Background

The geology of the Atlanta area in Georgia is dominated by the Appalachian Mountain Range and the processes that created it. Tucker is a suburb of Atlanta and is situated at the southern end of the Appalachian Mountains. The Appalachians lie just east of an early boundary of the ancestral North American continent during Precambrian times more than 1 billion years ago.

The rocks that are exposed in Henderson Park are metamorphic and igneous. The metamorphic rocks were formed during the mountain-building episodes (called orogenies) that grew the eastern margin of the North American continent. First to be seen on the field trip are metamorphic rocks trucked to the park from Arabia Mountain, an igneous stock (large igneous outcrop) located about 20 miles southeast of the park. These rocks typify the core of the Appalachian Mountains: highly metamorphosed by directed stress, high temperature, and chemically-active fluids. Several types are present: amphibolites, gneisses, and quartzites. Note the light-colored mineral veins in these rocks. The next stop is on the trail: an outcrop of quartzite rocks. The trail next leads to Henderson Waterfall, the location of foliated amphibolites that dip (tilt) from the horizontal. The strike, dip angle, and dip direction of these rocks will be measured with a Brunton Pocket Transit. After examining the waterfall rocks, the trail will lead to the final destination: an outcrop of granitic rock. The strike of a quartz dike/vein will be measured at this location.

The explanation of the formation of the Appalachians follows that of the formation of all collisional mountain structures: plate tectonics. Plate tectonics represents a paradigm in which the earth is believed to consist of a series of concentric shells distinguished from one another by their composition. The innermost shell is actually a solid sphere of iron and nickel nearly 2,500 kilometers (~1,500 miles) in diameter. The shell that surrounds the spherical inner core is called the outer core, composed of iron and nickel, and having an outer diameter of 6,800 kilometers (~4,150 miles). Surrounding the outer core is the mantle, composed of iron/magnesium-rich silicate minerals and having the chemical composition of a dark rock called peridotite. The outer diameter of the mantle is about 12,500 kilometers (~7,650 miles). The mantle consists of two zones or concentric spherical shells: lower mantle and upper mantle. Over very long periods of time (millions of years) parts of the lower mantle move upward in thin cylindrical shapes called mantle plumes, while other parts move downward along slabs of material descending from the shell above the outer mantle. These upward and downward movements of the mantle are responsible for some of the largest land and seafloor structures on earth. The movements are controlled by uneven distributions of heat within the earth: hotter regions tend to rise, while cooler regions tend to sink. The outermost shell of the earth's interior is called lithosphere, or sphere of rock, because of its rigidity and solid character. Its thickness atop the mantle varies from a few kilometers at mid-ocean ridges to about 280 kilometers beneath the Himalaya Mountains (Pasyanos, 2008). Lithosphere is underlain by a more pliable region of the upper mantle called the asthenosphere. The asthenosphere is not rigid, but behaves as a deformable solid that can flow when subjected to stress. The asthenosphere is deformable in a manner similar to hot wax because its constituent minerals are always near their melting temperature.

According to plate tectonics, the surface of the earth represents a jigsaw puzzle of lithospheric blocks, or plates, interlocked with one another, but able to move horizontally and vertically. Some plates are composed of a combination of continental and oceanic lithosphere, whereas others are entirely oceanic in nature. The upper zone of a lithospheric plate is called the crust. The crust makes up the bedrock sometimes seen in rock outcrops. The crust is underlain by a rigid layer of "frozen" asthenosphere. This zone of the upper mantle may be thought of as frozen to the base of the crust, and as such, it forms a single lithospheric structure with the crust. A tectonic plate, then, is a block of lithosphere that consists of rigid upper mantle frozen onto the base of the crustal rocks above. There are two types of earth crust: continental and oceanic. Continental crust is granitic in mineral composition, and oceanic crust is basaltic. Continental lithosphere is less dense (lighter) than oceanic lithosphere because the crustal part is less dense granitic rock. Oceanic lithosphere is more dense because its crustal part is more dense basaltic rock.

There are three types of plate boundaries: convergent, divergent, and transform. A convergent plate boundary exists where plates are converging with one another after the fashion of a collision. Where the convergence brings continental lithosphere into collision with oceanic lithosphere, the less dense continental lithosphere overrides the more dense oceanic lithosphere. The overridden oceanic lithosphere can sink (subduct) slowly into the mantle as the continental lithosphere rides above it, or it can sink rapidly as an oceanic lithospheric slab at a high angle with respect to the earth's surface. The slab's age, temperature, and resultant density determine whether it will sink slowly or rapidly and will also determine its angle of descent. The older, colder, more dense slabs sink most rapidly.
and at the steepest angles. The younger, warmer, less dense slabs can sink at very shallow angles of a few degrees from the earth's surface. As these slabs sink beneath the continental lithosphere, they release water and other volatiles (e.g., CO₂) that act as a catalyst to melting. The asthenosphere above the descending slab partially melts because of this catalyst. Being less dense than the solid that generated it, the partially-melted asthenosphere rises to the base of the crust as a hot plume of predominantly basaltic composition. These plumes of magma heat the crust above and can penetrate it, melt it, mix with it, and produce volcanoes. These volcanoes can form a line or an arc on the earth's surface called a continental volcanic arc. On the other hand, when two oceanic plates converge, the denser one subducts beneath the less dense one. The subducting plate releases volatiles into the asthenosphere above, which in turn generate magma. The basaltic magma rises toward the oceanic crust above, penetrates it, and produces volcanic islands that form a line or an arc. This string of volcanoes is called a volcanic island arc. Collisional mountain ranges form when two continental plates converge. Since neither of the continental plates is dense enough to subduct into the mantle, one may partially override the leading edge of the other and create a mountain range where the crust below is thicker than before the collision. A divergent plate boundary exists where plates pull apart from one another. A transform plate boundary exists where plates slip or grind past one another along a transform fault. A transform fault is a vertical crack in the lithosphere where two plates slip past one another in a purely horizontal motion. All of these tectonic movements have been involved in the formation of the Appalachian Mountains and the east coast of North America.

**Rodinia, Grenville Orogeny, and Taconic Orogeny**

A brief geologic history of the Appalachians begins with the convergence of proto-continents called cratons into an early supercontinent named Rodinia. Along the east coast of North America this convergence resulted in a period of mountain building known as the Grenville Orogeny, which lasted from roughly 1.2-1.0 billion years ago. These mountains eroded away until the next convergence called the Taconic Orogeny, which took place during the period 543-440 million years ago (abbreviated “Ma”). Vastly different tectonic events occurred in the northern and southern Appalachians during the Taconic Orogeny. As seen in Figure 1 of the summary below, titled “Formation of the Appalachian Mountains – General Geology,” convergence in the north between an oceanic portion of the Laurentian (North American) plate and the oceanic lithosphere of the Iapetus Ocean produced a subduction zone where the North American plate subducted beneath the Iapetus Ocean. This subduction generated a volcanic island arc that was subsequently thrust over the North American plate, producing metamorphic rocks in the process.

Events much more complicated took place in the southern Appalachians during the Taconic Orogeny. As shown in Figure 2, the oceanic lithosphere of the Iapetus Ocean is shown as a slab being subducted beneath the oceanic portion of the Laurentian plate. The subducting slab produced following effects:

1. A volcanic island arc. Refer to Figure 3 to see that the volcanic arc in Figure 2 should be located farther to the left, above the dehydrating slab fluids.
2. An extensional back-arc basin with an underwater divergent zone penetrating the continental slope-rise area.
3. The rising magma beneath the divergence zone provided the heat to melt the slope-rise sediments and produce the granitoids in the back-arc oceanic crust.
4. The rollback velocity v₁ of the Iapetus lithosphere exceeded the convergence velocity of the overriding Laurentian plate v₀. This caused the subduction zone to retreat towards the Iapetus Ocean and away from Laurentia.
5. The tension in the back-arc basin was produced both by the corner flow induced by the subducting slab and by v₁ > v₀.

**Acadian Orogeny**

The next significant event was the Acadian Orogeny. The mountain building associated with the Acadian Orogeny began about 375 million years ago in Canada and reached Georgia by 350 million years ago. The primary tectonic event during the Acadian Orogeny was the collision between Avalonia and the North American plate. Avalonia was a microcontinent that originated from one or more continental volcanic arcs, volcanic island arcs, or both, being either part of or accreted to the southern supercontinent named Gondwana. The igneous activity produced by subduction created the arcs between 730-570 million years ago. After the break up of Rodinia, Avalonia rifted from Gondwana during the opening of the Iapetus Ocean. It drifted northward and collided with Baltica first, then with Laurentia. It incorporated itself into Laurentia as an exotic or accreted terrane.
Alleghanian (Appalachian) Orogeny

The most recent mountain-building episode was the Alleghanian Orogeny. See the sequence of events in Figure 4. During the Pennsylvanian Period (318-299 million years ago) the African coast of Gondwana collided with the North American part of Euramerica as the Iapetus plate subducted beneath the North American craton Laurentia. The convergence of Gondwana with Euramerica became the final closing of the Iapetus Ocean. The convergence zone stretched from Newfoundland to the Marathon Mountain area of Texas. By the end of the Mesozoic Era (65 Ma), however, the Appalachians had eroded to an almost flat plain.

Miocene Epeirogenic Uplift

If the Appalachians eroded to an almost flat plain by 65 million years ago, and if there have been no orogenies along the east coast of North America since then, why are they a mountain range today? About 16-12 million years ago sedimentation rates and grain sizes delivered to offshore basins in the Atlantic and the Gulf of Mexico began to increase. This suggests that the Appalachian Mountains are being uplifted by some kind of tectonic process. One possibility is that fragments of the relic Farallon plate may be generating heat beneath the modern Appalachians. This heat would cause the rocks to expand and could produce a broad (epeirogenic) uplift of the mountains. There is also evidence of regions where the base of the crust under the mountains allow more heat to flow upward than in other regions. A third possibility is that portions of the thickened crust beneath the Appalachians are detaching and sinking into the mantle. This too would increase heat flow upward. (Gallen et al., 2013)

References


Taconic Orogeny (543-440 Ma)

Northern Appalachians

Eastern oceanic section of Laurentian plate generated a volcanic island arc as it subducted under the Iapetus Ocean. Continuous subduction brought the Laurentian plate into collision with the island arc. Continued convergence thrust the island arc and subduction zone sedimentary wedge over Laurentia, producing metasedimentary rocks underlain by marble. See USGS figure at right.


Southern Appalachians

As seen in the diagram below, Iapetus was subducting beneath Laurentia and was rolling back from Laurentia with a velocity \( v_r \) greater than the convergence velocity \( v_o \) of overriding Laurentia. A back-arc basin formed due to the tension caused by \( v_r > v_o \) combined with the corner flow caused by slab drag of the overlying asthenospheric wedge. Back-arc basin manifests a divergent zone where MORB-type mafic magma rises toward the surface of the mafic lithosphere. See attribution on next page.

Figure 1. Major events of the Taconic Orogeny in the north.

Figure 2. Schematic of the Taconic Orogeny in the south.
Figure 2 above:

![Image of a back-arc basin](https://commons.wikimedia.org/wiki/File:Cross-section_of_a_subduction_zone_and_back-arc_basin.jpg)

**Figure 3.** Illustration of the main features of a back-arc basin.


**Acadian Orogeny (375-325 Ma)**

Avalonia was a microcontinent that originated from one or more continental volcanic arcs, volcanic island arcs, or both, being either part of or accreted to Gondwana. The igneous activity produced by subduction created the arcs between 730-570 Ma. The microcontinent rifted from Gondwana during the opening of the Iapetus Ocean. It drifted northward and collided with Baltica first, then Laurentia, incorporating itself into Laurentia as an exotic terrane. The collision began in the Maritime Provinces of Canada and in northern New England during the Early to Middle Devonian Period (416-359 Ma), and moved southward down to Alabama during the Early Mississippian (350 Ma).

**Alleghanian Orogeny (325-260 Ma)**

During the Pennsylvanian Period the African part of Gondwana collided with the North American part of Euramerica as the Iapetus plate subducted beneath the North American craton Laurentia. The convergence of Gondwana with Euramerica became the final closing of the Iapetus Ocean. The convergence zone stretched from Newfoundland to the Marathon Mountain area of Texas. By the end of the Mesozoic Era (65 Ma), however, the Appalachians had eroded to an almost flat plain.
Figure 4. Sequence of events that took place during the Alleghanian Orogeny.

Miocene Epeirogenic Uplift (16-12 Ma)

Increased sedimentation rates and grain sizes delivered to offshore basins in the Atlantic and the Gulf of Mexico suggest relief rejuvenation in the Appalachian Mountains during the period 16-12 Ma. Although evidence is lacking of late Cenozoic deformation of the Appalachian region, there is strong geomorphological evidence that uplift has occurred. The west-draining southern Appalachians are in a transient state of adjustment to a newly-imposed regional base level, and are thus not in a dynamic equilibrium. Relief has increased >150% since the Miocene, suggesting that a dynamic mantle forcing is causing the epeirogenic uplift of the Appalachians. There is evidence of fragments of the relic Farallon slab beneath the modern Appalachians. There is also evidence of Moho holes, double Moho seismic arrivals, and localized seismic scatterers in the lithospheric mantle. Portions of the overthickened crust may have delaminated, which could drive the regional uplift and rejuvenation of the southern Appalachians. (Gallen et al., 2013)

References


Figure 2: Holm-Denoma, Christopher S., and Reshmi Das (2010), Bimodal Volcanism as Evidence for Paleozoic Extensional Accretionary Tectonism in the Southern Appalachians, *GSA Bulletin*, 122 (7-8) 1220-1234, doi:10.1130/B30051.1.


Figure 4: Title: "Appalachian Orogeny." File: Appalachian orogeny.jpg. Author: name unknown. USGS Public Domain, 8 February 2006. Image courtesy of the U.S. Geological Survey. Image and link to license at https://commons.wikimedia.org/wiki/File:Appalachian_orogeny.jpg