An overview of Shenandoah National Park's geologic story
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Part 1: Grenville Orogeny

The oldest rocks in Shenandoah National Park are the gneisses of the Pedlar Formation. Radiometric dating shows them to be about a billion years old. The distinctive "zebra-striping" of the Pedlar Formation is due to the development of metamorphic foliation ("gneissic banding"). In short, these rocks got squeezed. As they were squeezed, elongate mineral grains rotated into a new position, with their long axis perpendicular to the direction they were compressed in. Younger igneous rocks in the crystalline basement rock of the Blue Ridge (like the Old Rag Granite) do not have this foliation, indicating that they were intruded after the main compression happened. Granites get intruded into the Earth's crust when continents collide; they are the calling cards of orogenies, mountain-building events. In this case, the mountains that were built were called the Grenville Mountains, and they were piled up when the Congo craton collided with ancestral North America (sometimes called "Laurentia") and smeared out a block of crust between the two. This collision, which added a large block of new crust to the eastern edge of North America, completed the assembly of a supercontinent geologists call "Rodinia." Width of photograph is approximately one foot.
An illustration of the difference in texture between a **granite and a granite-gneiss**. Granite-gneisses (B) have foliation, indicating that they have been deformed after the original granite (A) cooled. In the Pedlar Formation, we see a lot of granite-gneiss, while the Old Rag Formation is dominantly granite. The Pedlar has been around longer (it is older), meaning that it has more opportunity to be squeezed by the mountain-building processes of the Grenville Orogeny. The Old Rag granites, on the other hand, were inserted into the crust rather later in the Grenville Orogeny, and so did not have the same opportunity to be deformed as the older Pedlar Formation.
The **Old Rag granite** is not as foliated as the Pedlar Formation, indicating that it was intruded into the Grenvillian crust after the bulk of the compressional deformation had ceased. Note the presence of blue quartz: quartz containing inclusions of the titanium-rich minerals ilmenite and rutile. Blue quartz is an indication these rocks have been metamorphosed twice: once during the Grenville Orogeny, and again later during the Appalachian Orogeny. *Width of photo is about six inches.*
Part 2: weathering and erosion of the Grenville Mountains

After the Grenville Orogeny ceased, the Earth-surface processes of weathering and erosion began wearing away at the uplifted mountains, dragging them down pebble by pebble, sand-grain by sand-grain. A discontinuous group of sedimentary rocks that resulted from this erosion is preserved in patches above the Pedlar and Old Rag Formations. These sediments, of the **Swift Run Formation**, are interpreted as steam valleys filled with sediment, draining the Grenville range. They are compositionally immature, with large, angular grains of feldspar. *Width of photograph is approximately six inches.*
Part 3: Rifting of Rodinia, and eruption of the Catoctin flood basalts.

The modern Afar Triangle region of Ethiopia (East Africa) provides an analogue for what Rodinia may have looked like during the rifting event which created the Iapetus Ocean basin. Normal faulting results in a down-dropped central basin (the "Great Rift Valley"). From its source in the mantle, lava travels upwards through the crust along a plumbing-like series of fractures. Fresh lava (which cools to form the igneous rock basalt) floods out over the surface. The same thing happened in Shenandoah about 700 million years ago. Some estimates put the volume of lava extruded at around 1000 cubic miles! We call it the Catoctin Formation.

Eventually, the rift valley shown will flood with ocean water, and be a skinny, narrow sea much like the modern Gulf of Aden or the Red Sea. This body of water will widen and widen (sea floor spreading) and eventually attain the dimensions of a proper ocean basin. In Shenandoah, the lavas remind us that Rodinia was rifting apart, and opening up the brand-new Iapetus Ocean basin. *Modified from a Google Earth image.*
Mike Nelson obligingly points out a thick, tabular zone of dark rock cutting across an area of much lighter rock. This distinctive stripe is a dike of the Catoctin Formation, cutting across the older gneiss of the Pedlar Formation. These feeder dikes were "plumbing" conduits that led from sources near the mantle upward to the surface of Rodinia. A build-up of excess heat beneath the Rodinia supercontinent caused it to break apart (much like excess heat in a microwaved potato will cause it to break apart). Stretching occurred in a WNW-ESE direction, causing fractures to open up that were oriented perpendicular to that, roughly NNE-SSW. These fractures popped open, and released pressure on the hot mantle rocks far below. This decompression allowed the ultramafic mantle rocks to partially melt, giving rise to a mafic-composition magma which gurgled upwards towards the surface. When it reached the surface, it spilled out over the landscape in a fissure eruption of the sort we see today in East Africa's Great Rift Valley.
A close-up of the contact between the granite-gneiss host rocks of the Pedlar Formation (right) and the dark, fine-grained basaltic feeder dikes of the Catoctin Formation (left), exposed near Little Devil's Staircase overlook on Skyline Drive. Quarter for scale.
The orientation of the feeder dikes can tell us something about the tectonic stresses the region was under when the dikes were intruded.


The consistent NNE-SSW orientation of the Catoctin feeder dikes tells us that the crust was extended (stretched) perpendicular to that orientation; that is, ESE-WNW. This is the direction that Rodinia broke apart in (red arrows). The initial orientation of the young, linear Iapetus Ocean would have been approximately parallel to the dike orientations. The modern Red Sea serves as an analogue for what this new ocean would have looked like, and nearby rifting in East Africa demonstrates that even in the modern world, continental rifting funnels mafic lava (basalt) to the surface.

A huge dike of metamorphosed basalt, cutting through the Pedlar Formation just north of Marys Rock Tunnel (left) on Skyline Drive. This dike is one of many feeder dikes which acted as conduits bringing molten rock to the surface (see above), but it is the largest that can be seen along Skyline Drive. Note the columnar jointing that extends perpendicular to the walls of the dike (see discussion in the next two photos below), indicating that cooling started at the edges and then worked its way into the warm center. Photo by Greg Beaudoin. *Width of dike is about eight feet.*
Weathered feeder dikes on Old Rag Mountain's "Summit Trail." Because meta-basalt is less stable than the granite it cuts across, it weathers away, leaving narrow slot-like areas. *Width of dikes is about 3 or 4 feet.*
When basaltic lava erupts onto the surface of the Earth, as it did during the extrusion of the Catoctin Formation, the lava loses heat quickly to the atmosphere. This loss of heat cools the lava down, and lets it solidify into igneous rock. As it cools, the basalt contracts in volume, for the reason that hot things are less dense than cold things. As it cools, it contracts equally across the surface of the flow, and forms **columnar jointing**. These examples are on the Limberlost Trail, south of Skyland. *Columns are about one foot in diameter.*
A cross-sectional view of the columns created when basalt contracts and experiences columnar jointing. This "soccer ball" pattern appears as the cooling rock contracts equally in every direction, resulting in evenly-spaced, equal-angle (about 120°) cracks opening up at the surface, and then extending down into the flow. The same pattern is seen as drying mud contracts and cracks into similar polygonal shapes. As above, the outcrop is on the Limberlost Trail, south of Skyland. *Pencil for scale.*
Columnar jointing in basalt

Some other examples of columnar jointing: the Giant's Causeway, County Antrim, Northern Ireland (as depicted on the cover of the Led Zeppelin album "Houses of the Holy"), and Devils Tower, Wyoming.
Another thing that erupting lava does is de-gas. Lava, like soda, is a solution of many components. Several varieties of gas are typically dissolved in magma. When the magma makes it to the surface of the Earth in an eruption (thereby dropping the name \textit{magma} and becoming \textit{lava} instead), it often loses some of these gases. The gases, which were stable under higher pressures deep in the Earth, spontaneously bubble out of solution when the pressure is released. Your soda will do the same thing when you pop the top: suddenly carbon dioxide (CO$_2$) which had been stable under pressure, now bubbles out of solution, making soft drinks "soft." CO$_2$ is also one of the most common volcanic gases, though water vapor is even more common. When the lava starts bubbling, some of the bubbles can be caught and preserved as little Swiss-Cheese-style holes in the rock. Geologists call these holes \textit{vesicles}, and they are readily seen in these two hand-samples from the NVCC Annandale Geology Lab. \textit{Width of photograph is approximately eight inches}. 
Here are some vesicles preserved in the Catoctin meta-basalt flows. These bubbles tell us that the lava was at sufficiently low pressures to allow degassing when it cooled. *Width of photograph is about four inches.*
When vesicles get filled in (usually by hydrothermal precipitation of soluble minerals by groundwater), amygdules form. These colorful amygdules are exposed in boulders of the Catoctin Formation along the Limberlost Trail, south of Skyland. They show concentric zonation, indicating their growth pattern: being precipitated around the edges of the vesicle hole first, then slowly filling in the rest of the void. The term amygdule comes from the Latin term for "almond", referring to their shapes: These ellipsoidal little nuggets first seemed almost like almonds studding a dessert pastry. *Width of photograph (foreground) is about three feet.*
Some of the lava of the Catoctin eruptions flowed over streambeds and other low-lying areas where bits of older rocks were lying in its path. Like pizza dough dropped on a pile of raisins will pick up some of the raisins in its sticky bulk, so too will lava pick up any stray clasts that are in its way. Here we see clasts of the Swift Run Formation (purple and white) caught up in the matrix of Catoctin lava (here metamorphosed to the green-colored mineral epidote). The angular shape of the Swift Run fragments show that they haven't moved very far in the hot lava -- otherwise they would have thermally eroded to rounder shapes, as will an ice cube left in a beverage for too long. Thus, we call this a volcanic breccia (an Italian word, it rhymes with "getcha").

Width of photograph is about one foot.
Location of **pillow basalts**, bread-loaf-shaped structures that form only when lava erupts under water. Map from Lukert and Mitra (1986): "Extrusional environments of part of the Catoctin Formation,"*Geological Society of America Centennial Field Guide, Southeastern Section.*
It wasn't just 24-hour eruptions, 7 days a week, during the extrusion of the Catoctin flood basalts. Rather, some evidence in the Park shows us that there were extended periods of calm amid all the volcanic chaos. This outcrop, at Signal Knob Overlook (Milepost 5.7) shows us a streambed conglomerate, sandwiched between two Catoctin lava flows. The geologic story imparted by such an arrangement of rocks is: (1) lava erupted, (2) things calmed down enough for a stream to establish itself draining along the top of the lava flow, carrying along pebbles and sand, (3) another eruption buried the stream under yet more lava. Width of photograph is about six inches.
A view to the south, looking at **Stony Man Mountain**. Shenandoah's answer to New Hampshire's Old Man of the Mountain, Stony Man is thought by imaginative folks to look like a reclining face, viewed in profile. It turns out that the underlying Catoctin Formation's various members, stacked up in sequence, determine the nature of this "face". Steps occur between each of the eruptions of the flood basalt, and certain formations are more easily eroded than others (like the volcanic breccia -- seen in the above photograph -- which forms the strongly concave depression that is Stony Man's upper lip).
A map-view image of the globe at the time Rodinia was breaking apart: notice in particular the orange areas, indicating Grenvillian mountain belts around the world. The Congo craton pulls away from North America (technically called "Laurentia" at this point) along with the Amazonia craton, opening up a long, skinny ocean: the Iapetus Ocean.
Once Rodinia broke apart and the tectonic plate boundary moved offshore (the mid-ocean ridge built up new oceanic crust on the floor of the Iapetus Ocean, and so progressively moved further and further out to sea), sea level rose and flooded ancestral North America (a.k.a. "Laurentia"). This rise in sea level deposited three distinct sedimentary formations which can be seen today in Shenandoah National Park, as well as the limestones which today make up the floor of the Shenandoah Valley to the west. Collectively called the **Chilhowee Group**, these sediments consist of: stream and river conglomerates and sandstones (**Weverton Formation**), lagoonal muds (**Hampton Formation**), and beach sands (**Erwin Formation**). This is a shot of the conglomerate at the base of the Weverton Formation. *Pen for scale.*
Here's another shot of a more "mature" (quartz-rich) area of the **Weverton Formation**. Remember that this had mud deposited atop it (Harpers Formation) and more mature quartz beach sand on top of that (Antietam Formation). On top of the uppermost beach sands were deposited limestones, but these limestones are not exposed in the Park today. A few miles further west, and a couple thousand feet lower in elevation, you can find them being etched into features like Luray Caverns. *Width of photograph is about four inches.*
This sea-level rise is documented in Shenandoah's classic example of a transgressive sequence of sediments. The Chilhowee Group records a progressively retreating shoreline, because certain sediments only get deposited in certain areas (top). By analogy with modern sedimentation (a uniformitarian approach), we can determine that rise in sea level would shift all the sedimentary types ("facies") above further inland. If our intrepid Cambrian SCUBA diver were to sit still as sea level rose (bottom), he would find himself buried in sediments representing further and further offshore environments, until nothing clastic (& therefore land-derived) was left, and so carbonates like limestone would cap off the sequence. This incursion of sea level over the margin of the continent was known as the Sauk Sea. (The Sauk Sea, therefore, can be thought of as that portion of the Iapetus Ocean which was overtop of North American continental crust.)
Scanning electron photomicrographs of sand grains deposited in the Sauk Sea show extreme **rounding and "frosting"** (small-scale pitting) on the surface of the grain. These features indicate the sediments were strongly worked by the wind before finally being deposited by water. It is thought that wind would have been a much more dominant force in physical weathering during the Proterozoic and Cambrian because of the absence of land vegetation then. (We know that the sediments were ultimately deposited by water because of the presence of aquatic ripple marks in the sediments, as well as trilobite fossils.)
So our overall stack of rock layers in Shenandoah National Park looks something like this in cross-section. Redrawn from Gathright, 1976.
Part 5: Deformation and metamorphism due to the Alleghenian Orogeny

The final phase of the **Alleghenian Orogeny** (sometimes called "the" Appalachian Orogeny) represented as a schematic cross section. As the Iapetus Ocean closed due to subduction, it grew narrower and narrower. Eventually it closed to nothing, and Africa (Gondwana) and North America (Laurasia) collided, raising up a series of mountains and completing the assembly of a second supercontinent, Pangea.
All older rocks were both metamorphosed (chemically altered under conditions of elevated temperature and pressure) and structurally deformed in an intense mountain-building event called the Appalachian Orogeny, which occurred about 300 million years ago. During this orogeny, the basalt of the Catoctin Formation was metamorphosed into a **greenstone**. Greenstones are metamorphic rocks characterized by a large amount of the green-colored metamorphic minerals chlorite and epidote. The epidote is a pistachio-green, whereas the chlorite is usually forest-green.

The second thing we can see in this picture is that our perfect 120º-120º-120º "soccer ball" pattern to the columnar joining no longer holds. The Catoctin's cooling **columns have been deformed**. Now our columns have been squashed (from top to bottom in this picture), resulting in angles of ~140º (more obtuse) and ~110º (more acute). Outcrop is on the Limberlost Trail, south of Skyland. *Large central column is about one foot wide (left to right).*
These ones are **even more squashed**: ~145° and ~90° angles show us these columns are not as equiangular as they must have been when they formed. Hence, they've been deformed, likely during the Appalachian Orogeny. As above, the direction of compression is from the top of the photo towards the bottom, resulting in extension from left to right. Outcrop is on the Limberlost Trail, south of Skyland. *Large central column is about one foot wide (left to right).*
During the Alleghanian Orogeny, about 300 million years ago, the ancient crystalline and meta-sedimentary rocks of the Blue Ridge province were broken off of the main part of the North American crust and shoved up and to the west over much younger sedimentary rocks. In general, the structure of the Blue Ridge Province is a vast, overturned fold, lopsided towards the west. Furthermore, the fold is detached from its roots in the "basement" rock of the east coast, and has travelled along a zinger of a fault, the Blue Ridge Thrust Fault, from an original position somewhere further east. Note that the Blue Ridge mountains are merely the westernmost portion of the Blue Ridge province, which actually extends much further east.
A delicious analogy for the Blue Ridge Thrust Fault. I baked a chocolate & peanut butter cake last week. Yesterday, I baked a carrot cake. The carrot cake is younger; the chocolate cake is older. Then I shoved the older cake on top of the younger cake by pushing sideways (A). Travelling along a layer of icing, the older chocolate cake moved up and over the younger carrot cake. The surface of contact between the two is the Blue Ridge Thrust Fault, shown as a dotted line (B). Arrows show relative motions of the two cakes. This thrust-faulted cake was served at the NOVA-Annandale end-of-semester party for the Mathematics, Science and Engineering Department, May 2006.
The overall sequence of events in Shenandoah National Park, as illustrated by Gathright (1976). From top to bottom:

Extrusion of lava flows.

Deposition of Weverton Formation conglomerates and sand.

Deposition of Harpers Formation mud.

Deposition of Antietam Formation barrier island sands.

Deposition of Tomstown Formation and other Cambrian/Ordovician carbonates (limestones).

Folding and faulting of all rock units during Alleghenian Orogeny.
Symptoms of the Alleghanian Orogeny expressed as a cross-section: felsic intrusions (e.g. granite, generated through partial melting of pre-existing rocks), deformation (folding and faulting), and metamorphism. Slices of oceanic crust (ophiolites) may also be present.
After the Alleghenian Orogeny, supercontinent-rifting ensued again (this time Pangea broke apart, and the Atlantic Ocean was born). The Appalachian mountain range was abandoned by the forces of tectonic uplift, and left to erosion and weathering. These surficial forces had their way with the great mountain range, reducing it to its roots.

A satellite photo (false-color image) of the Blue Ridge Mountains in Shenandoah National Park (below, right), and also the distinct form of Massanutten Mountain in the Shenandoah ("Great") Valley (center). "Warm" colors represent high elevations; lower elevations are green. The texture of the Blue Ridge is markedly different from the mountains to its northwest. This textural difference is entirely due to the rocks the respective provinces are made of. The Blue Ridge is hewn from metamorphosed sedimentary and igneous rocks, whereas the Valley and Ridge province is a series of folded sedimentary layers, only lightly metamorphosed. Note also the pronounced meanders of the North and South forks of the Shenandoah River, on either side of Massanutten. (NASA image)
Here's a look at the subsurface geology of the Shenandoah Valley, to the west of the Blue Ridge. A line of cross-section schematically "slices open" the Earth, revealing the structure of the rock layers underlying the Blue Ridge and Massanutten Mountain. **Massanutten is a structural syncline**, a down-folded package of rocks. Certain rocks (yellow) like sandstone are resistant to weathering, and form resistant ridges of rock. Others, like limestone and shale (blues, pink, purple, & green) are less resistant, and are easily eroded down into topographic valleys. The rocks of the Blue Ridge are represented here with a peach color, and shown shoved bodily overtop of younger layers along the Blue Ridge Thrust Fault. *Modified from a Google Earth image.*
Mountain ranges weather away after tectonic uplift has ceased, until eventually topographic relief is at a minimum, and only the symptoms of a mountain belt remain (folds, faults, regionally-metamorphosed rocks, felsic intrusive igneous rocks. The Appalachian Mountains we see today are largely due to differential weathering of the rocks beneath, with the Blue Ridge most resistant to weathering (and thus being the highest-elevation feature in the region).