Integrating Stratigraphy, Structure and Tectonics on the Outcrop

A Geologic Transect from the Blue Ridge, Across Page and Shenandoah Valleys, and into the Eastern Valley and Ridge

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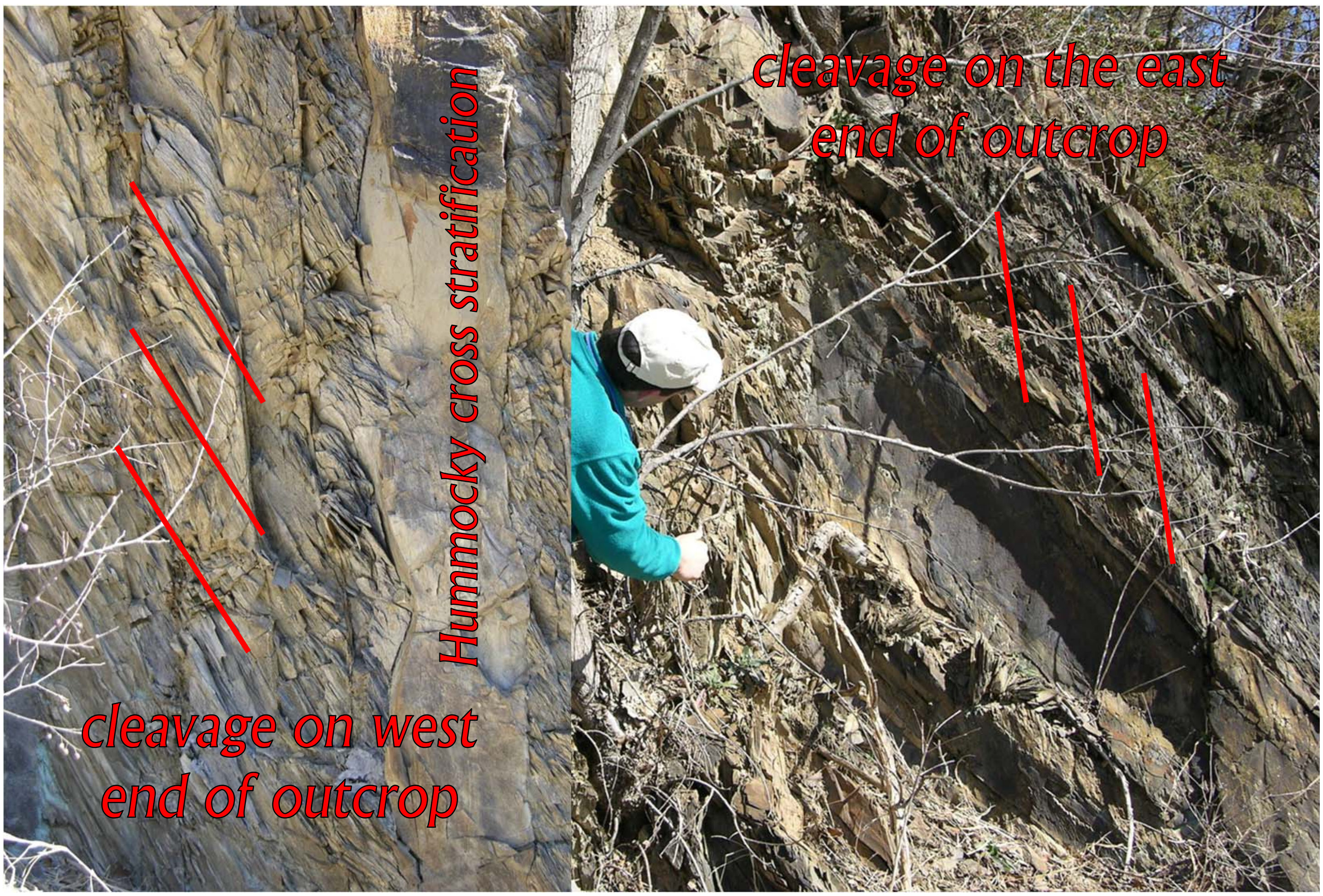

NAGT Field Trip
Spring, 2014 Meeting
James Madison University

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Introduction:

Stratigraphy, structure, and tectonics are not naturally compatible topics. Just sit in on the courses; there is virtually no overlap of subject, evidence, techniques, or tools, and structural geologists and stratigraphers have little common terminology—they can barely talk with each other. Yet, structure and stratigraphy are clearly related because both result from the dissipation of tectonic energy, and the evidence for each commonly exists in the same outcrop at the same time.

This field trip is based on a new course instituted 6 years ago in the revised JMU BA program by Lynn Fichter–stratigrapher–and Steve Whitmeyer–structural geologist–deliberately designed to use tectonics as an organizing and integrating principle for combining stratigraphy and structure in one course. It is titled “Stratigraphy, Structure, and Tectonics (SST). SST uses 5 field trips that together make an across-strike transect from the Allegheny Front in Pendleton Co., West Virginia to the eastern side of the Blue Ridge province, and provides evidence for virtually a complete history of the region—structurally, stratigraphically, and tectonically.

This field guide is based on one of those trips, the Rt 211-Rt 259 transect from the western flank of the Blue Ridge province northwest through Brocks Gap in Little North Mountain (Figure 1 - all the figures are in order at the back of the guide). We include most, but not all the stops the SST class makes on that trip, and mimic the strategy we take on the outcrop.

The deliverables for the SST course include 3 structural cross sections (including the Rt 211-Rt 259 transect for this trip), and a stratigraphic/tectonic history based on the sum total of all evidence seen on all the outcrops, interpreted through theoretical models developed in lecture. The 3 cross sections constitute a complete cross section from the Allegheny Front in Pendleton Co., West Virginia to the eastern side of the Blue Ridge province, with a nod to the Triassic basins and Atlantic rifting.

Exploring the S, S and T of an outcrop requires a deliberate and systematic strategy. It is important to keep evidence straight; what does each rock tell us, about what, at what scale of observation, and how does it do it. This requires looking at a rock through more than one lens: a stratigraphic lens, a structural lens, and several tectonic lenses. We begin with empirical data: what do we immediately see in the outcrop, and what is its immediate interpretation. Only when that is clear do we start looking at regional contexts and constructing tectonic histories from all the outcrops. Each stop on the field trip is organized this way.

On the 5 field trips that are part of the course it is common for some formations to be seen more than once, including stops that are germane to constructing a complete stratigraphic/tectonic history but which we will not see on this trip. Stratigraphic data gathering and interpretation is done only at the best locations, but a formation may be visited multiple times in other locations to gather structural data. When we first began the course we visited every available outcrop on the transect; since then we have trimmed them back to only those that efficiently provide the optimal information to make the necessary interpretations.

The Different Expressions of Tectonic Energy:

Tectonic energy drives everything in the geosphere, but the effects are not equally conspicuous. On the one hand, structural features (joints, folds, faults, etc.) in all their myriad forms, resulting from tectonic deformation, allow rich interpretations; rheological analysis is typically direct from data measurable on the outcrop.

Conversely, although the stratigraphic record also responds to tectonics, the evidence is much less direct, does not feed back directly to the responsible stresses, and usually requires interpretations within interpretations. For example, relative water depth can be interpreted with color, texture, flow regime, etc. but each of these lies within a theoretical framework of its own (geochemistry for color; and hydraulics for texture and flow regime).

Complicating the issue, water depth—accommodation space—is controlled by more than one variable—including subsidence, eustasy, sediment influx rates, compaction, loading, and climate—each of which may be operating largely independent of the others, and in different fractal time scales. Yet, the results look the same regardless of the mechanism—water responds to depth, not how the depth is created.

Also, large tectonic processes—such as foreland basin development—that control the evolution of the stratigraphic record cannot be seen in outcrop. We deduce they exist, that they represent subsidence from shallow into deep water, and that they influence the stratigraphic record, but we do not have direct outcrop evidence of the subsidence, or its rates, or the size and shape of the basin. Indeed, as trying to teach this stuff to undergraduates demonstrates, while observing any particular outcrop it is very difficult to imagine what is happening in the larger vertical, horizontal, and temporal contexts. We cannot 'see' foreland basins but have to imagine them fragment by fragment.

The result is, sedimentary-tectonic interpretations from stratigraphic outcrops are almost always inferences based on deductive arguments from a diversity of indirect data that must be synthesized from evidence gathered from accumulated specific outcrops. Sedimentary-tectonic interpretations require a predictive model that coordinates (plate) tectonic energies with sedimentary energies so that we can use stratigraphic observations to deduce the tectonic conditions that produced them. For SST our primary model is the Tectonic/Accommodation model.

The Tectonic/Accommodation Model:

Figure 2 is a theoretical Tectonic/Accommodation model (accommodation is the space available for sediment to fill). It is based on the plate tectonic concept that during a continent-continent collision or an arc-continent collision the over thrusting hinterland places a load on the foreland resulting in relatively rapid foreland basin subsidence and accommodation increase. Figure 2 models the tectonic subsidence portion of the model. Note: this is a time series diagram (not a cross section) showing the evolution of basin subsidence at a single geographic location. The geographic location is proximal to a hinterland where subsidence is greatest. (If it were a location distal from the hinterland, closer to the basin-to-craton transition, it would be a different diagram). The time series begins with cratonic or mature DCM conditions—slow subsidence, small accommodation space—interrupted by the sudden onset of tectonic activity and rapid subsidence into deep water conditions, followed by an exponential decay in subsidence rate. In the absence of deposition the result is a deep water basin.

The accommodation curve in Figure 2 says that initially accommodation space increases largely in concert with the increase in subsidence. Or, depth increases more rapidly than sedimentation can keep up. In time, however, subsidence rates slow while sedimentation rates increase (it takes time for sediments to prograde across the basin from the eroding mountain) resulting in rapidly decreasing accommodation—filling of basin and shallowing water.

The Tectonic/Accommodation model presumes that an accumulating column of foreland basin sediments will reflect changing accommodation more than basin subsidence as the basin evolves. A predictive stratigraphic sequence would look like (bottom to top): 1) pre-tectonic shallow water deposits, 2) deep, quiet water, fine-grained, anoxic deposits, 3) mass transport deposits (e.g. debris flows, turbidity flows, etc.) down a steep underwater slope, resulting in a coarsening, shallowing upward sequence as the accommodation space fills, 4) distal to proximal shelf; coarsening, shallowing-upward facies, 5) shoreface deposits, 6) fluvial. Exactly what these deposits will look like depends on the specific basin, and variables such as, for example, the prevalence of tidal vs. storm energy on the shelf. This is where sedimentologic/stratigraphic knowledge and interpretation becomes requisite for making stratigraphic tectonic interpretations. These are extensively developed in the SST (and the following ASST—Advanced Structure, Stratigraphy, and Tectonics—course), but not here.

As an historical aside, during the 19^th^ and 20^th^ century development of geosynclinal theory—which took place with these very rocks—both Hall and Dana argued that subsidence and sedimentation kept up with each other and the miogeosyncline to exogeosyncline transformation (platform to foreland basin) filled completely with shallow water deposits. They would have categorically rejected this Tectonic/Accommodation model.

A Tectonic/Accommodation Model for the Ordovician Sequence of Page and Shenandoah Valleys

Figure 3 shows a new subsidence/accommodation model for the evolution of the Middle and Upper Ordovician strata of Page Valley developed by Lynn Fichter and Rick Diecchio. It is based on known stratigraphic thicknesses and ages, interpreted changes in relative sea-level and depths of sedimentation, and calculated isostatic response. It illustrates the total subsidence necessary over time to deposit the strata between the top of the Beekmantown and the base of the Massanutten, both of which are interpreted to have been deposited at sea-level. The "Cumulative thickness" curve on Figure 3 is equal to the subsidence necessary to accommodate the strata from the top of the Beekmantown to the base of the Massanutten Sandstone. The "Total subsidence at top of Beekmantown" curve is the cumulative thickness curve adjusted according to the interpreted water depth (below storm wave base) that existed during deposition of the Lincolnshire Limestone, Edinburg and Martinsburg Formations. The sediment filling the basin is illustrated by adding the thickness of each formation to the adjusted total subsidence curve.

This subsidence/accommodation model illustrates a possible isostatic effect of Taconic over-thrusting onto eastern North America. It is based on the tectonic concept that during a collisional event an over-thrusting hinterland places a load on the foreland resulting in relatively rapid foreland basin subsidence (e.g. Shumaker and Wilson, 1996). The tectonic subsidence appears as the steepest part of the total subsidence curve, given that total subsidence is due to both tectonic loading and sediment loading, among other factors.

The subsidence model starts with cratonic or mature passive continental margin conditions driven primarily by sediment load-induced isostatic subsidence (slow subsidence rate, small accommodation space, slow sediment accumulation), interrupted by the onset of rapid tectonic subsidence into deep water conditions, followed by an exponential decay in subsidence rate as sediment load-induced conditions return. The model depicts an evolving basin that fills with a predictable sequence of carbonate and clastic sediment. The sequence starts with shallow water deposits, followed by deep basin deposits, followed by shallow water deposits. These facies might look like (bottom to top): 1. pre-tectonic shallow water (carbonate) deposits, 2. deep, quiet water, fine-grained, anoxic (carbonate to clastic) deposits, 3. mass transport clastic deposits (e.g. debris flows, turbidity flows, etc.) down an underwater slope, resulting in a coarsening, shallowing upward sequence as the accommodation space fills, 4.

distal to proximal shelf, coarsening, shallowing upward facies, 5. shoreface deposits, 6. coastal facies, 7. meandering fluvial deposits, and 8. braided fluvial deposits.

Applying this model to Page Valley, during New Market deposition accommodation space increases largely in concert with the increase in subsidence due to sediment loading. Depth increases at about the same rate as sedimentation, and the depth of the depositional surface stays about the same. This would have been the case during the period in which most of the Cambrian-Ordovician carbonates were deposited. During Lincolnshire and Edinburg deposition, subsidence outpaces sedimentation rate and the basin gets deeper. During Martinsburg (immature submarine fan clastics) and Massanutten deposition (after the tectonic load has been emplaced) tectonic subsidence decreases exponentially.

Subsidence rates slow while sedimentation rates increase resulting in rapidly decreasing accommodation space, filling of the basin, and shallowing upward water depths and facies. The shift from deepening due to increasing accommodation from subsidence, to shallowing due to decreasing accommodation from deposition, probably happens during the transition from Edinburg deposition to Martinsburg deposition.

Field Trip Itinerary

Figure 1: the trip is an east-to-west transect across strike from the western edge of the Blue Ridge province, through Page Valley, over Massanutten Mountain, across the Shenandoah Valley, and through Great North Mountain (Brocks Gap) that marks the beginning the Valley and Ridge. It follows Routes 211 in the east, and Rt 259 in the west. Parts of this field guide were adapted from Whitmeyer, et.al. 2012

Figure 4 is the regional stratigraphic column showing the stratigraphy, location of field trip stops, and tectonic interpretations.

Stop One: Harpers Formation, Chilhowee Group.

Location: Location: lat 38.668839 long -78.379215. Route 211, west bound lane ~ ½ mile west of Park office

Exposure: 100 meter long, 20-30 meter high outcrop in median. Good shoulder, good parking.

Outcrop Features	
Stratigraphy	**Structure**
Storm shelf: interbedded sandstones and shales; sandstone with hummocky cross stratification (undulating bundles of laminations scouring into and intersection each other)	Strike/Dip: 012,60E. Overturned to the west. **Prediction:** it is not obvious these rocks are overturned; they appear quite normal (a stratigraphic analysis has not been done; sedimentary structures should have up indicators, however). If the rocks are right side up then traveling west we should go down section, into the Weverton or Grenville basement. A couple hundred yards west, however, on a side road is the Antietam fm., which is up section and also overturned. Stop 2 further west is the Beekmantown, also up section, but subhorizontal. Ergo, these are overturned (Figure 5).

Tectonics	
Sedimentary/Basin Tectonics	*Larger Tectonic Contexts*
Hummocky cross stratification is upper-lower flow regime combined-flow energy dissipated on a shelf with depths not usually exceeding 150 feet. These thicker sand units imply an environment much closer to shore and in shallower water. Aside from a shelf environment, hummocky cross stratification by itself gives no tectonic indicators since it can occur in many tectonic circumstances. Tectonic interpretations must be done in context of other formations/environments below and above - neither seen on this trip (but seen in the SST course). Harpers, however, is associated with rift and transition-to-drift formations elsewhere in the Blue Ridge, such as the Lynchburg, Swift Run, Mechum River, and Catoctin lava flows. The overlying Antietam formation is a quartzite with *Skolithus* and (were visible) abundant cross bedding indicating a prograding system, while at Swift Run gap to the south there are proximal Bouma sequences in the Weverton (?). Figure 6 are two reconstructions of the Blue Ridge.	**Rift Tectonics:** Harpers is part of the **Rift** of a Rift-to-Drift sequence (Figure 6). It is the middle of the Chilhowee Group (Weverton, Harpers, Antietam) and represents the stabilizing phase of the rifting of Rodinia in the late Proterozoic. **Alleghanian Orogeny:** Overturning of the rocks took place in the Alleghanian orogeny when the entire Blue Ridge was brought up from depth and thrust west to its present location as an overturned (break thrust) ramp anticline. East of the Blue Ridge mountain the Grenville basement is cut by a series of anastomosing shear zones (Ductile Deformation Zones) (e.g. Garth Run and White Oak shears) that indicate ductile deformation at great depth. These are dated as late Devonian and represent pre-Pennsylvanian initiation of Alleghanian deformation when the rocks of the Blue Ridge province were farther east, and deeper.
Metamorphism: These rocks, as well as the entire Blue Ridge, underwent low grade (greenschist) metamorphism during the Alleghanian orogeny. The fact that sedimentary rocks just to the west (e.g. Beekmantown fm.) are not metamorphosed is one of the pieces of evidence for these Blue Ridge rocks being in a different province from those to the west in Page Valley and the Blue Ridge and Page valley rocks being structurally juxtaposed.	

Stop Two: Beekmantown Formation; first exposure.

Location: Location: lat 38.677854 long -78.455312. Rt 340 ~ ½ mile north of 211 junction at Luray
Exposure: a long low outcrop right adjacent to the highway with little shoulder. Road is heavily traveled so use caution.

Outcrop Features	
Stratigraphy	**Structure**
Carbonate tidal flat: dolomites with algal laminates, black cherts, and karst breccias.	Strike/Dip: 078,08N

Tectonics	
Sedimentary/Basin Tectonics	*Larger Tectonic Contexts*
Passive margin carbonates: Beekmantown was deposited toward the end of a thick sequence of mostly shallow water carbonate formations (Shady through Lincolnshire) of dominantly tidal to shelf carbonate environments. The fact that 1000's of feet of shallow water carbonates could accumulate in succession tells us that sediment generation by the carbonate factory could easily keep up with subsidence.	This is the **Drift** of the *Rift-to-Drift* Sequence. Beekmantown and the other Cambro-Ordovician carbonates (Shady through Lincolnshire Fms.) are passive margin (Divergent Continental Margin) deposits laid down along a subsiding continental margin following the Rodinia rifting. Subsidence-to-stabilization is an exponential decay beginning with thermal decay (cooling and increasing density as continental margin drifts away from divergent plate boundary), followed by sediment loading (also an exponential decay).
Alleghanian deformation and Regional Structural Signatures: like all the rocks in this region these were caught up in the thrust stacking that accompanied construction of the Pangaea supercontinent and built the Appalachian mountains. This outcrop alone, however, tells us virtually nothing of those processes since, from this outcrop alone, we would assume the rocks are sub-horizontal and undeformed. The larger structural signature of this region consists of long areas of sub-horizontal, gently undulatory rocks, punctuated by periodic large scale—first order—break thrust ramp anticlines (like the Blue Ridge). We will see two more examples of this on our transect. Also present are smaller 2nd and 3rd order folds and faults—representing their fractal nature; a.k.a. Pumpelly's Rule—seen at some of the stops. Unless there is something special to comment on we will assume that all remaining stops fit into this Alleghanian thrust/fold belt signature.	

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Stop Three: Shenandoah River/Massanutten Mountain Overview

Location: Overlook of North Fork Shenandoah River valley and Massanutten Mountain in the distance from the crest of Rt. 211.

This stop is to gain perspective, and set up some predictive hypotheses of what should come next.

Massanutten Mountain Overview	
Stratigraphy	**Structure**
Exposures: Driving the long grade we just climbed traveling west from Luray are patchy outcrops of sub-horizontal Beekmantown Fm. From this high point looking west we see the North Fork Shenandoah River valley below, and Massanutten Mtn. in the distance. The next several stops take us to the top of New Market Gap, the low area seen along the crest of Massanutten Mtn. in the distance.	**Predictions:** Since we are at a high point, looking west, and sitting on the Beekmantown, it is reasonable to predict that as we continue west down to the river we will travel down section through the Conococheague, Elbrook, and what ever other formations might be exposed down section (Stonehenge, New Market and Lincolnshire are well preserved here). Taking the perspective that present evidence is the best predictor of what should come next, we would also predict that those formations will be sub-horizontal. The fact that these predictions turn out to be spectacularly wrong is insight into what the stratigraphy and structure can tell us about the geologic development of the region.

Stop Four: Edinburg Formation

Location: lat 38.38.34 long 78.31.34. Rt 658, off Rt 674, off Rt 211
Exposure: Quarry on the east bank of the Shenandoah River, South Fork; Hamburg

Outcrop Features

Stratigraphy	Structure
Deep water basin: black (weathering gray), amalgamated micrite, sometimes interbedded with thin black shale. Stratigraphic and sedimentary features are best observed not in the quarry but along the road just south of the quarry. Here the beds are sub-horizontal and overturned with minor folding and faulting. Beds are generally a few em thick, but some reach a thickness of half a meter or more.	Strike/Dip: 198,41W – S fold so much variability Large-scale (2nd order) recumbent fold; note that the left and right quarry walls are dipping opposite directions. The southeastern quarry wall contains the large-scale fold hinge. Also note large S fold at the left side of the northeast wall, down-dip slickenlines on bedding surfaces, and bent/warped cleavage in finer-grained beds. **Testing Our Prediction:** Note that at the previous overview stop we made a (simplistic) prediction that driving into the river valley we should go down section through sub-horizontal strata. Instead we have gone up section, into this Edinburg fold. The deduction is that the Beekmantown formation at the last two stops has been thrust up and over the Edinburg. That puts this stop as a drag fold in the foot wall of the thrust.

Tectonics

Sedimentary/Basin Tectonics	*Larger Tectonic Contexts*
Taconic foreland basin - initial filling stage: nominally, these rocks say low energy (micrite) and anoxic conditions (black). This does not automatically mean deep water or basin since similar facies could occur in a lagoon (an example is at the base of the Lincolnshire at Tumbling Run, Strasberg, Va.). Only in context of what is stratigraphically below and above can we understand the Edinburg as the initiation of foreland basin subsidence that corresponds with the beginning of the Tacoic orogeny. This is where the Tectonic/ Accommodation model becomes useful (Figures 2 and 3) since it establishes from a theoretical viewpoint predictions of what a foreland basin stratigraphic sequence filling should look like, and when we examine the sequence up section what these black micrites/shales of the Edinburg represents becomes clear. The Edinburg is interpreted to have been deposited in a deep-water anoxic environment by mass transport processes (turbidity or debris flows), during maximum subsidence of the Taconic foreland basin. The carbonates were most likely generated on a shallow western carbonate platform. It is not obvious from this stop alone that the Edinburg was deposited by mass flows down a slope into a deep-water anoxic basin. In other locations there are good examples of scours, slump, and soft sediment deformation features (e.g. Lowry and Cooper, 1970; Pritchard, 1980; Read, 1980) that suggest down-slope mass movement.	Folding in the quarry occurred during the Alleghanian orogeny, potentially in two episodes. Most folds observed in Page Valley are upright with sub-vertical axial planes. The folds in the quarry probably initially formed as upright, open folds similar to geometries seen elsewhere in Page Valley. The cryptic, west-directed thrust occurred later in the Alleghanian orogenic cycle and tightened and rotated the pre-existing footwall folds to horizontal. Ergo: there were multiple episodes of deformation in the Allgehanian. **It's a matter of scale:** Figure 7. Looking at this fold in the quarry it appears dramatic and important; few people are not impressed when first seeing it. But, human scales are not a good guide to the importance of a structure. Compared to structures in the surrounding area, for example the Massanutten Mtn. syncline, this fold is a small to medium sized and relatively unimportant structure. It does give us a clue to the presence of the thrust fault, but the surrounding area has considerable other evidence pointing to a large thrust fault. Figure 7 shows the scale of the Edinburg recumbent fold relative to the larger structural features in the region.

Stop Five: Upper Martinsburg (Cub Sandstone; first exposure).

Location: lat 38.38.32 long 78.33.15
Exposure: 50 meter long, ~ 8 meter high outcrop; badly weathered.

Outcrop Features	
Stratigraphy	**Structure**
Storm shelf: sub-vertical interbedded fine sandstones and shales of several cm thickness. Sandstones with megarippled tops and undulating bases, containing intersecting bundles of hummocky laminations. For as deeply weathered as this is it well shows hummocky signatures, but not the prograding parasequences that characterize the Cub Sandstone elsewhere (these are well developed on the road to Catherines Furnace a few miles south off Route 340.	Strike/Dip: 214,90E; foliation 020,48E; steeper than bedding; very high angle normal fault at east end of outcrop; Bedding is top to west. Beds are mostly subvertical with well developed cleavage in the shales. The structural complexity of the outcrop is hinted at by analyzing the cleavage at the eastern end of the outcrop (Figure 8).

Tectonics	
Sedimentary/Basin Tectonics	***Larger Tectonic Contexts***
Taconic foreland basin - final filling stages: The Cub SS represents the end of the Taconic foreland basin filling (Figure 3) when it has shallowed upward enough for storm wave to touch down and generate hummocky sequences.	At the outcrop scale this is a rich stop, both stratigrapically and structurally; there is a lot to be learned from close study. However, the fold and fault are 3rd order features and have little regional significance, with two caveats. First, there is not much outcrop along this stretch of highway, and anything that gives insight is useful. Second, because structure is fractal, we can anticipate that the nature of this small fold/fault reflects the nature of larger structures where we cannot see everything because of scale.

Stop Six: Middle Martinsburg Formation

Location: Location: lat 38.38.00 long -78.34.44 to 78.34.34. Long cut on north side of road at junction of Rt 340 and 211.
Exposure: 100 meter long, 40-50 meters tall; well exposed.

Outcrop Features	
Stratigraphy	**Structure**
Submarine fan: well developed Bouma sequences with mostly T_{ABD} units (graded bedding, high velocity laminations, laminated silts) of about dm thickness. Sands are very immature lithic, feldspathic, quartz wackes.	Strike/Dip: East 032,72E; Mid 210.78W; West 211,76W

Tectonics	
Sedimentary/Basin Tectonics	***Larger Tectonic Contexts***
Taconic foreland basin - middle filling stage: One of the frustrating things about the Martinsburg formation is that although there are decent or even excellent outcrops of the lower, middle, and upper portions, no where do we have outcrops that show how these transition. They differ from each other enough one might be tempted to think they are unrelated, except that mapping indicates they do stack in stratigraphic order. It is one of the enigmas of the Taconic foreland basin.	The consistent west dip of the middle Martinsburg at this location marks the eastern flank of the Massanutten synclinorium. This deformation is a response to Alleghanian thrust stacking during the Pennsylvanian. At this locality the Massanutten syncline seems simple and straight forward. We will see that is too simplistic.

Stop Seven: Upper Martinsburg (Cub Sandstone; second exposure); Massanutten Sandstone.

Location: lat 38.38.35.0400 long -78.36.48.70.
Exposure: Crest of Massanutten Mt., at New Market Gap, looking north. We view the outcrop from the south side of the highway. What is easily visible are thick sandstones in the roadcut. Above them in the woods is the Massanutten Sandstone, generally only visible in winter when the leaves have been shed.

Outcrop Features **Stratigraphy**	**Structure**
Cub SS: Proximal storm shelf: This does not look like the Cub Sandstone we saw at Stop 5 (interbedded sandstones and shales). The sandstones are thick and massive with little internal structure, at least from this distant vantage. But, these thick sandstones are consistent with proximal parasequences in a prograding shelf system. We see a similar coarsening, amalgamating upsection sequence at Catherines Furnace. **Massanutten SS:** we do not visit this formation on this trip. Consists of indurated, medium to coarse quartz arenite beds with planar and trough cross bedding. These have been interpreted as braided river deposits (Pratt, 1979).	Strike/Dip: 032,72E. Outcrop near the axis of the Massanutten synclinorium.

Tectonics *Sedimentary/Basin Tectonics*	*Larger Tectonic Contexts*
End of the Taconic orogeny: The enigma of the Massanutten SS is it contradictions. It is arguably a braided river system, but is quartz dominated and thereby very unlike most braided river systems which are lithic or feldspar rich. The enigma is yet to be resolved.	The end of the Taconic orogeny is believed to be an unconformity. A small angular unconformity is present in New York. The Cub SS-Massanuttten SS contact is not exposed in this region

Stop Eight: Upper Martinsburg (Cub Sandstone; third exposure).

Location: north side of Rt. 211 at the juncture of Rt 211 and Rt 620, on the west side of Massanutten Mtn.
Exposure: This stop is in a narrow, vertically sided drainage ditch that is easy to miss. We will not descend into the drainage ditch; the lesson can be made just looking at the surrounding topography. Nor are we particularly interested in the stratigraphy, which is very similar to Stop 5. It is the structure and tectonics we are after.

Outcrop Features **Structure and Tectonics**
Strike/Dip: 0.38, 85E, overturned to the west. Cleavage: 0.28, 40E. Tight overturned anticlinal fold projecting out from the western flank of Massanutten Mtn (Figure 9). The lesson of this outcrop is that what seems pretty straight forward may hide revealing complications. If we presume the Massanutten Mtn. contains a syncline—based on the evidence that units on the east side dip west, and units at the top of the gap are sub-horizontal—then we anticipate that rocks on the west side of Massanutten must dip east—to complete the syncline. And it makes perfect sense topographically since traveling west from the Mountain toward New Market takes us into the Shenandoah Valley, not into another fold. So we reasoned too. But, the Upper Martinsburg (Cub sandstone) exposed in the drainage ditch is overturned to the west, indicative of an anticlinal fold between the Valley and Massanutten Mtn (Figure 9). Nothing topographically would give any hint this fold exists. Indeed rocks exposed in the Valley and out to Little North Mountain undulate sub-horizontally. On reflection, this tight overturned anticlinal fold is not inconsistent with the folding (we will not see) several miles south of New Market gap. There, at Catherine Furnace, in a narrow cross section only a few miles across, the Massanutten Sandstone is not a single syncline, but two tight synclines with a tight anticline in between. Reasonably, the overturned anticline in the Cub Sandstone might extend south to that part of Massanutten Mtn, making two synclines and two anticlines. But, wait, there's more. Small east directed thrust faults have recently been mapped on the eastern side of Massanutten Mtn. This indicates two sequential stress episodes; the main Alleghanian one resulting in the west-directed folding/thrusting, the second directed east to produce the small back thrusts (Heller, et.al., 2007).

One hypothesis for all this is that during the Alleghanian orogeny the rocks of Massanutten Mtn., moving westward, came up against an immovable barrier that caused them to accordion fold to take up the stress, and, when that was not enough, to finally back thrust eastward. It is hard otherwise to explain how the very tough Massanutten sandstone got so tightly folded. What was that immovable barrier to the west?" Speculatively, just to the west is another major break thrust that ramped Valley Cambro-Ordovician carbonates up and over the clastics in Little North Mountain. This would have built a large topographic high to the west of Massanutten Mtn. that could not be climbed by the Massanutten strata. Instead they would have been scrunched between irresistible stress to the east and an immovable barrier to the west resulting in tighter folding than is normal for the region.

Stop Nine: Beekmantown, New Market, Lincolnshire Formations

Location: Lat 38.37.23 Lon 78.49.08; outcrop extends east down Rt 259 couple of hundred yards

Exposure: Representative exposure of the Beekmantown, New Market (small, mostly covered and hard to find outcrops a hundred or so yards east) and Lincolnshire (at the crest of the road we have found samples only with much hunting; but several miles east is an outcrop showing distinctive Lincolnshire facies).

This stop is representative of the sub-horizontal to low angle dipping as these formations ripple across the Shenandoah Valley from New Market to here. Scattered and generally small outcrops of each formation are exposed along the transect and show similar gentle dips.

Outcrop Features	
Stratigraphy	**Structure**
Carbonate tidal flats and shelf: • Beekmantown: gray-white algal laminated tidal dolomites. • Knox Unconformity (not exposed) • New Market: tidal micrites with birds eyes; algal laminates. • Lincolnshire: shelf fossil rich limestones and black cherts.	Strike/Dip: 030,28E **Prediction:** the rocks at this stop are dipping gently east, so continuing our transect west should take us down section; next stop would be the Conococheague.

Tectonics	
Sedimentary/Basin Tectonics	*Larger Tectonic Contexts*
Carbonate passive margin: Although to a carbonate stratigrapher the changes in these lithologies holds fascination, from a sedimentary tectonic perspective they simply represent tectonic stability. The most dramatic shift is from tidal environments to shelf environments, which, could easily be explained as a transgression. If, however, we could see the next formation up section–Edinburg (seen at Stop 4)–we would be aware of the beginning of a much more dramatic transition; the beginning subsidence of the Taconic foreland basin, discussed at Stop 4.	Same as Stop One

Stop Ten: Conococheague Formation

Location: Lat 38.38.20 Lon 78.51.04

Exposure: low outcrop on north side of road about 40 meters long, 4 meters high. Well exposed, good parking on the opposite side of the road. Look west the stop give a good view of Brocks Gap a mile or so away.

Outcrop Features	
Stratigraphy	**Structure**
Carbonate tidal flat: Gray white dolomite, but aside from that the outcrop is too deformed to provide much sedimentologic evidence. At other localities Conococheague has algal laminates, stromatolites, pelletal sands, flat pebble conglomerates, ribbon rock, and herringbone cross bedding.	Severely deformed. It is difficult to see bedding in this outcrop, and it depends on the quality of the light. Toward the left (west) end of the outcrop some vertical bedding can be detected, but it quickly folds over toward the east. We have not been able to palinspastically restore this outcrop

Tectonics	
Sedimentary/Basin Tectonics	***Larger Tectonic Contexts***
Same as Stop 2: Beekmantown Formation	Same as Stop 2: Beekmantown Formation **Alleghanian deformation:** Large swaths of the carbonate rocks along this transect from New Market to here show little or no structural deformation. The severity of this deformation compared to the rocks just to the east imply a major dislocation. As we will see at the Brocks Gap stop (look just to the west about a mile) there is a major jump up-section from the Conococheague to the Reedsville and Oswego, both overturned to the west. The deduction is the Conococheague and other carbonate formations were thrust up and over the Brocks Gap section, putting them in the hanging wall of the North Mountain fault. This structural patterns repeats in many places.

Stop Eleven: Brocks Gap Section: Reedsville, Oswego, Tuscarora, Rose Hill, Keefer Formations

Location: Lat 38.38.38 Lon 78.51.45; outcrop extends west through most of gap ending at the Oriskanhy at Chimney Rock. We will travel no farther than the Keefer.

Exposure: large dramatic road cut several hundred feet high. Depending on time we will either cross the road, climb the guard rail and examine the rocks closely, or more quickly, walk the opposite side of the road with the leader narrating what is on the opposite side of the road.

Outcrop Features	
Stratigraphy	**Structure**
This section contains the Reedsville, Oswego, Tuscarora, Rose Hill, Keefer, and covered formations up to the Oriskany exposed at Chimney Rock. The section is largely unique in that it is a mixture of formations some found to the west but not the east, and vice versa. Figure 10 shows an interpretation of the facies relationships.	Strike/Dip: 034,84E overturned to the west **Prediction:** the Oriskany at Chimney Rock is the last exposed outcrop of the Brocks Gap sequence, but since we have been climbing section all the way through the gap it would make sense that rocks to the west should get even younger, as we will go see next.

Brocks Gap Formation Descriptions

Reedsville formation (storm shelf): East end of outcrop: interbedded fine grained sandstones and shales (~ dm thickness), with scattered mega-rippled biosparite beds. Sandstone beds shrink and swell in thickness, and are composed of bundles of thickening and thinning laminations (hummocky cross stratification). Upsection sandstones thicken and amalgamate and contain reactivation surfaces.

Oswego formation (braided river): coarse to very coarse gray to white quartz sands with small quantities of lithic fragments. Thick bedded (1 to several dm), amalgamated, rapidly changing thickness, with scours and reactivation surfaces, and large scale planar and trough cross bedding. Upsection scattered gray mud pebbles or zones appear. In the upper third, red zones several meters thick appear alternating with Oswego gray sands; basic lithology does not change, just the addition of red staining. Mud pebbles are red in these zones.

Tuscsarora (beach): white quartz sandstone. Along the road there is only a couple of dm exposures, but at the top of the gap it is well exposed; quartz pebble beds dm to m in thickness (a large boulder of the quartz pebble conglomerate in next to the guard rail). Superficially, this small outcrop look similar to Oswego, but is whiter.

Rose Hill (clastic tidal systems): not exposed along the road, but exposed at the top of the gap. Elsewhere red, interbedded shales and rippled sandstones forming coarsening upward parasequences.

Keefer (beach): quartz sandstone, with occasional pebble zones. Not much can be seen along the road due to weathering, but on the west side, 50 yards or so up into the woods are broad surfaces with oscillatory stokes and sinusoidal ripples (at 90 degree to each other). *Skolithus* traces are in the float, and occasional pieces with cross bedding.

Tectonics	
Sedimentary/Basin Tectonics	***Larger Tectonic Contexts***
Taconic foreland basin - final filling and post orogenic stages: The Oswego problem. The Oswego is at its thickest at Brocks Gap, and most simply has an eastern sourceland. The nearest Ordovician exposures east of Brocks Gap are in the Massanutten area, but historically no traces of Oswego have been found there (acknowledging that in the Ordovician these regions were widely separated). Recently two small outcrops of possible Oswego have been found in the southern end of Massanutten Mtn. by Matt Heller, but this requires more study).	The Taconic foreland basin has complex stratigraphic relationships, representing its complex history. To begin, the stratigraphic sections vary markedly from east to west (Figure 4). In the Massanutten region the sequence begins with Edinburg basinal black micrites that transition up section into Martinsburg submarine fan Bouma sequences, Cub shelf shales, and the Massanutten braided river. Just a few miles west at Brocks Gap (Little North Mountain) none of these formations are present; instead there is Reedsville storm shelf, Oswego braided river, and Tuscarora beach. Further west at Germany valley the section is Trenton shelf carbonates, Reedville shelf clastics, Oswego coastal sand bars, Juniata tidal flats, and Tuscarora beach. The interpretation is the Taconic foreland basin was divided into two basins separated by a peripheral bulge (preserved at Little North Mountain) Figure 10. The eastern (flysch) basin subsided the fastest and deepest, and is the one the Tectonic/ Accommodation model is based on (Figure 3). Most of its sediments derived from generally eastern sources—the Carolina volcanic terrane. The Germany Valley western basin subsided less and more slowly developing environments that were never more than deep shelf. These sediments flowed in mostly from Pennsylvania and southern Virginia. The Little North Mountain peripheral bulge sediments derive from both east and west in a complex history. The issue has always been the Oswego which has an apparent eastern source that cannot be identified. The problem is too complex to explore more here, but has better perspective when we look at a palinspastic restoration (Figure 11). Rocks that are nearly juxtaposed today by Alleghanian thrusting, were during the Ordovician widely separated, with none of the in between rocks exposed. Makes it challenging to reconstruct the basin.

Stop Twelve: Brallier Formation

Location: Lat 38.38.52 Lon 78.53.05

Exposure: series of low outcrops along the north side of the road; exposed at several places along a few miles of the highway.

Outcrop Features	
Stratigraphy	**Structure**
Bouma sequences and Submarine fan: interbedded very fine grained, indurated sandstones (1 to a few cm thick) interbedded with shales of similar thickness. Sandstones are Bouma sequences with mostly T_{CDE} units. Ripples sometime seen on sandstone tops, while bases have clear flutes and scours. Leisagang stain often masks the internal structures but sometimes the climbing ripples of the T_C unit are seen.	Strike/Dip: 330,16 NE These subhorizontal units just a few miles west of the Brocks Gap overturned anticline indicate again the structural signature of this region: long areas of subhorizontal rocks, punctuated by periodic large scale—first order—break thrust ramp anticlines. Smaller 2nd and 3rd order folds and faults are also present but none of our stops looks at them.

Tectonics	
Sedimentary/Basin Tectonics	***Larger Tectonic Contexts***
Acadian Foreland Basin: the Brallier (and Needmore and Millboro that come before it) are the first formations to show up after the carbonates and quartz sandstones of the late Silurian-early Devonian tectonic calm. The black shales of the Needmore and Millboro indicate deep water deposition, as does the Bouma sequences of the Brallier. Thus, these formations represent the initiation of rapid foreland basin subsidence.	The driver of the Acadian foreland basin subsidence in this region is enigmatic. No distinct terrane in the Mid-Atlantic piedmont is associated with the Acadian. On the other hand, older piedmont thrusts have evidence of right lateral strike-slip reactivation, as if a terrane had slid down the coast. The foreland basin has features of a typical foreland basin, but there is no evidence of the thrust-stacking that usually accompanies foreland basin subsidence.

Thus Endith the Field Trip

List of Figures

Figure 11. Interpretive cross sections across northern Virginia showing the progressive development of the Iapetan passive continental margin into the deep and shallow Taconic clastic basins (top two cross sections). Bottom cross section shows present-day geology after the Alleghenian orogeny foreshortened the orogenic belt. Rock units that are now geographically close were in the Ordovician widely separated (Diecchio,1993, fig 7).

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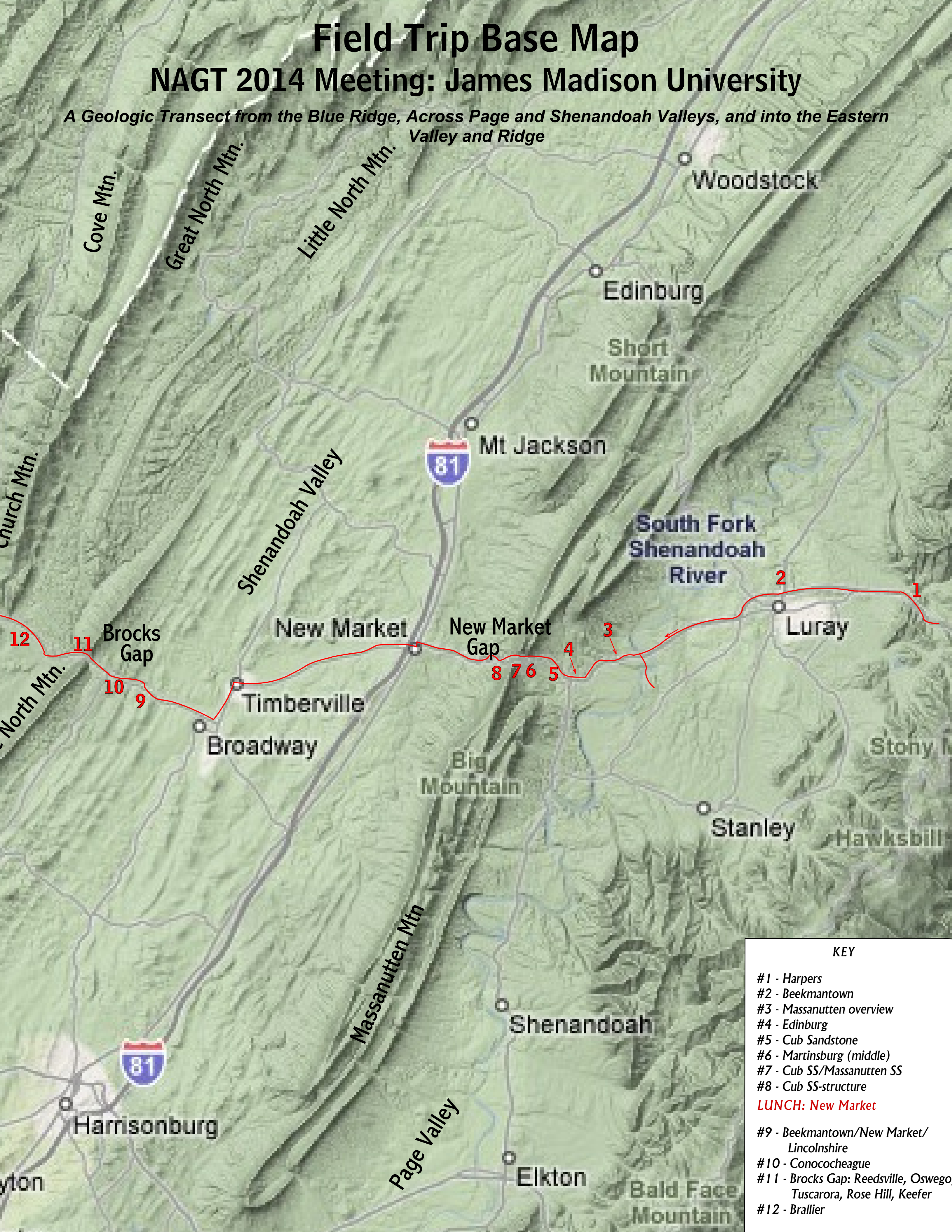
Field Trip Base Map

NAGT 2014 Meeting: James Madison University

A Geologic Transect from the Blue Ridge, Across Page and Shenandoah Valleys, and into the Eastern Valley and Ridge



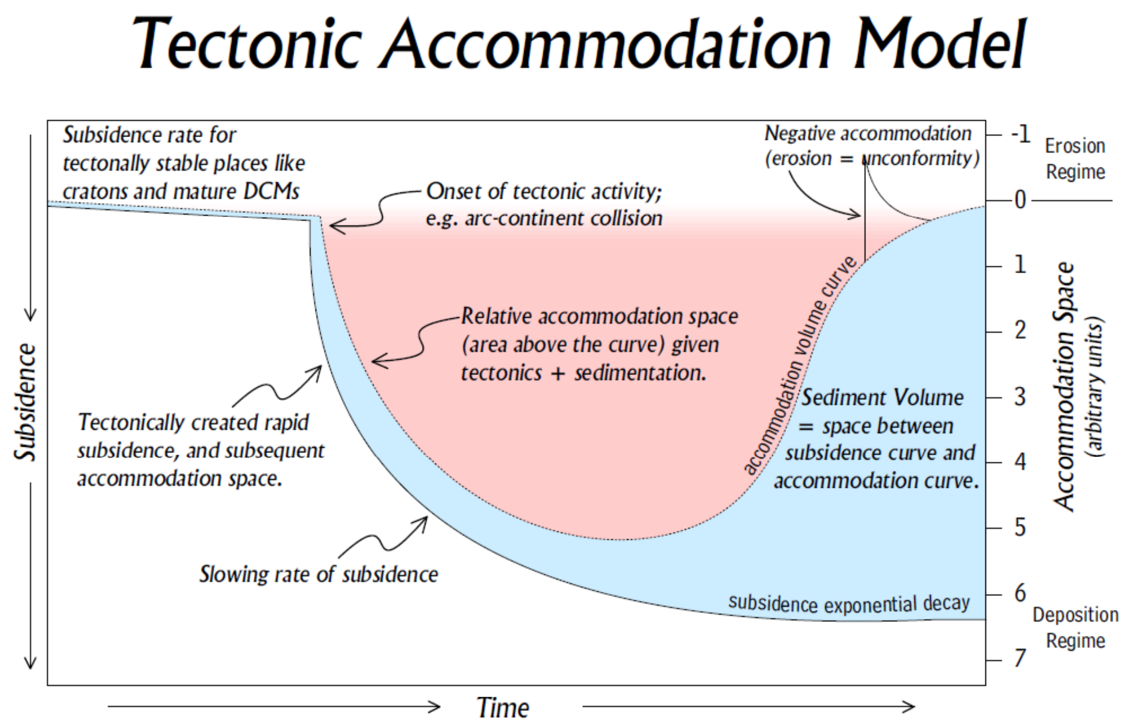


Figure 2. Theoretical Model For the Tectonic Creation of a Foreland Basin, and the Subsequent Filling of the Accomodation Space by Sedimentation.

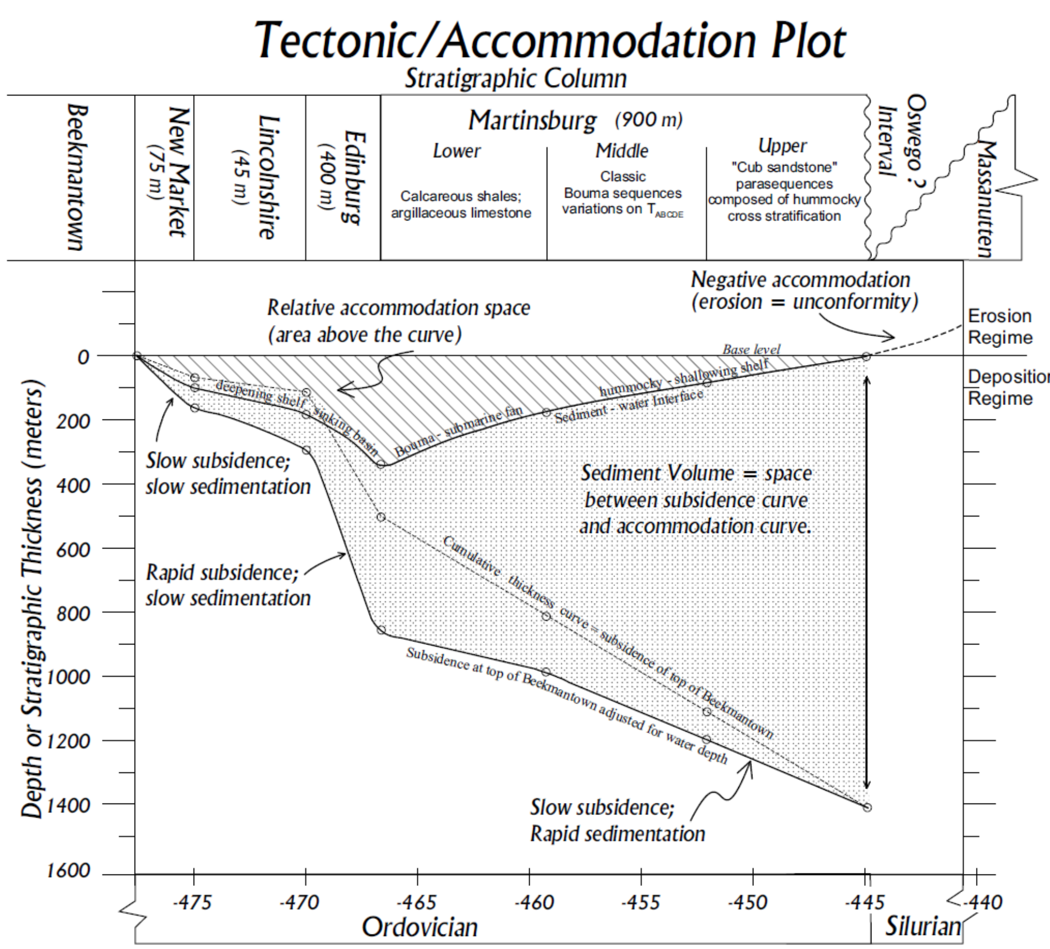


Figure 3. The theoretical Tectonic/Accomodation plot drafted using actual data from the Page Valley Taconic Section.

NAGT: Spring 2014 Field Trip: JMU

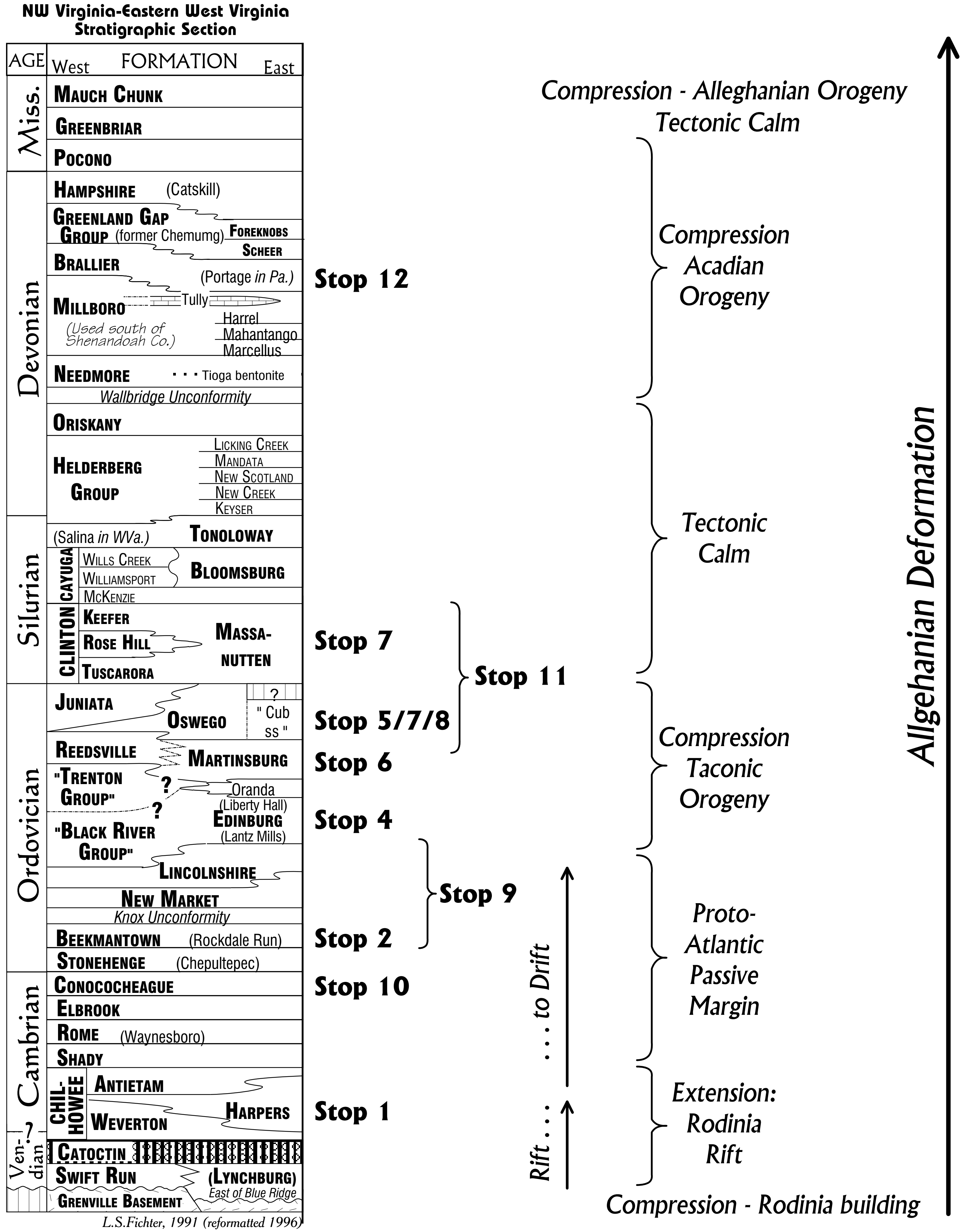


Figure 4. Regional stratigraphic column showing the stratigraphy, location of field trip stops, and tectonic interpretations.

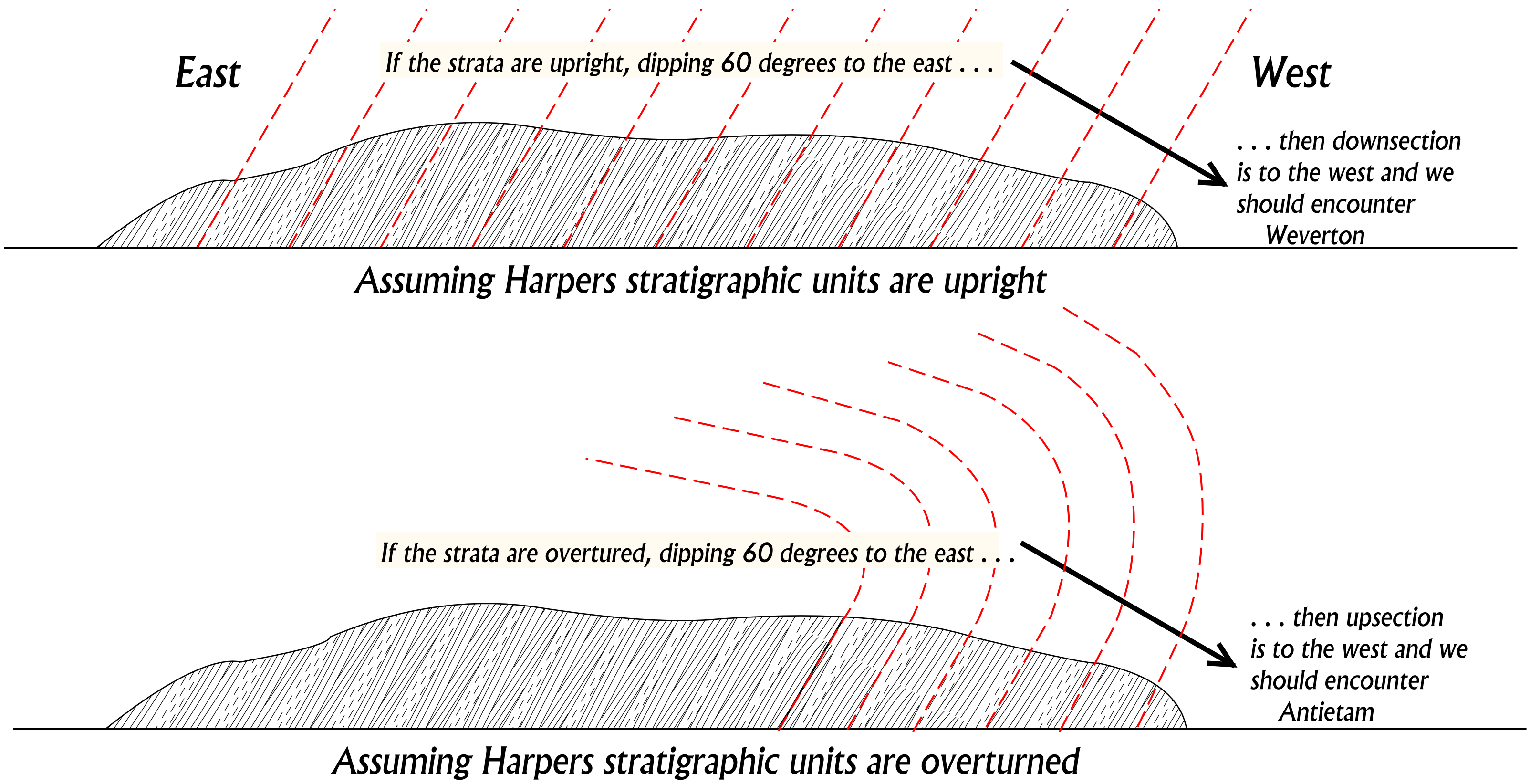
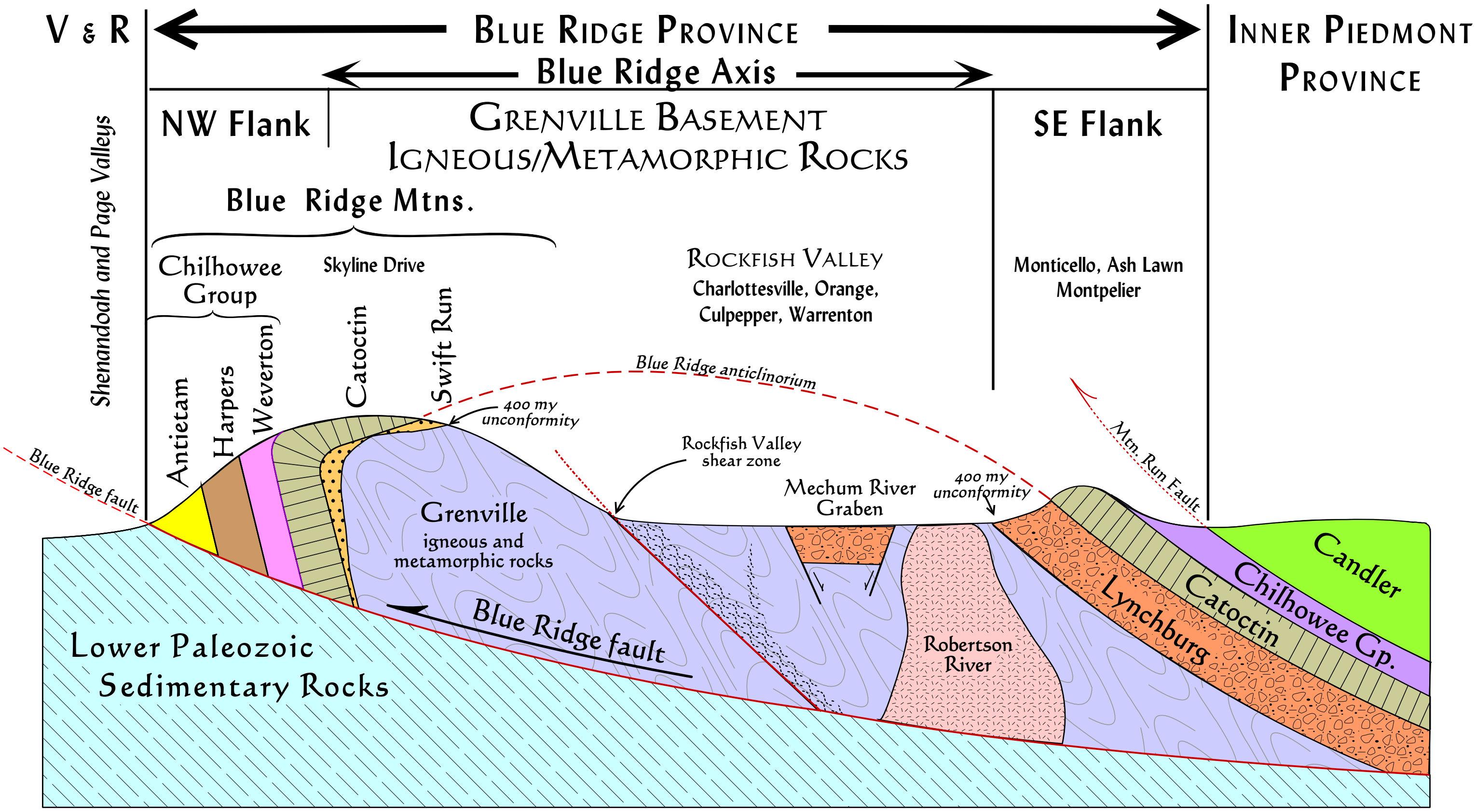
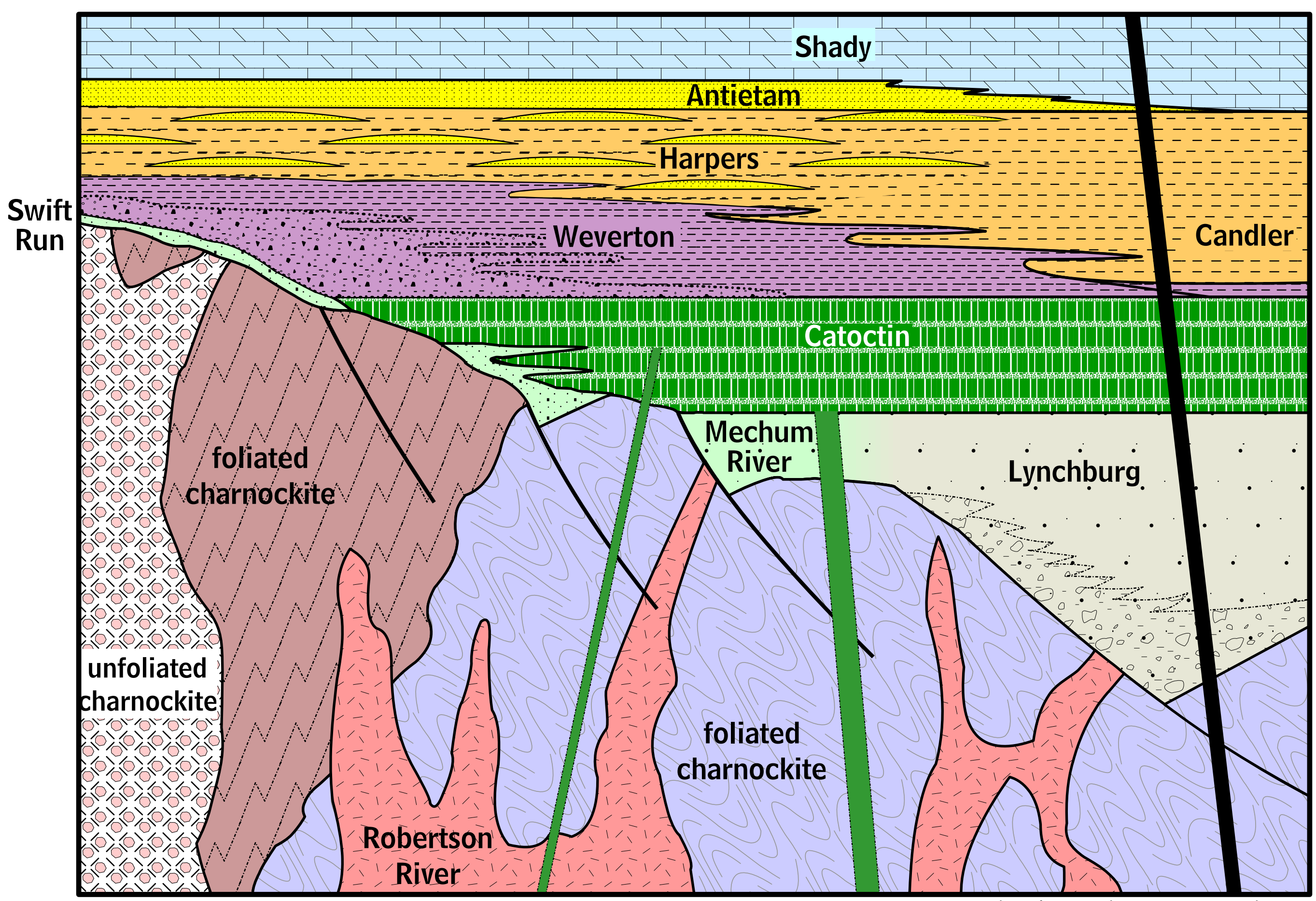


Figure 5. Predictive model of what should be found upsection if: 1) the Harpers at Stop 1 is right-side-up - Weverton to the west, or 2) overturned - Antietam to the west.



Conceptual Cross Section of the Blue Ridge Province of Central Virginia



L.S. Fichter/Steve Whitmeyer - revised 2012

Figure 6. Interpretive Blue Ridge cross section (top drawing), and reconstructed Blue Ridge showing facies relationships.

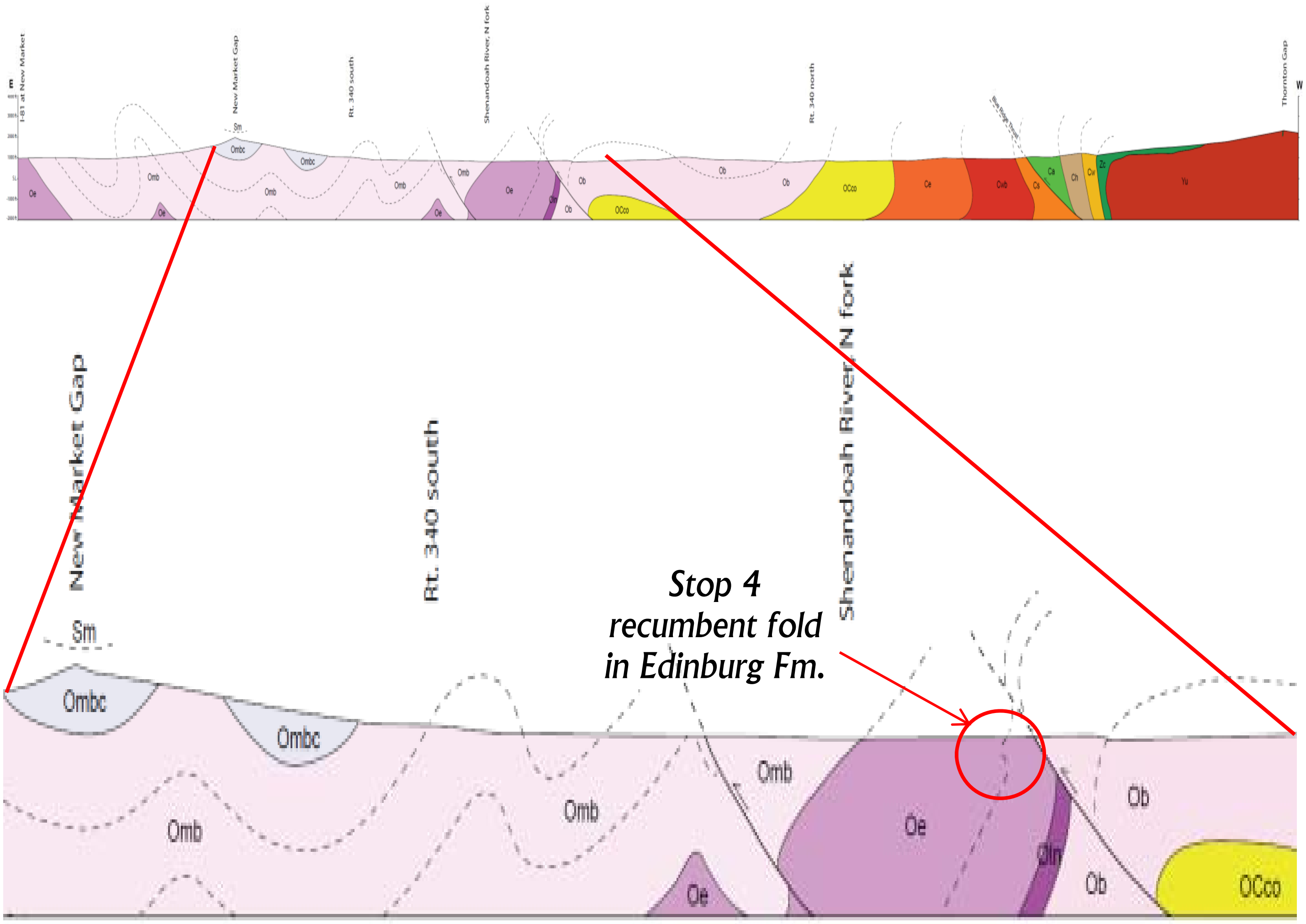


Figure 7. Detail of a structural cross section across Page valley showing the scale of the Edinburg recumbent fold at Stop 4 relative to the larger structural features. The Edinburg fold is a 2nd order feature..

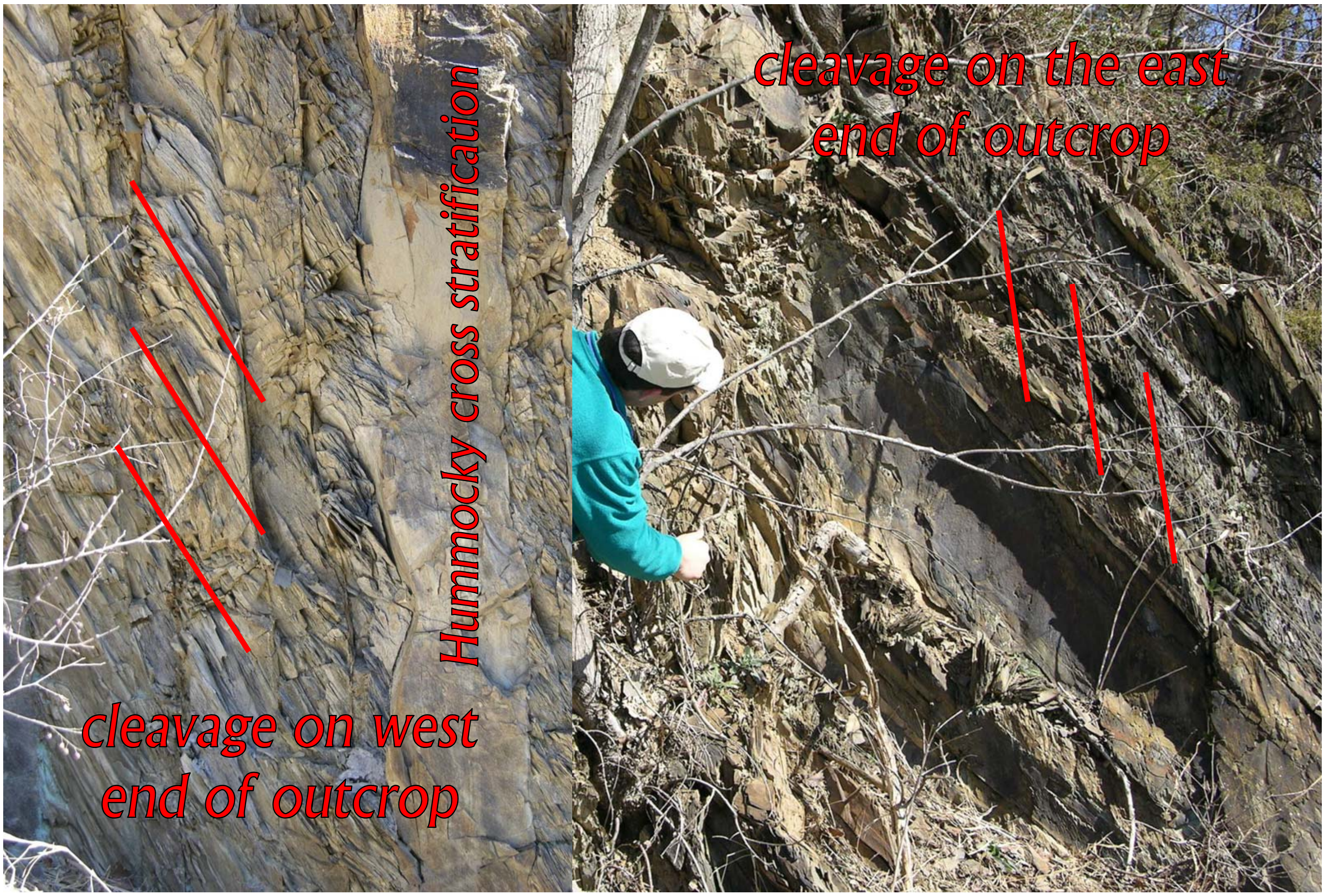


Figure 8. Stop Five Cub Sandstone (upper Martinsburg). Two section of the east end of the outcrop about 10 feet apart showing the different cleavage relationships. Analysis of these indicate a faulted anticlinal 3rd order fold. Structures this small have little regional significance, but the outcrop provides excellent opportunities for both stratigraphic and structural analysis.

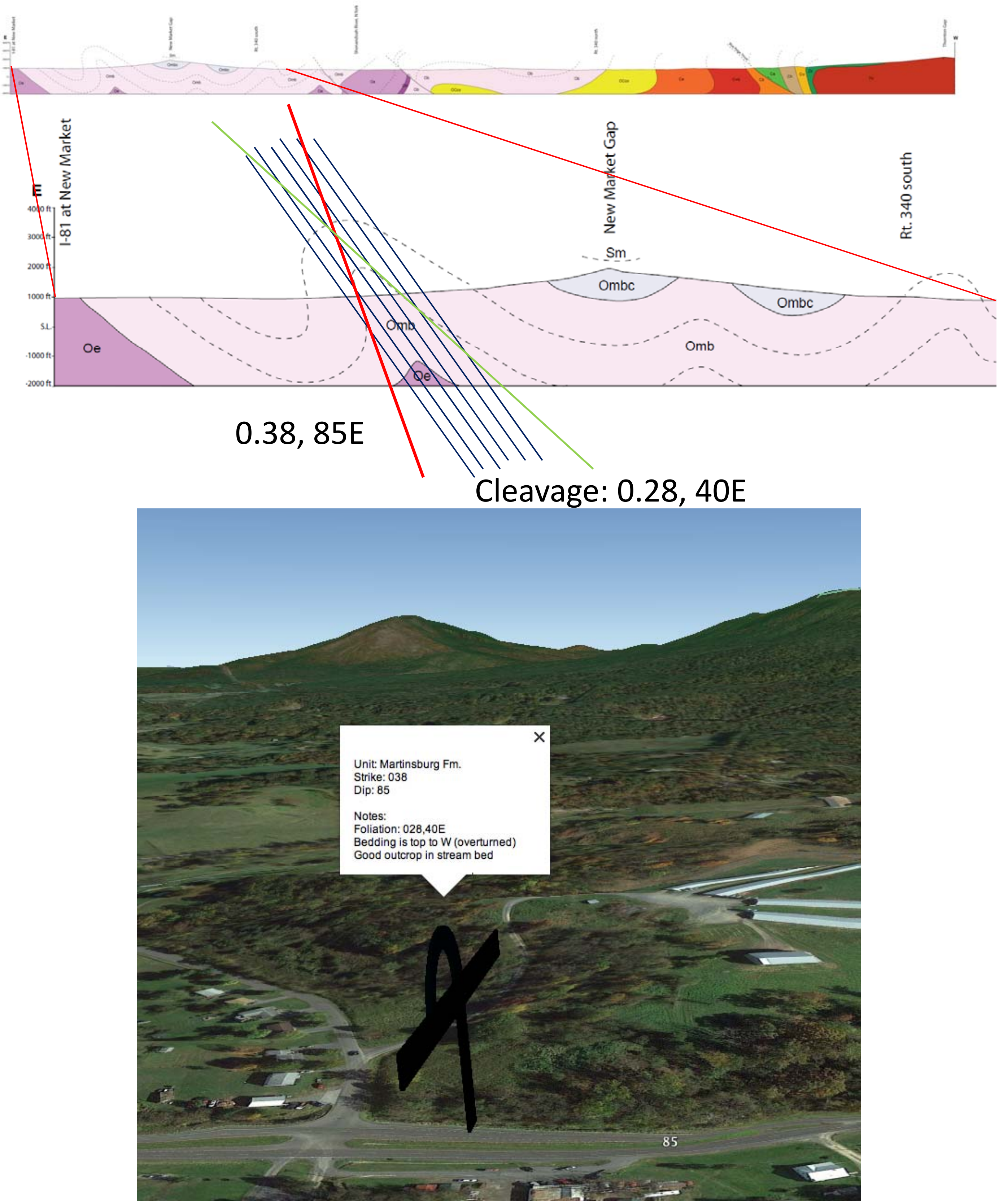


Figure 9. Stop Eight Cub Sandstone (upper Martinsburg). A tiny unremarkable outcrop in the drainage ditch, except that the beds are overturned to the west, and the cleavage patterns indicate an anticline. There is no topographic clue that this overturned anticline exists, and no trace of the Massanutten sandstone to the west. Thus, the necessity of detailed structural analysis to understand the region.

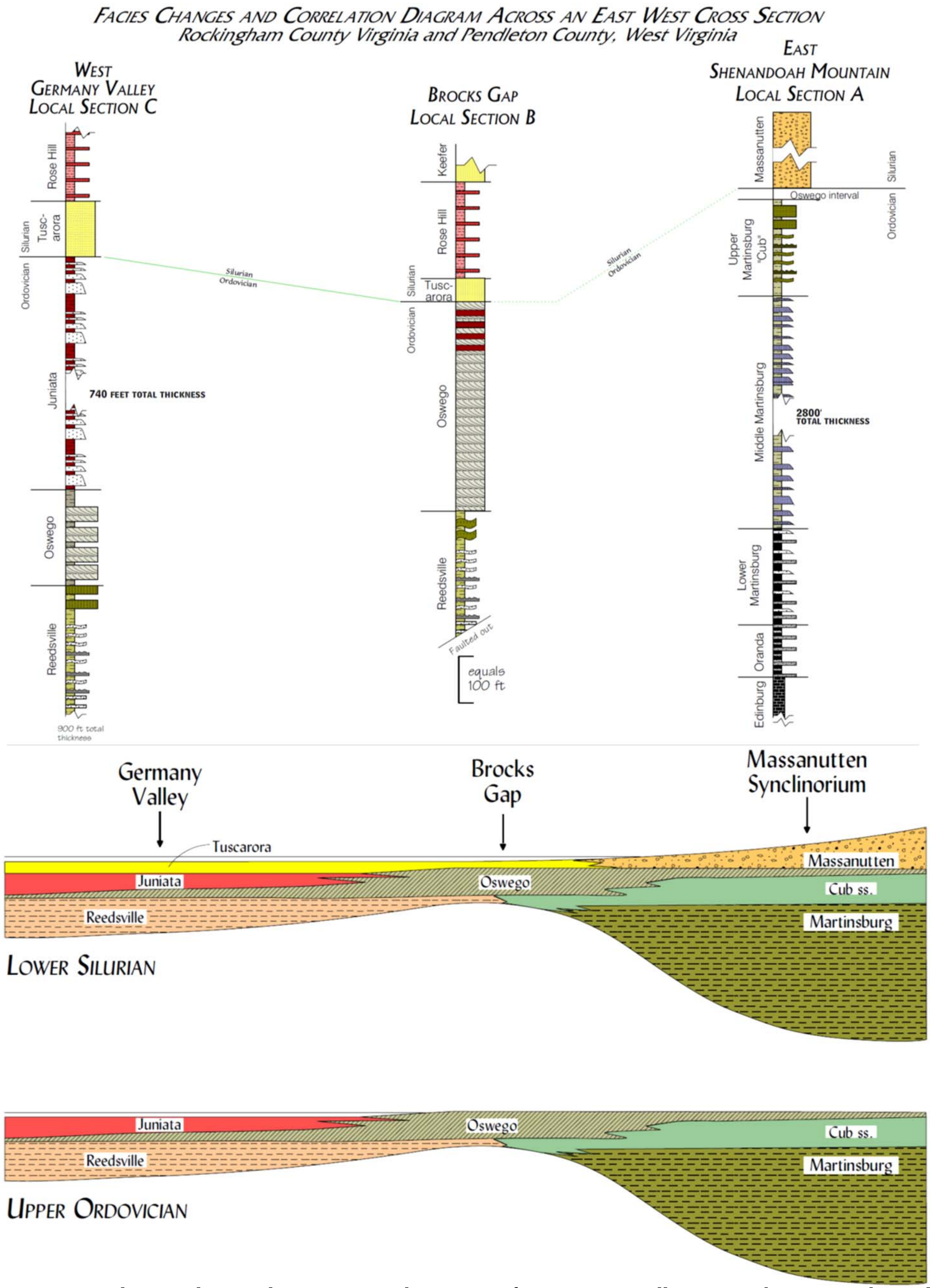


Figure 10. Top: Ordovician-lower Silurian stratigraphic sections from German Valley, to Brocks Gap, to Shenandoah Mtn. Although time equivalents these three sections differ markedly in their stratigraphic sequences and depositional environments. Bottom: two interpretive cross sections showing how the Taconic foreland basin was divided into two basins separated by a peripheral bulge (preserved at Little North Mountain).

Interpretive Cross Sections From Eastern West Virginia Across Northern Virginia Showing Deep and Shallow Taconic Facies Relative to Present Geology

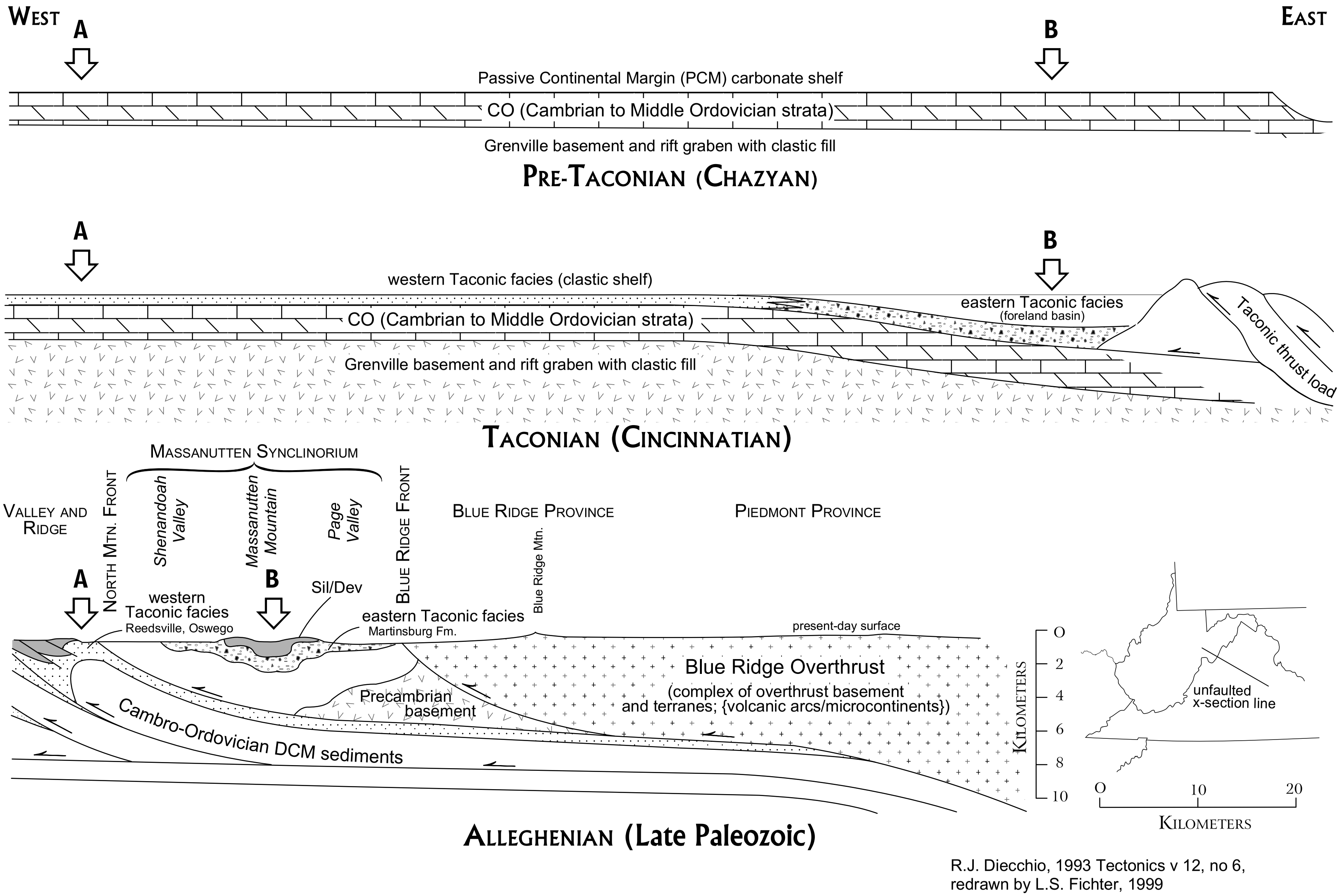


Figure 11 - Interpretive cross sections across northern Virginia showing the progressive development of the Iapetan passive continental margin into the deep and shallow Taconic clastic basins (top two cross sections). Bottom cross section shows present-day geology after the Alleghenian orogeny foreshortened the orogenic belt. Rock units that are now geographically close were in the Ordovician widely separated (Diecchio,1993, fig 7).