

# Brief Geologic History Of Virginia and the Mid-Atlantic Region

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The sixteen stage history is contained in the cross sections in a separate document. The cross section line runs northwest-southeast across central Virginia; events slightly off the line are sometimes included in the cross sections, but generally rocks and events northeast and southwest of the line are left out. On the other hand, references to current locations of rocks is keyed into the Generalized Geologic Map of Virginia, plate xx, to help keep things straight spatially.

Time scale is based on Harlan, et. al. When referring to time Ma means millions of years, and Ga billions of years. Although we have a lot of radiometric dates, the timing of events is often imprecise. Not only do different authors give different age ranges, the events themselves vary in timing from the piedmont to the Valley and Ridge, and from the northern to the southern Appalachians.

The history is written to flow as a story for each cross section, and references are minimal. More complete references appear in the detailed chapters later in the book. When discussing geologic history, past, present, and future are fluid; I have tried to discuss events as if we are there at each stage experiencing what is happening at the time it is happening. But, when discussing geologic history it is difficult to avoid references to events that “may have”, or “have been” or “will” or “had become” something.

Although the history is written to be self contained, knowledge of basic plate tectonics and the Wilson Cycle is helpful. Specific rock names are kept at a minimum, but are sometimes used where the distinction is important for the interpretation. Technical terms are italicized when they first appear. Terms in ***bold italic*** are labeled on the cross sections. Compass directions are always present day unless otherwise indicated. Finally, there is an awkwardness between the use of sediment names and sedimentary rock names. Rock names are used throughout, even though in the present tense it is a sediment that is deposited.

## Cross Sections A, B, C, D - Grenville Orogeny

- ▶ *Early- Mid Proterozoic: Country rock 1800-1100 Ma; intrusions 1150-1050 Ma; metamorphism 1000-900 Ma*
- ▶ *Current Location: Exposed record primarily in the Blue Ridge province, with isolated piedmont outcrops (Sauratown Mountain, Goochland, Baltimore Dome); subsurface Grenville rocks underlie most of the eastern third of North America.*

**I**n the beginning . . . ; when we go hunting for the very oldest event in a region there is usually not much to go on, and this is true of the mid-Atlantic. We have known for a long time that the oldest rocks in Virginia are in the Blue Ridge, identified with the billion year old ***Grenville Orogeny***, a Himalayan-sized mountain building event. But, these “Grenville” rocks are highly metamorphosed (making them hard to read), and contain traces of even older events.

The oldest evidence in the Blue Ridge are scant traces of 1800 Ma sediments (Cross Section A), followed by 1100 Ma volcanics (Cross Section B). Both these records are pre-Grenville and preserved without basement; that is, without the underlying rocks they were originally deposited on. We presume the basement was continental crust, i.e. granite, but its size, shape, and position are unknown. Not much to go on, and a pretty vague picture, but this is typical for the oldest rocks in a region. At least we know that 1.8 billion years ago, half the age of the earth, some piece of Virginia already existed.

The Grenville orogeny is sometimes seen as a single event, but is at least two distinct mountain building events. The first was caused by a subduction under the North American edge (Cross Section B); it generated the 1050-1150 Ma igneous intrusions now found in the Blue Ridge, and built an Andean sized mountain (highest Andean peak is Mount Aconcagua at 22,831 feet [6,959 meters] on the border of Argentina and Chile.) The subduction was the closing phase of a Wilson cycle, however, and shortly South America collided with North America for the second event. For many years we believed this continent was Africa, but have recently learned it was in fact South America colliding. With the collision South America rides up over eastern North America,

depressing North American crust deep enough to cause the 900-1000 Ma high grade metamorphism that pervades all Blue Ridge rocks, while assembling the **Rodinia** supercontinent (Cross Section C).

The Grenville orogeny is thus the culmination of a series of events whose roots go back to at least 1800 Ma. But imagine these 30,000 foot Grenville mountains stretching 4000 km from Newfoundland down the east coast of *Laurentia* (the name for ancient North America used here until the name changes again in cross section L) and across into Texas. And imagine them forming a backbone down the center of Rodinia between North and South America while the foothills spread as far west as Michigan. A promising beginning.

### **Cross Section E - Early Rifting and the Crossnore Volcanic/Plutonic Complex**

- ▶ *Late Proterozoic; 690 to 540 Ma*
- ▶ *Location: Crossnore rocks are intruded into Grenville rocks of the Blue Ridge province. The axial graben is found today on the east side of the Blue Ridge mountains. The half graben of the Rome Trough are located in western Pennsylvania, West Virginia, and Kentucky, buried under thousands of feet of sedimentary rocks.*

**M**ountains don't last long, and in less than 100 million years the Grenville mountains are eroded down virtually to sea level, a *peneplane*, creating a profound unconformity across the eastern third of North America (Cross Section D). By 800 Ma the igneous and metamorphic core of the mountain is exposed; rocks that not too long ago were red hot are now, on cold nights, wet with dew. You can walk dry shod from Virginia to South America without breaking a sweat. These ancient igneous/metamorphic rocks are called the *basement* because all the other rocks are deposited on top of them.

Beginning about 690 Ma, however, a rifting event begins that eventually rips the Rodinia supercontinent apart. We first notice something is happening when the region swells upward into a broad, high dome several kilometers above sea level, and about a thousand kilometers in diameter - a *hot spot* - driven by heat from a ***mantle magma plume*** below. At depth the hot rock is plastic, and the continental crust between Laurentia and South America stretches and thins, like taffy or silly putty. Near the surface, however, the cold and brittle rocks crack as they dome to form blocks of crust that rotate down along curved *normal faults (listric faults)* into the stretched-open spaces, forming valleys (*graben*) bordered on each side by higher blocks (*horsts*). Initially small, the *scarps* (cliffs formed by the faulting) grow to hundreds then thousands of feet elevation, until the region is a jumble of dislocated mountain-sized blocks. In the center is an ***axial graben*** with a major listric fault on each side. Sediments eroding from the major horsts bordering the axial graben - the ***continental terraces*** - fill the graben. Half graben, with listric faults on only one side, form on both sides of the axial graben. The best known at this time is the ***Rome Trough*** buried in the subsurface of Kentucky, West Virginia, and western Pennsylvania.

***Crossnore*** volcanic/plutonic igneous activity, driven by the heat below, accompanies the horst and graben formation. Magmas penetrating into the Grenville basement rocks form batholiths of pink granite (e.g. Crossnore, Robertson River, and Striped Rock plutons), and these in turn send magma to the surface to form massive volcanos, such as those at Mt. Rogers, Virginia. and South Mountain, Pennsylvania. Simultaneously, mafic (basaltic) lavas spill out onto the valley floors where they mix with sediment eroding from the horst mountains.

One more image is needed to appreciate this interval. Between about 750-580 Ma, the Earth underwent four extremely severe, global-wide, glaciation events, all together called Snowball Earth. Each glaciation episode lasted about 10 million years. Temperatures on the earth dropped to -50 degrees Celsius, cold enough that the oceans froze as much as a kilometer deep even in the tropics, where the Mid-Atlantic region lay at this time. Thus, picturing the world at this time, imagine a scarred and rugged landscape, shaken by earthquakes, smothered by eruptions, stark and barren (because aside from bacteria and possibly lichens nothing lives out on the land), and occasionally everything covered with glacial ice. A stark, harsh, uncompromising world, this Virginia.

### **Cross Section F - Rift . . . Initiation of the proto-Atlantic (Iapetan) Ocean**

- ▶ *Earliest Cambrian: about 540-540 Ma*
- ▶ *Current Location: Blue Ridge province and Western (Inner) Piedmont*

**T**he opening of an ocean basin is a **Rift-to-Drift** sequence. **Rift** events fracture a continent into pieces, and **Drift** events occur during the opening of the ocean basin. Each produces a distinctive rock record. Rift rocks are many thousands of feet of coarse sediments deposited in narrow graben valleys in alluvial fans, braided rivers, and submarine fans. Often they are intermixed with volcanics and lava flows.

Rifting events, once initiated, usually proceeds rapidly, normally taking 10 to 20 million years, but the drift phase can last more than 100 million years. It is not clear why the proto-Atlantic rifting event, initiated with the first Crossnore volcanics at 690 Ma, stuttered for 120 million years before moving into the drift phase. It may be related to a widespread period of anorogenic magmatism, massive igneous activity within the Laurentian continent not associated with mountain building, that took place in a 1000 km wide belt from southern California to Labrador. Near the center of Laurentia this anorogenic magmatism is associated with large, failed rift systems; rifts that began but never opened into ocean basins.

Nonetheless, by 540 Ma the first definitive evidence that the proto-Atlantic ocean basin is beginning to open appears as the **Catoctin lava flows**. Along present day Skyline Drive north of the Little Stony Man overlook, these lavas flowed across Grenville basement, and this region is interpreted as the continental terrace west of the axial rift. To the east, however, from Charlottesville north through the Culpepper and Warrenton regions, the Catoctin lavas lie above thousands of feet of rift sediments filling the axial graben. These lava flows are “pillowed” telling us they formed under water, and that the sea has invaded the axial graben.

Observe several things in cross section F. First, **oceanic lithosphere** is just beginning to form as the proto-Atlantic initiates. Little is preserved of this proto-Atlantic ocean floor, but at this stage it is little wider than the Red Sea. Second, notice that the axial graben is not torn in two by the rifting but stays with North America where it is found today preserved northeast of Charlottesville. Third, notice the mantle magma plume, originally positioned under the axial graben, is now centered in the new ocean basin. This means that the heat that caused Rodinia to dome and rift in cross section E has moved away so the two new continental edges cool, becomes denser, and sink. The continental terrace is now below sea level.

### **Cross Section G - . . . To-Drift: Divergent Continental Margin (DCM)**

- ▶ *Cambrian-Early Ordovician; 540 - 480 Ma*
- ▶ *Current Location: Shenandoah/Page Valleys through the Great Valley of Maryland and Pennsylvania; slope and rise deposits down to the ancient ocean floor preserved within the Western (Inner) Piedmont*

**D**uring the early Cambrian the new continental edges of Laurentia and South America enter the full “**Drift**” phase. The proto-Atlantic is now wide enough South America has moved off the right side of cross section G. Over the next 100 million years the ocean widens to many thousands of kilometers.

As the drift phase continues the Laurentian continental edge becomes more and more tectonically quiet; indeed the entire Laurentian continent is flat and featureless from coast to coast. Drift stage rocks form as a slowly accumulating wedge of sediments, the **Divergent Continental Margin (DCM)**, that thicken toward the ocean basin. Subsidence and sedimentation accumulation go on at about the same rate and the rocks, event though eventually many kilometers thick, are widespread, shallow-water deposits.

The equator at this time runs down the center of Laurentia, and the continent is rotated clockwise so that Virginia and the east coast are in the southern tropics between 0° and 20°, looking south. West of the present Blue Ridge, tectonic stability and tropical climates result in carbonate rocks (limestone and dolomite). East of the Blue Ridge on the slope an rise leading down to the ocean floor the **Evington Group** is made of shale and sandstone (now metamorphosed to schist). Today these are exposed in a narrow strip along the Western (Inner) Piedmont east of Charlottesville.

The carbonate rocks, dominated by evidence of strong tidal activity, tell us the most about conditions at this time. Imagine the entire eastern Laurentia as a tidal flat stretching to the horizon. Every day a major tidal bore sweeps across the region, and then retreats, forming in the process such tidal features as flat pebble conglomerates, mudcracks, and stromatolites. It is not clear why tidal currents are so prominent at this time. It is true that during the Cambrian the moon was closer to the earth than it is now, and this might have resulted in some increase in tidal

levels, but it is probably not enough to explain the vast extent of the tidal deposits<sup>1</sup>. More likely tidal prominence resulted from a combination of increased tidal pull, location of the continent, shape of the ocean basins, and convergence of tidal forces. One way or another tidal features are characteristic of this tectonically stable, divergent continental margin.

### **Cross Section H and I - Exotic Volcanic Arcs and other Terrains**

- ▶ *Late Proterozoic- Early-Mid Cambrian; 620 - 525 Ma (550-525 Glover 22)*
- ▶ *Current Location: Piedmont; Maryland though the Carolinas*

**D**uring the Cambrian the Laurentian DCM rests in a long tectonic slumber. Nothing happens here for nearly 100 million years. The land all around is flat and featureless, baking in the tropical sun, and southward, out in the proto-Atlantic, the horizon stretches away endlessly. The tide rolls in and out - day after day, year after year, millennia after millennia. We could be forgiven for imagining, as the millions of years roll by, that this will go on forever.

Yet, beyond the horizon volcanic arcs and microcontinents we cannot yet see will soon have their fate tied to our own. Strung up and down the modern piedmont are as many as a dozen “suspect” terranes - crustal fragments that, even though part of North American today, formed elsewhere and were brought here by later events. Many of these are exotic; they began their history in unnamed ocean basin(s) even before Rodinia rifted and the proto-Atlantic opened. Observe in cross section H that they are different oceans on the two sides of the break line.

Among the oldest are the late Proterozoic to early Cambrian (620-545 Ma) *Virgilina* volcanic arc, and the somewhat younger *Potomac* and *Chopawamsic*<sup>2</sup> volcanic arcs, as well as the *Goochland* microcontinent. Today their piedmont locations and relationships are well known, but the events that brought them here are less certain<sup>3</sup>. Technically, it is impossible to show the origin and early history of these terranes on cross sections H-I, not only because their early history did not take place in the proto-Atlantic, but also because the cross sections would have to show both rifting and subduction going on at the same time in the same place.

Cross section H models an early phase of an ocean basin closing, after some of these early arcs had already formed. The Potomac and Chopawamsic exotic terranes, already old by this time, may have migrated into the closing proto-Atlantic ocean (the Virgilina, although older, is too far south to be included in this cross section), although we cannot yet reconstruct these events. The Potomac orogeny is a Late Proterozoic to Cambrian (620-545 Ma) volcanic arc system built along an east dipping subduction zone (present direction). By the time it enters cross section H its history is done; it is shown extinct and eroded. Its volcanic rocks are to the east, the **accretionary prism** (material scraped from, and accumulating above the subduction zone; also called *melange*) to the west, and lying unconformably across the entire eroded mass the **Popes Head formation**, a sedimentary layer, telling us its history is completed. The Chopawamsic orogeny, on the other hand, is still active at this time, also with an east dipping subduction zone, closing a **remnant ocean basin** (ROB) between it and the Potomac terrane; they will soon collide.

We have little idea how wide the proto-Atlantic is at this time, as indicated by the break lines, or its size and shape, or even where these volcanic arcs are actually located. However, beyond the eastern edge of the cross section H, somewhere in the world, is the Goochland microcontinent, Gondwana (South America+Africa), and Baltica (western Europe+Siberia). All that we really know for sure is that ocean basins are beginning to close and eventually all these terranes will come to Laurentia.

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<sup>1</sup> The moon has been moving away from the earth at an average rate of rate of 2.16 cm/year over the past 650 million years, with the current rate of retreat being  $3.82 \pm 0.07$  cm/year. This means not only were Cambrian years longer (400 days), but the days were shorter (22 hours). At this rate of retreat the moon in the Cambrian would have look slightly larger than it does now. Earlier in geology time the moon would have looked dramatically bigger in the sky, perhaps as much as 20 times its present appearance.

<sup>2</sup> Chopawamsic is a central Virginia name for a long arc system that includes the equivalent/identical James Run in Maryland and Milton (Charlotte belt) in southern Virginia and North Carolina.

<sup>3</sup> There are two mutually exclusive interpretations for these events. Gates (19) and Glover (19) argue the Cambrian orogenic event preserved in the piedmont took place during an arc collision with Laurentia. They call it the Carolina or Carolinian orogeny. Hibbard and Samson (1995) consider these Cambrian events to have taken place exotic to Laurentia even before the proto-Atlantic drift phase began. They refer to this event as the Potomac orogeny. The second scenario is followed here.

### **Cross Section H - Potomac/Chopawamsic Terrane Amalgamation**

- ▶ *Mid-Late Cambrian; 540 - 525 Ma*
- ▶ *Current Location: Events preserved in the Central Volcanic-Plutonic Belt of the Piedmont, but transpired in an exotic (non- proto-Atlantic) ocean before arriving here*

An **amalgamation** is the joining together of separate terranes through subduction and collision events to form a composite terrane. The composite can contain one or more volcanic arcs, microcontinents, accretionary prisms (=melanges), and/or fragments of oceanic crust. The piedmont today contains a number of composite terranes, although it is controversial how many, when they formed, where they formed, or the order in which they formed. Some composite terranes certainly amalgamated in the proto-Atlantic, or some adjacent ocean, long before coming to Laurentia. Others may have amalgamated as they arrived here in Laurentia. The only thing that everyone agrees on is that today all these lie scrunched together side by side in the piedmont.

Cross section I is based on the fact that in the piedmont today the Potomac terrane is overthrust along its eastern edge by the Chopawamsic terrane along the **Chopawamsic fault** (requiring an east dipping subduction zone). Furthermore, these two arcs are welded together by the Cambrian **Occoquan granite**, a  $\sim 525 \pm$  Ma stitching pluton<sup>1</sup>, meaning the amalgamation took place probably in the mid Cambrian. Finally, the Occoquan also intrudes the Pope's Head formation indicating the Potomac was extinct and eroded before it collided with the Chopawamsic.

The Chopawamsic in turn is overthrust on its east by the Goochland microcontinent along the **Spotsylvania fault**. Although The Goochland is composed of Grenville age rocks ( $1031 \pm 94$  Ma), we are still debating whether the Goochland is an original piece of Laurentia torn out during the proto-Atlantic rifting, and later returned, or a fragment of some other unknown continent that happens to have rocks of the same age as the Grenville. There is little evidence of when or where the [(Potomac/Chopawamsic)+Goochland] amalgamation occurred. It may have taken place before all these terranes arrived in Laurentia, or after; some models have the Goochland docking in the Late Paleozoic. Cross section H leaves it ambiguous by not having the remnant ocean basin closed yet.

### **Cross Section I - Carolina Terrane Amalgamation**

- ▶ *Mid Cambrian - Early Ordovician; 525 -  $\sim 485$  Ma*
- ▶ *Current Location: Western Piedmont*

In cross section I the terranes and ocean basins continue to evolve. The Goochland microcontinent collides with and overrides the Potomac/Chopawamsic volcanic arcs along the **Spotsylvania fault**, although the timing of this event may well be later; perhaps this amalgamation did not occur until after the Potomac/Chopawamsic docked with Laurentia. These terranes have also migrated into the proto-Atlantic ocean basin, and after the rifting event of cross section E-F is beginning its closing cycle.

More important in cross section I, an east dipping subduction zone develops under the composite (Potomac/Chopawamsic/?Goochland) terrane (now called the **Carolina terrane**). This creates a remnant ocean basin between Laurentia and Carolina that will soon close in the Taconic orogeny (cross section J), but along the way whole new sets of rocks are generated. In particular, subduction creates an accretionary prism in which forms the **Shores melange**, a severely deformed mix of trench sediments and ocean floor fragments developed above the subduction zone, and the **Hardware formation**, turbidity current sediments eroded from Carolina and deposited as underwater avalanches on the remnant ocean floor. The Hardware/Shores are the only evidence remaining of the subducted remnant ocean floor. Today they are preserved as slices of rock thrust up onto and over (obducted) the Laurentian edge along the Mountain Run fault by the Taconian Carolina/Laurentian collision (cross section J).

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<sup>1</sup> A stitching pluton is an igneous intrusion found within or cross cutting two different terranes indicating that the terranes or terrains were joined at the time of the intrusion.

Simultaneously with subduction numerous batholiths of volcanic arc magmas penetrate into the Carolina and related terranes stretching from South Carolina to New England. These culminate in cross section I and J with the Ellisville and Lahore (469-445 Ma) plutons <sup>1</sup>.

### **Cross Section I - Knox Unconformity**

- ▶ *Early Ordovician; 505 - ~485 Ma*
- ▶ *Current Location: The Knox unconformity is in Valley and Ridge DCM sediments; volcanic arcs in the Piedmont*

Carolina continues to converge on Laurentia, and in cross section I the proto-Atlantic remnant ocean has narrowed considerably. Standing on Laurentia, however, we still might remain heedless of the converging terrane, except that it is now close enough to dump occasional volcanic ash falls on this still tectonically stable divergent continental margin. But not all events in geologic history are dramatic, such as riftings and mountain buildings, and we still have to live with changing geologic events.

Sea level, for example, goes up and down all the time, but imperceptibly by human standards. Smaller sea level ups and downs of  $\pm 10$  feet (3 meters) require 10-20,000 years. The largest sea level changes, however, are  $\pm 750$  feet (250 meters) but require 2-300 million years to complete (compared to an orogeny that may take 10 million years). Sea level today is as low as it has ever been in the past billion years, leaving a lot of dry land for us to live on, but is now rising.

At the beginning of the Cambrian - cross section G - sea level was low like today, but began a rise that continued through cross section I, by which time the entire Laurentian continent is under the *Sauk* sea. Flying westward across the coastal margin of Virginia, then across the continent, nothing is visible below but water until the west coast, except perhaps for a few low islands of the transcontinental arch in the present western Great Plains and Rock Mountain region. During this time mostly tidal carbonate rocks accumulated across the Laurentian continent, including tens of thousands of feet along the eastern edge in the mid-Atlantic.

In the Early Ordovician, however, the Sauk sea drains from the continent, exposing it to erosion and non-deposition, leaving a gap in the record and forming the *Knox unconformity*. But, almost as soon as the continent drains, sea level rises again until by cross section J the entire continent is under the *Tippecanoe* sea. With the sea back, carbonate deposition resumes, adding hundreds feet more thickness. The unconformity does not look like much; after all it is a gap in time, not a hole in the rocks. The rocks are not the same, however.

Below the Knox unconformity the Sauk sea is populated by the archaic *Cambrian fauna* composed mostly of trilobites, inarticulate brachiopods, primitive snails, and other strange organisms. Above the Knox unconformity, however, marine life of the *Paleozoic fauna* explodes into the Tippecanoe sea. The number of invertebrate families increases from 50 to 400, and the sea is chock full of new brachiopods, bryozoans, corals, cephalopods, crinoids, and a host of other life. Because of the abundant new life the rocks are now fossil rich limestones, a condition to remain until the present day, although the life forms composing those rocks undergo many more changes.

### **Cross Section J - The Taconic Orogeny: Carolina Terrane/Queenstown, Martinsburg, and Reedsville/Juniata Clastic Wedges**

- ▶ *Middle to Late Ordovician; 485 - 438 Ma*
- ▶ *Current Location: Mountains located in the Piedmont, foreland basin in the Valley and Ridge*

Since cross section H the proto-Atlantic ocean has been closing, but not until cross section J is Laurentia affected. Now, however, the *Carolina terrane* converges and collides to build the Taconic mountains. Because the subduction zone dips eastward it acts like a ramp, and the terrane as it collides slides up and over the continental edge (*obducted*), building the Taconic mountains. As the mountains rise the continent to the west depresses into

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<sup>1</sup> Coler, et al. (2000) demonstrate that the Ellisville, Lahore, and related batholiths and associated volcanics are of middle Ordovician age, and that the Chopawamsic and related arcs must also be middle Ordovician. By this they argue that the Cambrian dates for the Chopawamsic are incorrect. These results dramatically change all traditional interpretations of this geology. On the other hand other evidence indicates the Middle Ordovician Chopawamsic batholiths developed on previous continental crust, and so the Chopawamsic is a composite terrane of some sort with a long history. At the simplest the Chopawamsic is itself a composite terrane with a complex history, and that volcanic rocks like the Ellisville and Lahore are only the youngest events recorded.

several *foreland basins*. The overriding terrane that forms the mountain is the *hinterland* and the fault zone between the two continents the *suture zone (Mtn Run fault)*.

The Taconic orogeny is the most complex in the mid-Atlantic, primarily because the Laurentian continental edge is a complex zig-zag with jutting promontories, alternating with deep recesses tucked inland toward the continent. In the mid-Atlantic, the Carolina terrane hit two promontories, one in the piedmont region of southern Virginia and the other in southeastern Pennsylvania/Maryland, building mountains probably as high as the Swiss Alps (14-15,000 feet) in each place. The collision also begins deformation of the Laurentian continental margin with movement along the Haysville-Fries-Rockfish Valley (*HFRV fault* (now exposed in the Blue Ridge province.)

Because of the ragged irregularity of the collision several foreland basins develop inland from the mountains. From the Pennsylvania mountain source sediment flows first west into the deep water Queenstown foreland basin in central Pennsylvania, and then southwest into the shallow-water Reedsville/Juniata basin of West Virginia (well exposed west of Franklin at Germany Valley.) From the southern Virginia mountain sediment flows northeast into the deep, long, narrow *Martinsburg foreland basin* trapped between the Taconic terrane on the east and the Little North Mountain arch on the west (this arch separates the Martinsburg and Reedsville/Juniata basins). The axis of the Martinsburg basin today runs down the axis of the Shenandoah valley, right under Massanutten Mountain.

Once a mountain is built the only thing left is for it to erode. By the time the mountain is completely eroded to sea level the foreland basins are filled to the top and the rugged topography smoothed out. The end of the Taconic orogeny also marks a transition in the evolution of life. In Taconic rocks at the northern end of Massanutten mountain are remains of some of the oldest land plants in the world. These first plants are small and simple, but they begin an invasion of the land that quickly picks up speed and intensity.

### ***Cross Section K - Orogenic Calm in the Central Appalachian Basin/ Evaporate Deposition***

- ▶ *Silurian and Early Devonian; 438 - ~385 Ma*
- ▶ *Current Location: Appalachian (Allegheny) Plateau, Valley and Ridge, eroded mountains in the Piedmont*

**B**y the Silurian the old Taconic mountains are gone. The piedmont, where the mountains once stood is now a low peneplain. The mountain which in the past supplied so much sediment now has little to give. The only piedmont records are the *Quantico/Arvonian* marine sediments deposited on the submerged eastern side of the terrane, or in basins faulted into the terrane.

West of the Blue Ridge the orogeny end is marked by the Tuscarora/Massanutten quartz sandstones (the Massanutten sandstone holds up Massanutten Mountain). They and their equivalents blanket the entire region west of the Blue Ridge from New York to Tennessee. Now in place of the foreland basins is the shallow *Central Appalachian Basin (CAB)*, filled with the Tippecanoe sea. Sea level is at another high stand and all of Laurentia is under water, although that water is still relatively shallow. Below the surface, however, the sea is divided into basins (areas of slightly deeper water) separated by arches (areas near or slightly above sea level). The Central Appalachian Basin is bordered in central Ohio and Kentucky by the Cincinnati arch, while its eastern shore lies somewhere in today's Shenandoah Valley.

It might seem after the complex Taconic orogeny that this interval in history would be uninteresting. But, the Silurian is unique in eastern Laurentian history for a widespread, 300-900 foot thick layers of salt (mostly halite and gypsum) deposited from central West Virginia north into Pennsylvania and west into Ohio. These salt deposits have been known for a long time, but before plate tectonic theory were hard to explain. Today, we can easily imagine continents drifting from one climatic belt to another, and during the Silurian eastern Laurentia drifts slightly southward, placing it in the same climatic belt as the Sarah desert. It will not stay here long, but enough to produce these thick Salina salt deposits.

### **Cross Section L - The Acadian Orogeny/Catskill-Pocono Clastic Wedge**

- ▶ *Middle Devonian to Early Mississippian; 385 - 360 Ma (Glover Tectonics of Va Blue Ridge, p 24)*
- ▶ *Current Location: Mountains in the piedmont; foreland basins Valley and Ridge and Allegheny (Appalachian) Plateau*

**I**n this Paleozoic Wilson Cycle, the Acadian is the second of the three closing orogenies to directly affect Laurentia. Mountain building begins in Newfoundland (Silurian and early Devonian metamorphism and structural deformation), and then builds southward into New York and Pennsylvania (mid-late Devonian **Catskill foreland basin**), and finally finishes in southern Virginia in the early Mississippian (**Pocono foreland basin**). Northward the mountain chain connects up with the several thousand mile long Caledonide mountains, built by a collision between Laurentia and Baltica (Scandinavia+Siberia). This new combined continent is named *Laurussia*, - as we will now refer to it - the beginning of the formation of the supercontinent Pangaea.

In contrast to the Taconic, no unambiguous central/southern Appalachian piedmont terranes are associated with the Acadian. With the exception of scattered, isolated outcrops, what terranes there are are east of the Taconic terrane (Carolina) buried under the coastal plain. Most piedmont evidence for the orogeny consists of Acadian overprinting of Carolina terrane rocks, including some volcanic activity (deduced from the Tioga ash deposits in the foreland basins), and re-metamorphism of Taconic rocks. The Taconic thrust faults are also reactivated, but significantly not as thrust faults, but as right-lateral faults. Right lateral movement tells us a terrane, sliding sideways like a runner into home plate, comes in from the northeast and scrapes and bumps its way along the Laurentian coast. Who this terrane might be is unclear, and several models are proposed, including simply a reactivation of the Carolina terrane, a sideswipe by part of Gondwana, a sideswipe by South America<sup>1</sup>, or a sideswipe collision by a southern extension of Avalon (or Avalonia)<sup>2</sup>. Because of the uncertainty we use the non-committal name "Acadian terrane".

Even if the causes of the Acadian orogeny are uncertain, what is clear is that the Wilson cycle begun in cross sections H and I (and no likely earlier) is now closing rapidly. Cross section K shows a presumed Acadian terrane just off the Laurentian coast, and then not much farther out the African coast of the supercontinent **Gondwana**, closing fast. By cross section L the ?Acadian terrane has side-swiped Laurussia to form the Acadian mountains. Observe in cross section K that the ?Acadian terrane is not moving right to left as terranes have in other cross sections, but out of the page toward you, while Laurentia moves into the page. Other reactivated faults throughout the Carolina terrane have similar reactivated movement at this time.

Note also in cross section L that with the Acadian orogeny the proto-Atlantic ocean closes. The proto-Atlantic opened as a single ocean, but subduction zones and microcontinents have subdivided it into additional ocean basins. Traditionally, the northern Appalachian Avalon terrane (= ?Acadian terrane) forms as a continental fragment rifted away from Gondwana, leaving the proto-Atlantic on its front side while opening the **Rheic ocean** on its back side. As the ?Acadian terrane (= ?Avalonia) collides with North America the proto-Atlantic is closed, leaving the Rheic ocean between North America and Gondwana.

West of the Blue Ridge the best and clearest evidence for the Acadian orogeny are the Catskill and Pocono clastic wedges. With the New York/Pennsylvania side swipe a foreland basin develops, deepest in eastern Pennsylvania and shallowing west and southwest. The basin fills quickly beginning with black, deep-water shales, then submarine fans, a shelf, and finally red meandering river deposits. In the western Valley and Ridge most of

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<sup>1</sup> Carolina reactivation (Glover, et al., 1977; Baird and Glover, 1997), Gondwana (southern Europe and West Africa) sideswipe (Glover, et al., 1989; Adams, et al., 1995), South American sideswipe (Dalziel, et al., 1994), and a southern Avalon sideswipe (Murphy, et al., 1995). Other models also exist.

<sup>2</sup> Traditionally the Avalon terrane, or Avalonia, is associated with the Acadian orogeny, but with time the Avalon schema has become muddled. Avalon originated as a microcontinental fragment that rifted away from Gondwana, crossed the proto-Atlantic, and docked with Laurentia in the Devonian (van der Pluym, et al., 1995, and references therein). Williams and Hatcher (1983) mapped this Avalon along the entire Appalachian length, both in the piedmont and subsurface under the coastal plain. Samson (1995) clearly split out the exposed southern/central Appalachian piedmont portions of Avalon as Carolina, confining Avalon to the northern Appalachians, where it is still associated with the Acadian. Glover, et al. (1997) then extended Carolina eastward under the coastal plain and continental shelf into the subsurface, eliminating the possibility of an Acadian terrane in the region. Sheridan, et al. (1999), however, still identify subsurface rocks east of Carolina as parts of Avalon. The issue remains unresolved.

the red rocks seen are these meandering river sediments<sup>1</sup>. By the early Mississippian the southern Virginia sideswipe produces the Pocono clastic wedge which spreads west and north, and then transgresses eastward across the now filled and subsiding Catskill foreland basin.

At the same time the foreland basin is subsiding sea level is rising, and by Devonian end the *Kaskaskia sea* covers the entire continent. Flying westward from the Acadian mountains one sees nothing but water until Nevada, where a volcanic chain is located. This is reverse geography for us. Today, Virginia's mountains are to the west and the coast to the east, in the Devonian the mountains are to the east, and the coast to the west.

Also by the Devonian Virginia drifts northward into the trade wind belt between the equator and about 20° south of the equator. This results in a change in climate from the desert conditions of the Silurian to a humid equatorial belt with abundant rainfall. Life also changes. At least five major groups of fish are common in the Devonian, including three that are now extinct. And in the late Devonian the first fish walked out of the meandering rivers into the flood plains and evolved into the Labrynthodont amphibians. Also a new and significant vegetation evolved, ranging from low, ground hugging plants that lived in dense patches around water, to tree size forms. In addition, the first arthropods and other invertebrates were entering the rivers and moving into the forests. It is no longer a barren land.

### ***Cross Section M - The Mississippian Orogenic Calm***

- ▶ *Middle Mississippian; 345 - 320 Ma*
- ▶ *Current Location: Allegheny plateau*

**N**orth of Virginia there is barely a break between the end of the Acadian orogeny and the beginning of the Alleghanian, but in West Virginia the *Greenbrier Group* of carbonate rocks indicates a tectonic calm. West of the Allegheny Front, the most characteristic Middle Mississippian rocks are oolitic and encrinoidal limestones. Oolites are tiny spheres of calcite that look like miniature pearls. They form today in very warm, clear, shallow, highly agitated waters such as those in the Bahamas, and conditions in the Greenbrier sea are similar. The encrinoidal limestones are composed of countless numbers of crinoid and lacy bryozoan skeletons. Swimming over this sea bottom is like swimming over a vast, chock-full garden of crinoids floating above the bottom on their stems, stretching as far as the eye can see, all across the continent. And among all these crinoids are corals, blastoids, and brachiopods. In the easternmost outcrops white carbonate beach sands and tidal flat deposits are present indicating the presence of shorelines, but how far east into Virginia the shore came is unknown.

We do have clues that during the Mississippian in the piedmont Alleghanian deformation is beginning (cross section M). One bit of evidence is that clastic sediments periodically enter the Greenbrier sea indicating the rise of source lands. More directly granite batholiths such as the Petersburg granite (320 Ma), outcropping now east of Richmond, indicate that tectonic activity is beginning in the east.

### ***Cross Section N - The Late Paleozoic Alleghanian Orogeny***

- ▶ *Late Mississippian, Pennsylvanian, and Permian; 320 - 250 Ma*
- ▶ *Current Location: Entire Mid-Atlantic is affected by severe structural deformation east of the Appalachian (Allegheny) Plateau (mild deformation west); sediments eroded from the mountain in the Allegheny plateau and west.*

**T**he closing phase of the Wilson Cycle begun in cross section E now comes to an end. West Africa (Gondwana) collides with eastern Laurussia, seals the ocean basin shut, and builds the Himalayan-sized *Alleghanian* mountain range. The Alleghanian is the last orogeny to affect Virginia up to the present day, and differs in significant ways from the earlier orogenies. The most dramatic effect is that the entire Laurussian eastern sea board is shuffled like a deck of cards. Since the Cambrian, layer after layer of sedimentary rocks have accumulated, beginning with rift sediments, then Cambro-Ordovician continental margin carbonates, then Taconic clastics, Silurian Central Appalachian Basin deposits, Acadian clastics, and finally Mississippian sediments. Africa shoves these inward toward the center of the North American continent, stacking them up in a series of thrust sheets, folding them along the way. Virtually every rock that formed in Virginia prior to the Alleghanian orogeny is moved from its place of

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<sup>1</sup> The Acadian meandering river formation is the red Hampshire, but there are other red formations. The one mostly likely to be confused with the Hampshire is the Taconic Juniata formation. Superficially they look alike, but are in fact very different.

origin to some other place. By the end of the Alleghanian all of Virginia except the far southwest is mountainous, but mountains that are 6-8 times higher than those today. This event dominates everything about Virginia to the present day. Most of the structural features now seen formed at this time, including the folded rocks exposed in road cuts, movement of the Blue Ridge rocks from their original site near Richmond to their present location, and generation of the structures that form the Valley and Ridge.

A mountain this size produces a lot of sediment, and most of it is spread as astronomically uncountable sand grains across eastern North America, across the Mississippi river valley (which did not exist in the late Paleozoic; river systems all flowed from east to west across the continent), and into the plains region of Texas, Oklahoma, and Kansas. Only a small outcrop belt in the southwestern corner of Virginia (including Scott, Russell, Tazewell, Lee, Wise, Dickenson, and Buchanan counties) contains the eastern-most parts of the sedimentary record.

Early in the mountain building marine shelf and shoreline environments (beach, lagoon, swamp) dominate. But, as the sediments spread westward, coal swamps and terrestrial environments take over. The Virginia coal swamps result in 120 coal beds, representing rapid changes in sea level. The tectonic conditions are different, but these shoreline environments are something like the east coast of Virginia and North Carolina today with their barrier islands, lagoons, and tidal marshes.

Life in the Pennsylvanian and Permian is rich and varied. In the marine environments clams and brachiopods are common. But it is the non-marine fossils that are most interesting. North America is now subtropical, warm, and wet. Imagine being there when the air is hot and heavy with humidity, and the ground dense with vegetation. Living in the coal swamps are many kinds of centipedes, millipedes, insects, (some as long as a foot), and dragon flies with wing spans 29 inches wide. And crawling among all this vegetation, and swimming in the lakes, swamps and rivers are many kinds of amphibians. Some of the amphibians are labrynthodonts up to six feet long, behaving something like crocodiles (which have not yet evolved). Smaller Lepospondyl amphibians are salamander-like in appearance (but are not at all like salamanders in their anatomy) while others are snake-like, or have bizarre wing shaped heads. And along with the amphibians are the earliest reptiles just coming out of the water. Life is rich and now affects both marine and terrestrial environments.

### ***Cross Section O - Rifting of Pangaea: Initiation of the Atlantic Ocean***

- ▶ *Triassic and Lower Jurassic; 230 - 175 Ma*
- ▶ *Current Location: Lateral Graben in the Piedmont, and below the Coastal Plain sediments; axial graben under the edge of the continental shelf*

**F**rom the last sediments deposited in southwest Virginia during the Pennsylvanian, through the Permian, and until the late Triassic there is no geologic record in the Mid-Atlantic. We only vaguely know what the region was like during this time. We do know the Mid-Atlantic lay deep within the supercontinent Pangaea, and that it was firmly connected to northwest Africa. We are reasonably sure that during the Permian remnants of the Alleghanian mountains remained in Virginia because sediments eroding from Virginia were deposited in West Virginia and southwest Pennsylvania.

During the lower Triassic the Mid-Atlantic is likely a low area with little topographic relief, and little or no geological activity. We know from other evidence that the seas has retreated, most of North America is land and that long river systems flow out of eastern sources and across the continent draining into the last of the continental seas in west Texas.

By the late Triassic, however, the supercontinent Pangaea, begins rifting apart. By the early Jurassic ocean crust is forming and the Atlantic ocean opening. A significant difference between the proto-Atlantic opening and the Atlantic opening is that the Atlantic rifting occurred much farther east in Virginia. Pieces of the early Cambrian proto-Atlantic rift graben are exposed today just east of the Blue Ridge, while the half graben are buried under West Virginia, Kentucky, and Pennsylvania. The Atlantic rift half graben, on the other hand, are scattered throughout the piedmont province, including the ***Culpepper***, Richmond, and Farmville basins. Indeed, the Culpepper half graben is faulted into the rocks of the proto-Atlantic axial graben. The Atlantic axial graben on the other hand is several hundred kilometers east of its half graben buried under the edge of the continental shelf.

The half graben, because they form by a block of the earth falling down, create closed basins - rivers flow in but can't get out - that filled with red lake shales. The distinctively deep red sedimentary rocks deposited in these lakes are common in the piedmont, for example, west of Manassas and east of Culpepper.

During the later stages of basin history the Triassic and lower Jurassic lake rocks are invaded by igneous magmas and lava flows (gabbros and basalts). The intrusions metamorphose the surrounding rocks, baking them

into red hornfels. The red crushed stone used in central Virginia, comes from Triassic sediments baked by an igneous intrusion. This igneous invasion accompanies the initiation of ocean crust formation a couple of hundred miles to the east. From this point on the Atlantic ocean basin opens quickly, and as it does the new continental margin cools and sinks below sea level leading to the modern divergent continental margin.

Preservation of fossils in the Triassic basins is not very good, perhaps because the dry climate of the time did not quickly bury dead organisms to be fossilized, but more and more fossils are being found, especially recently. The most common fossils are dinosaur footprints, and important finds have come from the Culpepper Stone Company quarry east of Culpepper, Virginia and in the Manassas region. Also skeletons of fish, small carnivorous dinosaurs, and very rare skeletons of aquatic reptiles and amphibians belonging to extinct groups are found. We also expect the first tiny mammals to be scurrying about in the undergrowth because it is in the late Triassic that mammals first appear. Remains of one has been found in North Carolina, although their fossils are rare.

### ***Cross Section P - The Mesozoic and Cenozoic Divergent Continental Margin***

- ▶ *Upper Jurassic, Cretaceous, and Cenozoic; 175 Ma - present*
- ▶ *Current Location: Coastal Plain*

**T**he Atlantic divergent continental margin along the entire Atlantic sea board is preserved in the coastal plain province, and under water along the continental shelf. The sedimentary record is a gently east-dipping, seaward-thickening wedge, similar to the proto-Atlantic DCM record. East of the Fall Line it buries Grenville age basement rock, volcanic arc terranes, and part or all of many Triassic rift basins, including the Atlantic axial graben.

The western feather edge of the coastal plain fluctuates continuously as sea level has gone up and down. Today the edge of the coastal plain, located at just about the fall line, is the farthest western extend of these sediments. During the Cretaceous, however, it is likely that most of the piedmont was under water, and the shoreline lapped up against the base of the Blue Ridge. Today sea level is slowly rising from a near all time low. The process is slow enough we do not notice it, but the large storms that lash the modern coast, and which cause erosion of the beaches and barrier islands is the work of these storms haltingly, but steadily, pushing the beaches and barrier islands farther and farther inland as the sea transgresses across eastern Virginia. If sea level rises as it always has in the past much of the mid-Atlantic will again be under water.

### ***Cross Section Q - Rejuvenation***

- ▶ *Late Cenozoic; 45 Ma - present*
- ▶ *Current Location: recognizable mostly in the Blue Ridge and Valley and Ridge*

**R**ejuvenation is gentle uplift occurring at the end of a mountain building cycle, after the mountain is eroded down to sea level. A mountain is like an iceberg; the part above the surface is buoyed up by a root zone below the surface. As the ice above the surface melts, as the iceberg becomes lighter, its root zone floats up more and more. That is, the iceberg stays in isostatic equilibrium; like a boat it floats in balance with its weight. Rejuvenation is analogous to this upward floating. As a mountain erodes its root zone floats upward, lifting the mountain and exposing it to more erosion. The process continues until the root zone disappears and the land surface stabilizes near sea level.

The modern Appalachians are rejuvenation mountains; there has not been a real mountain building - a plate tectonically driven mountain building - along the east coast since the Alleghanian orogeny, cross section N, over 250 million years ago. Instead the Appalachian root zone has been disappearing, in stages. At least four rejuvenation episodes are recognized: pre-Cretaceous, Miocene, and two late Cenozoic episodes.

Rejuvenation is recognized through peneplain surfaces, and water gaps. With a peneplain the entire region is eroded down to the flat surface near sea level, regardless of how soft or resistant the individual rocks are. With rejuvenation, however, the area is uplifted and erosion begins again. If there is a strong structural fabric, such as folds and faults, then the softer rocks are removed to form valleys while the resistant rocks resist to form ridges. This appears most notably in the Valley and Ridge province; the valleys are underlain by easily eroded sediments, while the ridges are tougher sandstones. The long parallel valleys and ridges reflect the underlying Alleghanian structural geology of thrust faults, anticlines and synclines.

The strongest testaments for rejuvenation are the water gaps that cut across a mountain range while still occupied by the river that cut them (e.g. James River and James River Gorge). For such a gap to form the river

must exist before the uplift, and because the area was peneplaned, had to flow across resistant and non-resistant rock units alike. As the region rejuvenated, however, the rivers, working to maintain their courses across the structural trend, are forced to erode harder on the resistant units eventually cutting the water gap.

### ***Cross Section X - The Future***

- ▶ *The Future*
- ▶ ?

**M**id-Atlantic geology is the result of nearly 2 billion years of history representing the closing phase of one Wilson cycle (Grenville orogeny), a second Wilson cycle (proto-Atlantic rifting through Alleghanian orogeny), and the opening phase of a third Wilson cycle. There is no reason to believe these Wilson cycles will stop, and at some time in the future the Atlantic Wilson cycle will begin its closing phase. Geologically, this may be soon (perhaps a few tens of millions of years) since the Atlantic is a large, mature ocean basin. We have no idea, of course, how it will close, where the subduction will form, or how many will form. What we can be sure of is that the history of Virginia is not done, and the geology will become much more interesting, and complicated, in the future.

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