The Catoctin Formation — Virginia is for Lavas

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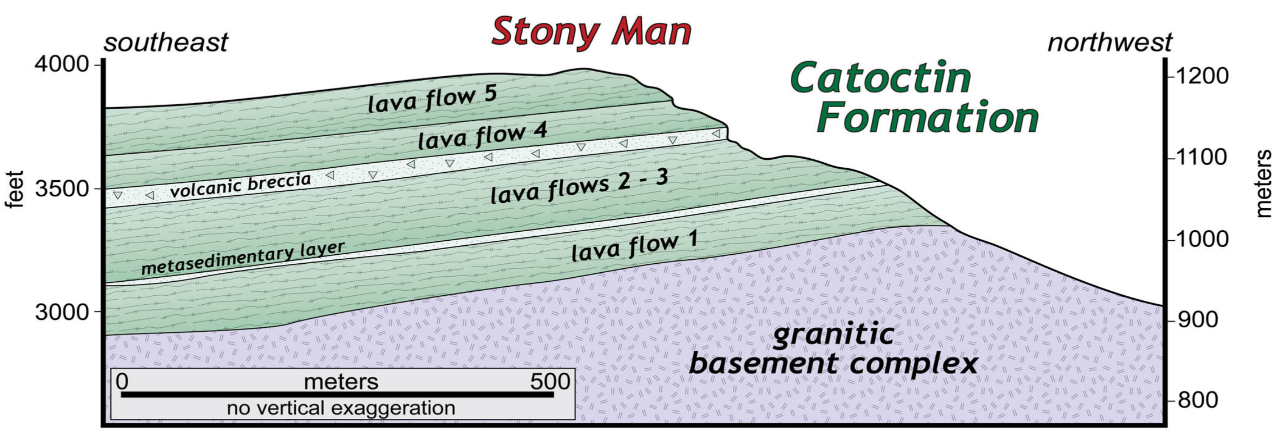
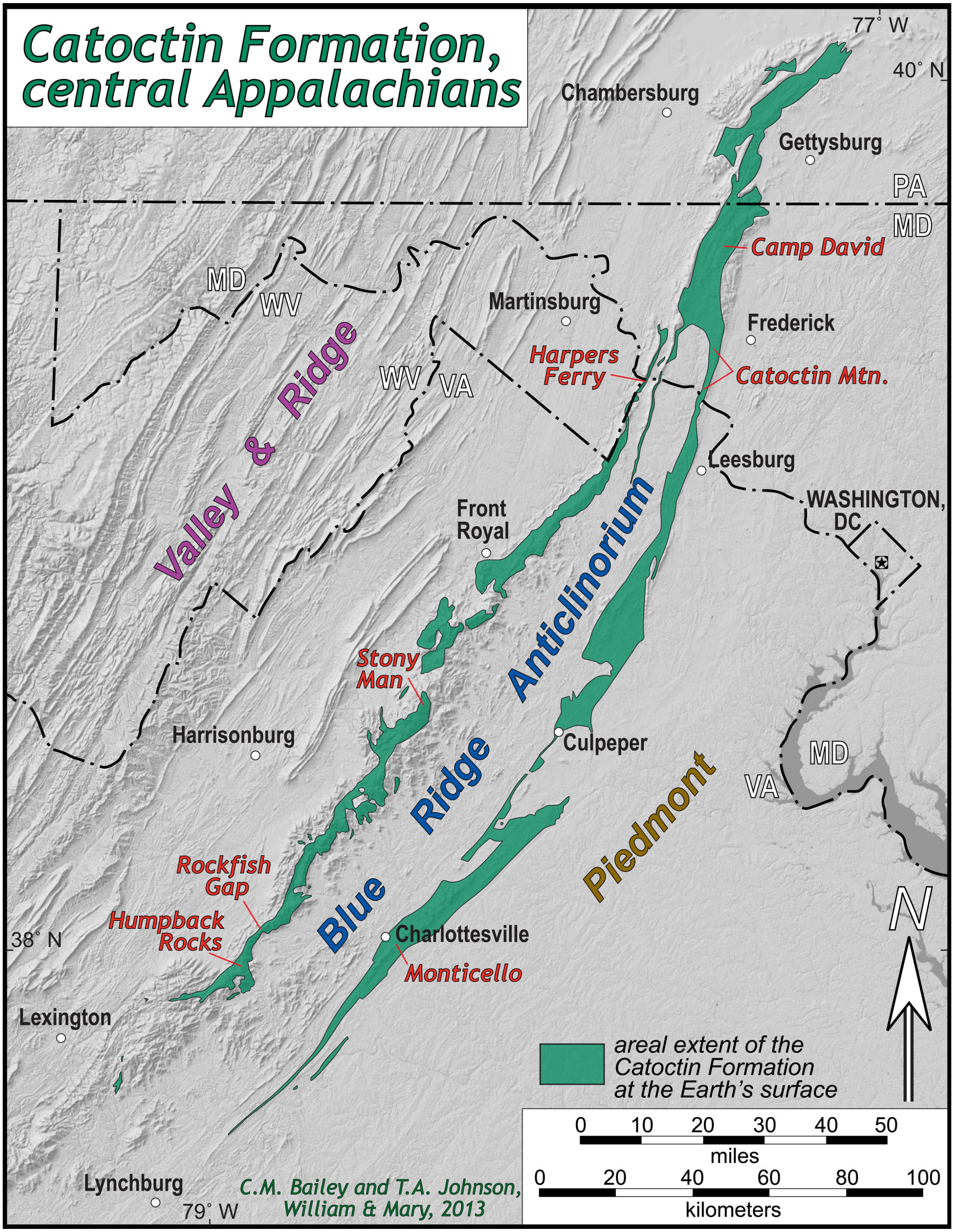
Stony Man is a high peak in Virginia's Blue Ridge Mountains that tops out at just over 1200 m (4,000'). Drive south from Thornton Gap along the Skyline Drive and you'll see the impressive cliffs of Stony Man's northwestern face. These are the cliffs that give the mountain its name, as the cliffs and slopes have a vague resemblance to a reclining man's forehead, eye, nose, and beard. Climb to the top and you'll see peculiar bluish-green rocks exposed on the summit that are ancient lava flows, part of a geologic unit known as the **Catoctin Formation**. From the presidential retreat at Camp David to Jefferson's Monticello, from Harpers Ferry to Humpback Rocks, the Catoctin Formation underlies much of the Blue Ridge. This distinctive geologic unit tells us much about the long geologic history of the Blue Ridge and central Appalachians.

Stony Man's summit and northwestern slope, Shenandoah National Park, Virginia. Cliffs expose metabasaltic greenstone of the Neoproterozoic Catoctin Formation. (CMB photo).



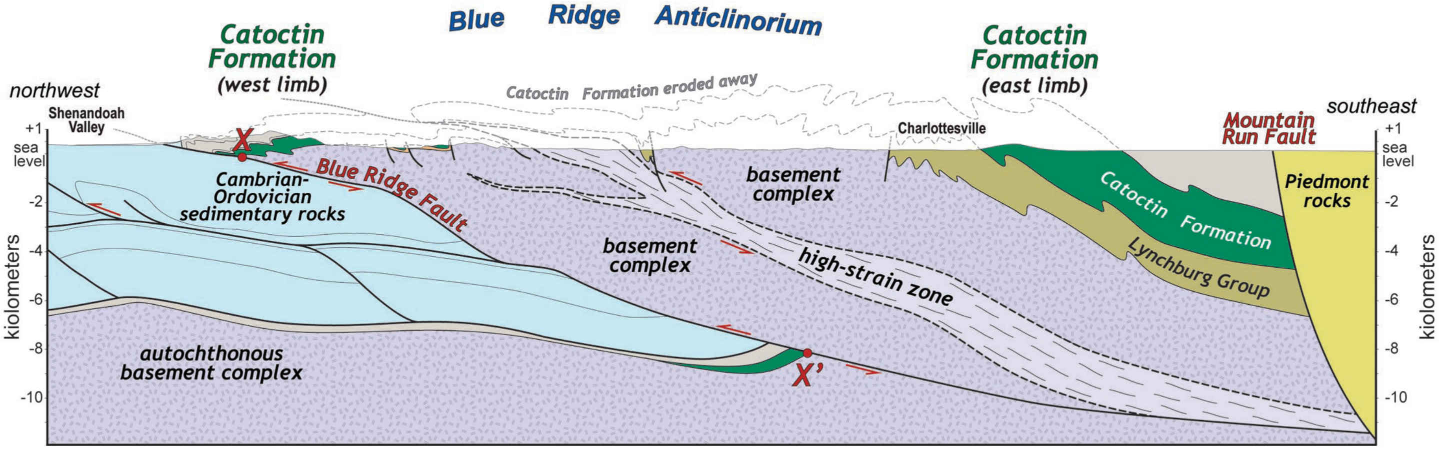
Geologic cross section of Stony Man summit area (modified from Badger, 1999).

The Catoctin Formation was first named by Arthur Keith in 1894 and takes its name for exposures on Catoctin Mountain, a long ridge that stretches from Maryland into northern Virginia. The word Catoctin is rooted in the old Algonquin term Kittockton. The exact meaning of the term has become a point of contention; among historians the translation "speckled mountain" is preferred, however local tradition holds that that Catoctin means "place of many deer" (Kenny, 1984).



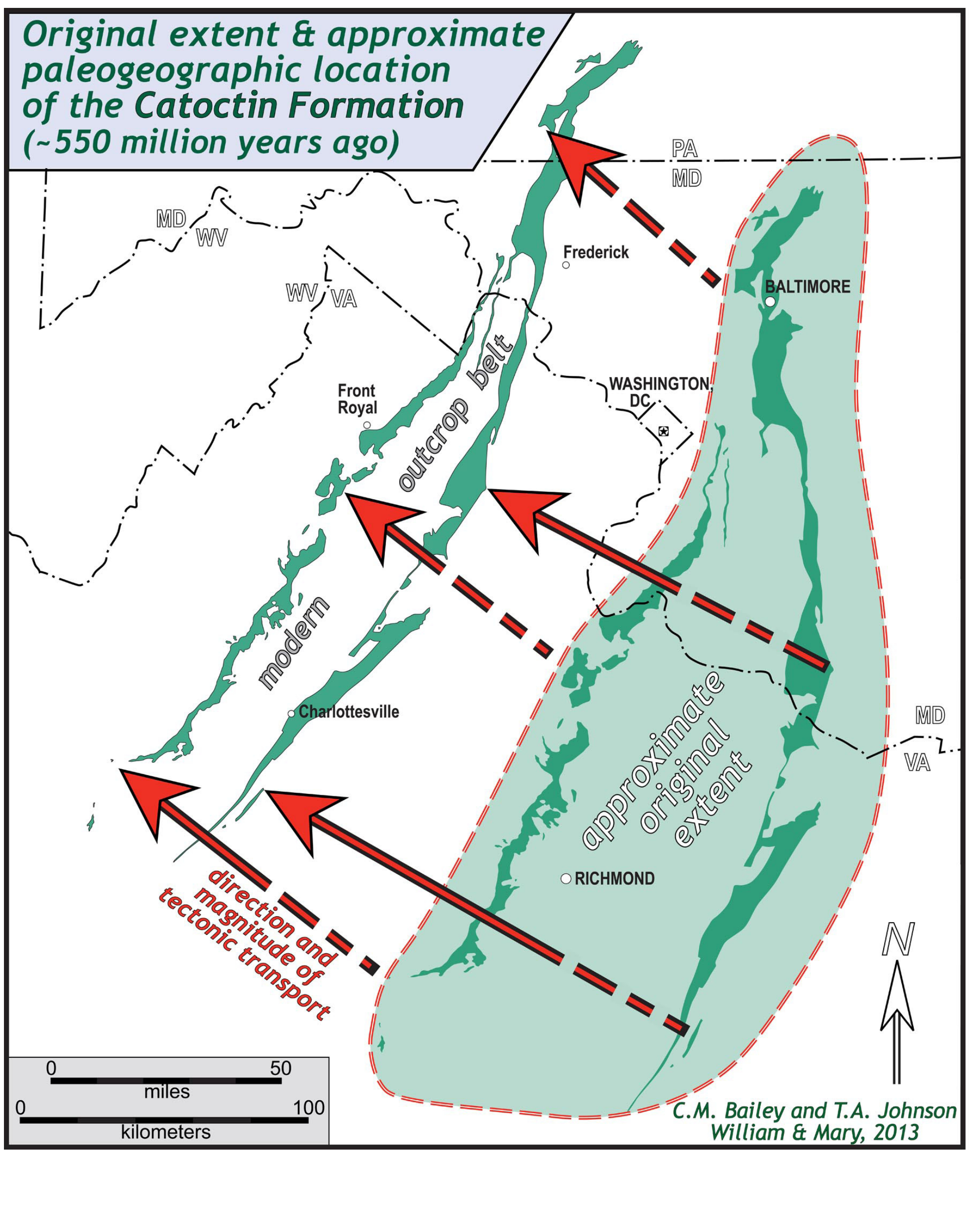
Map illustrating the distribution of the Catoctin Formation in the central Appalachians.

Origin of the name aside, the Catoctin Formation is a geologic unit that crops out over a large tract in the Blue Ridge region of Virginia, eastern West Virginia, Maryland, and southern Pennsylvania. Its current geographic extent does not, however, represent the original extent of the Catoctin Formation. In southern Pennsylvania and Maryland, the Catoctin Formation crops out in one contiguous area, but in Virginia there is an eastern and western outcrop belt of the formation. The Catoctin Formation is exposed on both limbs of the *Blue Ridge anticlinorium*, a complex regional-scale fold that has been breached by erosion thereby exposing older rocks in the center and younger rocks such as the Catoctin Formation along the flanks. Originally, the eastern and western belts were contiguous, but erosion has removed the younger Catoctin Formation to expose older rocks in the central Blue Ridge.



Blue Ridge cross section in central Virginia, note the Catoctin Formation is exposed in both a western and eastern belt. Points X (hanging wall cutoff) and X' (footwall cutoff) were originally connected prior to slip along the Blue Ridge fault system.

Interestingly, in deep wells drilled to the west of the Blue Ridge, the Catoctin Formation has not been encountered at depth and is thin or absent in a few valleys along the western edge of Shenandoah National Park. The ancient lavas of the Catoctin Formation likely were never extruded to the west of the Blue Ridge region. Seismic data from the eastern Blue Ridge indicates that the Catoctin occurs in the subsurface eastward of its outcrop belt and is likely truncated along the Mountain Run fault.



To reconstruct the paleogeography of the Catoctin Formation we've restored the Blue Ridge by taking into account the deformation that these rocks enjoyed during the tectonic monkey business that created the Appalachian's geologic structure. We accomplished this by 1) unfolding the strata, 2) unslipping the faults, and 3) unstraining the rocks (conceptually, of course!).

The Catoctin Formation is exposed both at Monticello in the eastern Blue Ridge and at Rockfish Gap in the western Blue Ridge, a distance of 38 km (24 mi.) apart. Prior to deformation, the Catoctin metabasalts at these respective locales were ~55 km (40 mi.) apart and located some 70 to 120 km to the southeast of their present location. The original extent of the Catoctin Formation was far more expansive than its current outcrop belt, occupying an area of more than 30,000 km^2.

The Catoctin Formation is composed primarily of metabasalt, commonly referred to as **greenstone** due to the rock's greenish tint. When the original basalt was metamorphosed, igneous minerals such as pyroxene, plagioclase, and olivine were converted to new minerals (chlorite, actinolite, and epidote), which give the rock a gray-green color. The Catoctin Formation also contains discontinuous layers of metasedimentary rock (including phyllite, quartzite, and even marble), as well as volcanic breccia and metarhyolite.

View of greenstone at an outcrop (hammer head 12 cm wide) and in petrographic thin section.

In some outcrops the metabasalt reveals its igneous heritage with well-preserved feldspar *phenocrysts* and *vesicles*. Vesicles are small irregularly shaped pores within the rock that formed as gas bubbles in the magma and were then frozen while the lava solidified. Commonly, vesicles are later filled with secondary minerals, such as quartz or epidote, and thus become *amygdules*. Vesicular and amygdaloidal basalts occur throughout the Catoctin Formation, and typically delineate the tops of individual lava flows.

Catoctin phenocrysts and amygdules.

As the Catoctin lavas cooled, columnar joints developed in many flows. Columns form as the rock volumetrically contracts during cooling. As a lava flow cools, both from its top and bottom surface, these cooling cracks propagate inward, forming hexagonal columns. *Columnar joints* are best developed in lava flows that extrude onto a landscape. These columns are common in the Catoctin Formation's western outcrop belt and indicate the flows were extruded on land.

In contrast, at a number of outcrops in the eastern Blue Ridge, *pillow lavas* are preserved in the Catoctin metabasalt. Pillow lavas are bulbous to lobate masses formed as lava rapidly cools underwater, forming a glassy shell as the surrounding water quenches the lava. It appears that Catoctin lavas in the eastern Blue Ridge were extruded in a subaqueous environment, perhaps beneath the waters of a nascent ocean.

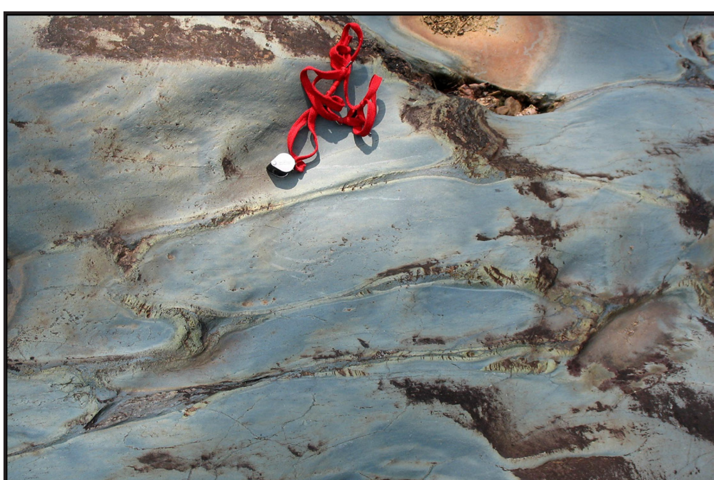
Thin layers of metasedimentary rock, volcanic breccia, and metatuff commonly demark the boundary between Catoctin lava flows. What do these interlayers represent? The meta-sedimentary rock formed as sediment, eroded from exposed highlands, and was deposited on top of flows prior to the next eruption. The volcanic breccia formed when the upper surface of a lava flow solidified then fractured while the lava on the interior continued to flow. The metatuff layers are altered volcanic ash that formed as gas periodically escaped from the volcanic plumbing system, expelling pyroclastic materials as dense palls of gritty ash that fell back, blanketing the earth's surface.

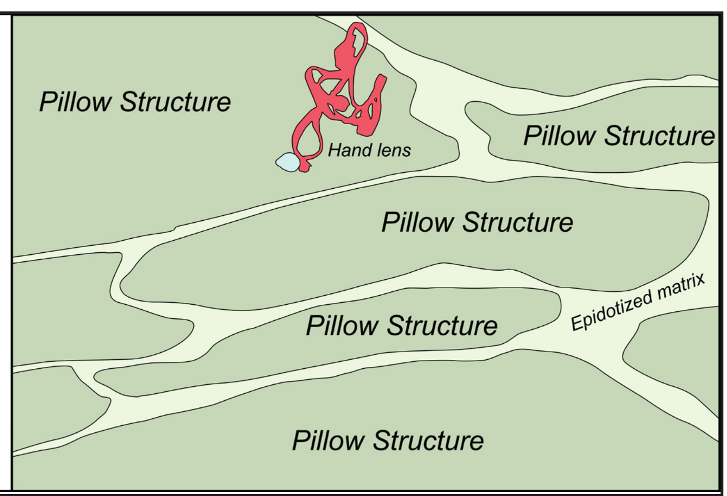
Columnar joints in the Catoctin Formation exposed along the Skyline Drive in Shenandoah National Park.

How old are the ancient lavas of the Catoctin Formation? When did a vast volcanic plain cover the terrain that would become central and northern Virginia?

Metabasalt dikes commonly intrude and cut older granitic rocks in the Blue Ridge, and in rare cases these feeder dikes can be traced upward into metabasalt flows that covered the granitic rocks. Based on these cross cutting relations, the Catoctin Formation is clearly younger than the old Blue Ridge granites that crystallized between 1.2 and 1.0 billion years ago.

The Catoctin metabasalts are overlain by a sequence of sedimentary rocks known as the Chilhowee Group. The Chilhowee Group contains fossils, including a partial *Hyolithid*, the resting trace of a trilobite, and *Skolithos*, distinctive trace fossils formed by burrowing creatures. These fossils are characteristic of sediments deposited during the early Cambrian period some 520 to 540 million years ago (Simpson and Sundberg, 1987).





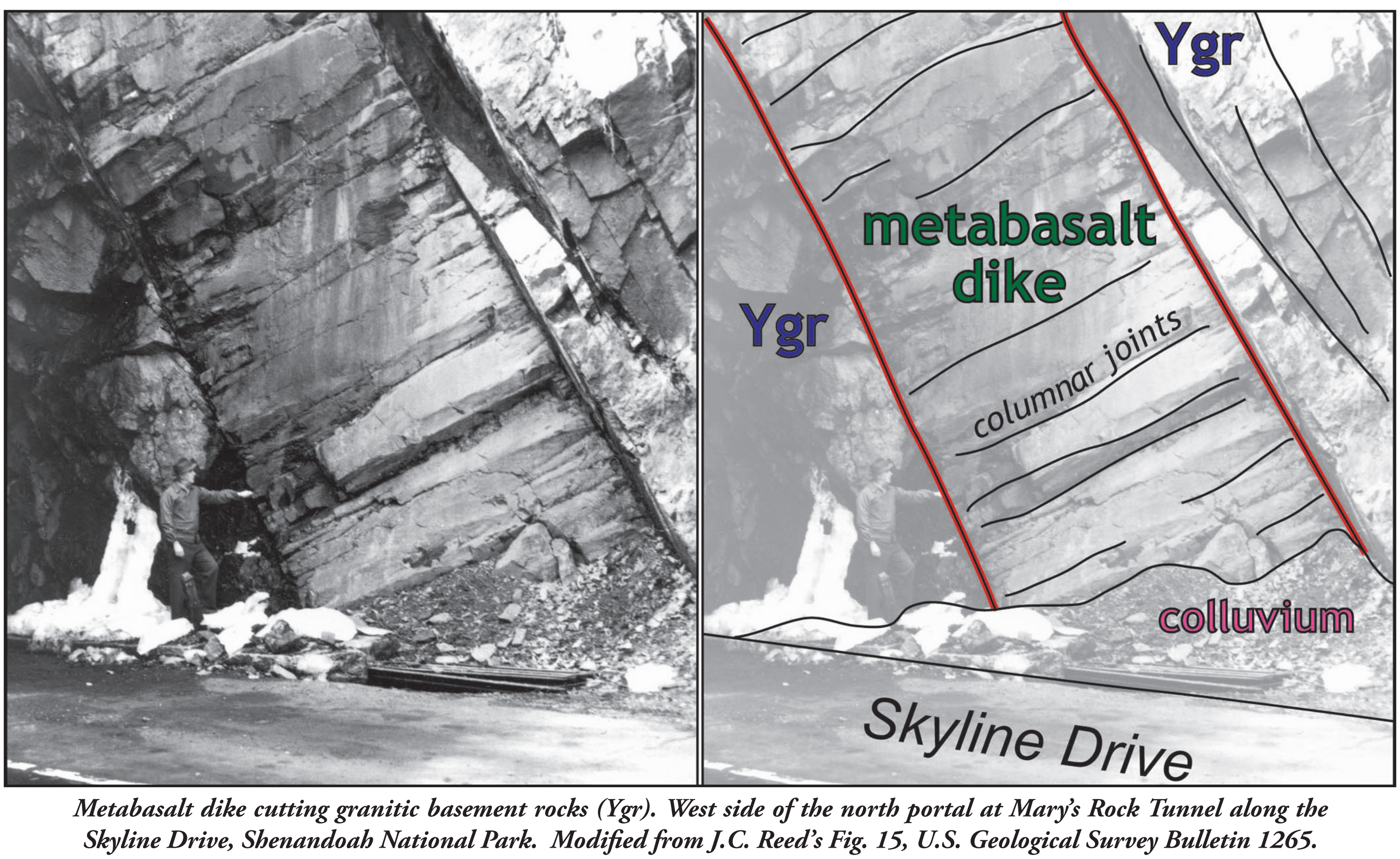
Pillow structures in the Catoctin Formation exposed along the south bank of the Hardware River in southern Albemarle County, VA.

Geologists have attempted to date the Catoctin lavas with varying degrees of success. In 1988, Badger and Sinha reported a late Precambrian age of 570 ± 36 Ma for the Catoctin Formation based on the Rubidium/Strontium (Rb-Sr) dating technique, however this isotopic system can be readily disturbed by later metamorphism.

Close–up view of a hand sample of metaconglomerate, from the Catoctin Formation in the western Blue Ridge.

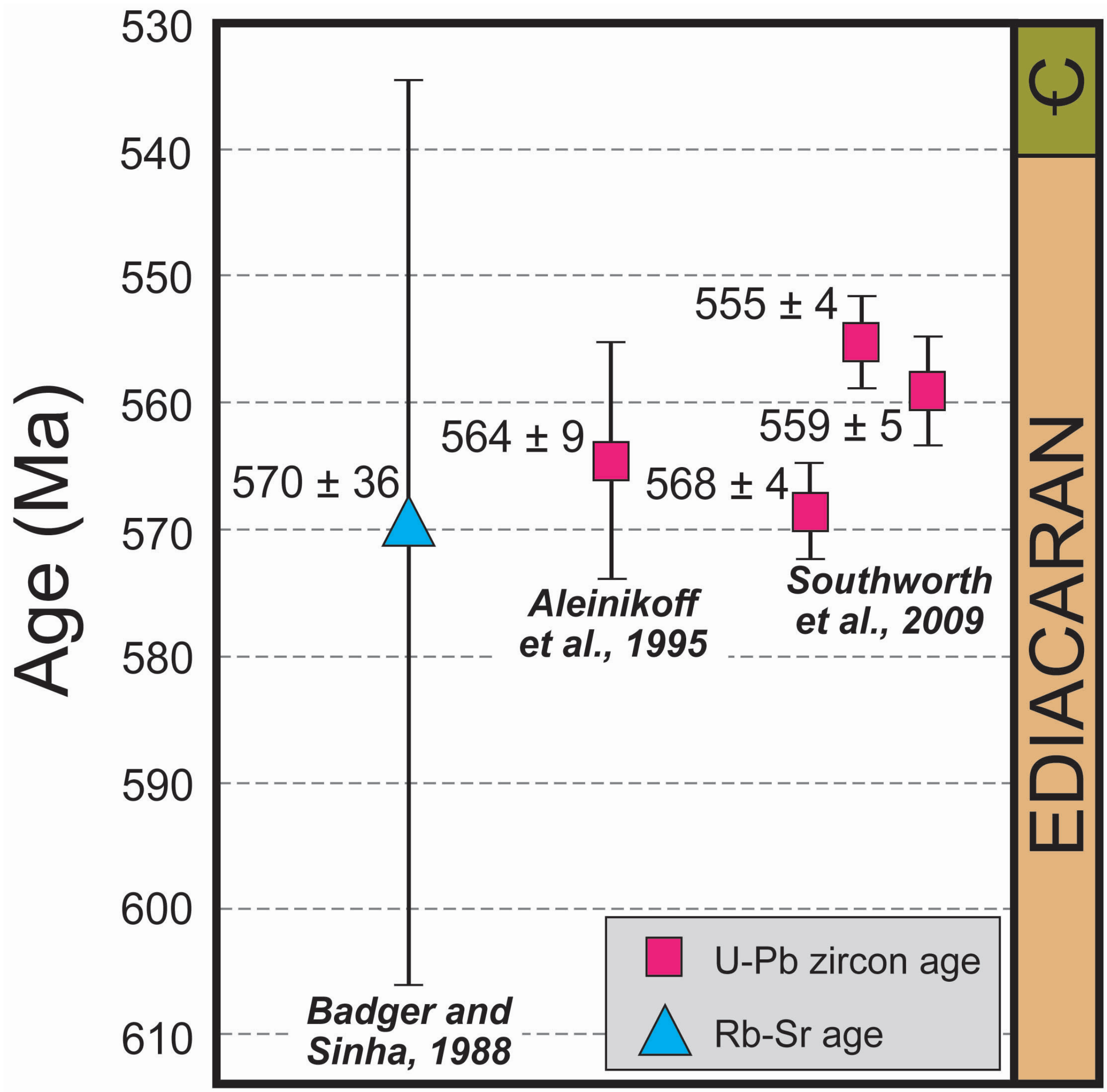
Zircon, $ZrSiO_4$, is a high temperature igneous mineral that is ideal for geochronological studies. Zircon crystals invariably contain a small amount of uranium, a radioactive element that decays to lead at a constant and well-known rate. By comparing the ratio of certain uranium and lead isotopes in a given crystal, it is possible to discern the age of crystal and, by association, the rock in which it is situated. However, silica-poor mafic igneous rocks, such as basalt, commonly lack zircons and thus cannot typically be dated with this technique.

Yet, all is not lost as the Catoctin Formation is composed of more than just metamorphosed basalt; in northern Virginia, western Maryland, and southern Pennsylvania, metarhyolite is interlayered with the metabasalt. Rhyolites are felsic volcanic rocks that typically contain zircon and can be dated with the U-Pb method. Based upon U-Pb ages from metarhyolites in the Catoctin Formation, the extrusion of this volcanic complex occurred around 570-550 million years ago (Aleinikoff et al., 1995; Southworth et al., 2009) during the Ediacaran Period at the end of the Neoproterozoic Era.



Metabasalt dike cutting granitic basement rocks (Ygr). West side of the north portal at Mary's Rock Tunnel along the Skyline Drive, Shenandoah National Park. Modified from J.C. Reed's Fig. 15, U.S. Geological Survey Bulletin 1265.

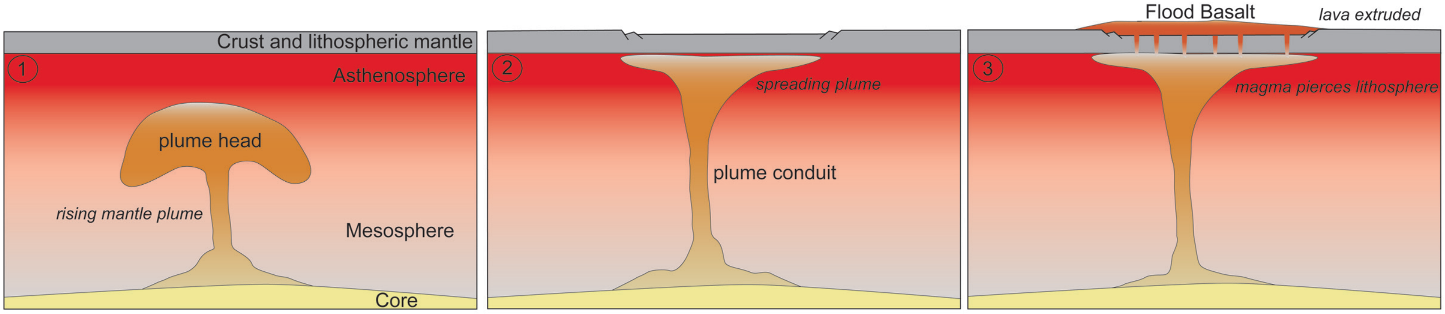
Metarhyolites in the Catoctin Formation may represent either heavily fractionated components of the original mantle melt or associated crustal melts resulting from the emplacement of magma into the upper crust. The limited geographic extent of metarhyolites in the Catoctin Formation is puzzling. Based upon textural evidence, the Catoctin metarhyolites were likely expelled as viscous glassy lava flows and welded tuffs (Fauth, 1978). The discontinuous nature and apparent thinning of the metarhyolite beds towards the southwest are indictative of a small eruptive center near the northern terminus of the outcrop belt.



Graph illustrating isotopic ages and their associated uncertainty for the Catoctin Formation.

What is a sequence of volcanic rocks doing in the Blue Ridge?

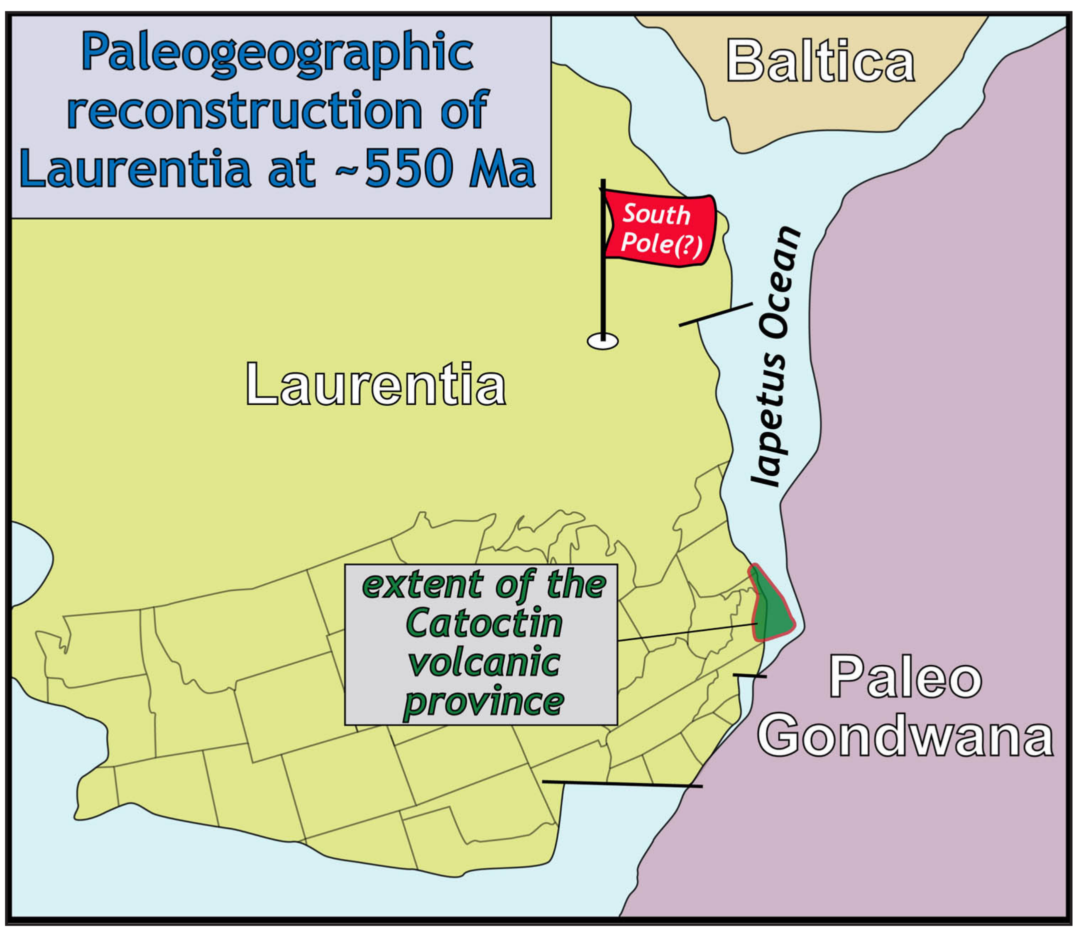
The Catoctin Formation is likely a *continental flood basalt* associated with late stage rifting that broke apart the Rodinian supercontinent and created the Iapetus Ocean. Flood basalts from large igneous provinces where low viscosity basaltic lava floods vast areas of the Earth's surface. Due to the lava's low viscosity, flood basalts are generally extruded quite rapidly, geologically speaking. In the case of the Catoctin Formation, more than 30,000 cubic kilometers of lava were extruded in a few million years. The origin of flood basalts is widely debated, however the most common explanation involves a combination of decompressional melting due to both continental rifting and the rise of a hot and expansive *mantle plume*. The origin of mantle plumes is also poorly understood, but likely involves a buoyant melt produced near the mantle-core boundary, which proceeds to rapidly rise through the mantle, melts other rocks, and drives extrusion of volcanic rocks at the surface.



Schematic diagram of a rising mantle plume 1) moving through the mesosphere 2) spreading in the asthenosphere 3) piercing the lithosphere and extruding onto the surface.

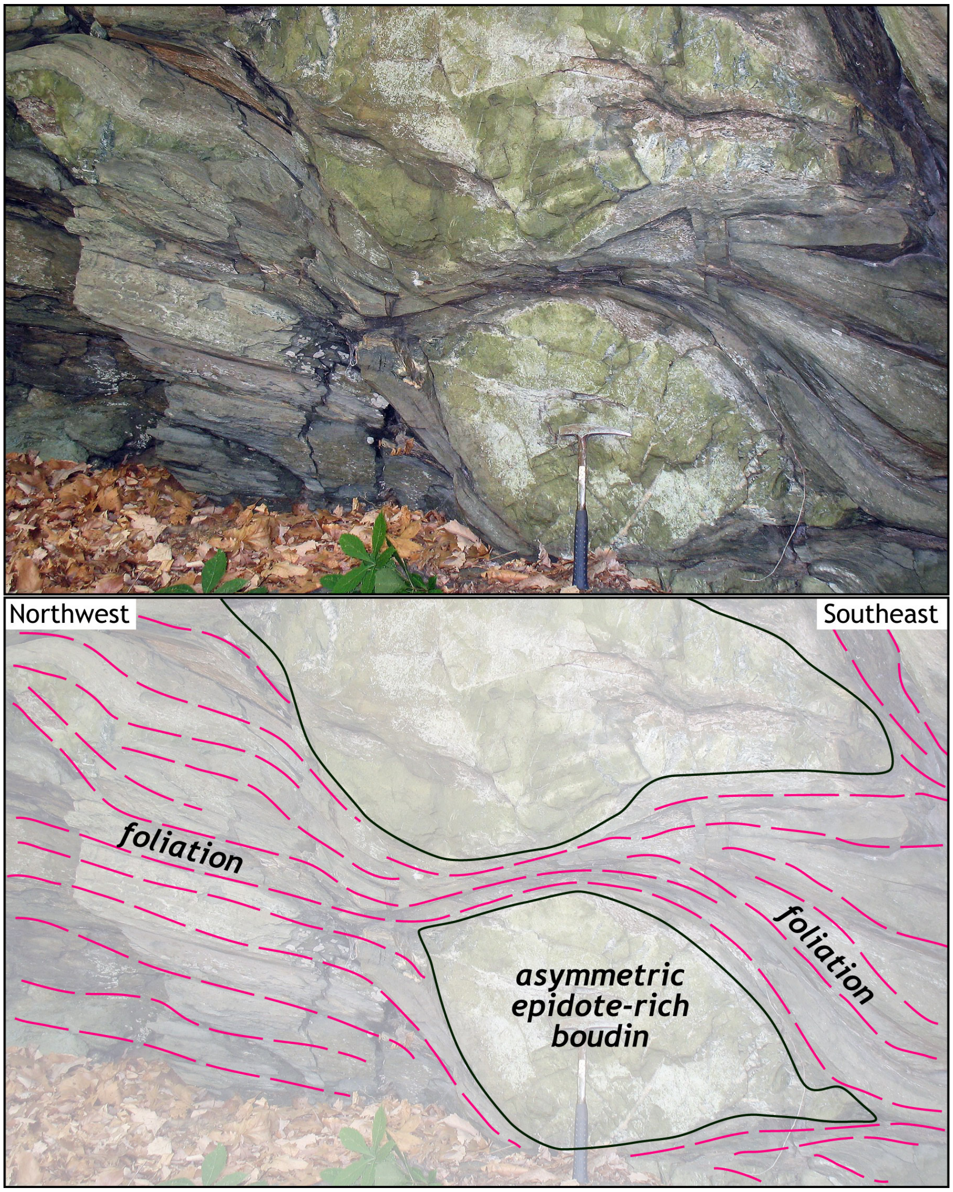
Throughout geologic time, the cycle of assembly and dispersal of so-called supercontinents has been one of the most dramatic examples of plate tectonics at work. The supercontinent Rodinia is hypothesized to have been formed in the Late Mesoproterozoic and Early Neoproterozoic. At its core was Laurentia, a large landmass composed of what is now modern day North America, Greenland, and northern Scotland. As supercontinents are wont to do, Rodinia began rifting apart some 600-550 million years ago; the tectonic plates began to once again change direction and slowly drifted away from one another, forming new oceans and closing others. One of these new oceans that was created (and later destroyed during the creation of the most recent supercontinent, Pangea) was the Iapetus. The Iapetus formed between the eastern edge of the Laurentian craton and almalgam of tectonic blocks that would eventually be formed into what is referred to as Gondwana. It was during this period of rifting that the volcanic rocks of the Catoctin Formation were extruded on Laurentia's margin.

A key method by which geologists have discerned the cycle of supercontinent formation and dissolution has been through paleomagnetism, which is the study of the magnetic properties in certain minerals as a means to reconstruct the past location of tectonic plates. Although paleomagnetism has played an integral part in developing the theories of plate tectonics and continental drift, paleomagnetism in old rocks is complex. Take for instance the plight of Rodinia, different researchers have constructed multiple iterations of the supercontinent's configuration and location. One study, focused on the Catoctin Formation in particular, places Laurentia near the South Pole at the end of the Neoproterozoic.



Paleogeographic reconstruction of Laurentia and surrounding continents at ~550 Ma. Note Laurentia was in the southern hemisphere (data from numerous sources).

How did a vast plateau of volcanic rocks that were buried beneath kilometers of shallow marine sedimentary rocks become the foliated greenstones that undergird the Blue Ridge Mountains? The answer to this question involves a complex history of deformation, metamorphism, and uplift.



Strongly foliated Catoctin greenstone with boudins.

The timing of deformation and metamorphism in the Blue Ridge region has long been a point of contention amongst research geologists. In years past, some workers argued that significant ductile deformation occurred during the late Ordovician Taconic Orogeny while others suggested Blue Ridge structures developed during the late Paleozoic Alleghanian Orogeny. Recent geochronological studies indicate that the pentrative deformation and metamorphism, the tectonic event that produced the distinctive foliation in the Catoctin Formation, occurred between 320 and 350 million years ago during the Carboniferous Period. Some twenty to thirty million years later Blue Ridge rocks were thrust over sedimentary rocks of the Valley & Ridge province, along the cleverly named Blue Ridge fault system.

The mountains produced during the Alleghanian Orogeny were jagged and tall, likely rivalling the size of today's Himalayas. However during the million of years since their uplift, the Blue Ridge has slowly been beaten down and rounded ridges have come to replace rugged mountains. As the processes of weathering and erosion continued their interplay, different rock types eroded at different rates resulting in the modern topography of the Blue Ridge. Compared the overlying stratified rocks of the Chilhowee Group and underlying granitic basement complex; the fine-grained metavolcanic rocks of the Catoctin Formation are particularly resistant to erosion.

The great American author Nathaniel Hawthorne once noted "mountains are earth's undecaying monuments." Here in the central Appalachians much of that monument is shaped from the basaltic rocks of the Catoctin Formation, a unit birthed by fire during the breakup of ancient Laurentia and later changed to greenstone during the growth of the new Pangean supercontinent.

A Top 22 List of Articles on the Catoctin Formation:

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