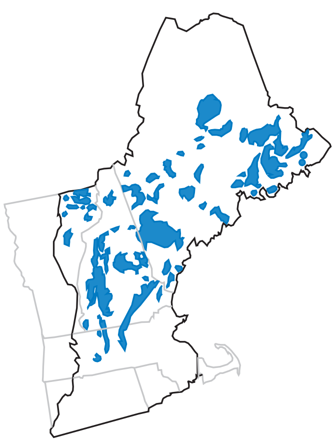


Figure 2.31: Devonian igneous intrusions in the Exotic Terrane.

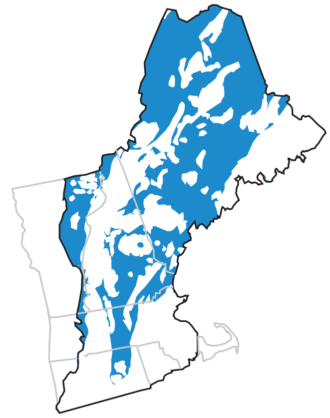


Figure 2.29: Silurian and Devonian rocks exposed in the Exotic Terrane.

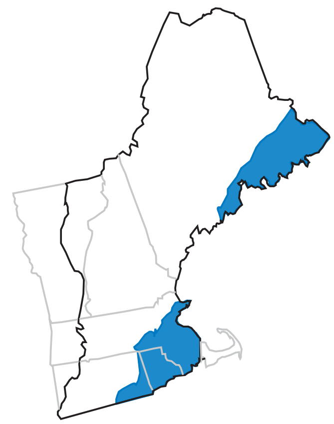
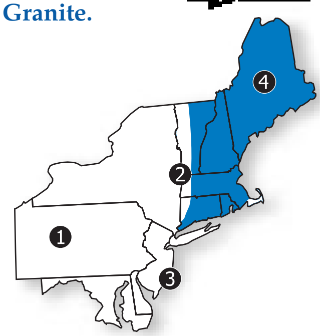


Figure 2.30: Avalonia rocks exposed in the Exotic Terrane.

Pluton *is another name for a large intrusion. The term is derived from Pluto (Hades), the ancient Greek god of the underworld.*

see Non-Mineral Resources, p.166, for more on **Barre Granite.**

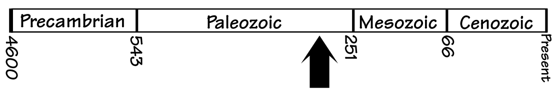


see *Minerals*, p. 144, for more on **pegmatites.**

Pegmatites

Pegmatite dikes are frequently found near the Taconic and Acadian igneous intrusions. Hot, molten magma rising through the crust from deep magma chambers (which eventually formed igneous intrusions) put significant pressure on the overlying rocks. The pressure caused the crust to crack in many places, creating additional pathways for magma to intrude and crystallize in dikes. The heat from the rising magma also partially melted some of the overlying crust. Partial melting and the escape of volatiles from slow cooling of continental crust created a unique rock type rich in rare elements: a pegmatite. Their very large crystals, which range anywhere from 2 cm to as much as 5 meters across, easily distinguish pegmatites!

Pennsylvanian Rocks



The youngest rocks of the Paleozoic era in the Exotic Terrane Region, approximately 315 million years old, are found in basin deposits of Massachusetts and Rhode Island. The basins formed as Avalonia collided with North America and the compression downwarped the crust slightly. The basins preserve Pennsylvanian-age sedimentary rocks including sandstone, conglomerate, and siltstone, all of which have experienced varying degrees of metamorphism. They also have layers of coal, which were mined in the past for steam engines and heating homes. The Narragansett Basin, the largest of the Pennsylvanian basins, has layers of anthracite coal up to 12 meters thick and the greatest number of plant fossil species than any other coal basin worldwide. Several smaller basins are found close by, including the Norfolk, Woonsocket, and Northern Scituate Basins *(Figure 2.32)*.

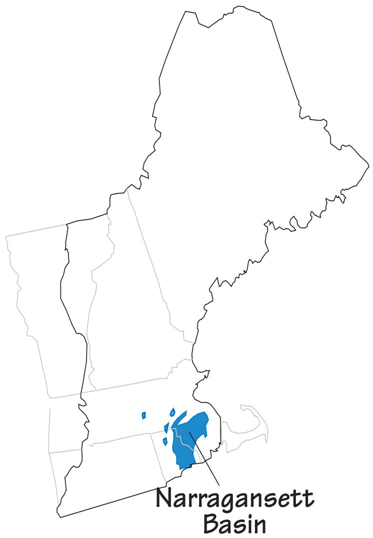
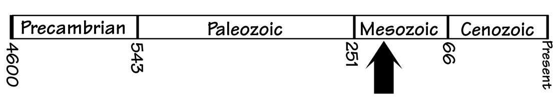


Figure 2.32: Pennsylvanian-age basins in the Exotic Terrane.

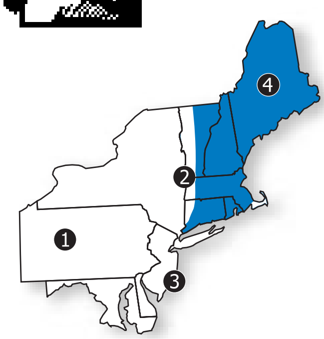
Triassic-Jurassic Rocks



see *Geologic History*, p. 16, for more on **rift basins.**

see *Rocks*, p.44, for more on **rift basins**.

Similar to the Triassic ***rift basin*** of the Appalachian/Piedmont, there is a rift basin that cuts through the Exotic Terrane Region as well, known as the Connecticut Valley Rift Basin. This basin, which cuts through the Iapetus Terrane of the Exotic Terrane region, may have once been continuous with the Newark Rift Basin. The process of formation of the two basins was the same, occurring as the continents of Pangea separated and North America pulled apart from Africa. Likewise, the rocks of the basins are similar, consisting of



ridges of basalt and reddish-brown sedimentary rocks *(Figure 2.33)*.

In New Hampshire and southern Maine, late Triassic through Cretaceous igneous intrusions are exposed in a curious arc that extends up into Canada *(Figure 2.34)*. Known as the White Mountain Series, these intrusions are not related to the Rift Basin lava flows, which produced quickly cooled basalts. Rather, these intrusions formed deep within the crust as plumes of magma rose from the mantle. The magma originated at what some geologists think may have been a ***hot spot***. As the plate moved over the hot spot, magma pushed upwards through the crust to form the string of plutons visible at the surface today through erosion. The intrusions form the core of certain mountains in central New Hampshire.

Hot Spots

Hot spots form from plumes of magma rising off the mantle. Though the hot spot remains fixed, the plates of the lithosphere are moving above it. Magma from the hot spot pushes its way up through the crust, creating an igneous intrusion and sometimes a volcano. As the plate continues to move over the hot spot, magma pushes up next to the previous volcano to form another intrusion or volcano. This gradually produces a chain of volcanic islands such as the Hawaiian Islands or a series of plutons as in New Hampshire (Figure A). Erosion of the volcanoes may eventually wear down the crust to reveal the igneous intrusions that were the magma chamber of the volcano (Figure B). This is one of the proposed explanations for the exposures of the White Mountain Series.

Figures by J. Houghton.

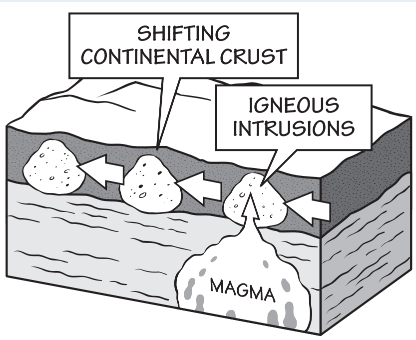


Figure A

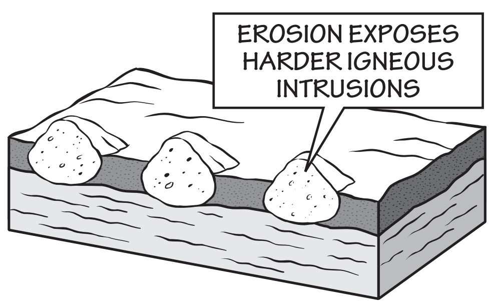


Figure B

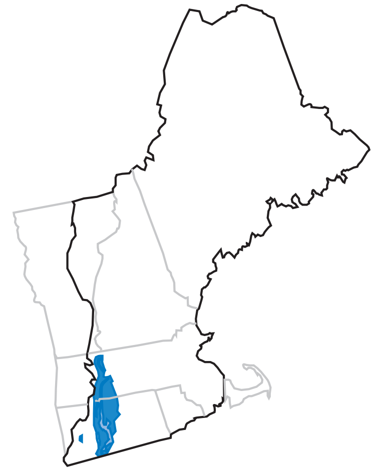


Figure 2.33: Triassic rift basin in the Exotic Terrane.

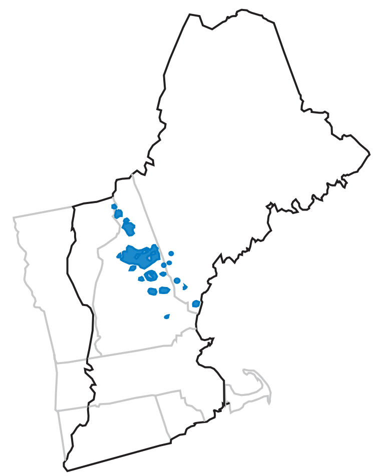


Figure 2.34: The White Mountain Series intrusions in New Hampshire and Maine.