4-2010

3D Restoration of the Sugar Hollow Rift Basin Blue Ridge, Virginia

Andrew K. Laskowski
College of William and Mary

3D Restoration of the Sugar Hollow Rift Basin, Blue Ridge, Virginia

A thesis submitted in partial fulfillment of the requirements for the degree of
Bachelor of Science in Geology
from the College of William and Mary in Virginia,

by

Andrew K. Laskowski

Accepted for High Honors
(Honors, High Honors)

Professor Christopher Bailey (Geology), director

Professor Ryan Thigpen (Geology)

Professor Mike Kordosky (Physics)

Williamsburg, Virginia
April 15, 2010

Table of Contents

List of Figures

Abstract

The tectonic processes of supercontinent breakup create rift structures that are often preserved along the passive margin of continents. The resultant structures and rocks are the foundation from which collisional orogenic structures are eventually created. At Sugar Hollow, 15km northwest of Charlottesville, Virginia, ancient Iapetan rift structures are preserved on the eastern margin of Laurentia in the Virginia Blue Ridge. This location preserves a ~10km^2 eastward-thickening graben complex consisting of 8 originally-normal faults that reaches a maximum thickness of ~300m. Some of the 8 faults were reactivated past the null point during the Paleozoic—producing apparent thrust geometry. To better understand the original structures that accommodated the opening of the Iapetan Ocean at the close of the Neoproterozoic, the basin was restored to its post-rift state using Midland Valley's *Move* software. During this process, layers were unfolded and fault blocks were restored to their maximum extensional state, revealing ~12% shortening. However, penetrative ductile deformation was not accounted for during this restoration. Therefore, strain and vorticity analysis were used to better understand the intensity and geometry of ductile deformation across the basin. Using this data, a fully restored 3D model of the Sugar Hollow basin was created. This model revealed additional shortening of ~13%, suggesting that penetrative strain may be at least as important of a restoration consideration as faulting and folding. Consequently, strain and vorticity analysis should be integrated into cross section restoration whenever possible.

Introduction

First order tectonic processes break continents apart to form ocean basins. Hundreds of million years later these old and dense ocean basins are consumed by subduction processes that ultimately lead to tectonic collision, which raises mountains and creates supercontinents. Supercontinents are inherently unstable, and eventually succumb to rifting and subsequent breakup; as such the supercontinent cycle begins anew. It is the rifted continental margin and the overlying passive margin deposits that are the foundation upon which later contractional structures develop in collisional mountain belts. Original rift basins and their bounding normal faults may be reactivated during later crustal contraction such that faults are inverted and reactivated as thrusts, and shortening occurs across sedimentary basins producing an array of complex geologic structures (Fig. 1a) (Williams and others, 1989; McClay and Buchanan, 1992). The geometry of rift structures influences the style of deformation associated with later contraction; favorably oriented normal faults may be reactivated as thrusts or the geometry and mechanical contrast across those structures may serve to buttress and localize strain and shortening in weak rift sediments (Butler, 1989; Chen, 1998; Bailey and others, 2002).

Conversely, to understand the geometry of ancient continental rifts, deformation associated with later contractional deformation must be removed. Depending on the degree of reactivation, penetrative strain, and metamorphism this may or may not be a difficult task. Traditionally, restoration involves restoring post-rift strata (Fig. 1a) to an original subhorizontal attitude by restoring contacts across faults and unfolding layers. Although a number of workers have restored inverted basins (Butler, 1989; Bailey and others, 2002), studies that account for penetrative ductile strain—an artifact whose contribution to shortening during deformation cannot be expressed in simple cross section models—are commonly 0-lacking.

The role that penetrative strain's magnitude as well as the type of strain play may be significant. Consider an original graben structure filled with rift sediment (Figure 1b) that is later homogenously deformed such that the material is deformed to a uniform strain ratio (R_s) of 2.62. A simple shear deformation ($W_m = 1$) produces a rotation of the original normal faults such that some faults change dip direction, foliation in the rift rocks dips moderately, and the basin neither thickens nor thins in the vertical dimension (Figure 1b). Conversely, a pure shear deformation ($W_m = 1$) produces horizontal shortening and vertical thickening of the basin. In this case, fabrics would be subvertical and the original normal faults are steepened (Figure 1b). General shear ($0 < W_m < 1$) is more complex and the final geometry dependent on the overall vorticity and whether the orientation of the bulk shortening direction is horizontal or vertical (Figure 1b).

Rodinia, a Proterozoic supercontinent, broke apart at the close of the Neoproterozoic (750 to 550 Ma), producing a series of ocean basins that reordered the global geography and set the stage for later Phanerozoic tectonics. The Paleozoic Appalachian orogen is built upon a foundation of structures formed during rifting along the southeastern margin of Rodinia (Figure 2). In the central Appalachians, the contact between the Mesoproterozoic basement complex and the overlying Neoproterozoic rift to Early Paleozoic passive margin sequence forms a profound boundary that provides evidence as to the nature of rifting along Rodinia's Laurentian margin. Understanding the geometry of Neoproterozoic rifting and the formation of the Iapetus Ocean is a complex task, requiring restoration of Paleozoic contractional structures and the associated penetrative strain to their pre-Appalachian configuration. A number of models have been proposed for the geometry of the Laurentia margin at the opening of the Iapetus Ocean, but these models are regional in scope and pay little attention to the significance of Paleozoic contractional deformation (Rankin 1975; Thomas, 1977; 1991; 2006)

The primary motivation for this study is to decipher the geometry and kinematics of Proterozoic rocks and later structures in the central Virginia Blue Ridge (Figure 2) that may have originally developed in the Neoproterozoic during the rifting and breakup of Rodinia. At Sugar Hollow, 15km northwest of Charlottesville, Virginia, evidence for this disassembly is exposed in a 10km^2 Iapetan rift basin. Traditional unfolding and fault restoration of the basin in Midland Valley's *Move* software was paired with secondary restoration of quantified ductile strain in Adobe *Illustrator*, yielding a fully restored 3D model of the Sugar Hollow area's structural geometry immediately following Iapetan rifting. This process highlights the importance of quantifying penetrative ductile deformation during any restoration process, as intermediate results depending solely on unfolding and unfaulting of the basin accounted for only ~50% of the total shortening.

Geologic Setting

The central and southern Appalachian Blue Ridge province forms a large basement massif at the hinterland edge of the foreland fold-and-thrust belt. In north-central Virginia, the Blue Ridge is an anticlinorium comprised of Mesoproterozoic basement granitoids overlain by Neoproterozoic to Early Paleozoic cover rocks on the flanks and in fault-bounded inliers; collectively this package forms an imbricated set of thrust sheets that were emplaced over lower Paleozoic strata during contractional deformation in the late Paleozoic (Mitra, 1979; Evans, 1989).

The Mesoproterozoic basement complex includes a suite of granitoids and granitoid gneisses formed during the long-lived Grenvillian orogen between 1.0 and 1.2 Ga (Bartholomew and Lewis, 1984; Tollo and others, 2004). In the eastern Blue Ridge a distinctive suite of 680 to 730 Ma granitoid plutons intrudes the Mesoproterozoic rocks (Tollo and Aleinikoff, 1996; Tollo and others, 2004). Proterozoic granitoids are unconformably overlain by sequence of Neoproterozoic to early Cambrian metasedimentary and metavolcanic rocks that record sedimentation and magmatism associated with Laurentian rifting and the opening of the Iapetus Ocean (Rankin, 1975; Wehr and Glover, 1985; Bailey and others, 2007a). Neoproterozoic rifting in the Virginia Blue Ridge occurred during two temporally distinct episodes: an early unsuccessful event between 680 and 765 Ma (Aleinikoff and others, 1995; Tollo and others, 2004) and a second event between 550 and 575 Ma that led to the opening of the Iapetus Ocean and the development of a southeast-facing passive margin (Badger and Sinha, 1988; Aleinikoff and others, 1995; Simpson and Eriksson, 1989).

In the western Blue Ridge a late Neoproterozoic cover sequence of metasedimentary and metavolcanic rocks unconformably overlies the basement complex, this includes the Swift Run Formation, Catoctin Formation, and Chilhowee Group (Fig. 3). The Swift Run Formation is a heterogeneous clastic unit of highly variable thickness (absent to ~300 m) that crops out below metabasalts of the Catoctin Formation and in outliers surrounded by basement (Figs. 3 & 4) (Gathright, 1977; Gattuso and others, 2009). At a number of locations clastic rocks are interlayered with metabasaltic greenstone, geometry consistent with a coeval relationship between the Swift Run Formation and the lower Catoctin Formation (King, 1950; Gattuso and others, 2009). The Catoctin Formation is dominated by metabasaltic greenstone that were extruded over a large region (>4000 km^2) and generated from mantle-derived tholeiitic magmas (Badger and Sinha, 2004). In the western Blue Ridge the Catoctin Formation is 400 to 900 meters thick and thins towards the west and southwest. Metadiabase dikes of similar composition to Catoctin metabasalts intrude the basement complex (as well as older Neoproterozoic rocks) and are likely feeder dikes for the overlying Catoctin lava flows. Geochronologic data indicates that Catoctin volcanism occurred between 570 and 550 Ma (Badger and Sinha, 1988; Aleinikoff and others, 1995). Paleomagnetic data from the Catoctin Formation are complex, but broadly compatible with a high southerly latitude (60˚ S) for the Virginia Blue Ridge during extrusion (Meert and others, 1994). The siliciclastic Chilhowee Group includes the

Weverton, Harpers, and Antietam formations and ranges from 500 to 900 meters in total thickness (Fig. 3). Collectively, the Chilhowee Group records a fluvial to shallow-marine transgressive sequence (2nd-supersequence) (Simpson and Eriksson, 1990; Read and Eriksson, *in press*). Trace fossils and sparse body fossil in the Chilhowee Group bracket the age of the Chilhowee Group between the earliest Cambrian and early Middle Cambrian (<545 Ma to ~515 Ma).

The Swift Run Formation was first described on the western limb of the Blue Ridge anticlinorium from central to northern Virginia by Jonas and Stose (1939), who first established the correct age relations between the Blue Ridge basement and cover sequence. Rock types in the Swift Run Formation include quartz-sericite phyllite, conglomerate, arkosic sandstone, arkosic quartzite, graywacke, slate, tuff or rhyolite tuff, minor greenstone, and some marble to the north (Stose and Stose, 1946; Bloomer, 1950; King, 1950; Vernon, 1952; Gathright and others, 1977). King (1949) recognized the provenance of the Swift Run Formation's coarse-grained lithologies as being the granitoid basement. Sedimentary rocks of the Swift Run and Catoctin formations were deposited via alluvial, fluvial, and lacustrine processes (Dilliard and others, 1999). The Swift Run Formation shows substantial variation in thickness at local scales (Jonas and Stose, 1939; King, 1950, Werner, 1966; Gathright, 1976). Reed (1955) attributed the highly variable thickness to original topography, where the thickest deposits represent Neoproterozoic valleys containing coarse basal sediments and very thin areas were original highlands.

In central Virginia the main outcrop belt of the Swift Run Formation occurs at the base of the Catoctin Formation along the western limb of the Blue Ridge anticlinorium. Five outliers of Swift Run (± Catoctin lithologies) occur to the east and are surrounded by Mesoproterozoic basement (Fig. 4). From north to south these outliers include the Brokenback Mtn., Free Union, Pigeontop, Lickinghole Creek, Little Yellow Mountain, and Stony Creeks outliers (Fig. 4). Nelson (1962) and Allen (1963) first recognized some Swift Run and Catoctin outliers. Nelson (1962) proposed that the basement and cover sequence formed a large dome complex to the northeast of Sugar Hollow and portrayed small outliers as synclinal infolds (Fig. 4). Gathright and others (1977) recognized mylonitic basement rocks in the Rockfish Valley high-strain zone and interpreted the Stony Creek outlier (Fig. 4) as a tectonic window that exposes cover rocks beneath a low-angle basement thrust sheet. Most recently, Forte and others (2005), Olney and others (2007), Gattuso and others, (2009) identified faults and high-strain zone along the margins of some inliers and suggested these structures may be reactivated Neoproterozoic normal faults

Regional deformation and metamorphism in the western Blue Ridge occurred just prior to and during the early Alleghanian Orogeny (330-275 Ma) (Bailey and others, 2006; 2007b). Blue Ridge rocks reached the greenschist facies, with the Mesoproterozoic basement rocks reaching a maximum of 500° C in the east, Neoproterozoic and Cambrian cover rocks in the eastern Blue Ridge geologic province reaching at most 400° C, and those to the west reaching 350° C maximum (Bailey and others, 2007b). $^{40}Ar/^{39}Ar$ cooling ages for central Virginia Blue Ridge rocks range from about 355 to 310 Ma from dating of white mica (Wooton and others, 2005; Bailey and others, 2007b). This deformation event produced the prominent southeast-dipping foliation in all Blue Ridge rock units (except the Mesozoic dikes). A network of anastomosing high-strain zones formed penetrative fabrics that developed when grains were stretched, rotated, and recrystallized (Bailey and Simpson, 1993) (Figure 3). Kinematic analysis of the mylonites indicates top-to-the-NW shear (Bailey and Simpson, 1993). Estimates of regional northwest to southeast crustal shortening range from 50 to 70 percent (Bailey, 1994). The modern anticlinorium developed late in the orogeny, as the entire Blue Ridge sequence was translated up a tectonic ramp that thrusted east to west over Cambrian and Ordovician sedimentary rocks (Evans, 1989). More recent events include Mesozoic rifting that formed continental fault-bounded basins throughout, creating the Atlantic Ocean. Although similar to the Neoproterozoic rift sequence in the half-graben structure, the Mesozoic conglomerate rocks differ greatly from the rock type of the Swift Run and Catoctin formations. Mesozoic rift magmatism produced the extrusion of diabase dikes exposed throughout the Blue Ridge and Piedmont regions. Apatite fission-track dating reveals that rocks currently exposed in the Blue Ridge cooled below 60° C during the Jurassic and Cretaceous, indicating that they have been near the surface for more than 100 million years (Naeser and others, 1999).

Methodology

The bedrock geology of the Sugar Hollow area was mapped between 2006 and 2010 (Figure 5). Completed 7.5′ quadrangles of the area have recently been submitted for publication (Lamoreaux and others, 2009; Lederer and others, 2009). Geological mapping was accomplished by collecting over 500 structure measurement and rock type information stations referenced using handheld GPS. Tectonic and stratigraphic contacts were drawn on a topographic basement from field observations, rock type information, and digitized structural data using *Adobe Illustrator*.

The contacts of the White Hall high-strain zone were drawn on the geologic map of Sugar Hollow (Figure 5) by collecting qualitative strain data. Each measurement or rock type station was assigned a deformation value between 0 and 5, each corresponding to a different intensity of ductile strain. 0, representing the lowest strain intensity, indicates that a rock was massive (foliation absent). 5, the highest level of strain, indicates that a rock was mylonitic to ultramylonitic. Referenced strain information was then used to draw the high-strain zone contacts, which were generally placed between mylonitic and non-mylonitic rocks (Figure 11).

Seven oriented samples were collected during the field mapping process for petrographic, strain, and vorticity analysis. Sections were cut in three mutually perpendicular orientations (foliation normal and lineation parallel, foliation parallel and lineation parallel, and foliation normal and lineation normal). These sections were analyzed under a petrographic microscope for petrological, microstructural, and strain data.

Rocks in Sugar Hollow were restored using a combination of 3D model restoration in *Move* and strain and vorticity analysis in thin-section. The combination of these two methods measured shortening in Sugar Hollow during the Paleozoic by revealing the original depositional geometry of the Sugar Hollow graben complex.

Five NW-SE oriented cross sections (M, L, X, D, and T; Figure 6) were drawn from map pattern in *Adobe Illustrator* using downplunge-projection of contacts based on bedding data within the Swift Run Formation. These cross sections were checked for consistency in *Move* by examining the intersections of each section's contacts in 3D. Sections were exported as jpeg images for use within Midland Valley's *Move* software suite. Images were cropped to a known elevation and length in *Photoshop* so that they could be referenced to UTM NAD 83 Zone 19N coordinates. For each cross section, the topographic profile was traced as a polyline from the imported image to create a referenced topographic surface. Below this surface, rock polygons were created by tracing stratigraphic and tectonic contacts interpreted from the map pattern. Tectonic contacts were given a separate color scheme and attributed as faults within the software for easy identification in the 3D model. Once the cross sections were digitized, they were inserted into 3D *Move* to form a 3D array. Tectonic and stratigraphic contacts were interpolated across data voids using 3D *Move*'s "make surface from line" function, which uses an interpolation algorithm to link two or more contacts in a cross section by a single gridded surface.

An 1/9 arc-second (10 m) National Elevation Dataset digital elevation model (DEM) was clipped to the study area in *ArcGIS* and imported to *Move* for use in the model. A georeferenced image export of the geologic map of Sugar Hollow was projected onto this DEM to complete the visualization of the 3D geology of Sugar

Hollow (Figure 7). The final version of the model includes interpolated stratigraphic and tectonic contacts, present day topography, and the geologic map of bedrock at the surface. The major advantage of using *Move* to create this model was the program's capability to perform 3D restoration and to export 3D surface data as ASCII points for analysis in a variety of software platforms.

The basement-cover contact in Sugar Hollow was converted to a point cloud based on a 100 x 100 cell grid in 3D *Move* and exported as ASCII data. This data was imported into ArcMap and processed using the Kriging tool to create a raster layer describing the elevation of the contact throughout the basin. This raster was contoured and exported to an image file to create the structure contour map of the basement-cover contact (Figure 8).

3D restoration of the Sugar Hollow basin was achieved by restoring fault blocks across faults using 3D *Move*'s structural modeling functions. In addition, layers were unfolded to datum, revealing significant shortening across the basin during the Paleozoic. Throughout this processs, total displacement for each geocellular rock volume was tracked using *Move*'s tracking toolbar. This data was colormapped in the program to identify locations of maximum lateral displacement relative to the NW corner of Sugar Hollow (Figure 13). Five restored cross sections on the same NW-SE transects as the original set were exported from this model using *Move's* "draw section from line" tool. These sections were imported to *Adobe Illustrator* for the second phase of restoration, this time incorporating strain and vorticity data to account for penetrative ductile strain (Figure 14).

Strain analysis was performed at sample locations SHO1, SH02, SH03 and DL20 to capture the variation in strain intensity and to better describe strain partitioning in Sugar Hollow (Figure 12). The Rs/phi method (Onasch, 1984), which involves measuring the axial ratio and orientation of plastically-deforming clasts in lineation-parallel, foliation-normal thin sections, was applied on each of these samples. Resultant strain ellipses, which were calculated using Chew's (2003) *Excel* spreadsheet for Rs/phi analysis, were transposed onto the partially restored cross-sections that were exported from *Move* (Figure 14). These strain ellipses were restored to an originally circular geometry using *Illustrator's* shear tool, which deforms assuming simple shear. Cross-sections were redrawn to match this new geometry, revealing additional shortening across the basin. However, because general shear conditions are commonly recorded in Blue Ridge rocks (Bailey and others, 1994, Bailey and others, 2002, Bailey and others, 2003), kinematic vorticity analysis was used to assess the validity of the assumption of simple shear.

The kinematic vorticity number (Wm) for a basement mylonite from sample location DL18 was determined by plotting 153 measured rigid feldspar grains on a Rigid Grain Net (Jessup and others, 2007; Appendix 2). These measurements were made on a lineation-parallel thin section, where rigid feldspar grains were selected at random for measurement using a mechanical stage. This methodology was chosen because quartz grains were deforming plastically—rendering them unusable for Rigid Grain Net analysis. The curves on the Rigid Grain Net, which are based on the mathematics of the Porphyroclast Hyperbolic Distribution (PHD) method (Simpson an De Paor, 1997), graphically illustrate the relative contribution of pure and simple shear for a given ductile deformation. The axial ratio cutoff, which is used to determine the Wm value (kinematic vorticity number) of the rock, was defined by plotting the orientation (phi angle) and axial ratio of the rigid feldspar clasts. The Wm number was then expressed in percent simple shear and integrated into the Sugar Hollow basin restoration process.

Structural Geometry

The Swift Run Formation in Sugar Hollow crops out over 12 km^2, making it the largest body of Swift Run Formation in the western limb of the Blue Ridge anticlinorium (Figure 3). Geological mapping within the Sugar Hollow area at the 1:24,000 scale reveals eight southwest-northeast striking faults (labeled 1-8; Figure 5) within an eastward-thickening basin. Of the eight faults, only the southern third of fault 7 appears normal in map pattern. Instead, faults 1-6 and 8 place basement on Swift Run Formation or Swift Run Formation on Catoctin Formation, producing a reverse map pattern. Maximum displacement across these faults is ~ 40m. However, the structural geometry of Sugar Hollow, revealed in cross section (Figure 6), suggests that faults 1-6 and 8 may have originally accommodated crustal extension as normal faults. The dramatic eastward-thickening of the basin across these faults suggests that normal faulting created accommodation space for Swift Run Formation deposition. Given that these sediments are arkosic—suggesting proximal deposition during a tectonic event—and that reactivated normal faults are exposed, the deposition of the Swift Run formation is consistent with Iapetan Rifting at the close of the Neoproterozoic.

Rocks in Sugar Hollow were penetratively deformed at the greenschist facies during Paleozoic contractional deformation, which in some locations overprinted relict foliations in the Mesoproterozoic basement complex. The resultant foliation is tightly clustered around an average orientation of 030° 39° SE—along strike with the Blue Ridge anticlinorium (Figure 10). Therefore, penetrative deformation likely formed in response to a principal axis of strain oriented west-northwest—which is consistent with the orientation of tectonic collisions on the eastern margin of Laurentia during the Paleozoic (Figure 2). Mineral elongation lineations in the White Hall high-strain zone and eastern part of the Sugar Hollow basin consistently plunge moderately to the southeast and in most locations record a mean trend and plunge of 119° 44°, yielding a SE-directed principal stretching axis that plunges in the plane of foliation (Figure 10). Poles to bedding illustrate folding with parallel fold-hinges oriented 219° 02° (Figure 10). These folds are common throughout Sugar Hollow, and are illustrated on the Sugar Hollow cross sections (Figure 6).

To the northwest of Sugar Hollow, near Charlottesville Reservoir, the Swift Run Formation crops out in its typical ~ 20m thick section and is locally absent at an erosional window of Mesoproterozoic basement only ~100m to the north. Across fault #1, which displays an apparent thrust-geometry with displacement of ~40m, the Swift Run Formation doubles its thickness, eventually reaching a thickness of 100m under the Moorman's River, ~500m southeast of Charlottesville Reservoir. Near fault two, this thickened packet of sediment begins to show asymmetric, NW-verging folds that intensify to the southeast across Sugar Hollow. Bedding measurements (Figure 10) indicate that these folds have parallel, non-plunging fold axes oriented at 220°. The Swift Run Formation achieves its maximum thickness of ~300 m to the southeast of fault #6, under Doyle's River. The basement-cover structure contour map (Figure 8) reveals that this maximum thickness coincides with the lowest elevation on the Swift Run-basement structure contour map (Figure 8), suggesting that original depositional geometry strongly controls unit thickness. Total thickening of the Swift Run Formation across this NW-SE transect approaches 1,500%, and is likely due to a combination of original depositional geometry controlled by Iapetan rift-generated accommodation space and Paleozoic contractional deformation as evidenced by asymmetric, NW-verging folds and penetrative ductile strain.

The Swift Run Formation at Sugar Hollow is bounded to the southeast by the mylonitic White Hall high-strain zone. Numerous qualitative indicators in outcrop support this top to the northwest sense of shear (Figure 9). Simple three-point problems indicate that fault #7, at the eastern edge of the high-strain zone, dips to the southeast in the northern 2/3 of its exposure—within the White Hall high-strain-zone. However, in the southern 1/3 of the fault, the same measurement reveals that the fault dips to the northwest (Figures 5, 6, 7). Near the Pigeon Top outlier—an anomalous body of Swift Run Formation to the southeast of Buck's Elbow Mountain—this section of the fault places Swift Run and Catoctin Formations on massive basement. As a result, Fault #7 likely preserves its original orientation here, as these rocks record no ductile strain. Therefore, ductile deformation in the White Hall high-strain zone likely rotated this fault to a southeast-dipping, apparent thrust fault geometry where it was affected by the high-strain zone. Based on this evidence alone, fault #7 qualitatively restores to a northwest-dipping normal fault within an extensional graben complex.

Strain and Vorticity Analysis

Rocks in the Sugar Hollow area are penetratively strained to varying degrees, as evidenced by qualitative outcrop and thin section observations (Figures 9, 12). However, Paleozoic contractional deformation in the western limb of the Blue Ridge anticlinorium cannot be fully understood without quantifying penetrative ductile strain using strain and kinematic vorticity analysis. In the Sugar Hollow area, penetrative strain ranges from very low in the northwest near Charlottesville Reservoir to high in mylonitic rocks in the White Hall high-strain zone ~8km to the southeast (Figure 12).

In low strain samples (SH01, SH02), quartz clasts show evidence for internal subgrain development and minor grain boundary bulging recrystallization. In these sections, all large quartz grains show undulatory extinction. However, clasts from these sample locations remain angular and matrix supported with no strong preferred grain shape alignment. Feldspar grains are unstrained. Therefore, these sample locations were likely deformed at the greenschist facies (Gatusso, 2009), with temperature conditions 280 and 400 degrees Celsius. At high-strain sample locations including DL17, DL18, DL20, and SH04, percent matrix decreases relative to the low-strain samples (Figure 12). At these locations, quartz grains show core and mantle structures, indicative of subgrain rotation recrystallization at temperatures between 400 and 500 degrees Celsius. At these temperature conditions, Feldspar grains remained undeformed but took on a strong preferred alignment. At some places in Sugar Hollow, oriented samples yielded freely rotating rigid clasts within a ductily deforming matrix. Samples suitable for both strain and vorticity analysis were successfully collected at these high-strain locations.

Strain analysis was performed at sample locations SHO1, SHO2, SHO3, and DL20 using the Rs/phi method on foliation-normal, lineation-parallel thin sections. At each location, the long axis of elliptical grains was parallel to foliation. The strain ratio was determined by measuring plastically deforming quartz grains selected using a mechanical stage on a petrographic microscope. Quartz grains were selected because they were the only mineral behaving ductily in the greenschist facies during ductile deformation. Therefore, these grains provide the best minimum estimate of strain. Strain ratios were determined using the spreadsheet presented by Chew (2003) for finite strain analysis under the Rs/phi method. At SH01, 60 ductily deforming quartz clasts were measured, producing a minimum ductile strain estimate of 1.3:1. At SHO2, 32 grain measurements produced a strain ratio of 1.7:1. At SH03, 60 grain measurements produced a strain ratio of 2.0:1. Finally, at DL20, in the White Hall high-strain zone, 48 measurements produced a strain ratio of 3.2:1 (Appendix 1). These estimates are considered minimum estimates, as the matrix-supported Swift Run Formation likely partitioned strain preferentially to its ductily deforming matrix (see photomicrographs, Figure 12).

Strain data quantitatively supports outcrop and thin-section evidence for strain gradient across the Sugar Hollow area. This strain gradient, even outside the boundaries of the high-strain zone, is likely influenced by the anastomosing White

Hall high-strain zone, which composes a small part of a regional high-strain zone along-strike of the Blue Ridge anticlinorium. This high-strain zone was mapped based on a qualitative ductile deformation scale (Figure 11). If this pattern of strain partitioning in the Sugar Hollow area is common throughout the region, we may expect that high-strain zones are the predominate method of strain accommodation in the Blue Ridge anticlinorium. It is important to understand the geometry of deformation in these zones, both for the purpose of quantitatively restoring the Sugar Hollow basin to its pre-Paleozoic state and for understanding Paleozoic contractional deformation across the Blue Ridge anticlinorium as a whole.

Qualitative field observations indicate that rocks in Sugar Hollow experienced top-to-the-northwest shearing (Figure 9c,h). However, to fully describe shearing with regard to shape change of rocks during deformation, kinematic vorticity analysis was applied. This method, which produces a dimensionless value of finite stretching relative to rotation (the kinematic vorticity number, Wk), yields results that can profoundly influence the character of restorations that account for penetrative strain (Figure 1b). The oriented sample most suited for kinematic vorticity analysis was DL18 (Figure 12a), which is located in the White Hall high-strain zone just east of Sugar Hollow. The axial ratio and Φ angles for 154 feldspar grains were measured and plotted on a Rigid Grain Net (Jessup and others, 2007), which produced a clearly defined cutoff corresponding to a Wk value between 0.70 and 0.75 (Appendix 2). This cutoff corresponds to 50% pure and 50% simple shear, placing the shear zone firmly within general shear conditions (Forte & Bailey, 2007). Consequently, we can expect that this style of ductile deformation would have resulted in both vertical and lateral shortening of rocks in Sugar Hollow during northwest-directed contractional deformation in the Paleozoic. Considering kinematic vorticity and strain analysis in tandem enables quantitative restoration of the Sugar Hollow basin

3D Restoration of the Sugar Hollow Basin

At Sugar Hollow, Iapetan-rift structures were reactivated during the Paleozoic to produce a complicated, partially overprinted structure. In order to better understand this original extensional geometry and regional Paleozoic contractional deformation during the assembly of Laurentia, rocks in Sugar Hollow were restored to their post-Iapetan rift state using *Move*, strain analysis, and kinematic vorticity analysis.

The 3D model of the present-day Sugar Hollow area (Figure 7), created in *Move*, revealed minimum shortening estimates of ~12% due to unfolding of the basement-cover contact and fault-block restoration, in which the Swift Run-Catoctin Formation contact was restored to a common elevation datum (Figure 13). However, this retrodeformation could not have accounted for the accumulation of ductile strain across the basin, as restorations were based only on cross-sections interpreted from map pattern. Accordingly, strain and vorticity data were integrated into this process to produce a more accurate restored model.

Oriented strain ellipses, determined using strain analysis, were distributed across partially restored cross sections from Sugar Hollow in four specific domains (Figure 14). These domains were chosen based on proximity to strain analysis sample location (Figure 12) and guided by qualitative strain indicators in outcrop

(Figure 11). These oriented strain ellipses were restored to an undeformed state in *Illustrator* using the simple shear tool, revealing additional shortening due to Paleozoic contractional deformation. Restored ellipses were used to construct new, fully deformed cross sections (Figure 14). Sections reveal total minimum shortening estimates of ~25% across Sugar Hollow, which is equivalent to ~2km of northwest-oriented displacement for a rock at the eastern extent of Sugar Hollow during the Paleozoic.

Kinematic vorticity analysis was used to assess the validity of the assumption of general shear during the restoration process. The results of this analysis, reported above in the Strain and Vorticity analysis section, indicate that our assumption is incorrect, as the White Hall high-strain zone experienced general shear. Therefore, the same restoration process, when carried out under general shear conditions, would have produced a different initial basin geometry (Figure 1b; 1d). However, this assumption provides a good approximation of bulk ductile deformation's affect on the structural geometry of Sugar Hollow—specifically the rotation of faults within the White Hall high-strain zone during shearing. Using these results, a 3D visualization of the Iapetan-rift geometry of the Sugar Hollow area was created in *Move*, visually articulating the Iapetan-rift graben complex (Figure 15).

Discussion

The Swift Run Formation at Sugar Hollow crops out in its largest known exposure. Its arkosic sediments, which vary from phyllite to conglomerate within the basin, record the initial terrestrial phase of rift sedimentation that resulted from the collapse of the Proterozoic supercontinent Rodinia. Upon detailed geological investigation, Sugar Hollow also contains a well-preserved structural geometry that restores to a northeast-striking graben complex. Thus, Sugar Hollow provides sedimentological and structural evidence that the Swift Run Formation represents a major tectonic division on the eastern margin of Laurentia. At this exposure, eight originally-normal faults record supercontinent collapse, a process marked by the opening of new ocean basins that completely reorder global geometry. Eventually, these disassembled land masses collide again, as evidenced in Sugar Hollow by Palezoic contractional deformation. Although very small from a plate tectonics perspective, Sugar Hollow preserves both rifting and contractional deformation, making it a unique test site for restoration techniques that allow visualization of a piece of the earth's crust throughout geologic history.

When continental land masses collide, tectonic forces initiate faulting and folding to accommodate crustal shortening. At Sugar Hollow, these processes are evidenced by mapped faults and folds that shorten rocks parallel to the direction of principal strain. In addition to these processes, penetrative ductile strain is accumulated in rocks at depth. The Sugar Hollow area records both faulting, folding, and penetrative strain, revealing patterns in strain accommodation. Interestingly, the White Hall high-strain zone, which experienced ~ 1 kilometer of displacement during northwest-directed shearing in the Paleozoic (Bailey and others, 1994), is primarily exposed in the competent rocks of the Blue Ridge basement complex. Ductile deformation across the tectonically-weaker rift sediments in Sugar Hollow seems to be controlled by proximity to this zone. Strain was also partitioned to brittle processes within the Sugar Hollow basin itself. Basement buttressing occurred when Sugar Hollow's lithologically weak fault zones were reactivated. During this event, the stronger, granitic basement rock forced folding of the weaker, rift generated sediments of the Swift Run Formation, dramatically changing the structural geometry of the Sugar Hollow area (Figure 1a). In this manner, tectonic processes, which repeatedly divide and reassemble supercontinents, come full-circle.

Strain and vorticity analysis are widely applicable techniques that can be used to refine basic tectonic reconstructions, improving their accuracy. However, most restorations do not incorporate these data. At Sugar Hollow, simple unfolding and fault restoration reconstructions only account for ~ 50% of the total shortening across the basin. To fully understand the changes in structural geometry that occur during a cycle of rifting and reassembly, strain and vorticity must be taken into account. This study identified a graben complex based on the restoration of penetrative strain, which rotated faults within the domains of high-strain to an apparently southeast-dipping geometry. Without considering penetrative strain, the basin would have restored to a half-graben complex.

Vorticity analysis further refines the penetrative strain restoration process by measuring shape change during contractional deformation. Figure 1b illustrates the different possibilities for basin restoration under different shear conditions. In this study, the Sugar Hollow basin was initially restored assuming simple shear, which isolates shortening to one horizontal direction. During this restoration process, ~25% shortening due to Paleozoic contractional deformation was measured. However, measurement of the kinematic vorticity number (Wm) in the White Hall high-strain zone indicates that this assumption is invalid. To improve our Sugar Hollow restoration model, the geometric possibilities of general shear must be fully explored. If the measured Wm value of 0.75, which corresponds to 50% simple and 50% pure shear (Forte & Bailey, 2007), was applied across the basin assuming horizontal shortening, we would produce a final geometry similar to that exposed today (Figure 1b). However, a similar but distinct geometry could also have been produced assuming vertical shortening. The restored geometry of the basin would be further complicated if shape change was modulated for deformation intensity, which grades from very low to mylonitic across the study area.

This study comprehensively restored the Sugar Hollow Iapetan Rift basin to its pre-Paleozoic geometry using a combination of traditional restoration techniques, strain analysis, and vorticity analysis. During this process, the structural geometry of the study area was for different stages in its geologic history. Kinematic vorticity analysis leaves unanswered questions, as the type of shearing was shown to profoundly affect restored structural geometry in Sugar Hollow. Importantly, general shear conditions produce dramatically different restored geometries than those of the commonly assumed simple shear restoration model. Therefore, kinematic vorticity analysis provides valuable information for the restoration process of any geological feature that has experienced penetrative strain.

Conclusions

The Sugar Hollow basin, in the western limb of the Blue Ridge anticlinorium, preserves Iapetan rift structures that were later modified by Paleozoic contractional deformation. These structures—which include 8 originally normal faults in an eastward-thickening graben complex—accommodated crustal shortening by fault reactivation and buttressing within this weak zone of faulted rift sediments. Complete restoration of the basin to its pre-Paleozoic state reveals the importance of strain partitioning to high-strain zones in the Blue Ridge anticlinorium, such as the White Hall high-strain zone, that controlled the intensity of ductile deformation across the study area.

The Sugar Hollow basin was mapped at the 1:24,000 scale, displaying in detail the largest and best preserved body of Swift Run Formation in the Blue Ridge. The Mesoproterozoic basement, Swift Run Formation, and overlying units are penetratively foliated with the average orientation of ~030° 40° SE. In addition, the rocks were folded during the Paleozoic, with parallel, non-plunging fold hinges trending 220. Finally, the principal stretching axis was determined to dip to the southeast in the plane of foliation. Our proposed Iapetan rift model best explains this anomalous body of metasedimentary rocks, which are much thicker and aerially extensive than the typical Swift Run Formation section.

Quantitative investigation of penetrative strain revealed a pronounced strain gradient across the Sugar Hollow study area. Minimum estimates of ductile strain were greatest in the White Hall high-strain zone, where the strain ratio was measured at 3.2:1 using the Rs/phi method (Onasch,1984). However, the same measurements—applied across the basin—steadily decreased in value to the northwest, where minimum strain estimates were only 1.2:1. Therefore, the White Hall High-strain zone, which bounds the basin to the southeast (Figure 4), likely controls ductile strain intensity across the basin. Kinematic vorticity analysis using the Rigid Grain Net (Jessup and others, 2007) of rocks within this high-strain zone indicates general shear conditions.

The Sugar Hollow area was restored to its Neoproterozoic graben geometry, yielding minimum shortening of materials in Sugar Hollow of ~25% during the Paleozoic. If penetrative strain was not quantified and integrated into this model, total shortening estimates would have been ~12%. This finding illustrates that at Sugar Hollow, and likely at many other locations affected by contractional deformation during major orogenic events, penetrative strain can produce at least as much shortening as brittle deformation can. Additionally, penetrative deformation, depending on shear geometry as measured by kinematic vorticity analysis, can produce drastically different restored geometries (Figure 1). Therefore, wherever possible, penetrative strain should be taken into account when retro-deforming rock bodies and structures.

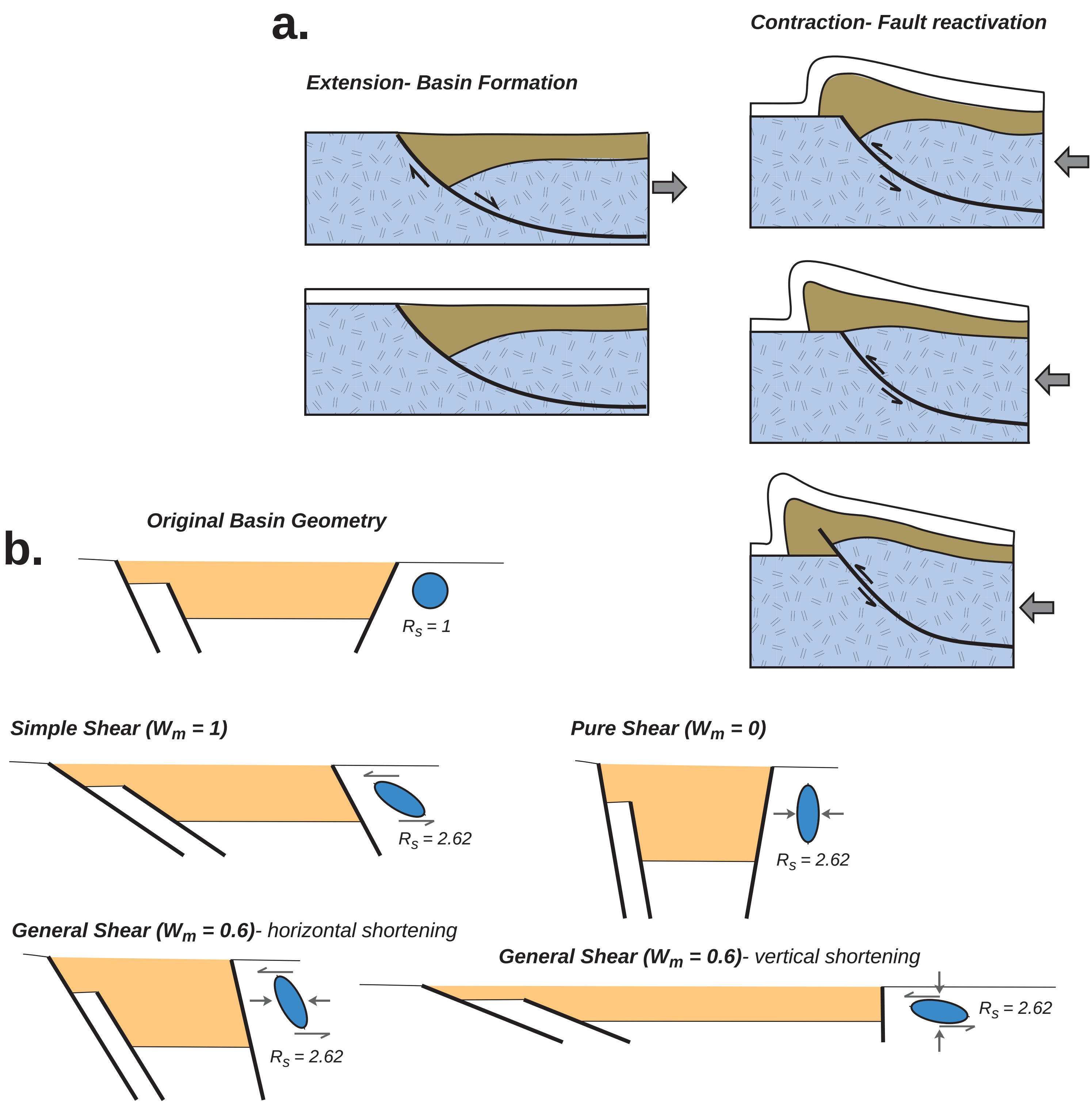


Figure 1 - The tectonics of basin inversion. **a.** Tectonic inversion of normal fault in a half-graben. At left, the original packet of rift-related sediment is shown in-filling accomodation space created by initial slip along the normal fault. At right, the same basin is shown, this time with the fault reactivated as a thrust fault. Shortening is accommodated by folding the weaker sedimentary layers in a fault-bend fold above the fault, which is eventually reactivated past the null point. **b.** An original graben complex that is subjected to penetrative strain of varying geometries between two end members-pure and simple shear. Note that the type of shearing has drastic effects on the apparent geometry of faults across the basin.

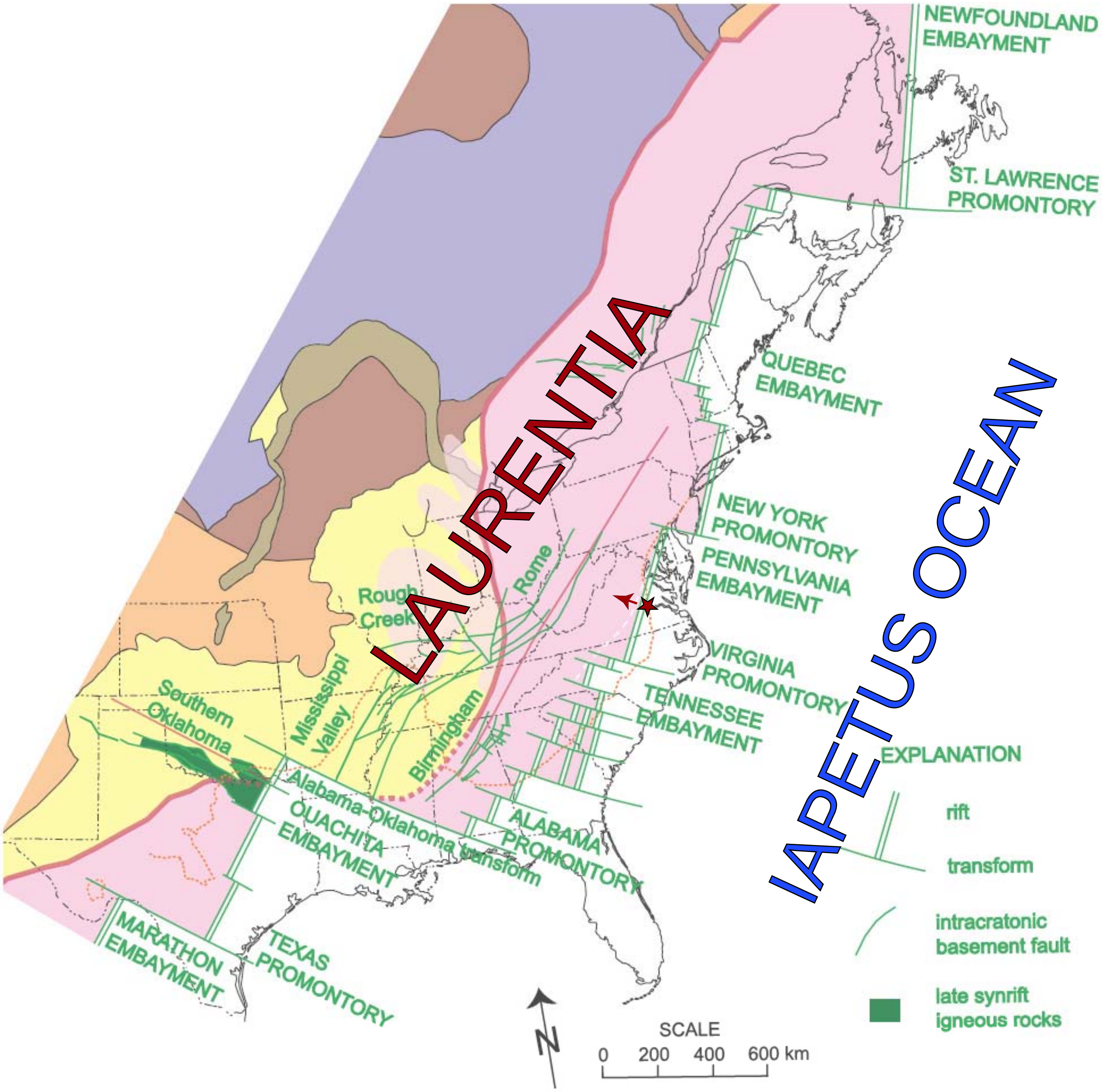


Figure 2 - Tectonic map of Iapetan Rifting at the close of the Neoproterozoic (540 Ma). This study identified new evidence of Iapetan Rifting in the Virginia Blue Ridge-marked by the red star, significantly inland from the previously mapped extent of rift structures on the eastern margin of Laurentia. Modified from Thomas (2006).

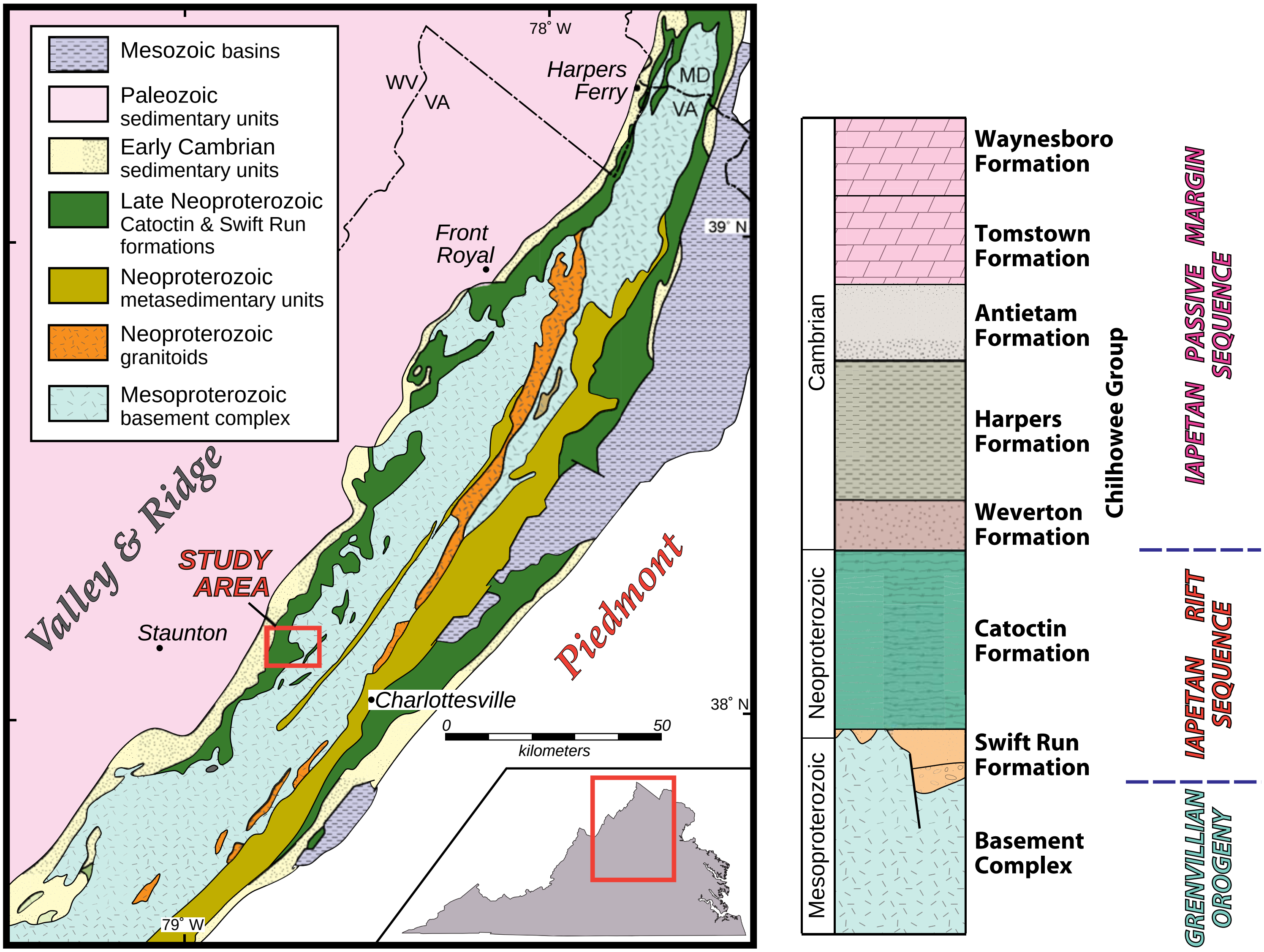


Figure 3 - Stratigraphy and geology of the Blue Ridge anticlinorium, north-central Virginia. The Sugar Hollow study area is located in the western limb of the Blue Ridge anticlinorium, between the Mesoproterozoic basement complex and the Neoproterozoic Catoctin Formation. The geology of the Blue Ridge anticlinorium records a classic "rift-to-drift" sequence of rock units, beginning with the rift sediments of the Swift Run formation, progressing to the extrusion of the volcanic rocks of the Catoctin Formation, and ending with the deposition of the Chilhowee Group, which records sea level transgression immediately following rifting. For a detalied description of rock types in the Sugar Hollow area, see Figure 5.

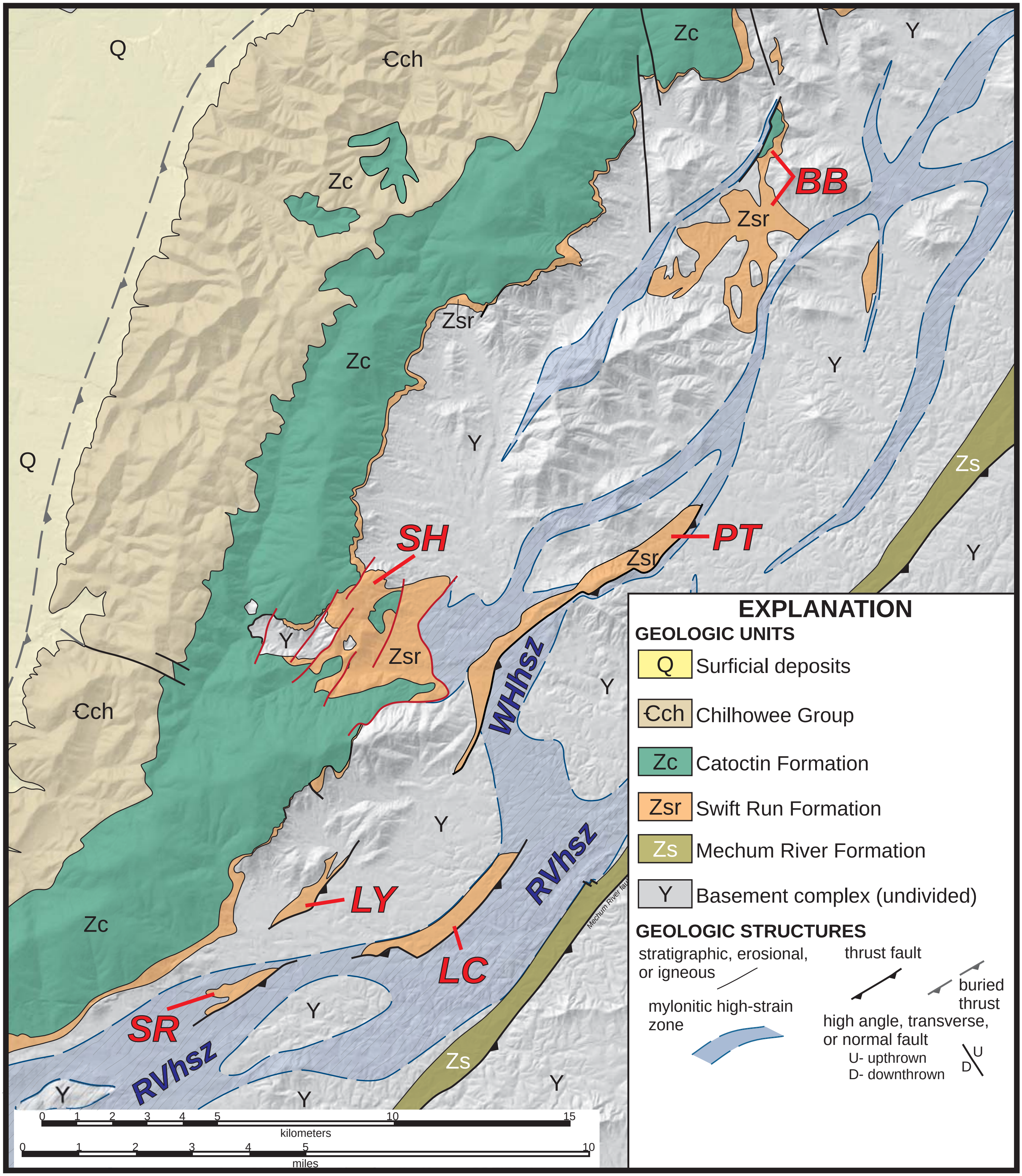


Figure 4 - Geologic map of the southern Shenandoah National Park study area, in the western limb of the Blue Ridge anticlinorium. The Swift Run Formation (SRF) is exposed to the north and south of Sugar Hollow in its typical <20m thickness. At Sugar Hollow (SH), SRF is anomalously thick and crops out in four "outliers" from the main belt - Stony Run (SR), Lickinghole Creek (LC), Little Yellow Mountain (LY), and Pigeon Top (PT). The faults in Sugar Hollow, highlighted in red, are preserved Iapetan rift structures that were partially reactivated in the Paleozoic. Anastomosing exposures of the Rockfish Valley (RVhsz) and White Hall high strain zones (WHhsz) bound SRF exposure to the east.

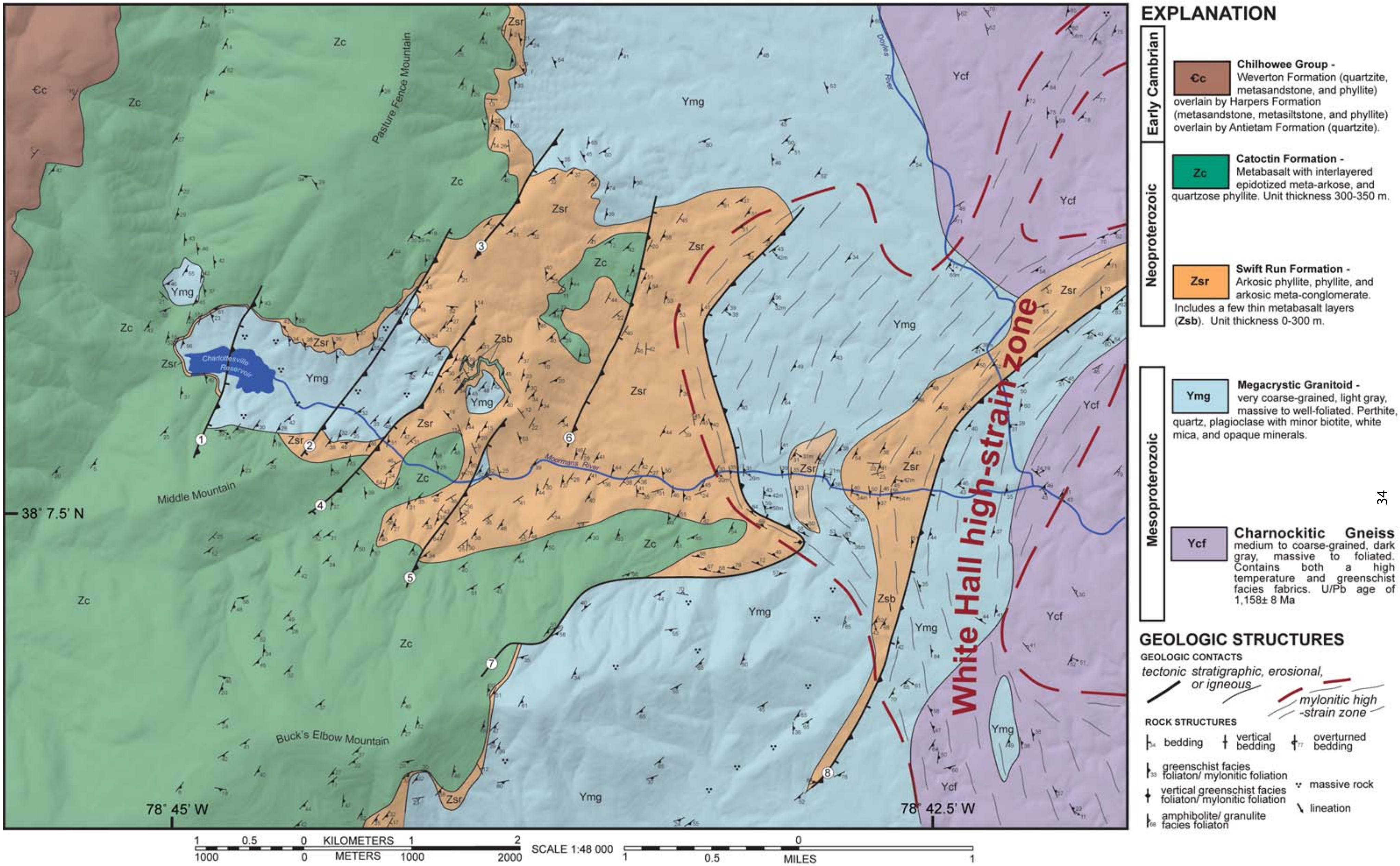


Figure 5 - Geologic map of the Sugar Hollow study area.

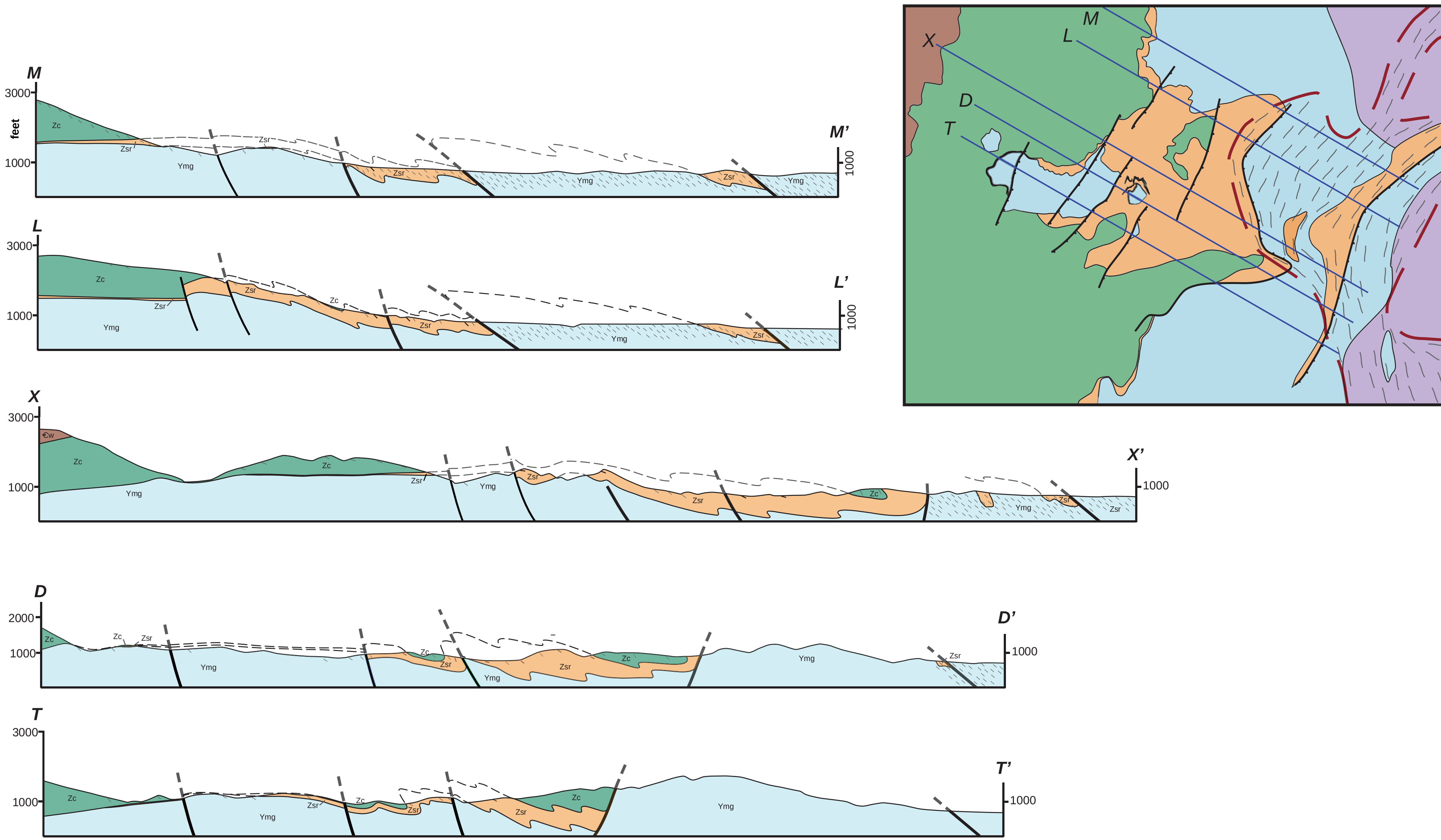


Figure 6 - Cross sections (1:48,000; no vertical exaggeration) of the Sugar Hollow area. Dashed lines represent interpreted rock contacts above the current day topographic profile. See figure 5 for a detailed description of rock units. Cross sections, which were interpreted from map pattern using bedding and rock type data, were the principal component used in the construction of the 3D model of Sugar Hollow (figure 7). Inset map shows cross section locations.

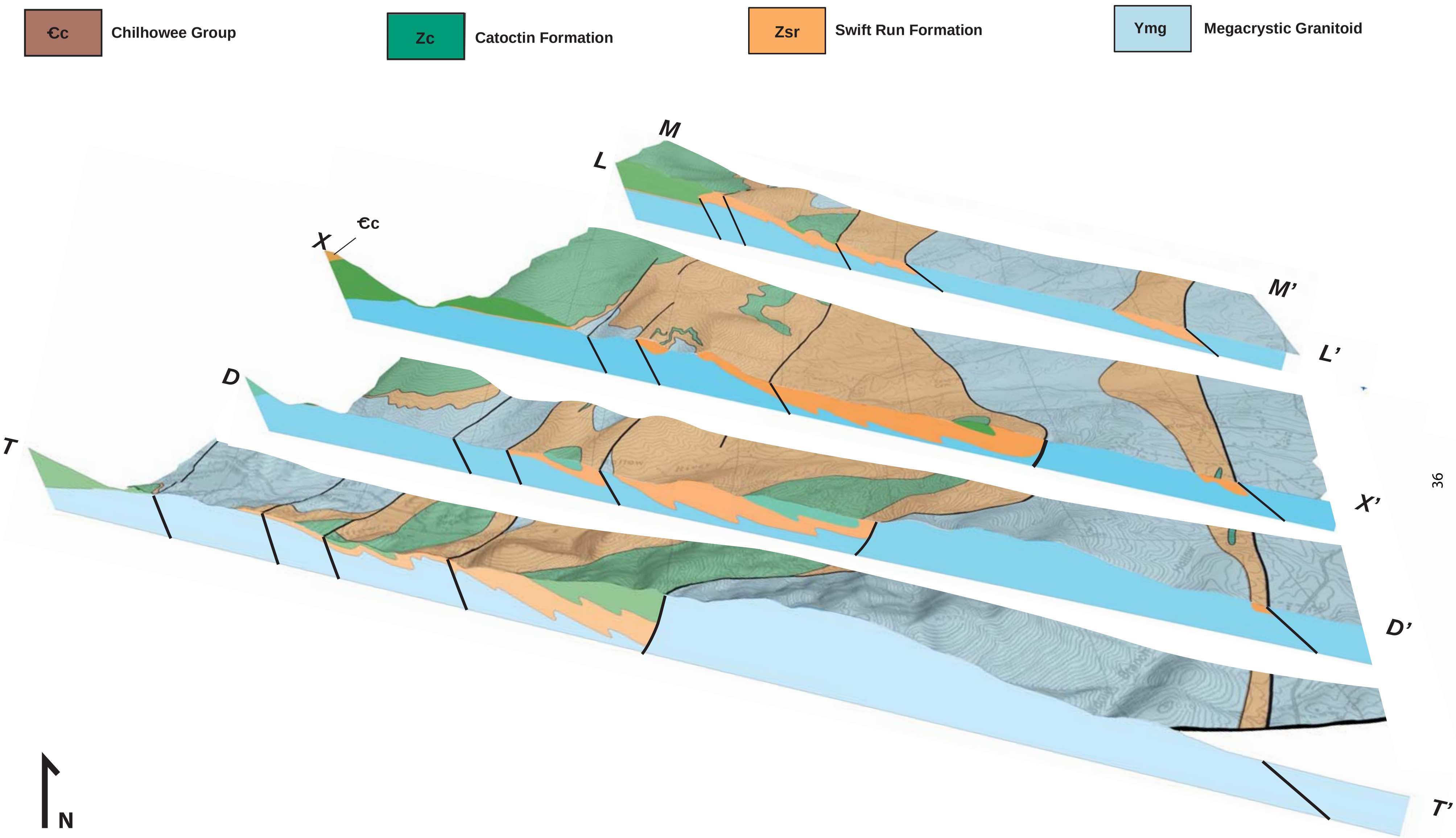


Figure 7 - 3D block diagram of the geology of Sugar Hollow. View is oblique to the north. Cross section labels refer to the sections from figure 6, which were used to create this figure in Midland Valley's *Move* software suite. The geologic map of Sugar Hollow (figure 5) was projected onto a 10m digital elevation model (DEM), shown here paired with topographic contours.

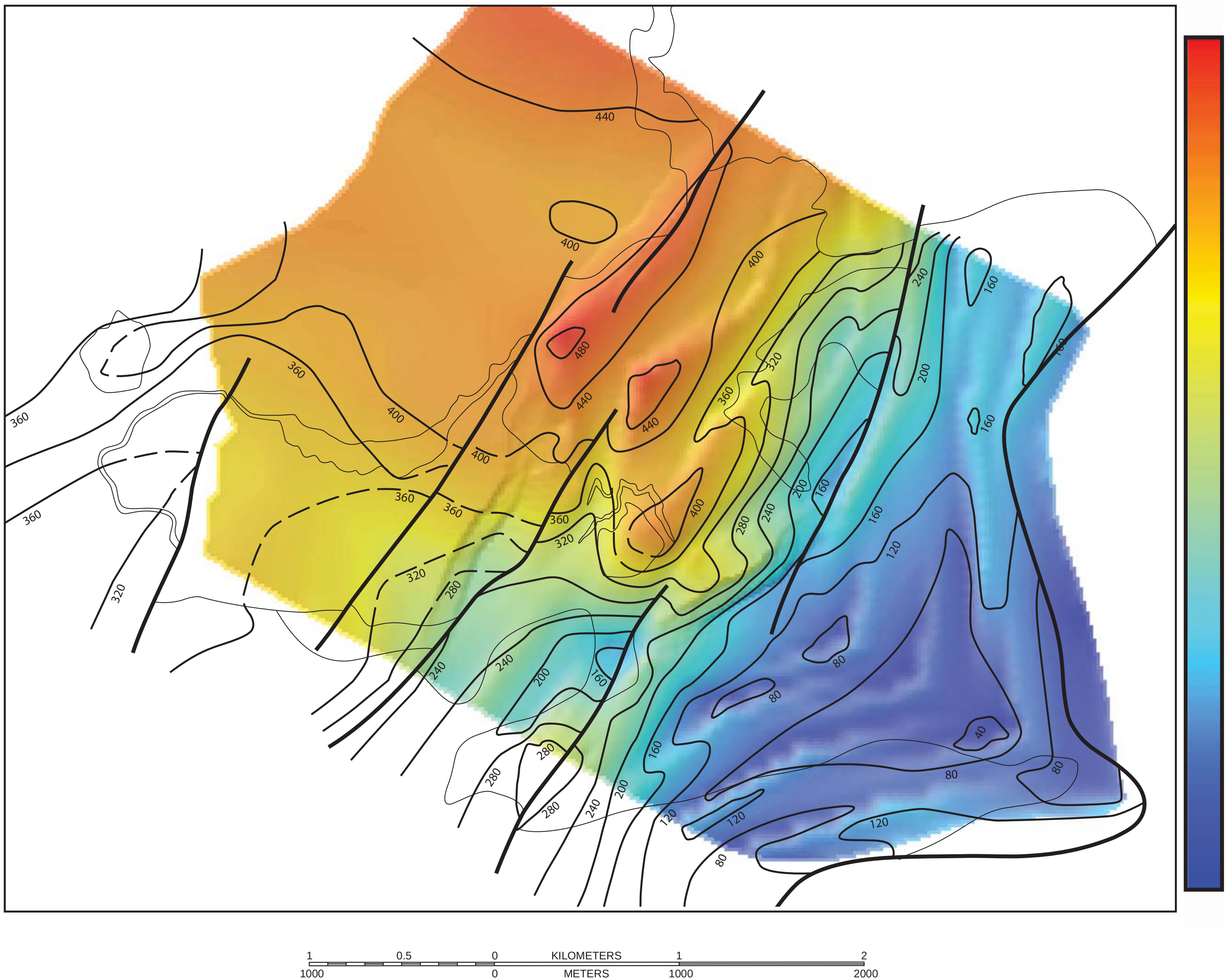


Figure 8 - Structure contour map of the basement-cover contact at Sugar Hollow. Faults are thick black lines and contoured elevations of the contact are labeled with meters above sea level (40 meter contour interval). Geologic contacts at the surface at thin grey lines. A digital elevation model of this surface was created in *Move* and *ArcMAP*. Elevation of any point on this surface is given by the color ramp at right.

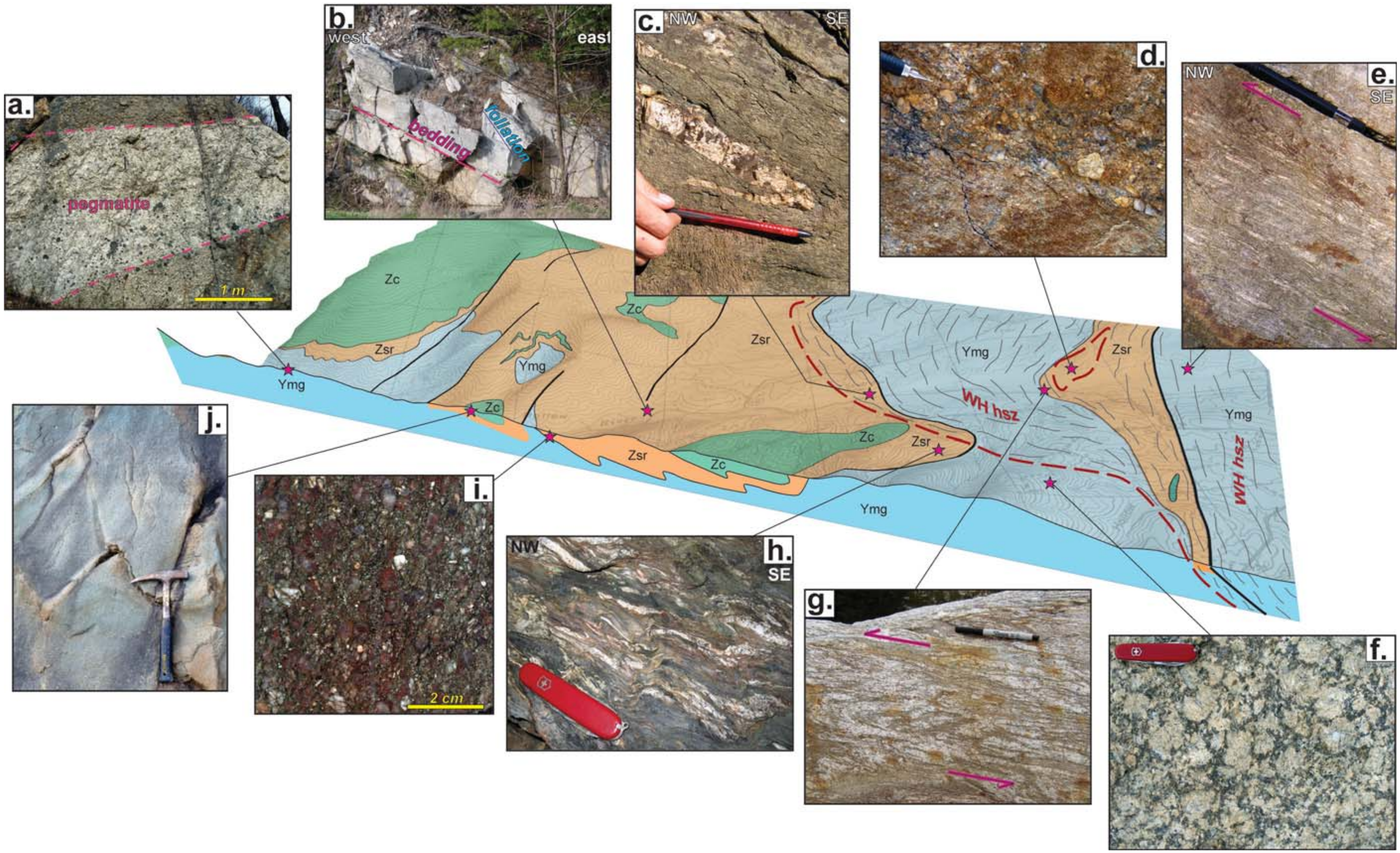


Figure 9 - **a.** Massive to weakly deformed megacrystic granite cut by 1.5 m thick pegmatite dike/sill (note pen for scale). **b.** Thickly bedded meta-arkose of the Swift Run Formation, bedding is upright and dips moderately to the southeast. **c.** Folded K-feldspar and quartz vein in arkosic mylonite from the White Hall high-strain zone. Fold is axial planar to penetrative foliation. **d.** Weakly deformed pebbly meta-arkose from the Pigeontop outlier. **e.** Mylonite derived from basement protolith from the White Hall high-strain zone. **f.** Massive megacrystic granite. **g.** Asymmetric folds developed in arkosic mylonite with numerous K-feldspar and quartz veins, top-to-the northwest shear sense. **h.** Asymmetric folds in quartz veins and Swift Run Formation phyllite. **i.** Granule meta-arkose/conglomerate of the Swift Run Formation with rubified quartz and feldspar clasts. **j.** Greenstone of the Catoctin Formation.

Structural Elements

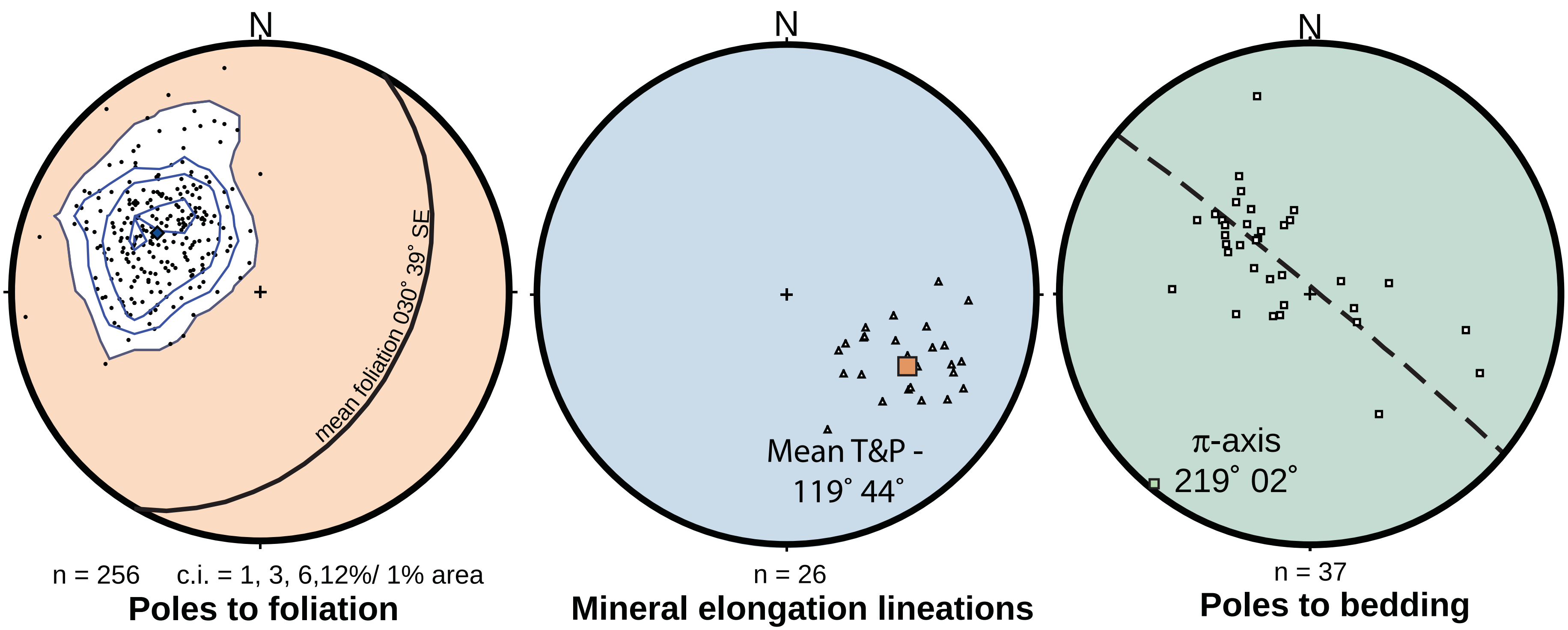


Figure 10 - Foliations in Sugar Hollow consistently strike NE/SW and dip ~40° to the SE. Mineral elongation lineations occur in the foliation and consistently plunge down dip to the SE. Poles to bedding plot along a great circle indicative of gently to non-plunging asymmetric folds with parallel fold axes.

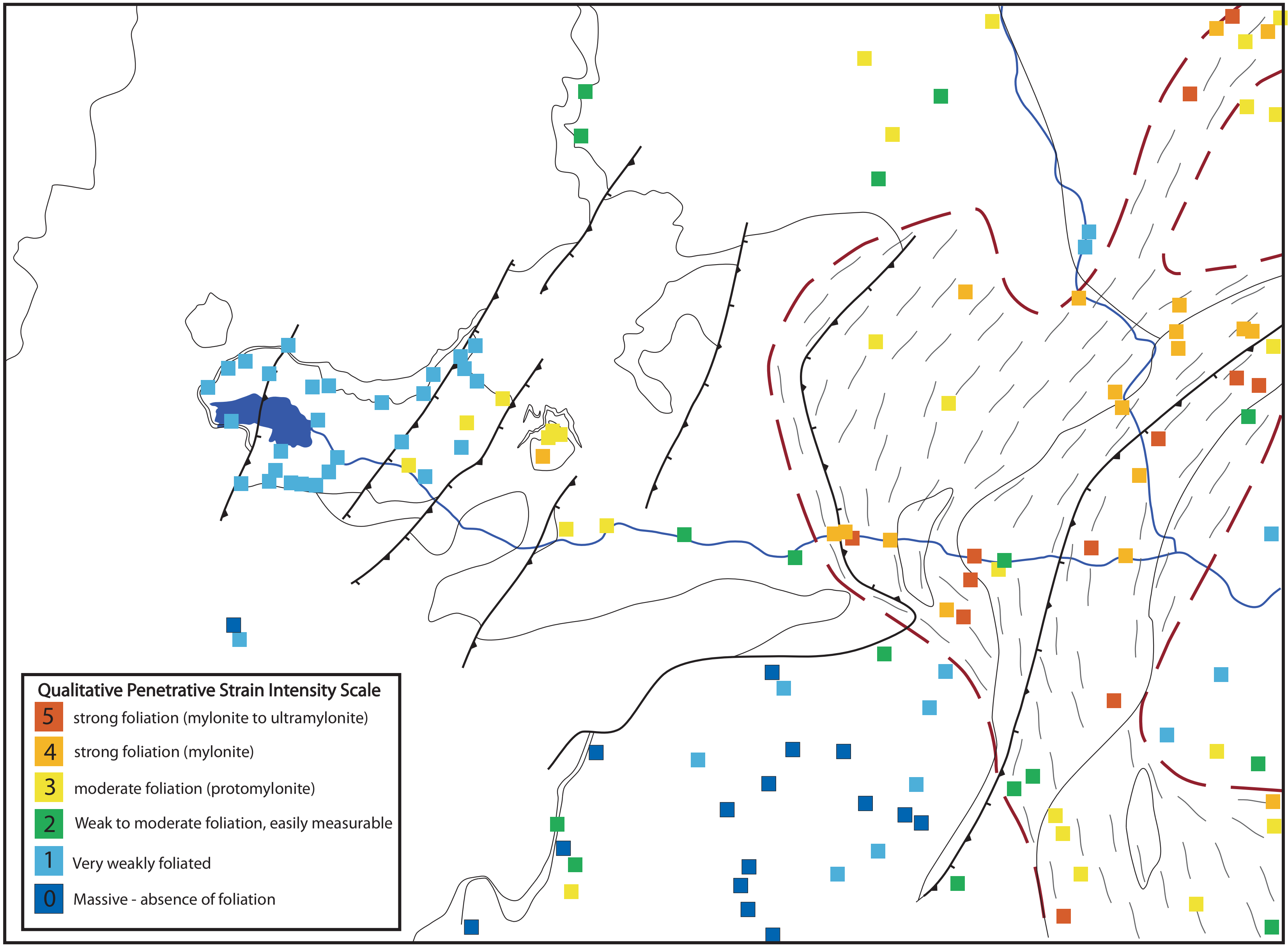


Figure 11 - Qualitative strain intensity map for the Sugar Hollow study area. Each measured outcrop was assigned a strain value from the qualitative penetrative strain intensity scale. From this data, the contacts of the White Hall high strain zone (shown here in dashed red) were drawn. As a general rule, the cutoff for inclusion within the high strain zone was between foliated rocks in category 2 or below and mylonitic rocks in categories 3 and above.

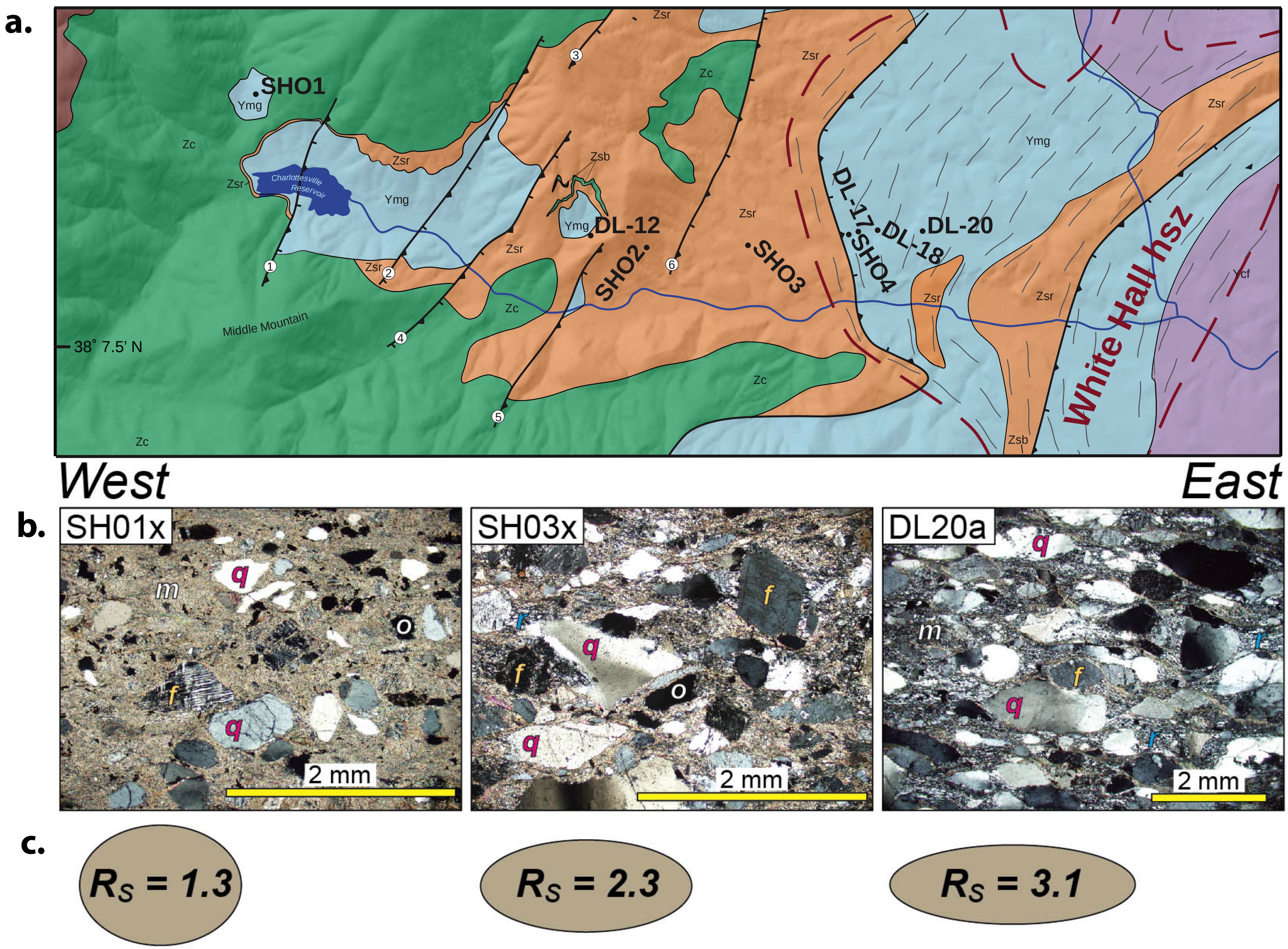


Figure 12 - **a.** Sugar Hollow geologic map showing sample locations SH01-4 and DL12-20. **b**. Photomicrographs of thin sections from sample locations SH01,SH03, and DL20. Each view is in the foliation-normal, lineation-parallel plane. Quartz, feldspar, and mica grains are labeled as q, f, and m, respectively. Strain analysis was performed at each location, which quantified the strain gradient evident in thin section. **c.** Representative strain ellipses determined via strain analysis for each thin section (Appendix 1)

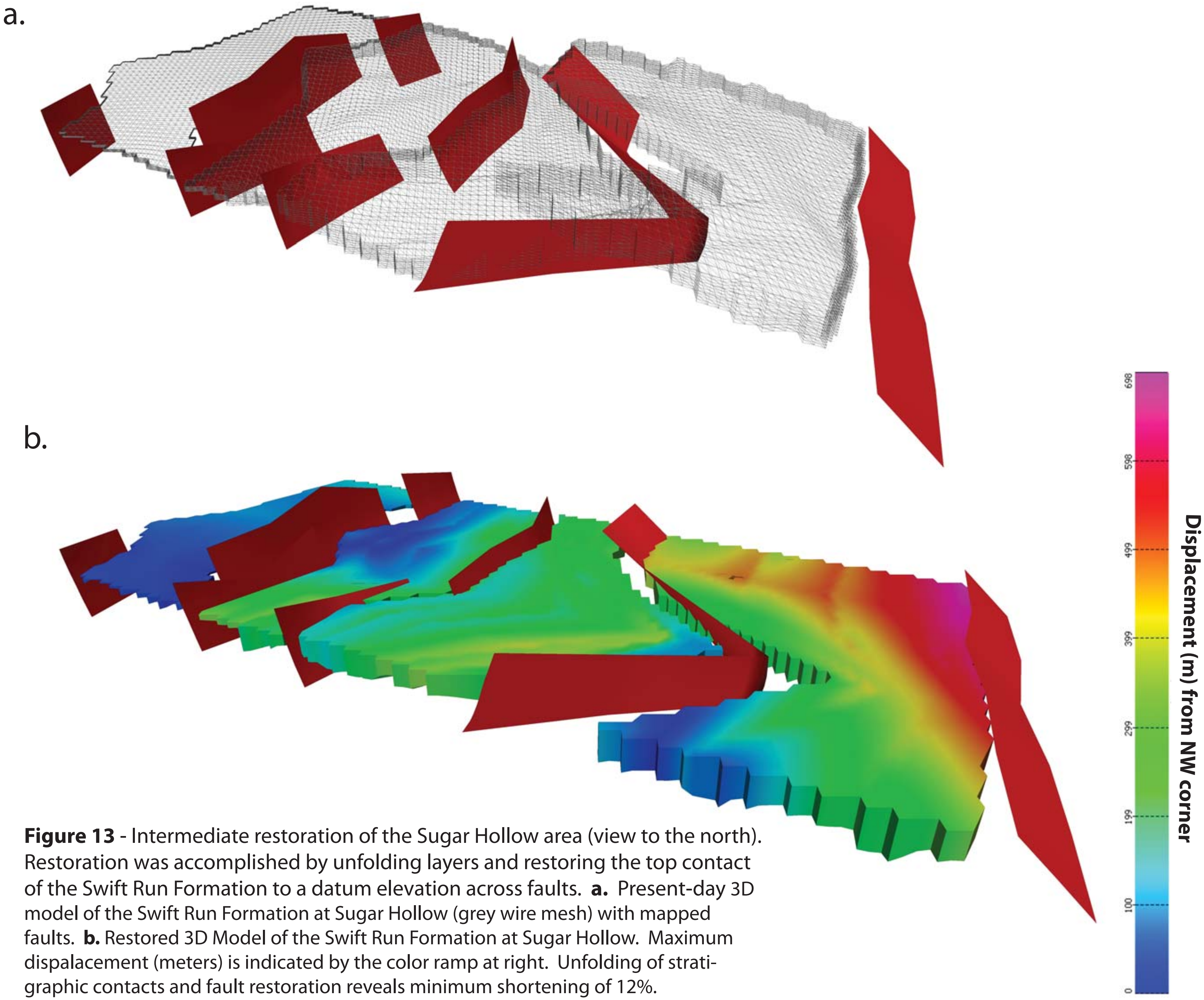


Figure 13 - Intermediate restoration of the Sugar Hollow area (view to the north). Restoration was accomplished by unfolding layers and restoring the top contact of the Swift Run Formation to a datum elevation across faults. **a.** Present-day 3D model of the Swift Run Formation at Sugar Hollow (grey wire mesh) with mapped faults. **b.** Restored 3D Model of the Swift Run Formation at Sugar Hollow. Maximum dispalacement (meters) is indicated by the color ramp at right. Unfolding of stratigraphic contacts and fault restoration reveals minimum shortening of 12%.

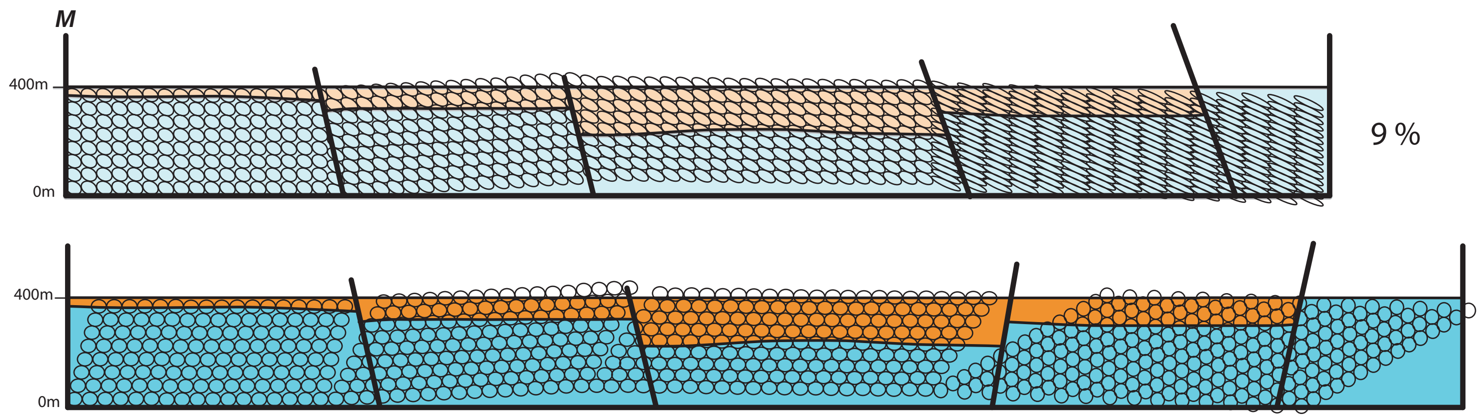


Figure 14 - Restoration of intermediate cross sections to account for penetrative strain, as measured by strain analysis. Strain ellipses (Figure 12) were distributed across each of the sections exported from Move's intermediate model so that they could be restored to their initally circular condition using Illustrator's shear tool. This method, which assumes simple shear, calculated 9% initial shortening of section M during the Paleozoic. Combining each of the two restoration methods enabled for the calculation of total shortening for each section. Total shortening values are reported at left. If penetrative strain was left unaccounted for, calculated shortening would have been 50% less.

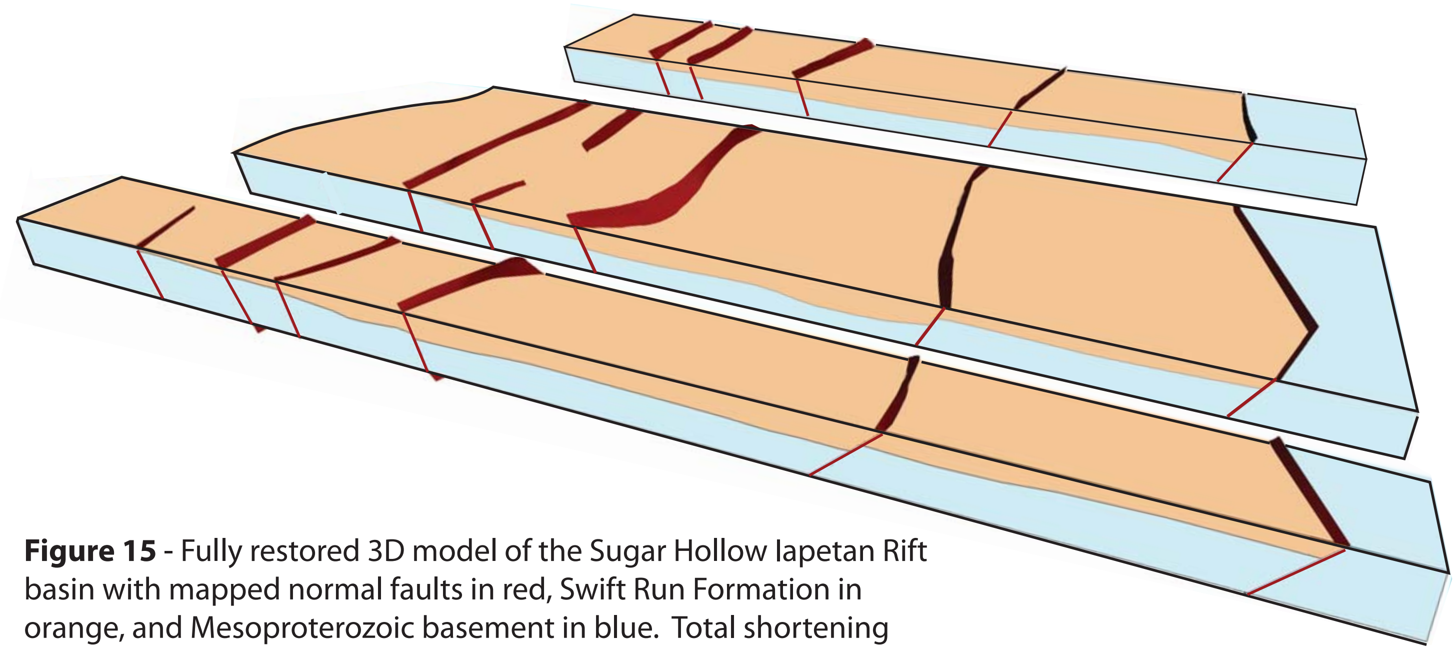


Figure 15 - Fully restored 3D model of the Sugar Hollow Iapetan Rift basin with mapped normal faults in red, Swift Run Formation in orange, and Mesoproterozoic basement in blue. Total shortening across the basin averages 23% during the Proterozoic due to faulting, folding, and penetrative strain. View from the south.

Acknowledgements

I would like to start of by thanking my research advisor, Chuck Bailey, without whom I may have never had the chance to study geology. His dedication to teaching in the classroom as well as in the field sparked in me a great desire to conduct geological research. As one of the foremost experts on Appalachian geology, he has been an invaluable wealth of information.

Thanks to Ryan Thigpen for his training on *Move* and for his guidance. He opened my eyes to Structural Geology beyond the realm of Chuck Bailey, and showed me the best mountain bike trails in Williamsburg. Also, Midland Valley deserves a huge "thank you" for providing the William & Mary Department of Geology with an academic license for their software, the complexities of which consumed many a night in the lab—with great reward.

I owe another huge "thank you" to Graham Lederer, Ari Hartmann, Friedrich Knuth, Crystal Lemon, Meghan Lamoreaux, JoBeth Carbaugh, Trevor Buckley, Jessica Ball, Joe Olney, Owen Nichols, and Eric Tadlock for spending many hot summer days mapping in the Brown's Cove and Crozet Quadrangles. In addition, I would like to thank all of the students who participated in Chuck Bailey's Spring '08 Advanced Structural Geology Seminar course at William & Mary for their assistance in the field and for their collaboration in the lab. Graham Lederer, John Garber, Ali Snell and Brian Kneiser in particular were great collaborators and good friends.

This research was supported by an undergraduate research grant from the Southeastern Section of the Geological Society of America.

References

Aleinikoff, J.N., Zartman, R.E., Walter, M., Rankin, D.W., Lyttle, P.T., and Burton, W.C., 1995, U-Pb ages of metarhyolites of the Catoctin and Mount Rogers formations, Central and Southern Appalachians; evidence for two pulses of Iapetan rifting: American Journal of Science, v. 295, p. 428.

Allen, R.M., 1963, Geology and mineral resources of Greene and Madison Counties: Virginia: Virginia Division of Mineral Resources Bulletin, v. 81, p. 78.

Badger, R.L., and Sinha, A.K, 1988, Age and Sr isotopic signature of the Catoctin volcanic province; implications for subcrustal mantle evolution: Geology, v. 16, p. 91.

Badger, R.L., and Sinha, A.K., 2004, Geochemical stratigraphy and petrogenesis of the Catoctin volcanic province, central Appalachians, *in* Tollo, R. P., McLelland, J., Corriveau, L., and Bartholomew, M. J., eds., Geological Society of America Memoir, v. 197, p. 435.

Bailey, C.M., Polvi, L.E., and Forte, A.M., 2007, Pure shear dominated high-strain zones in basement terranes: Geological Society of America Memoirs, v. 200, p. 93.

Bailey, C.M., Giorgis, S., and Coiner, L., 2002, Tectonic inversion and basement buttressing: an example from the central Appalachian Blue Ridge province: Journal of Structural Geology, v. 24, p. 925-936.

Bailey, C.M., and Simpson, C., 1993, Extensional and contractional deformation in the Blue Ridge Province, Virginia: Bulletin of the Geological Society of America, v. 105, p. 411.

Bailey, C.M., 1994, Temporal, kinematic, and strain analysis of granite tectonites from the central Appalachians. Ph.D. thesis, Johns Hopkins University.

Bailey, C.M., Southworth, S., and Tollo, R.P., 2006, Tectonic history of the Blue Ridge, north-central Virginia: Excursions in Geology and History: Field Trips in the Middle Atlantic States: Boulder, the Geological Society of America, p. 22.

Bailey, C.M., Berquist, P., Mager, S., Knight, B., Shotwell, N., and Gilmer, A., 2003, Bedrock Geology of the Madison 7.5′ quadrangle: Virginia: Virginia Division of Mineral Resources Publication, v. 157, p. 22.

Bartholomew, M.J., and Lewis, S.E., 1984, Evolution of Grenville massifs in the Blue Ridge geologic province, southern and central Appalachians: The Grenville Event in the Appalachians and Related Topics, p. 229–254.

Bloomer, R.O., 1950, Late pre-Cambrian or Lower Cambrian formations in central Virginia: American Journal of Science, v. 248, p. 753.

Butler, R., 1989, The influence of pre-existing basin structure on thrust system evolution in the Western Alps: Geological Society London Special Publications, v. 44, p. 105.

Chen, A., 1998, Geometric and kinematic evolution of basement-cored structures: Intraplate orogenesis within the Yanshan orogen, northern China: Tectonophysics, v. 292, p. 17-42.

Chew, D.M., 2003, An Excel spreadsheet for finite strain analysis using the Rf/phi technique: Computers & Geosciences, v. 29, p. 795-799.

Dilliard, K.A., Simpson E.L., Noto R.C., Wizevich M., 1999, Characterization of fluvial deposits interbedded with flood basalts, Neoproterozoic Catoctin Formation, Central Appalachians, USA: Precambrian Research, v. 97, no. 1, p. 115-134.

Evans, M.A., 1989, The structural geometry and evolution of foreland thrust systems, northern Virginia: Bulletin of the Geological Society of America, v. 101, p. 339.

Forte, A.M., and Bailey, C.M., 2007, Testing the utility of the porphyroclast hyperbolic distribution method of kinematic vorticity analysis: Journal of Structural Geology, v. 29, p. 983-1001.

Forte, A.M., Wooton, K., Hasty, B., and Bailey, C.M., 2005, Bedrock geology of the Swift Run Gap 7.5′ Quadrangle: Blue Ridge Province, Virginia: Geological Society of America Abstracts with Programs, v. 37, p. 34.

Furcron, A., 1969, Late Precambrian and Early Paleozoic erosional and depositional sequences of northern and central Virginia: Precambrian-Paleozoic Appalachian Problems: Georgia Geological Survey Bulletin, v. 86, p. 57-88.

Gatusso, A., 2009, Tectonic Significance of the Late Neoproterozoic Swift Run Formation and Basement-Cover Unconformity in the Virginia Blue Ridge: Undergraduate Thesis, College of William & Mary.

Gathright, T.M., Henika, W.S., and Sullivan, J.L., 1977, Geology of the Waynesboro East and Waynesboro West quadrangles, Virginia: Commonwealth of Virginia, Dept. of Conservation and Economic Development, Division of Mineral Resources Publication.

Gathright, T.M., and Thomas, M., 1976, Geology of the Shenandoah National Park, Virginia: Virginia Division of Mineral Resources Bulletin, v. 86, p. 93.

Jessup, M.J., Law, R.D., and Frassi, C., 2007, The Rigid Grain Net (RGN): An alternative method for estimating mean kinematic vorticity number (Wm): Journal of Structural Geology, v. 29, p. 411-421.

Jonas, A.I., and Stose, G.W., 1939, Age relation of the pre-Cambrian rocks in the Catoctin Mountain-Blue Ridge and Mount Rogers anticlinoria in Virginia: American Journal of Science, v. 237, p. 575.

King, P.B., 1950, Tectonic framework of southeastern United States: Association of Petroleum Geologists Bulletin, v. 34, p. 635-671.

King, P.B., 1949, The floor of the Shenandoah Valley [Virginia]: American Journal of Science, v. 247, p. 73.

Kline, S., Conley, J., and Evans, N., 1990, Hyaloclastite pillow breccia in the Catoctin metabasalt of the eastern limb of the Blue Ridge anticlinorium in Virginia: Southeastern, Geology, v. 30, p. 241–258.

Lamoreaux, M.H., Bailey, C.M., Olney, J., Nicholls, O.G., and Tadlock, J.E., 2010, Geologic Map of the Browns Cove Quadrangle, Virginia scale 1:24,000: Virginia Divison of Geology and Mineral Resources Open File Report, v. 09-XX.

Lederer, G.W., Gattuso, A.P., Bailey, C.M., Hartmann, A.D., Lemon, C.M., and Knuth, F.A., 2010, Geologic Map of the Crozet Quadrangle, Virginia scale 1:24,000: Virginia Division of Geology and Mineral Resources Open File Report, v. 09-01, p. in press.

McClay, K., Buchanan, P., 1992, Thrust faults in inverted extensional basins: Thrust Tectonics, p. 93-104.

Meert, J.G., Van der Voo, R., and Payne, T.W., 1994, Paleomagnetism of the Catoctin volcanic province: a new Vendian–Cambrian apparent polar wander path for North America: Journal of Geophysical Research, v. 99, p. 4625–4641.

Mitra, G., 1979, Ductile deformation zones in Blue Ridge basement rocks and estimation of finite strains: Geological Society of America Bulletin, v. 90, p. 935.

Naeser, N., Naeser, C., Morgan III, B., Schultz, A., and Southworth, C., 1999, Paleozoic to Recent cooling history of the Blue Ridge Province, Virginia, North Carolina, and Tennessee, from apatite and zircon fission-track analysis: Geological Society of America Abstracts with Programs, p. 117.

Nelson, W.A., 1962, Geology and mineral resources of Albemarle County: Virginia Division of Mineral Resources Bulletin, v. 77, p. 92.

Olney, J., Lamoreaux, M., Tadlock, J., Nicholls, O., and Bailey, C.M., 2007, Bedrock geology of the Browns Cove 7.5' quadrangle: Blue Ridge Province, Virginia: Geological Society of America Abstracts with Program, v. 32, p. 38.

Rankin, D.W., 1975, The continental margin of eastern North America in the southern Appalachians: The opening and closing of the proto-Atlantic Ocean: American Journal of Science, v. 275, p. 298-336.

Reed Jr, J.C., 1955, Catoctin Formation near Luray, Virginia: Bulletin of the Geological Society of America, v. 66, p. 871.

Simpson, C., and De Paor, D., 1997, Practical analysis of general shear zones using the porphyroclast hyperbolic distribution method: an example from the Scandinavian Caledonides: Evolution of Geological Structures in Micro-to Macro-Scales, Chapman and Hall, London, p. 169–184.

Simpson, C., and De Paor, D., 1993, Strain and kinematic analysis in general shear zones: Journal of Structural Geology, v. 15, p. 1.

Simpson, E.L., and Eriksson, K.A., 1990, Early Cambrian progradational and transgressive sedimentation patterns in Virginia: an example of the early history of a passive margin: Journal of Sedimentary Petrology, v. 60, p. 84-100.

Simpson, E.L., and Eriksson, K.A., 1989, Rift to incipient passive-margin sedimentation within the late Proterozoic to early Cambrian Unicoi Formation of southern and central Virginia: Geological Society of America Bulletin, v. 101, p. 42-54.

Stose, A.J., and Stose, G.W., 1946, Geology of Carroll and Frederick Counties: The Physical Features of Carroll County and Frederick County: Maryland Dept.Geology, Mines and Water Resources Special Publication.

Thomas, W.A., 2006, Tectonic inheritance at a continental margin: GSA Today, v. 16, p. 4-11.

Thomas, W.A., 1991, The Appalachian-Ouachita rifted margin of southeastern North America: Geological Society of America Bulletin, v. 103, p. 415.

Thomas, W.A., 1977, Evolution of Appalachian-Ouachita salients and recesses from reentrants and promontories in the continental margin: American Journal of Science, v. 277, p. 1233.

Tollo, R.P., Aleinikoff, J.N., Bartholomew, M.J., and Rankin, D.W., 2004, Neoproterozoic A-type granitoids of the central and southern Appalachians: Intraplate magmatism associated with episodic rifting of the Rodinian supercontinent: Precambrian Research, v. 128, p. 3-38.

Tollo, R.P., and Aleinikoff, J.N., 1996, Petrology and U-Pb geochronology of the Robertson River igneous suite: Blue Ridge Province, Virginia: American Journal of Science, v. 296 p. 1045-1090.

Vernon, R., 1952, Geology of the Crozet-Pastern Fence Mountain area: Albemarle County, Virginia: MS Thesis, University of Virginia.

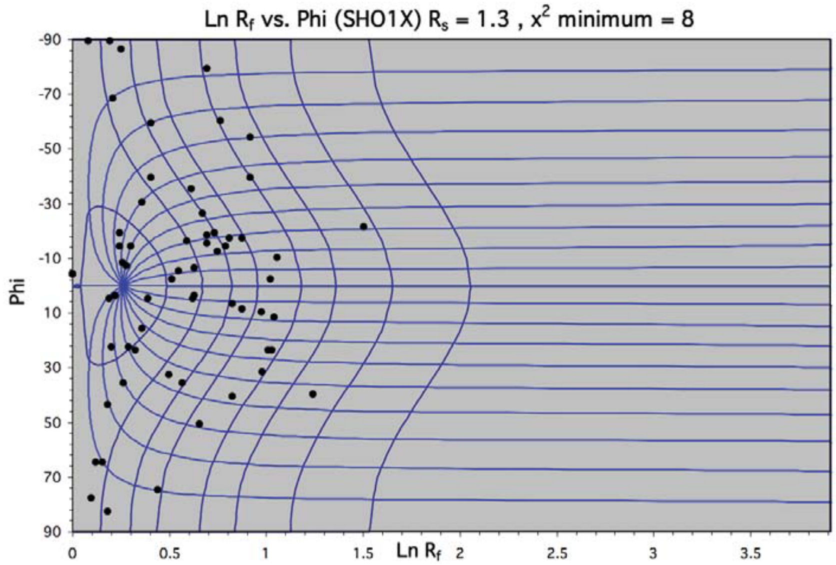
Wehr, F., and Glover III, L., 1985, Stratigraphy and tectonics of the Virginia-North Carolina Blue Ridge: Evolution of a late Proterozoic-early Paleozoic hinge zone: Bulletin of the Geological Society of America, v. 96, p. 285.

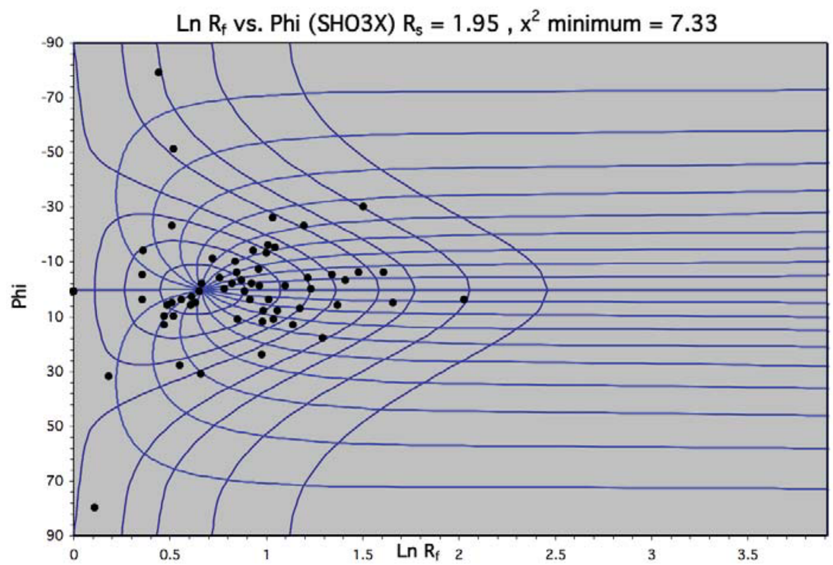
Werner, H., 1966, Geology of the Vesuvius Quadrangle, Virginia: Charlottesville, Virginia: Virginia Division of Mineral Resources Report, v. 7.

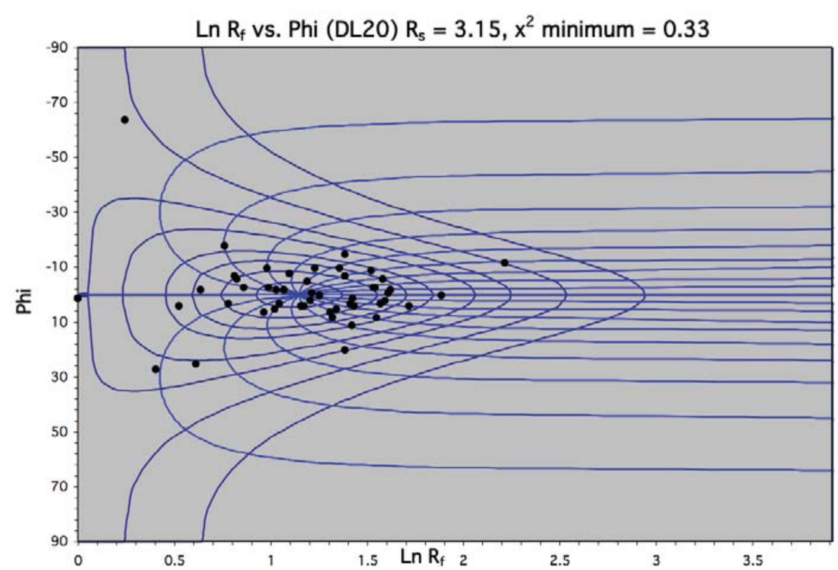
Williams, G., Powell, C., and Cooper, M., 1989, Geometry and kinematics of inversion tectonics: Geological Society of London Special Publications, v. 44, p. 3.

Wooton, K.M., Bailey, C.M., and Kunk, M.J., The nature and timing of deformation in the Blue Ridge Province, Greene County, Virginia, Geological Society of America Abstracts with Programs, p. 36.

Appendix 1: Strain Analysis Data







Appendix 2: Rigid Grain Net Vorticity Data