SLIDING AND PUSHING TO THE SOUTH: GRAVITATIONAL COLLAPSE OF THE PALEOZOIC THRUST STACK AND HINTERLAND-DIRECTED ALLEGHANIAN(?) BACK THRUSTING, INNER PIEDMONT, TRANSYLVANIA AND HENDERSON COUNTIES, NORTH CAROLINA, AND GREENVILLE COUNTY, SOUTH CAROLINA

Carolina Geological Society – Guidebook for the 80th Annual Meeting

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Carolina Geological Society

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Special thanks to Furman Field Assistants.

Cover Photograph Triple Falls along Little River, Dupont State Forest, NC with exposures of Henderson Gneiss.

Sliding and pushing to the south: gravitational collapse of the Paleozoic thrust stack and hinterland-directed Alleghanian(?) back thrusting, Inner Piedmont, Transylvania and Henderson Counties, North Carolina and Greenville County, South Carolina."

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John Stuart Mill, commenting on Charles Darwin's newly published treatise on Natural Selection (1859), said "… though he cannot be said to have proved the truth of his doctrines, he does seem to have proved that it may be true, which I take to be as great a triumph as knowledge and ingenuity could possibly achieve on such a question." (J. Browne, 2002, p. 186)

Introduction

The emphasis of the 2019 Carolina Geological Society field trip is to view the field evidence for two separate aspects of the complex tectonic history of the Inner Piedmont (IP) in adjoining North Carolina and South Carolina, southern Appalachians. They are: 1) southwestward movements along retrograde shear zones, interpreted as due to gravitational collapse of portions of the Paleozoic ductile thrust stack; and 2) subsequent development of southward brittle thrusting in the region, interpreted as due to hinterland-directed back thrusting produced during Alleghanian(?) northwestward thrusting. Multiple interpretations of these geologic features are possible, so the ultimate meaning of the geologic evidence rests with the participants. The axiom runs: 'Two geologists, three (four?) interpretations'. Input is welcome. The field trip area lies within Standingstone Mountain quadrangle, Transylvania and Henderson Counties, North Carolina, and Standingstone Mountain and Cleveland quadrangles, Greenville County, South Carolina.

Earlier geologic reports and geologic maps covering this part of the IP were completed by members of the U.S. Geological Survey from the mid-1980s to the late 1990s (Nelson, 1986; Nelson and others, 1986, 1987, 1998). Our earlier geologic descriptions (Garihan and others, 1988, 1990, 1993; Garihan and Ranson, 1992, and references therein; Garihan, 2012) emphasized cataclastic zones and IP brittle faulting. Geologic maps covering South Carolina portions of the Mountain Bridge Area and farther east (Figure 1a) were completed by Furman

University Earth Science faculty, students, and members of the S. C. Geological Survey. Adjacent quadrangles in North Carolina were mapped by the North Carolina Geological Survey: for example, the Brevard 7.5-minute quadrangle of Cattanach and Bozdog (2011). The results of new mapping in Horse Shoe, Pisgah Forest, and Brevard quadrangles, North Carolina are described by Cattanach and others (2012, CGS Guidebook). The Mountain Bridge Wilderness Area in South Carolina and the Dupont State Forest in North Carolina both have outstanding hiking trails, scenic views, and access to geology that are worth a future visit.

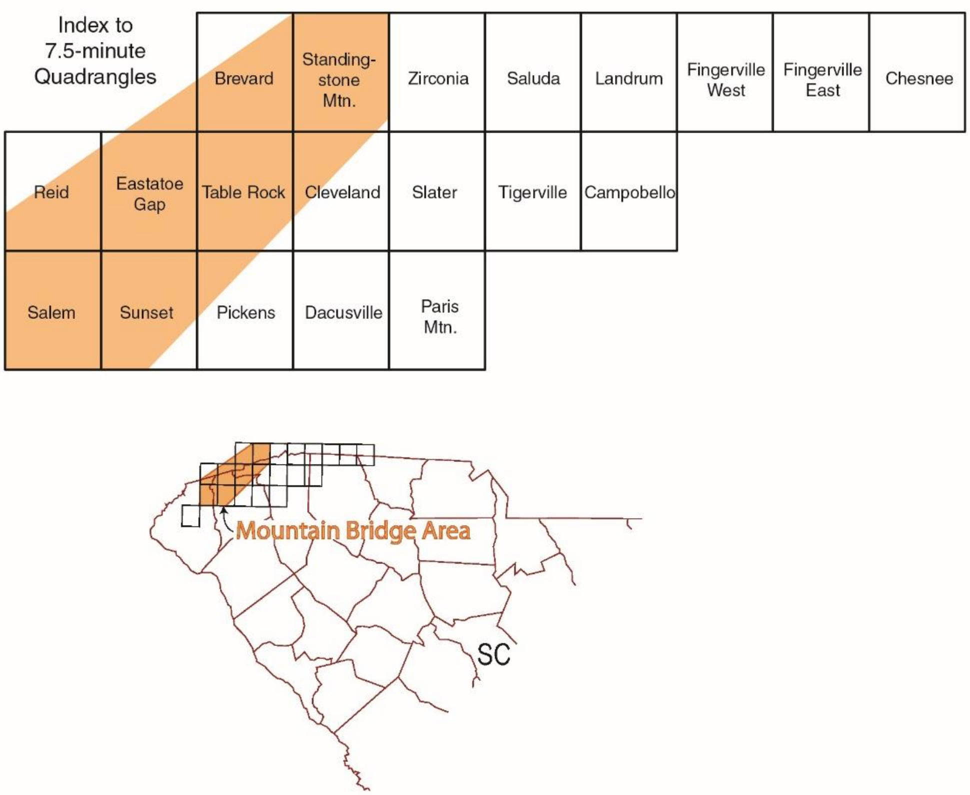

Figure 1a. Index to 7.5-minute quadrangles in the Mountain Bridge Area, and to those mapped farther east, South Carolina, including North Carolina portions of Standingstone Mountain and Zirconia quadrangles.

The trip leaders co-led field excursions in the area as part of the David S. Snipes/Clemson University Hydrology Symposium Guidebook series in 2010, 2012, 2013, and 2017. Some stops from the 2010 and 2017 guidebooks have been re-examined and updated for this 2019 CGS trip.

Summary discussions and primers covering a broad range of IP features, structures, and history not described here are provided by Davis (1993, CGS Guidebook), Hatcher (1993 and 2002 CGS Guidebooks), and Bream (2002). A recent interpretation of the Paleozoic and Mesozoic tectonic history of the field trip area is by Garihan (2018). Our earlier 2001 and 2012 CGS field excursions considered various geologic aspects of the upstate South Carolina region.

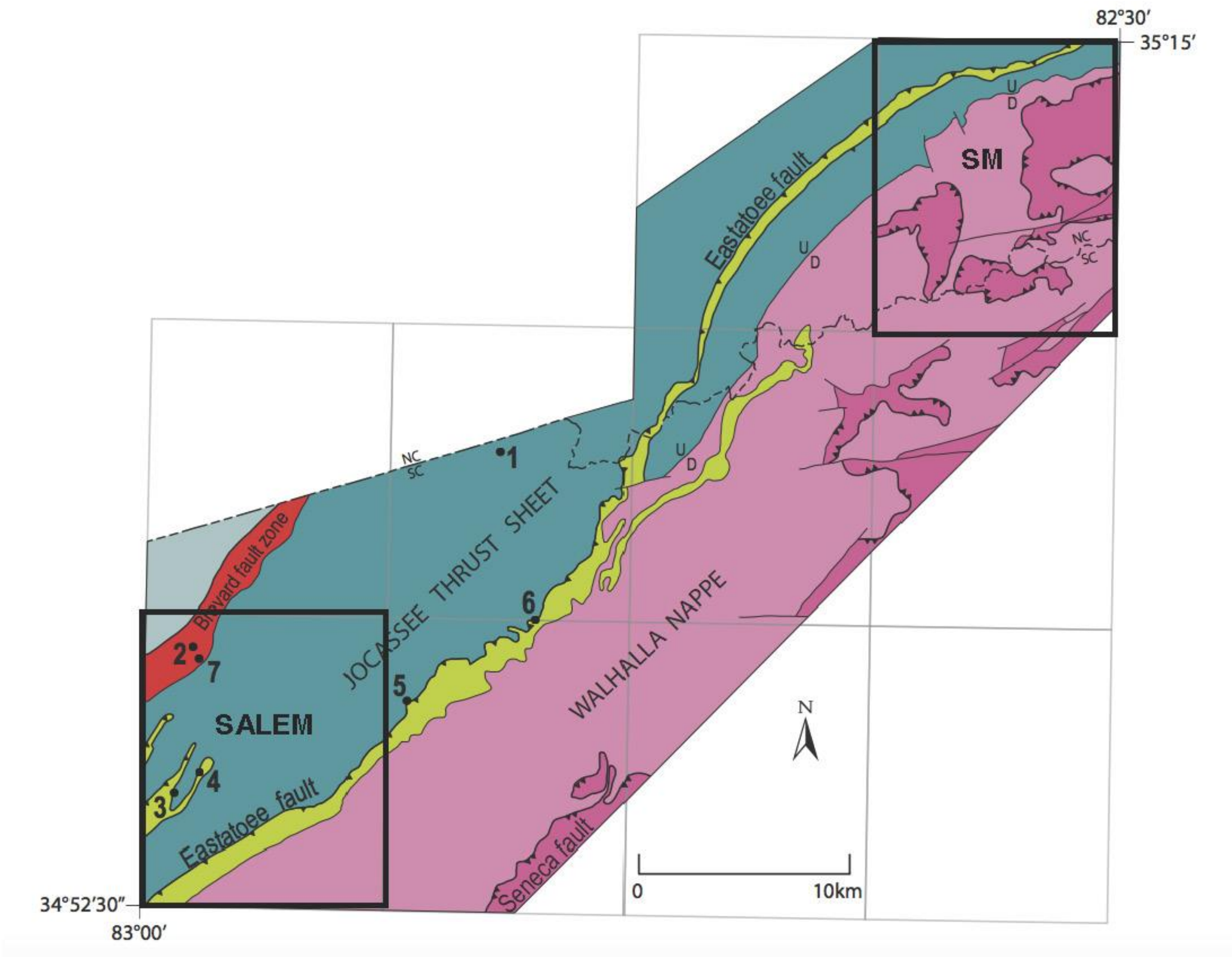

Figure 1b. Generalized geology of Mountain Bridge area, the shaded portion of Figure 1a. The Brevard zone and three thrust sheets are labeled. Henderson Gneiss is forest green. The Eastatoee fault (single sawtooth line) lies at the base of the Walhalla thrust sheet. Chauga River Formation and Poor Mountain amphibolite are light green. The Seneca fault (double sawtooth line) lies at the base of the Six Mile thrust sheet (darker rose color). SM = Standingstone Mountain quad. Numbered locations are features described in Garihan and Clendenin (2007).

Of interest here are our two themes: gravitational collapse features and back thrusts in Cleveland, Table Rock, and, particularly, Standingstone Mountain 7.5-minute quadrangles (Garihan, 2005a; Garihan and Ranson, 2003, 2007). Optional stop localities are included as additional field examples of these themes, for example the Pinnacle Mountain trail shear zone and the Cliff Ridge area Caesars Head back thrust exposures.

A regional tectono-stratigraphic summary of the structural stacking order of metamorphic units is given in Figure 2. Moving upward, three stacked thrust sheets (Jocassee, Walhalla, and Six Mile) are separated, respectively, by the Eastatoee ductile thrust (at the base of the Walhalla) and the Seneca ductile thrust (at the base of the Six Mile). At Dismal Creek and at Mulligan's View, the Eastatoee and the Seneca faults, respectively, are cut by younger thrusts related to Alleghanian(?) faulting.

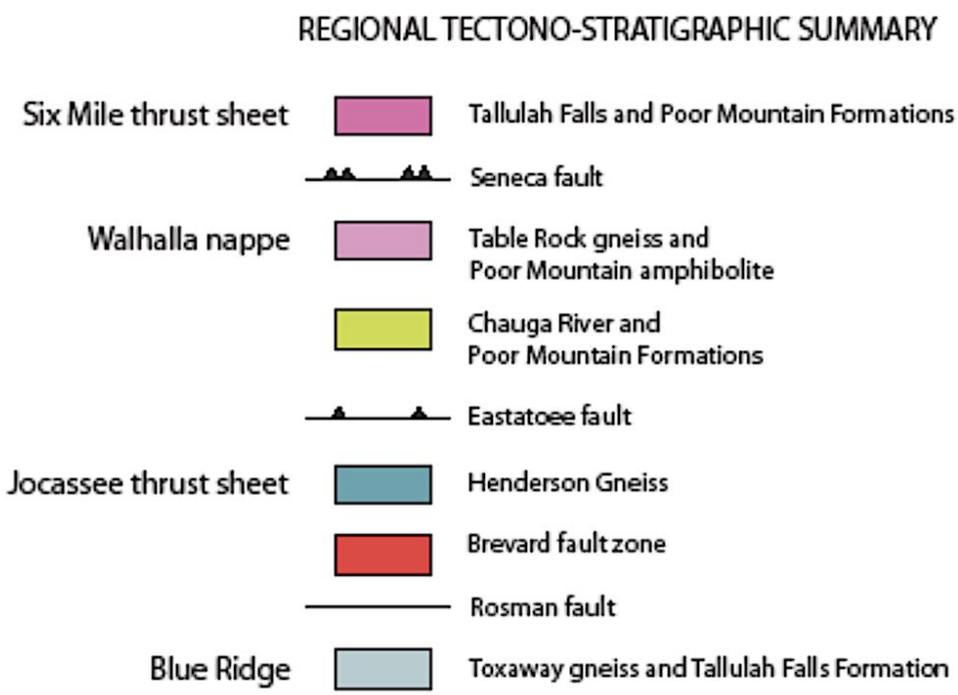

Figure 2. Regional tectono-stratigraphic summary involving three thrust sheets. Rock unit colors match Figure 1b.

General Tectonic Summary

A recent Paleozoic-Mesozoic tectonic history for this IP region (Garihan, 2018) summarizes a deformational sequence consisting, in order, of: 1) Late Ordovician supra-subduction zone granitic intrusion into metasedimentary and metaigneous protoliths; 2) Early- to Mid-Paleozoic polyphase folding and thrust stacking episodes; 3) regional Type-1 interference folding, **4) SW-directed gravitational collapse of an oversteepened thrust stack;** 5) possible formation of structural windows related to regional Mid-Paleozoic (Acadian) dextral transpression; **6) Late Paleozoic (Alleghanian?) thrusting and hinterland-directed, brittle back thrusting and folding;** and 7) a sequence of Mesozoic brittle faulting episodes and diabase dike intrusion related to systematic changes in regional extension direction.

Items 4 and **6** of the history are covered in this guide. To avoid re-cycling peripheral details here of the field trip area's protracted structural and metamorphic history, Garihan (2018) provides background references to the Mountain Bridge Area and quadrangles mapped to the east (Figure 1).

Geology of Standingstone Mountain quadrangle (SM)

(the quadrangle without a stoplight)

Standingstone Mountain 7.5-minute quadrangle (SM) is situated within the rugged part of the IP, lying across the North Carolina-South Carolina state line at the Eastern Continental Divide (~3000 feet elevation). The escarpment of the Blue Ridge Front winds its way across the southern margin of SM, with lines of impressive exfoliation domes (balds) formed on Table Rock gneiss and, less commonly, the more feldspathic Henderson Gneiss. The highest elevations in SM are 3600 - 3700 feet; local relief across this rugged landscape is 1400 - 2000 feet. Dupont State Forest in North Carolina provides public access to the scenic landscape via extensive hiking and horseback riding trails. Triple Falls and Mine Mountain are trip stops within Dupont State Forest.

Five Paleozoic, fault-bound crystalline rock packages or sheets occur in this quadrangle (Garihan, 2002). Stacked structurally lowest to highest, respectively northwest to southeast, they are (Figure 3): 1) Henderson Gneiss; 2) the Eastatoee fault, with hanging wall Chauga River Formation muscovite-biotite-feldspar-quartz schist and gneiss/metasiltstone; 3) an

Alleghanian(?) fault, with hanging wall Henderson Gneiss; 4) the Slicking Gap fault, with hanging wall Table Rock gneiss; and 5) the Seneca fault, with hanging wall Poor Mountain and Tallulah Falls Formations of the Six Mile thrust sheet. Geology of SM quadrangle was mapped at 1:24,000 scale by Garihan and Ranson (2007).

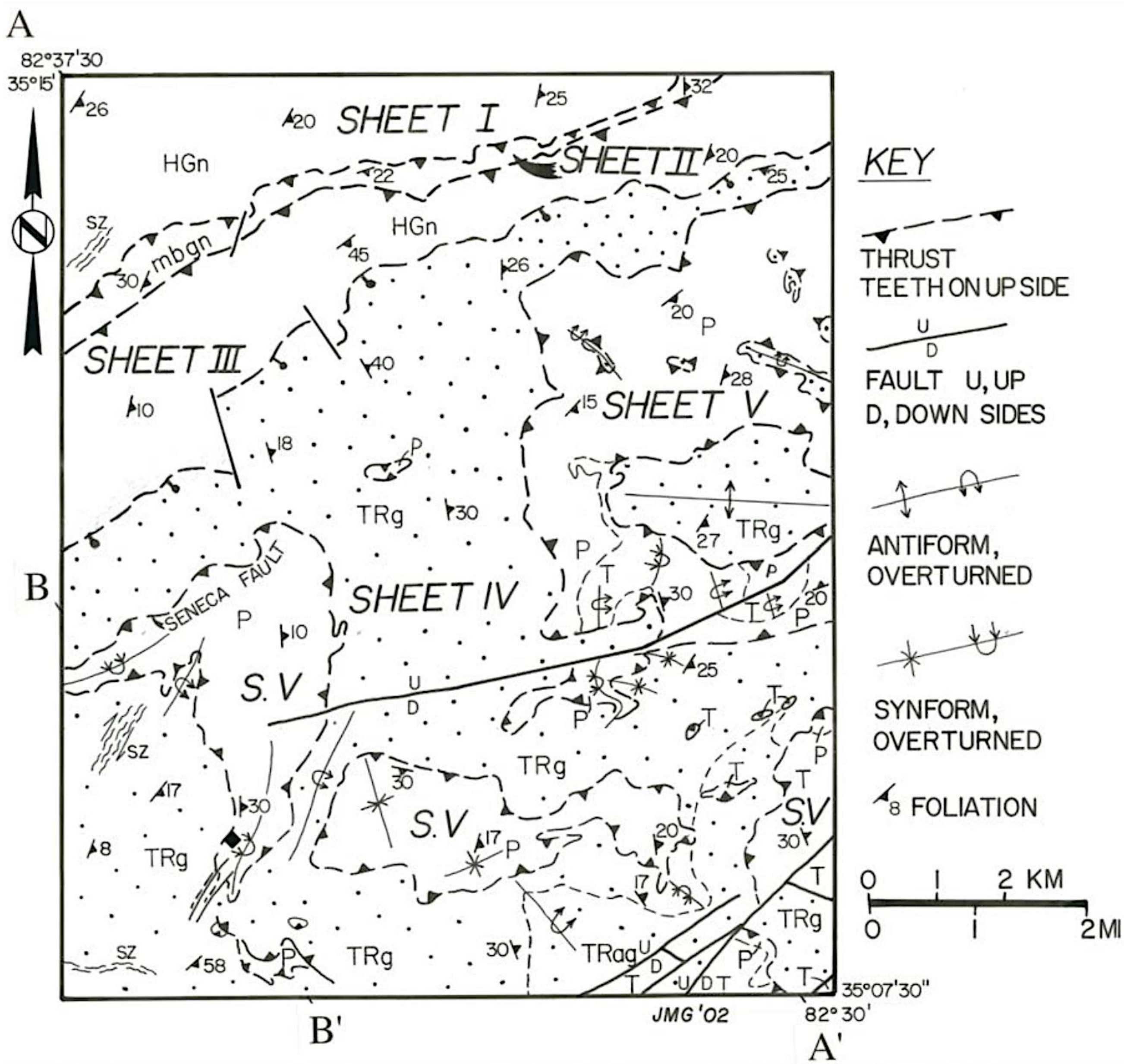

Figure 3. Generalized geologic map of Standingstone Mountain quadrangle, NC-SC. Sheets I-V are labeled; Sheet IV with stippled pattern is Table Rock gneiss. Henderson Gneiss- HGn, Chauga River Formation- mbgn, Table Rock gneiss- TRg, Table Rock augen gneiss- TRag, Poor Mountain Formation- P, Tallulah Falls Formation- T, shear zone in HGn- sz, Slicking Gap fault- bar and ball on down side. Cross sections A-A', B-B' are shown in Garihan (2002).

Henderson Gneiss. Lower sheet.

In northwest SM, muscovite-biotite-two feldspar augen Henderson Gneiss underlies a belt 1-2 km wide along the Crab Creek drainage (Figure 4a). Leucocratic, poorly foliated, granitoid gneiss and pegmatite are subordinate lithologies. Typical Henderson gneiss is saprolitic to unweathered, fine- to medium-crystalline, and well foliated. It is moderately well layered compositionally (alternating more mafic and more felsic layers) on a scale of millimeters to tens of centimeters. Rounded to ovoid to lenticular microcline augen or porphyroclasts average 0.5 – 1 cm in long dimension; they may be sparsely distributed across an exposure. Henderson Gneiss is variably mylonitic. Many pink microcline augen in hand specimen have thin, gray margins of myrmekite ± fine-crystalline, recrystallized microcline. Individual feldspar augen margins in places are asymmetric (winged) as a result of ductile shearing. The base of the lowest rock package lies outside SM quadrangle, but it is inferred to be bounded below by the easternmost fault in the regional Brevard fault zone (Hatcher, 2001). Garihan and Clendenin (2007) consider the Henderson Gneiss exposures as part of the Jocassee thrust sheet. Typical Henderson Gneiss mylonite occurs at the Dismal Creek stop.

Chauga River Formation.

Muscovite-biotite-feldspar-quartz schist and gneiss/metasiltstone in SM underlies a narrow, arcuate belt (0.1-0.8 km wide) striking N55˚-75˚E. It is bound on its north edge by the Eastatoee thrust and on the south by an unnamed Paleozoic fault (Figures 4a, 4b). Initially the belt was interpreted as a NW-vergent, overturned synform which had folded the Eastatoee fault (Garihan and Ranson, 2007). Viewed from the The Pinnacle to the south (Figures 4a, 5), Chauga River Formation rocks form a prominent resistant ridge (200-500 feet relief) (Figure 4c). Impressive waterfalls are produced on Chauga River ledges along north-flowing tributaries of west-flowing Crab Creek, for example at Shoal Creek (Figures 4d).

The Chauga River Formation is a uniformly hard, dark, fine-crystalline, poorly to moderately layered muscovite-biotite-feldspar-quartz gneiss. Its variable texture suggests original siltstone-shaley protoliths; it is locally ‘pebbly’ in appearance in coarser zones. SC Survey geologist Rob Morrow, who has mapped in the ‘slate belt’, suggested some portions may have a volcanic protolith.

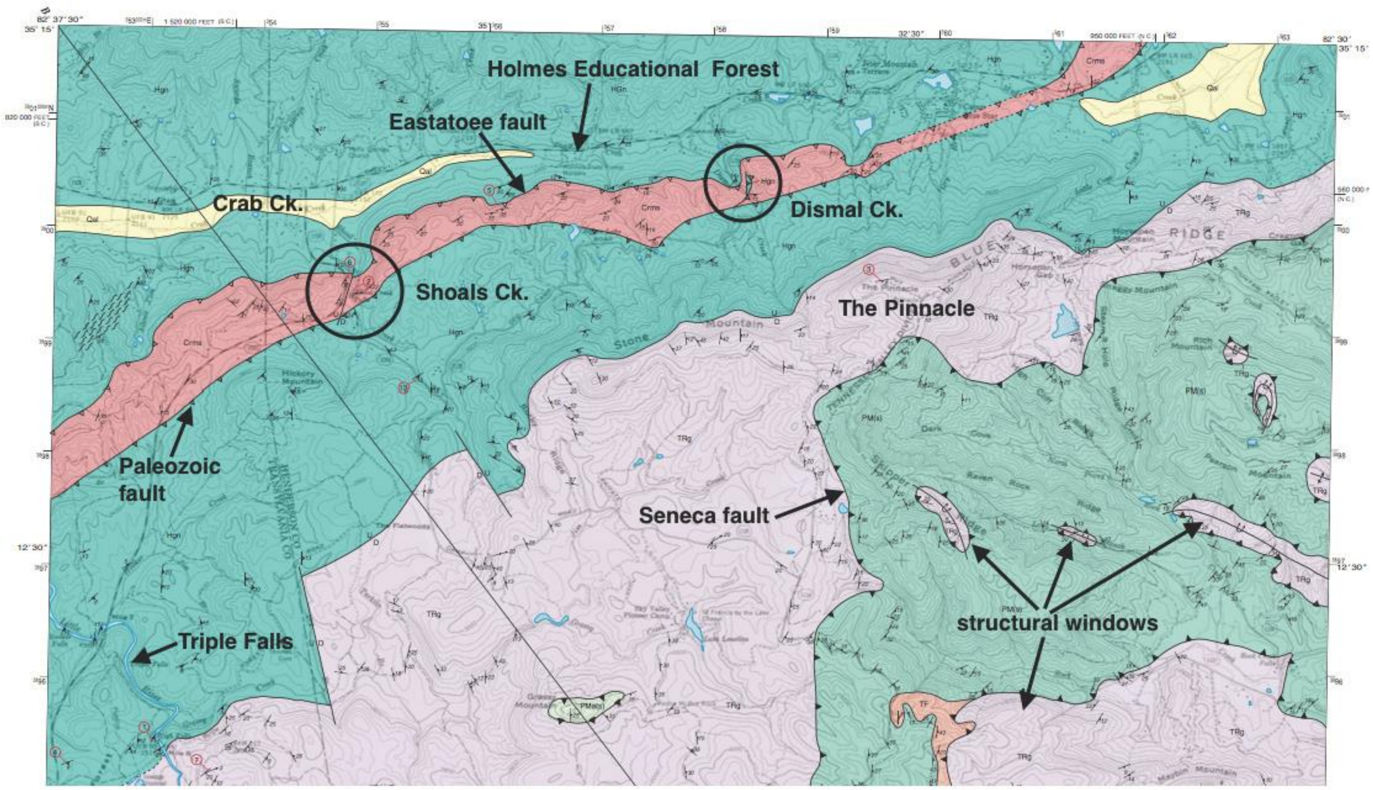

Figure 4a. Geologic map of northern Standingstone Mountain quadrangle. Henderson Gneiss- HGn, Chauga River Formation- Crms, Table Rock gneiss- TRg, PM(s)- Poor Mountain Formation, Tallulah Falls Formation- TF, Slicking Gap fault- unlabeled. Several faults and stops are indicated.

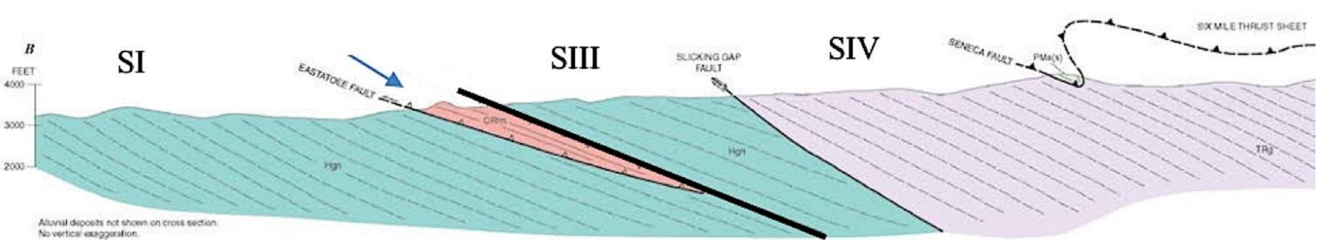

Figure 4b. Cross section along line B in Figure 4a; same rock unit labels. Paleozoic thrust at base of sheet III HGn- heavy line. Chauga River Formation- blue arrow.

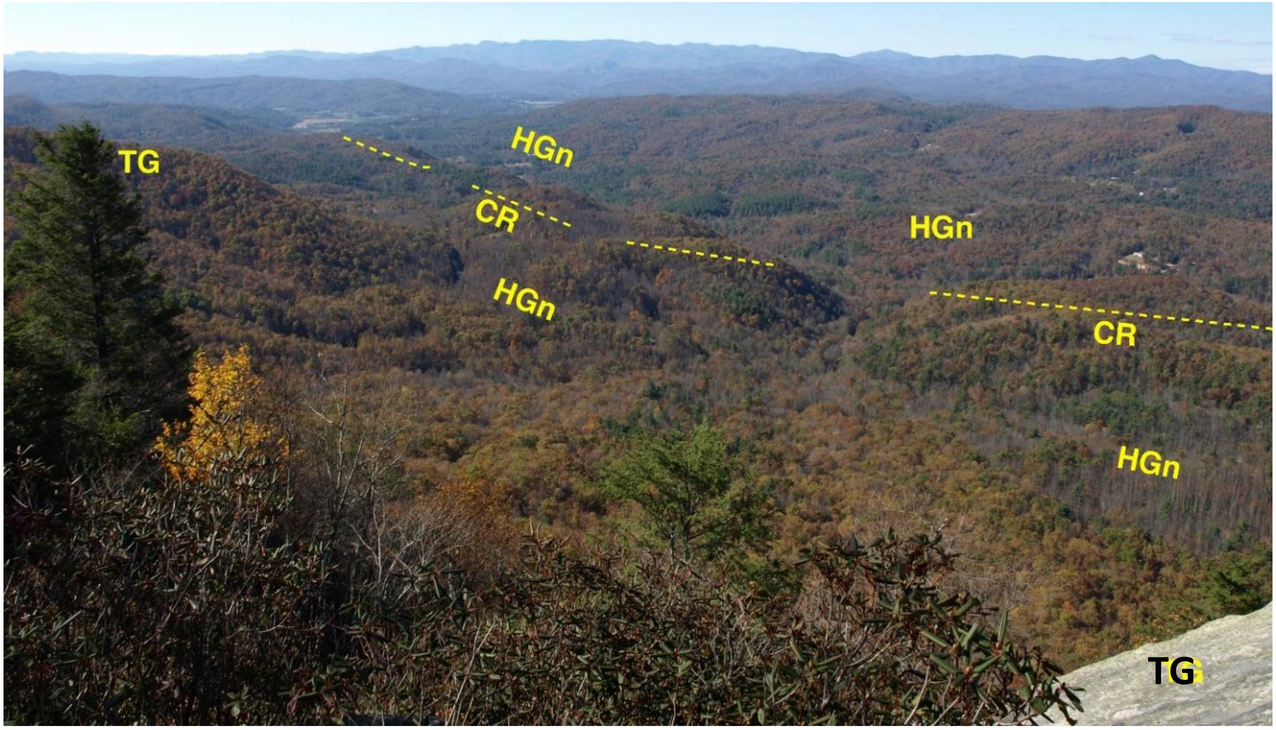

Figure 4c. View northwest from The Pinnacle (location on Figure 4a). Chauga River Formation rocks underlie the ridge (CR, crest marked with dashed line), flanked on both sides by valleys of Henderson Gneiss- HGn. Table Rock gneiss (TG), foreground, underlies The Pinnacle.

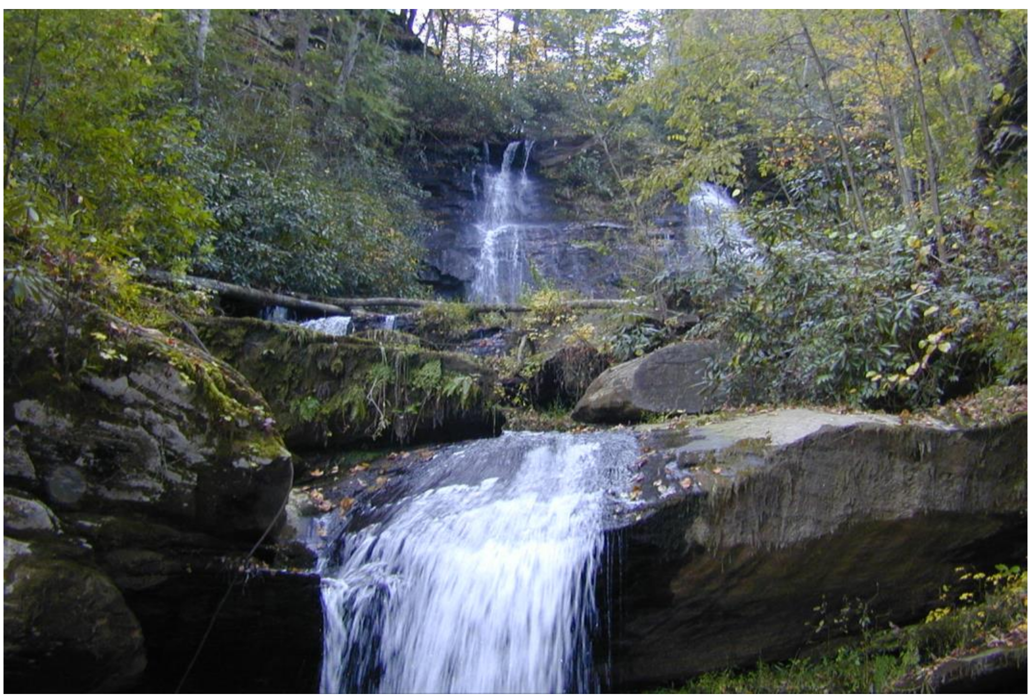

Figure 4d. Falls along Shoal Creek, a north-flowing tributary of Crab Creek (UTM: 354781 3899437), near Saturday optional stop 1-4. Jointed, gently south-dipping Chauga River Formation ledges of metasiltstone. View to the south.

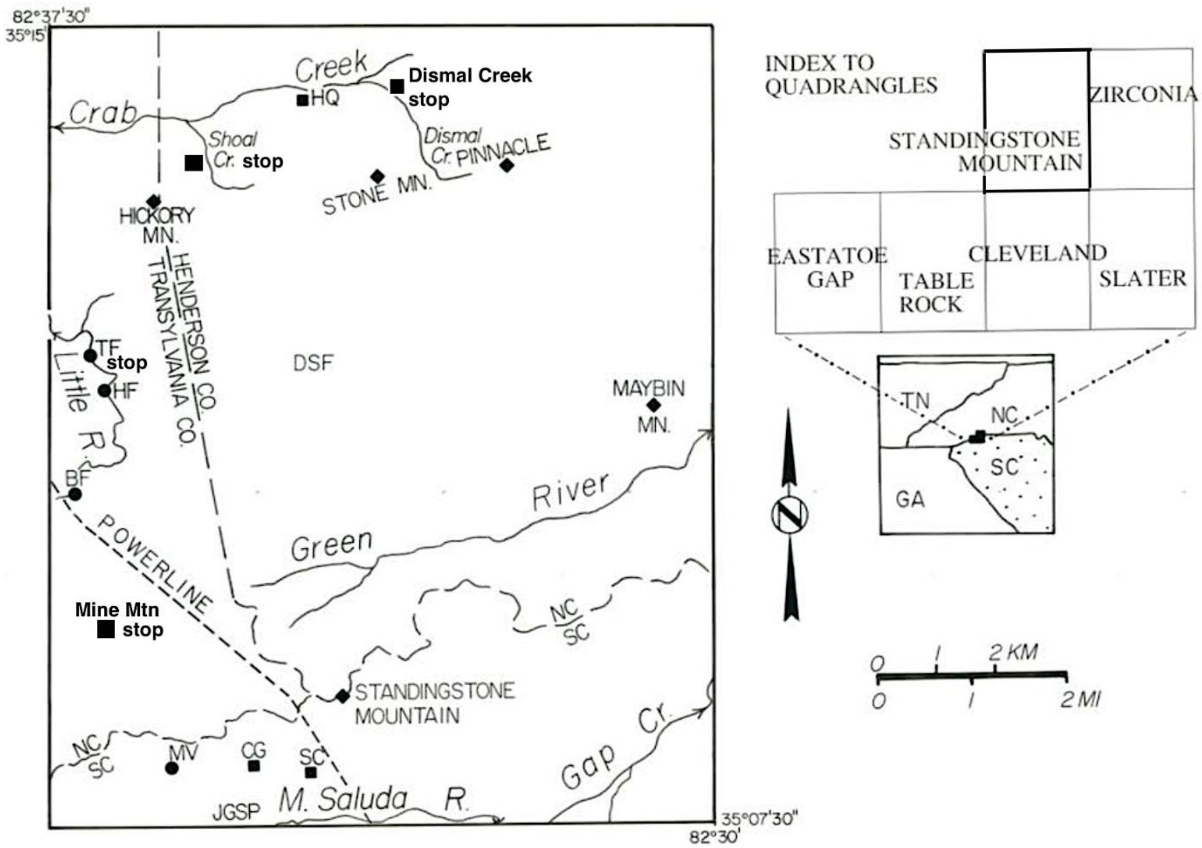

Figure 5. Selected features and stops, Standingstone Mountain quadrangle, NC-SC, with index to quadrangles. Bridal Veil Falls- BF, Dupont State Forest- DSF, Camp Greenville- CG, High Falls- HF, Holmes Educational Forest Headquarters- HQ, Jones Gap State Park- JGSP, Mulligan's View- MV, Symmes Chapel- SC, Triple Falls- TF.

Henderson Gneiss.

Henderson Gneiss, the third rock package upward (Figure 3, sheet III), underlies a zone 0.7-3 km wide, with the same lithologies as the Henderson Gneiss sheet I structurally below. Henderson foliation attitudes within these two belts (lower belt: N32°E, 13°SE; n=60 versus upper belt: N37°E, 19°SE; n=34) are similar. Well-jointed exposures of Henderson Gneiss occur within Dupont State Forest at the Triple Falls stop (Figure 4a) and further up Little River at High Falls. The strike directions of Henderson Gneiss foliation in sheet III appear truncated by the strike of the Slicking Gap normal fault at the top of its exposure belt. In a few places this fault is offset by small faults of north-northwest strike (local offsets of 0.5-1 km) (Figure 4a).

Table Rock gneiss (TG).

The fourth rock package (sheet IV) upward contains resistant, quartzose Table Rock Plutonic Suite biotite gneiss and biotite-feldspar augen gneiss (TG). The latter augen gneiss, which is *not* Henderson Gneiss, is Late Ordovician, U-Pb dated at 450 Ma (Ranson and others, 1999). Locally minor interlayered amphibolite and minor schist are present. We will see retrograde muscovite-quartz schists as single or multiple shear zones within Table Rock quartzo-feldspathic gneiss at Mine Mountain.

Poor Mountain and Tallulah Falls Formations. Upper sheet.

Rocks of the Poor Mountain and Tallulah Falls Formations lie at the higher elevations of SM (2200-3600 feet) (Figure 3, sheet V). They comprise discontinuous klippen of the Six Mile thrust sheet, with the Seneca fault at its base (Figure 4b). The irregular regional trace of the Seneca fault in central and south SM is due to a combination of factors: 1) a shallow regional southeastward dip; 2) the rugged relief in the region, prompted by Cenozoic uplift and deep erosion; and 3) the irregularity of the fault surface. The latter is produced by several phases of folding that deform the Seneca fault surface.

Post-Seneca emplacement, SW-vergent, overturned antiformal folding of the Seneca fault surface has produced several structural windows. They expose footwall Table Rock gneiss at structural culmination positions of this later fold set with an earlier NW-vergent, overturned antiformal fold set. That is, at these culmination locations the Seneca thrust has been arched up and subsequently eroded through, exposing underlying footwall rocks at the surface. On the SM geologic map (Figure 4a), these structural windows are shown as Table Rock gneiss exposure areas (pink, TRg) surrounded by Six Mile rocks (green, PM(s)). The fault enclosing each window is the Seneca fault (sawtooth line).

Rocks of the Poor Mountain Formation in the Six Mile sheet include abundant amphibolite, garnet-mica schist, biotite-muscovite gneiss, and metaquartzite. Rocks of the Tallulah Falls Formation include muscovite-biotite-sillimanite gneiss, muscovite-biotite-sillimanite schist, biotite-porphyroblastic feldspar gneiss, biotite gneiss, minor amphibolite, and calc-silicate gneiss. The units contain quartz-feldspar (granitoid) layers and lenses, which serve to substantially thicken the metamorphic sequence.

Item 4, Tectonic Summary - Description of Retrograde Shear Zones

After the regional Eastatoee and Seneca ductile thrusts were emplaced, a variety of ductile features developed within the Walhalla-Six Mile thrust stack. Those features primarily indicate a top-to-the-SW sense of shear. The ductile features are: 1) small-scale ductile normal faults, 2) shear sense indicators in schist and locally in gneiss, and 3) and sheared, asymmetric quartzo-feldspathic lenses in schist. These features are identified in Chauga River Formation garnet schist, Table Rock gneiss (TG), Poor Mountain Formation amphibolite and quartzite, and Tallulah Falls Formation paragneiss and schist (Figure 2). These ductile features are scattered at various structural levels in the thrust stack.

Retrograde shear zones of ductile muscovite-quartz schist (generally a few meters thick) and finer biotite-coarser muscovite quartzo-feldspathic TG are present. Muscovite formed at the expense of K-feldspar under greenschist facies conditions. Muscovite in TG typically is up to five modal percent of the rock and fine-crystalline. However, in the retrograde shear zones, coarser muscovite may exceed forty modal percent. Mica growth is interpreted to have been facilitated by fluids moving through the gneiss (TG).

Mine Mountain shear zone.

Mine Mountain is located in southwest SM in an area underlain by TG and lesser amphibolite (Figures 5, 6A). A greenschist-facies, ductile shear zone comprised of a moderately weathered, partially iron-stained, red to tan to white, fine- to medium-crystalline garnet-muscovite-quartz schist with accessory pyrite crops out on Mine Mountain and is named for it. Schistosity is deflected locally around meter-scale lenses of quartz-feldspar pegmatite. The single or multiple shear zones are more resistant than the surrounding saprolitic gneiss and generally form ledges along strike. Abundant float is shed downslope. Innumerable shallow pits have been dug along the length of the shear zone, with old tailings dumped nearby. However, no sulfides other than pyrite were noted. Shear zone thickness is variable along strike, ranging from a few meters to tens of meters. In places there are several parallel shear zones, separated by TG.

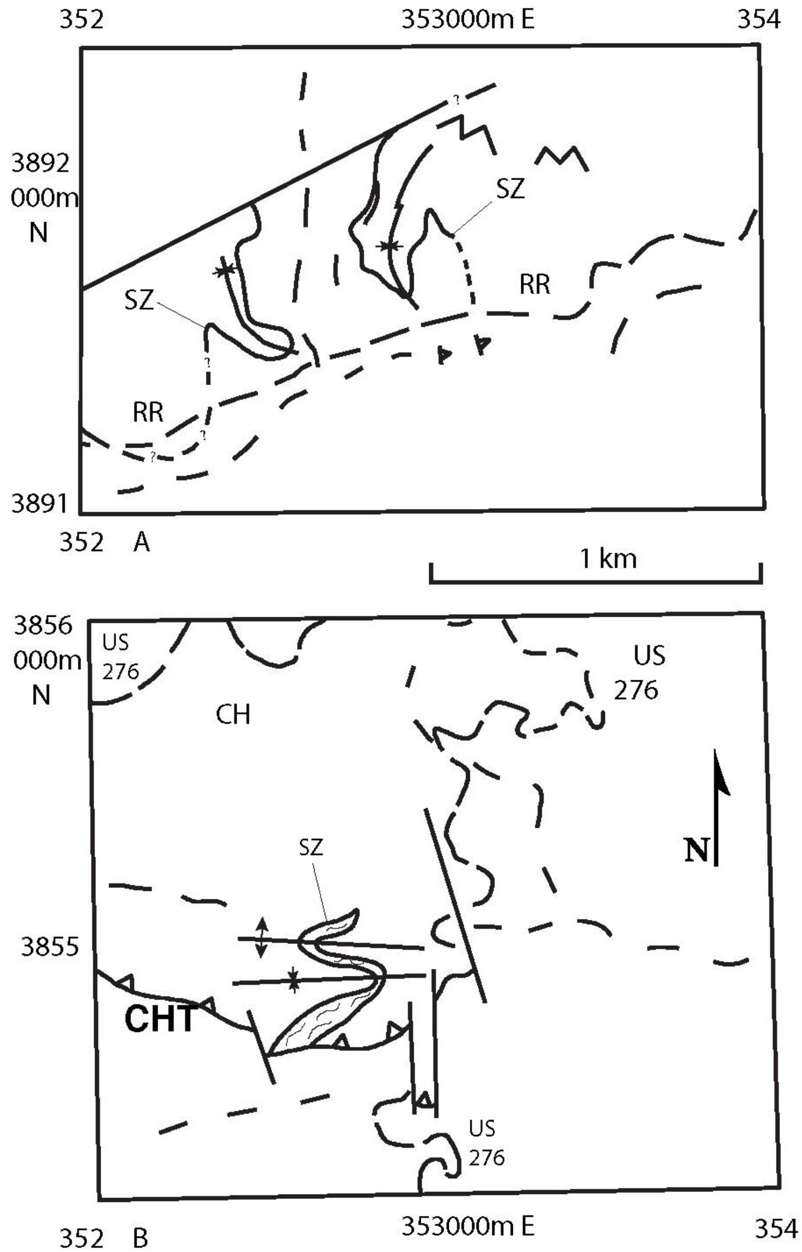

Figure 6 A, B. Geologic sketch maps of two shear zones. UTM grid coordinates are shown. **A.** Folded Mine Mountain shear zone, Standingstone Mountain quadrangle. Mine Mountain- MM; Reasonover Road- RR; shear zone- SZ. Fault (motion sense unknown) truncates the MM shear zone to the north. Drainages are shown as unlabeled, wider-spaced, dashed lines. **B.** Folded Pinnacle Mountain trail shear zone, Cleveland quadrangle. Optional Stop 2a-4, Sunday. Caesars Head community- CH; shear zone- SZ; Caesars Head fault truncating the shear zone- CHT, open sawtooth line. US 276 labeled. Drainages shown as unlabeled, wider-spaced, dashed lines.

The texture in the shear zone varies little along the length of the zone. Thin lenses and discontinuous layers of clear, glassy, fine-crystalline, equigranular quartz, euhedral to tapered garnet, and limonite after euhedral pyrite are embedded in anastomosing mica zones (Figure 7). This fabric resembles a strongly flattened honeycomb geometry, with cell walls being the schistose micas, mainly muscovite. Millimeter- to centimeter-scale chevron folding of schistosity is locally present.

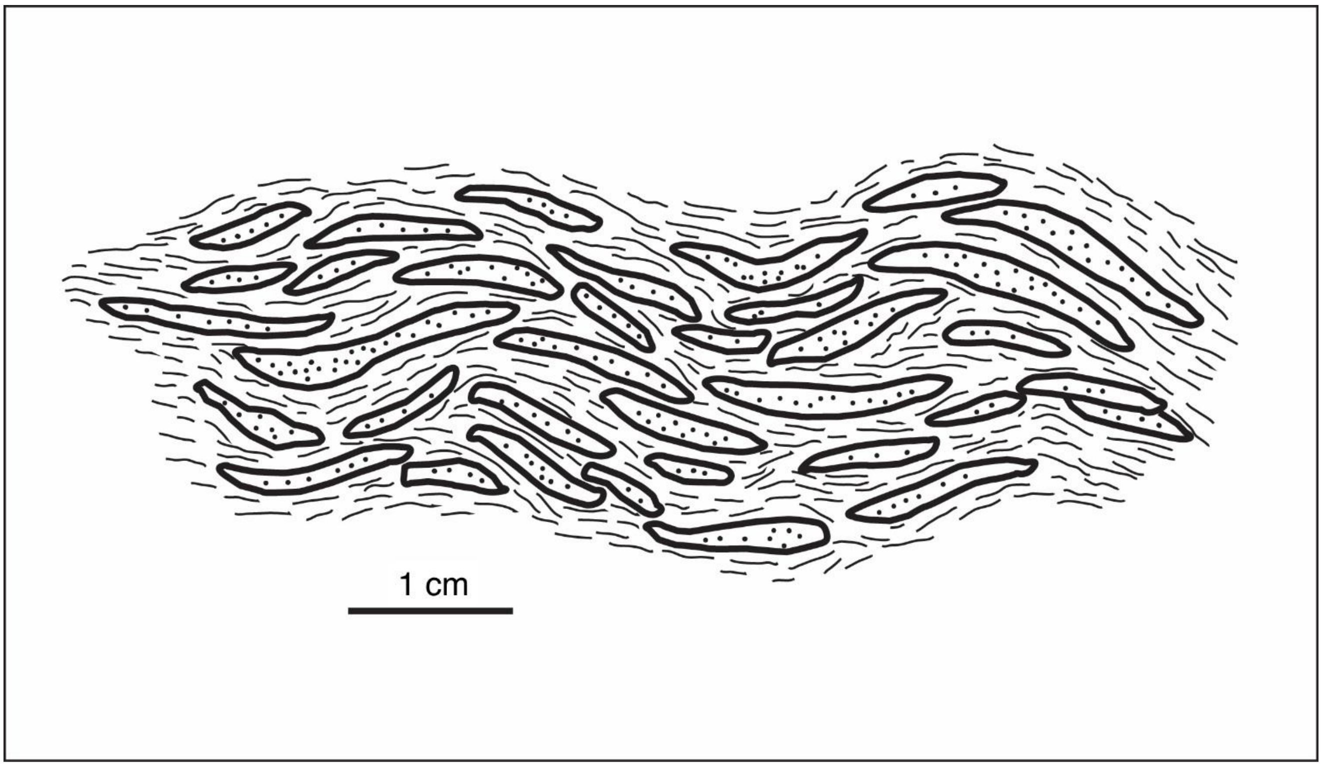

Figure 7. Sketch of a typical Mine Mountain shear zone texture, muscovite-quartz schist. Fine-crystalline, equigranular quartz forms lenses; aligned, anastomosing muscovite around lenses is represented by lines: dubbed a ‘marching worms’ texture.

Other ductile shear zones.

Other retrograde shear zones are present across the region, including the Pinnacle Mountain trail shear zone (Figure 6B). Garnet-muscovite shear zones are present as low ledges or pavements in isolated areas of TG. The orientation of schistosity is approximately parallel to the foliation or compositional layering of adjacent gneiss. Along US Rt. 276 east of Caesars Head in Cleveland quadrangle, a one-meter thick shear zone composed of minor fine biotite, coarse muscovite, and quartz within muscovite TG shows S-C structure indicating top-to-the-SW movement. Centimeter-scale, gently plunging, overturned folds in the shear zone also verge southwest. Several NE-striking, SE-dipping shear zones (<1 m wide to map scale) of garnet-muscovite-quartz with two intersecting schistosities are present in northern Sunset quadrangle on Wadakoe Mountain, Howell Mountain, and along Sunset Community Road northeast of Sunset, SC (Garihan, 2005b, map unit PMc). Along Sunset Community Road, the muscovite lineation on schistosity plunges 40° in the direction N50°E, consistent with regional top-to-the-SW overall movement on the majority of shear zones. Micaceous shear zones also occur within TG along the lip of the Blue Ridge Front (circled areas, Figure 21).

Secondary Fabrics, Chauga River Formation

In the Mountain Bridge Area, Chauga River Formation garnet schist and garnet gneiss/metasiltstone in the hanging wall of the Eastatoee fault forms a continuous belt of resistant rocks between Salem and SM quadrangles (Figure 1b). Schistosity in Chauga River Formation rocks is a secondary foliation, as indicated by intrafolial folds and lenticular amphibolite enclaves preserving internal isoclines with foliation truncated at the margins.

Two end-member lithologies, locally interlayered, make up the range in compositional variation. The first is a hard, dark-gray, fine-crystalline, poorly layered, equigranular metasiltstone containing garnet, muscovite, biotite, and feldspar that is locally porphyroclastic, and quartz. The second is a schistose rock that is a dark, fine- to medium-crystalline garnet-muscovite-biotite button schist. Almandine garnet (1-2 mm, up to 5 mm) is idioblastic.

Shear fabric, folds, and boudinage are common in ledge and cliff exposures of Chauga River Formation rocks (Figures 8a, b, c). Shear fabric is particularly well-developed in schist in Sunset, Eastatoe Gap, Salem, and Standingstone Mountain quadrangles. Button schist consists of coarse muscovite flakes or aggregates of finer muscovite that form conspicuous buttons in a groundmass of fine-crystalline biotite.

Item 4 – Discussion of Gravitational Collapse

In the study area, crustal instability in a thickened, deformed thrust stack is interpreted to have led to an episode of gravitational collapse, which was predominately top-to-the-SW. Post-compression gravitational collapse in the evolution of world-wide mountain systems has been described by Dewey (1988). Crustal 'gravitational collapse' is defined by Rey and others (2001, p. 439) as: *"The gravity-driven ductile flow that effectively reduces lateral contrasts in gravitational potential energy."* In their regime termed 'divergent collapse', material particles move away from the region of high potential energy, that is the thickened, deformed domain, as would be expected in a subduction zone or continent-continent collision tectonic setting.

Figure 8a. S-C' fabric, Chauga River Formation garnet button schist, Eastatoe Gap quadrangle. S surfaces dip gently left, C' surfaces dip steeply upper left to lower right. View is to the east; top-to-right shear sense. Lens cap is 3 cm.

Figure 8b. S-C-C' fabric, Chauga River Formation schist, road cut north side of Highway 11, Salem quadrangle (Figure 1b). Reflective S surfaces of muscovite buttons dip gently right. C surfaces horizontal. C' surfaces upper right to lower left. View is to the north; shear sense top-to-left. Upper scale is in cm.

Figure 8c. Asymmetric quartzo-feldspathic lenses, Chauga River Formation saprolitic schist. View is to the northwest; top-to-left shear sense. Hammer is 40 cm. Location forgotten.

Greenschist-grade features such as ductile normal faults, shear fabrics, and asymmetric quartzo-feldspathic lenses in schist are developed in Chauga River Formation garnet schist, TG, Poor Mountain Formation amphibolite, and Tallulah Falls Formation schist and paragneiss units. Extensional structures appear to have developed at all infrastructural levels within a presumably warm, plastic orogenic wedge of thickened crust. Under amphibolite facies conditions, these migmatitic, mylonitic rocks had been polyphase folded, thrust duplicated, and pervasively thickened by abundant felsic magmatism and metamorphic 'sweat-outs'.

In the study area, kinematic indicators show a range of movement directions: consistently top-to-the-SW, but also locally to the -S and -SE. These features are interpreted as resulting from gravitational collapse of the thrust stack, with movements focused at a rheological contrast near its base – within weak Chauga River schist, with more rigid Poor Mountain amphibolite above, and also at multiple levels in the crystalline thrust stack.

The extent of overall stack collapse in the study area, whole or some degree of partial collapse, is difficult to evaluate, based on the evidence. If many *through-going* detachment horizons at levels throughout the crustal stack (cf. Jolivet and others, 1990), one might suspect the collapse is relatively extensive. However, the more localized, distributed collapse evident here suggests partial collapse of unknown extent.

Timing of Events

A significant, indeed problematic, aspect of the region's tectonic history is that structures probably associated with different orogenic events show top-to-the-SW movement in the study region. This makes sequencing or timing of events of similar transport direction subject to interpretation. For example, sets of NW-striking, SW-vergent, overturned folds occur on both the Walhalla and Six Mile thrust sheets: one set *predates* the Seneca fault (that is, is truncated by its trace) and a later, NW-striking, SW-vergent, overturned fold set is *synchronous with or post-dates* Seneca fault emplacement (that is, folds deform the fault surface). In this case, the Seneca fault serves as an important marker event in distinguishing between earlier and later folding events involving SW transport. An interesting consideration for these SW-directed features is whether such structures are the result of a progressive deformational scheme (Fossen, 2018) or, as classically interpreted, are due to multiphase events.

A significant observation for timing is the direct linkages that exist between older features formed initially in the IP *outside* the Brevard zone and their later incorporation *into* the Brevard zone. Those structures are: 1) the older Eastatoee ductile thrust, which was incorporated into the Brevard zone and duplicated by later imbricate thrusting within it (Clendenin and Garihan, 2008); and 2) the top-to-the-SW (dextral) shear fabric marking Chauga River Formation horse blocks in the Brevard zone. Bobyarchick (1988, see his Figure 30) recognized in the Brevard zone what is called here the Eastatoee fault, as well as other thrusts that placed Henderson Gneiss *onto* Chauga River Formation rocks. In the South Carolina portion of the Brevard zone, Clendenin and Garihan (2008, See maps; 2012) mapped two major faults with Henderson Gneiss *onto* Chauga River Formation juxtaposition: the North and the South Boundary faults. These two faults bracket a complex zone of imbricated Henderson Gneiss and Chauga River Formation rocks that constitute the southeast part of the Brevard zone in South Carolina. The top-to-the-SW shear fabric is present in the Chauga River Formation (Figure 1b, part of the pale green band crossing six quadrangles), and the regional occurrence of this fabric negates it being unique to the Brevard Zone. By interpretation here it is older than the Brevard Zone.

If the emplacement of crystalline thrust sheets and development of the nearby Brevard zone were both part of Acadian orogenesis (Hatcher, 2001), then gravitational collapse of the thrust stack took place between those deformational events. If this is true, three distinct major tectonic events would necessarily have occurred within a limited time interval. This time interval would be < 20? million years, as interpreted from data of Hatcher and Merschat, 2006. An alternate explanation is that thrust sheet emplacement and subsequent gravitational collapse in the field trip area were part of Taconic orogenesis. Garihan (2018) suggests a Taconic age for displacements on contemporaneous Eastatoee and Seneca faults, based on mutual folding and Late Ordovician (Ranson and others, 1999) TG intrusive relationships in Sunset and Eastatoe Gap (Garihan and others, 2005b) quadrangles.

Henderson Gneiss in the footwall of the Eastatoee fault is mylonitic where present in the Mountain Bridge area. Widespread sigma, delta, and S-C and S-C-C' shear sense indicators in Henderson Gneiss are top-to-the-SW (dextral). These shear sense indicators were assigned to 'earlier Alleghanian' mylonitization by Bobyarchick (1988). Dennis (2007) gives Mid-Late

Devonian ages to mylonitic Henderson Gneiss. Hatcher (2001) assigns the dextral, 'chlorite-muscovite stable' S-C fabric in the Brevard zone to 'late Paleozoic' (Alleghanian) reactivation. In the immediate footwall of the ductile Eastatoee fault, Henderson Gneiss typically is modified to a fine-crystalline, recrystallized texture with small microcline augen porphyroclasts remaining (Garihan and Clendenin, 2007).

Here the Chauga River dextral fabrics are considered older than the Alleghanian and possibly older than the Acadian. If the explanation offered here is true, its extensional fabrics developed initially during top-to-the-SW gravitational collapse at or near the base of the thrust stack. Such regional shear fabric developed in the Chauga River prior its incorporation into the Brevard Zone does not, of course, preclude later reactivation or displacement by dextral Acadian or Alleghanian events.

Item 6, Tectonic Summary – Description of Thrusting and Back Thrusting

In Cleveland, Table Rock, Standingstone Mountain, and Zirconia quadrangles (Figure 9), the south-directed, broadly arcuate Caesars Head fault system has emplaced Table Rock gneiss (TG) generally southward over Six Mile thrust sheet rocks (Compton and Garihan, 2013). The Seneca fault and overlying rocks were carried in the hanging wall of individual Caesars Head faults (shown by the blue arrows, Figure 10).

The eastern-most remnant of the Caesars Head system fault system is preserved as a klippe on Hyde Mountain in southern Zirconia quadrangle (Garihan and Ranson, 2008) and adjoining northern Slater quadrangle (Garihan and others, 2005a). There TG augen gneiss rests on the Six Mile thrust sheet (Tallulah Falls gneiss). The isolated klippe at Hyde Mountain is ~7 km southeast of the erosional trace of the nearest Caesars Head fault, located across a NE-striking zone of complex oblique-slip faulting (Figure 9). Clearly the hanging wall cover rocks of the Caesars Head faults were regionally more extensive than the erosional remnants currently present.

Back thrusting has deformed the footwall rocks. The SW- to SE-directed compression associated with emplacement of Walhalla rocks over Six Mile rocks has broadly folded the Walhalla rocks, Six Mile rocks, and the intervening Seneca fault surface into upright to inclined, E-W- and NE-striking folds. These structures are present southeast of Caesars Head, along and southeast of Campbell Mountain (Figure 10).

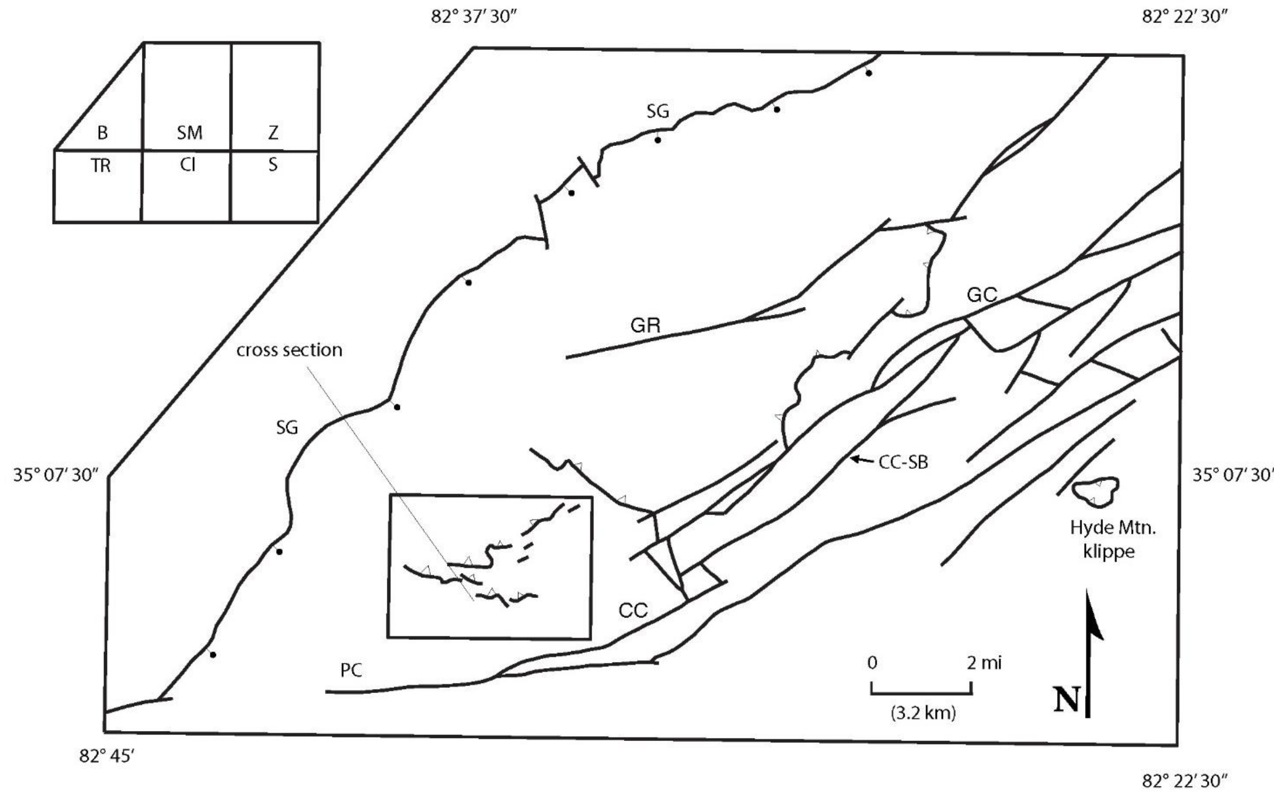

Figure 9. Generalized fault map. Quadrangles: Brevard- B; Standingstone Mountain- SM; Zirconia- Z; Slater- S; Cleveland- Cl; Table Rock- TR. Major faults: Civitan Camp fault- CC; Cox Creek-Short Branch fault- CC- SB; Gap Creek fault- GC: Green River fault- GR; Palmetto Cove fault- PC; Slicking Gap normal fault, with bar and ball on the downthrown side- SG; Caesars Head system faults- open sawtooth lines. Location of Hyde Mountain klippe outlier is shown. Rectangle is the location of Figure 10. Cross section location is for Figure 11.

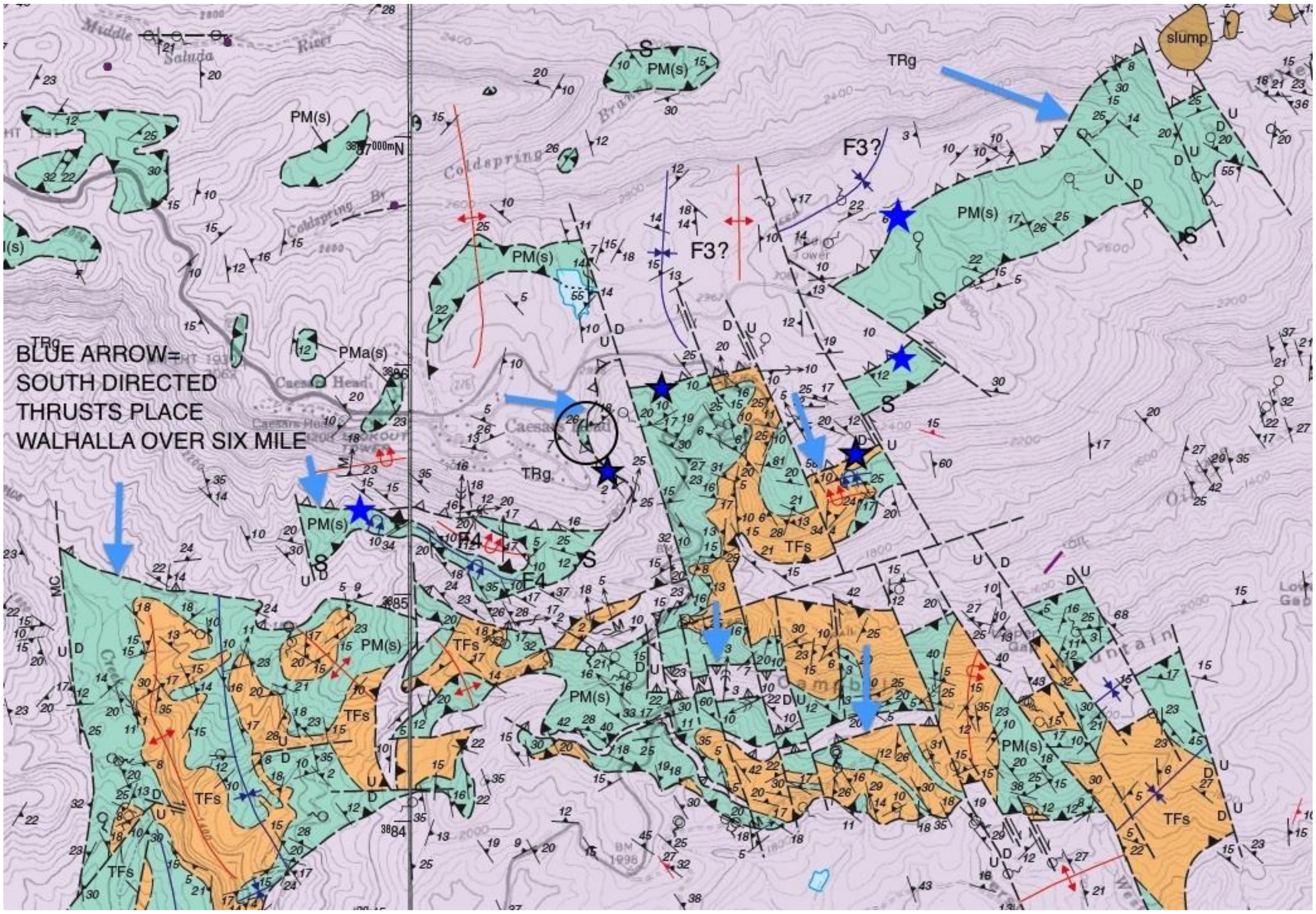

Figure 10. Geologic detail. Caesars Head system faults- open sawtooth lines, blue arrows; Seneca fault- closed sawtooth lines, labeled S. Eastern Table Rock (left) and western Cleveland (right) quadrangles. Walhalla gneisses- TRg, pink; Tallulah Falls schist- TRs, orange; Poor Mountain amphibolite- PM(s), green. The back thrust, labeled with blue stars, places Table Rock gneiss (Walhalla thrust sheet) south over Poor Mountain Formation (Six Mile thrust sheet). Location of Figure 10 is the rectangle on Figure 9. Circled area is Sunday Optional Stop 2a-3.

Item 6 – Discussion of Thrusting and Back Thrusting

Alleghanian(?) NW-directed thrusting was accompanied farther south and east by back thrusts of the Caesars Head brittle fault system. During the back-thrusting event, Walhalla thrust sheet rocks were thrust to the southwest, south, and southeast. Macro-scale E-W folding associated with southward back thrusting affected Six Mile sheet rocks and folded and truncated the older, collapse-related Pinnacle Mountain trail shear zone (Figure 6B). The NW-directed thrust is referred to as Alleghanian(?) because early- and mid-Paleozoic events in the IP tend to be ductile in nature, and associated Caesars Head faults are brittle features.

The array of Caesars Head hinterland-directed back thrusts is shown in Figures 9 and 10. An interpretative cross section (Figure 11) shows their structural relationship to the NW-directed Paleozoic thrust in SM. At the Dismal Creek location Henderson Gneiss, the Eastatoee fault, and Chauga River Formation rocks have been duplicated at the apparent leading edge of the Paleozoic thrust (Figures 4a, 11 cross section). The Caesars Head back thrusts emplaced Walhalla thrust sheet TG generally southward over Six Mile thrust sheet rocks. "Hidden" thrusts also are present that place TG over TG in the hanging wall of at least one Caesars Head back thrust. An example is seen in the Rainbow Falls hike.

A number of conditions have been described that may result in back thrusting. Ferrill and Dunne (1989) indicate back thrusts, and consequently hinterland-verging folds, develop when forward progression along a thrust surface is impeded at a branchline or tip line location; subsequently motion is hinterland-directed. Folding also has been related to the inhibition of forward thrust fault propagation (Butler and Coward, 1988). Meso-scale field observations by Serra (1977) suggest back thrusts form at or near the base of a thrust ramp when a rigid unit encounters resistance during foreland motion. Speculatively, if the mass of unlayered, rigid TG made it difficult to nucleate more NW-directed thrusts, back thrusts might develop at the higher structural levels of rheologically diverse Six Mile rocks and then propagate downward by underthrusting. The thrusts also might be positioned to utilize older strain softened zones in TG or form near weaker ductile shear zones already present.

The Slicking Gap normal fault may merge with the Alleghanian(?) thrust at depth (Figure 11). The fault either formed during relaxation of Alleghanian(?) compression or during Mesozoic extension (Garihan, 2018; See discussion of Mesozoic faulting sequence).

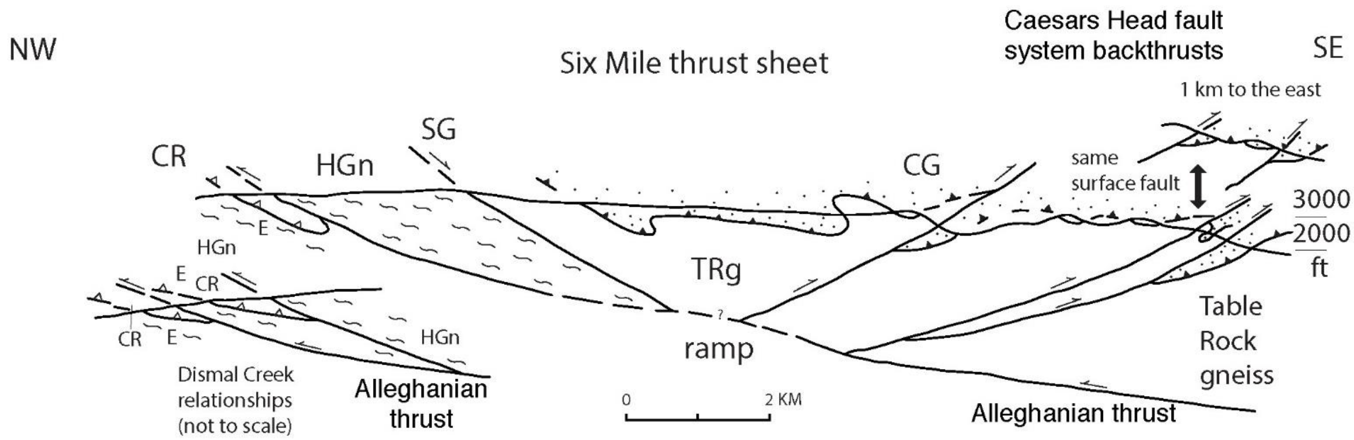

Figure 11. Interpretive cross section across Standingstone Mountain and northern Cleveland quadrangles. The Eastatoee thrust, E (open sawteeth), has Chauga River Formation, CR, and Henderson Gneiss, HGn, in its hanging wall and footwall, respectively. The Alleghanian(?), NW-directed thrust cuts the Eastatoee fault, and it duplicates it at Dismal Creek. Shown is the relationship of this thrust to its hinterland-directed Caesars Head system back thrusts. Ramp is hypothetical. The Slicking Gap normal fault, SG, is interpreted to merge with the thrust at depth. Table Rock gneiss- TRg, Six Mile thrust sheet- dotted pattern. Sawtooth line between Six Mile thrust sheet and TRg is the folded Seneca fault. Camp Greenville- CG. The first back thrust southeast of CG is shown in Figures 25a, 25b. Cross section location is shown on Figure 9.

Field Trip Stops – Saturday.

Field Trip Stops (where Lat/Longs listed: NAD83/WGS84)

Stop 1-1. Mine Mountain. On US Rt. 276, at Cedar Mountain, North Carolina, follow Reasonover Road to the east. Farther on, enter the Fawn Lake Access parking area, Dupont State Forest (35.160755, -82.604498). From the parking area and information kiosk, walk west (left) uphill along Fawn Lake Road. At the sign to the west (left), follow Mine Mountain Trail 56 uphill, gradually skirting the north side of the ridge to its crest. Pass an exposure and float of thinly layered, fine-crystalline biotite quartzo-feldspathic gneiss (Table Rock gneiss). Along the trail there are abundant pieces of fine-crystalline amphibolite and Table Rock gneiss. Watch for trail bikers!

Along the top follow the trail to the west to view fresh float and small ledge exposures of garnet-muscovite-quartz schist of the shear zone. We will stop on the trail at a small, underwhelming exposure (Figure 12) at the northern limit of the western limb of the eastern syncline (Figure 13, square position; 35.163823, -82.614735). A cliff exposure along strike to the south (Figure 14) shows top-to-southwest shear sense indicators. Time, large-group safety concerns, steep slopes, rhododendron thickets, scattered small exposures, and private property considerations all conspire to discourage viewing those locations farther south with better-developed shear sense indicators; they occur generally in the more micaceous rocks. Many such small exposures lead to a bigger picture!

The Mine Mountain shear zone was subsequently folded, with map-scale synforms showing arcuate axial traces (Figure 13). An S-C’ fabric is well developed, particularly along both limbs of the eastern synform. On the western limb of the eastern synform, the orientation of C’ shear bands indicate top-to-the-SW movement (Figure 15a). On that synform’s eastern limb, the sense of shear is reversed due to later folding, indicating top-to-the-NE (Figure 15b). The Mine Mountain shear zone is truncated to the north by a NE-striking fault of unknown displacement.

Figure 12. Small exposure of garnet-reflective muscovite-quartz schist at the end of the Mine Mountain trail traverse. C' surfaces- array of white lines. View approximately to the east; interpretation of C' surfaces: top-to-right (south). Location is at square on Figure 13.

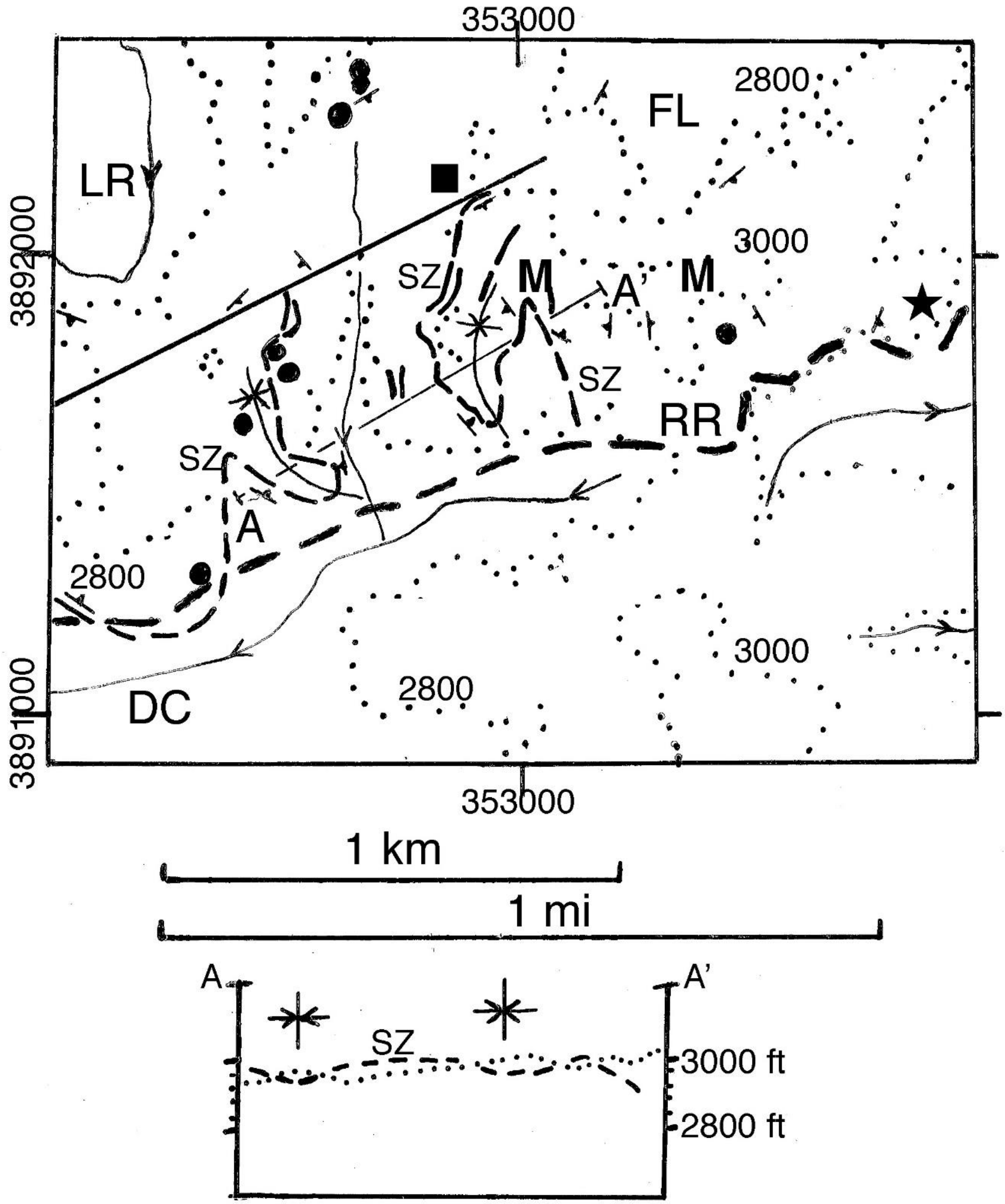

Figure 13. Geologic map and cross section of the Mine Mountain area, southwestern Standingstone Mountain quadrangle. Duncan Creek- DC, Fawn Lake- FL, Little River- LF, Mine Mountain- **MM**, Reasonover Road- RR, Mine Mountain shear zone- SZ, 2800 ft and 3000 ft topographic contours- dotted; springs- dots; end of traverse- square, Figure 12 location; Fawn Lake parking area- star, fault with unknown displacement - heavy line, cross section A–A' position and interpretation.

Figure 14. Shear zone cliff exposure on west limb of eastern syncline (Figure 13). Differentially weathered micaceous zones stand out in relief. View to east.

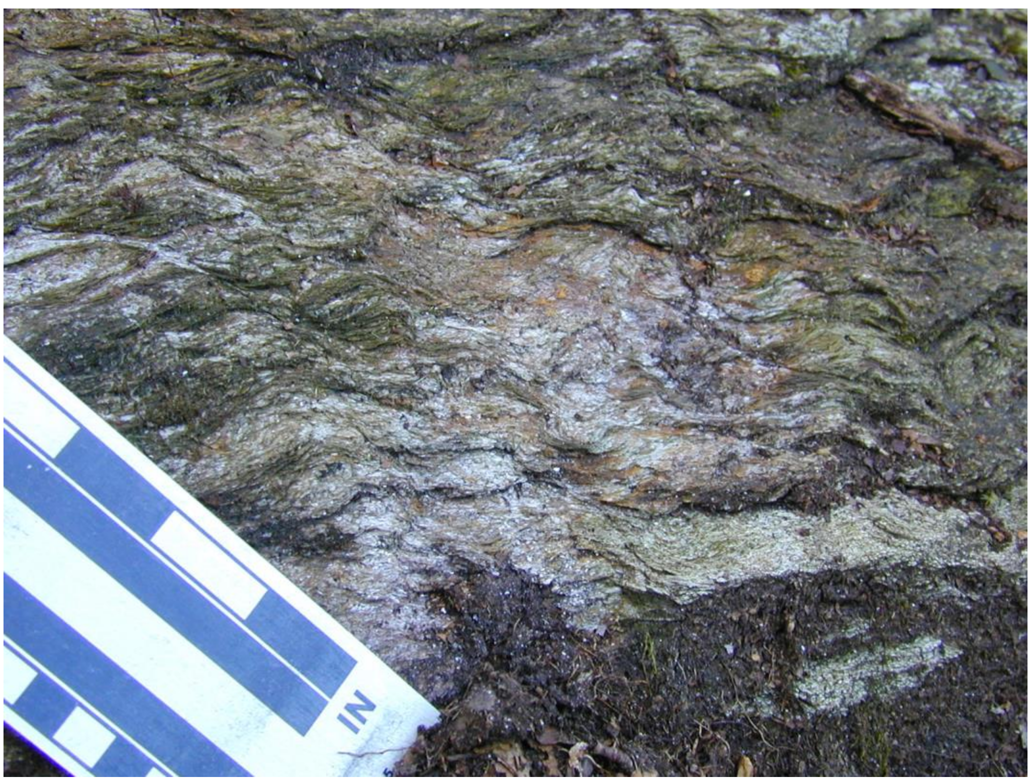

Figure 15a. S-C' fabric, *west limb* of eastern syncline (Figure 13). S surfaces dip gently left. C' surfaces parallel to edge of scale. View is to the southeast; top-to-right (SW) shear sense. Scale is in inches.

Figure 15b. S-C-C' fabric, *east limb* of eastern syncline (Figure 13). Prominent white quartz lenses. S surfaces dip gently left, approximately parallel to the pencil. C surfaces are horizontal. Poorly developed C' surfaces dip upper left to lower right. View is to the northwest; top-to-right (NE) shear sense. Folding of the shear zone has reversed the shear sense direction of Figure 15a.

Stop 1-2. Lunch. Holmes Educational Forest. Crab Creek Road (Figures 4a at HQ, and 5). The lunch site is along the Crab Creek alluvial valley, at the base of a ridge of resistant Chauga River Formation rocks (~400 ft relief). Trails cross exposures with a variety of features all indicating top-to-SW.

If time permits, follow Wildcat Trail uphill to a ledge with small rotated boudins in Chauga River Formation muscovite-biotite gneiss/metasiltstone (UTM: 356063, 3900187) (Figure 16a). They are interpreted to be the result of back-rotation of "long" boudins in a felsic layer during dextral simple shearing (See Fossen, 2010, p. 275). Farther uphill, an exposure (UTM: 356018, 3900141) (Figure 16b) has a 4-5 cm thick schist layer sandwiched between hard, dark, poorly layered biotite-muscovite gneiss layers. Schistosity in the schist layer (N2°E, 28°SE) is discordant to compositional layering (N80°E, 35°SE) between gneiss and schist. Vergence of small folds, feldspar sigma structures, and small, sigmoidal quartz-feldspar lenses in the schist indicate top-to-SW movement. The meso-scale features in both exposures are attributed to southwest gravitational collapse.

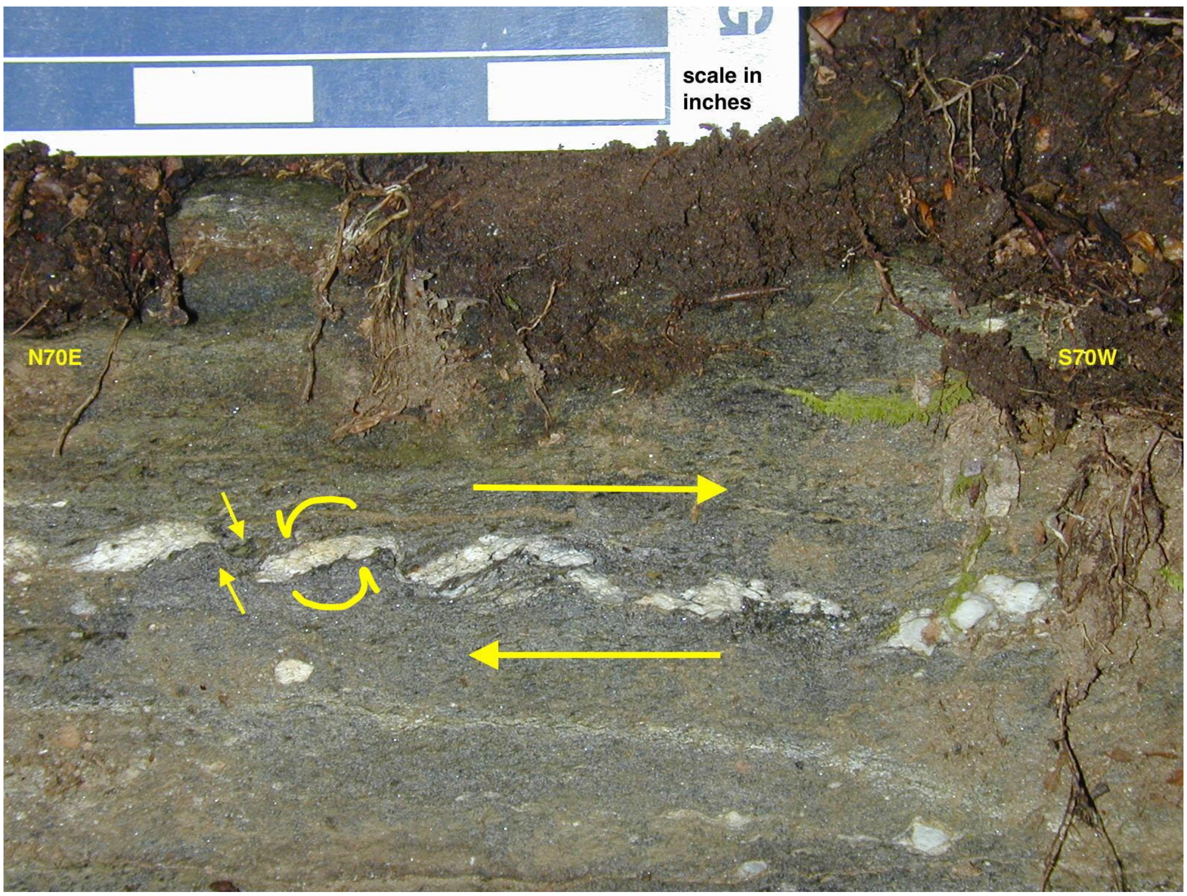

Figure 16a. Back-rotated boudins in felsic layer, Chauga River Formation. Attributed to dextral simple shearing. Wildcat Trail, Holmes Educational Forest.

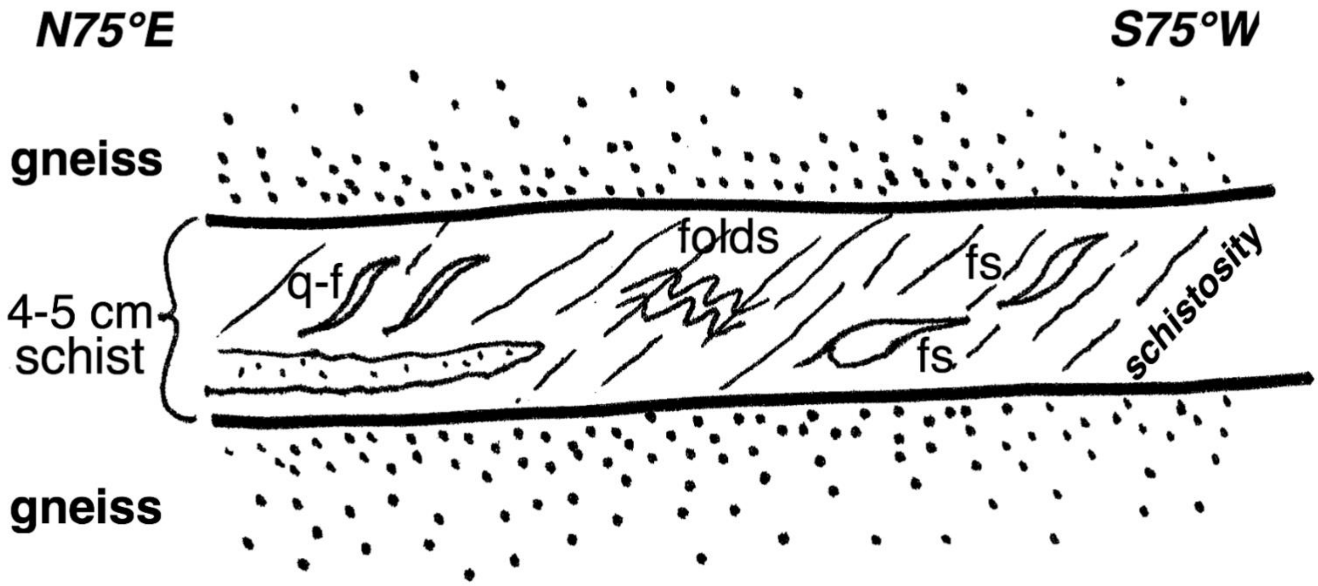

Figure 16b. Field sketch of top-to-SW shear sense features in thin schist layer, Chauga River Formation. Southwest vergence of small folds, sigmoidal quartz-feldspar lenses- q-f; feldspar sigma structures- fs. Dark, hard, poorly layered muscovite-biotite gneiss/metasiltstone- gneiss. Wildcat Trail, Holmes Educational Forest.

Stop 1-3. Dismal Creek. (35.2370, -82.5562). Continue east on Crab Creek Road (SR 1127). Turn south (right) onto Old CCC Camp Road. Exposures are on Old CCC Camp Road ~1 km south of its intersection with Crab Creek Road.

The purpose of this traverse is to see a splay of a NW-directed Paleozoic thrust, duplicating the Eastatoee fault. Later we will see back thrusts associated with this thrust.

We will traverse along the northeast side of the road. A sketch cross section shows the geologic relationships, south to north (Figure 17). Rock exposures are at the dot positions. Hanging wall Chauga River Formation is separated from footwall Henderson Gneiss by the Eastatoee fault (E). The more southern Paleozoic fault on the figure (P) is not exposed. A 10m, joint-bound exposure of Chauga River Formation occurs at the southern (upper) end of the traverse (Figures 17, point 1; 18a). A Paleozoic thrust (P) between points 3 and 2 (Figure 18b) has duplicated the Eastatoee fault. As exposed, it is interpreted to be the leading-edge splay of

Paleozoic thrusting. Approximately 60 feet of Henderson Gneiss is exposed along the road (Figures 17, at point 2; 18c), flanked north and south by Chauga River rocks. At point 3 below the Paleozoic thrust, the Chauga River Formation contains a lenticular quartzo-feldspathic lens (Figure 18d). The south-dipping, anastomosing fracture system in the exposure is likely related to the Paleozoic fault above. The northern Eastatoee fault position (Figures 17, point 4; 18e) lies between CRfm (Chauga River Formation) and Henderson Gneiss (HGn). An exposure of Henderson Gneiss mylonite is present below the Eastatoee fault (Figure 18f).

At the outcrop, the Chauga River Formation is micaceous with visible quartz and feldspar crystals up to 1 cm in length. The unit varies from micaceous to quartzose and feldspathic, which probably reflects differences in its protolith (shaly to sandy). At the Dismal Creek exposures, thin light gray, siltier layers locally outline isoclinal folds with axial planar schistosity. Shape-modified K-feldspar porphyroclasts (generally < 0.5-1 cm in long dimension, parallel to foliation) are rounded or tapered by deformation. Is this lithology metasedimentary or metavolcanic or both?

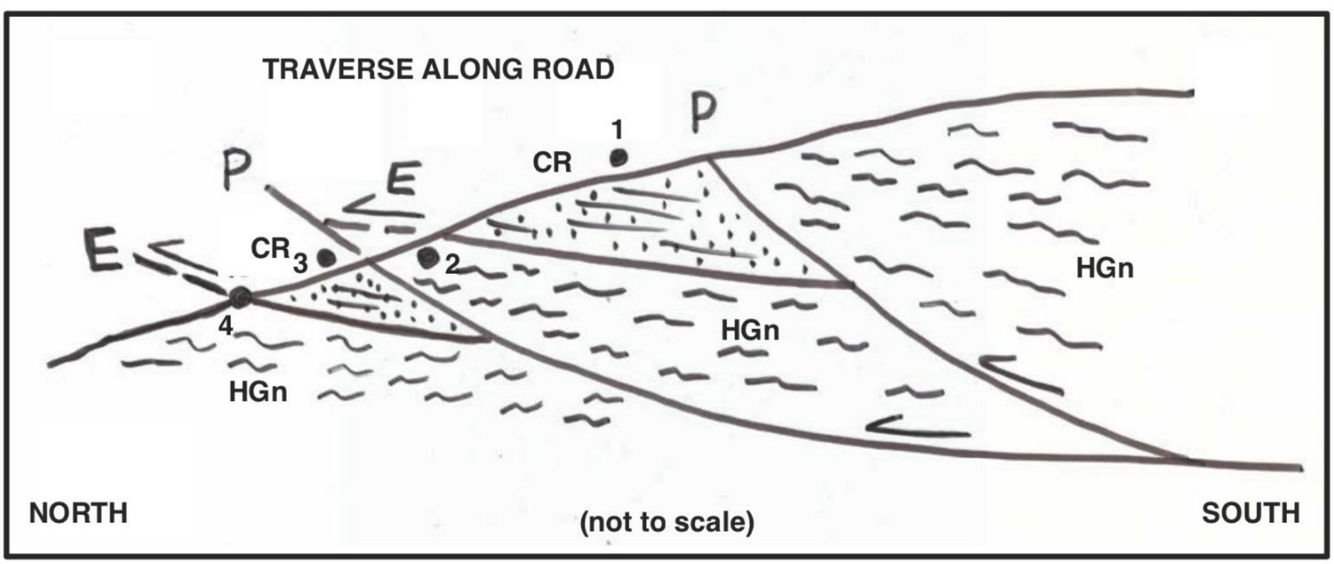

Figure 17. Schematic cross-section of fault relationships along Dismal Creek traverse: Eastatoee fault- E; Paleozoic thrust- P; Henderson Gneiss- HGn; Chauga River Formation- CR; locations along traverse- points 1 through 4.

Figure 18a. Exposure of Chauga River Formation rocks, point 1 on Figure 17. South end of Dismal Creek traverse. View to the northeast.

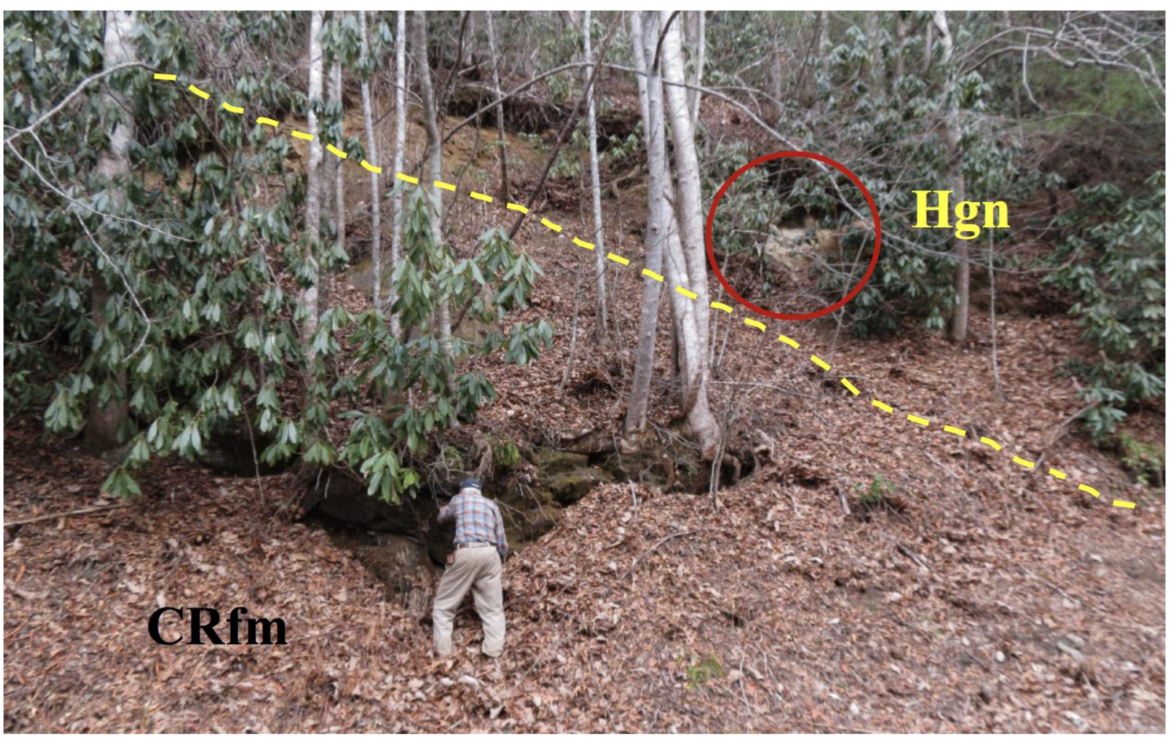

Figure 18b. View from point 3 (Chauga River Formation- CRfm) across Paleozoic fault (yellow dashed line) toward point 2 (Henderson Gneiss- HGn), Figure 17. View to the southeast.

Figure 18c. Henderson Gneiss at point 2, Figure 17.

Figure 18d. Exposure of Chauga River Formation at point 3, Figure 17. South-dipping fractures at orange notebook, related to the Paleozoic thrust above this exposure.

Figure 18e. Eastatoee fault (dashed line) between Henderson Gneiss (HGn) in the footwall and Chauga River Formation (CRfm) in the hanging wall, point 4, Figure 17.

Figure 18f. Henderson Gneiss exposure, a short distance north of point 4. Sheared augen are microcline. Shear sense?

Optional Stop 1-4. Shoal Creek. (35.230021; -82.595637). Continue south on Old CCC Camp Road. Farther on, turn west (right) onto Sky Valley Road (SR 1260). Park at its intersection with Dupont Road (SR 1257). Steep, jointed exposures are on the west side of the road (Figure 4a).

Walking north to south uphill on the west side, float indicates the approximate position of the unexposed Eastatoee thrust between Chauga River rocks and Henderson Gneiss. In the more schistose zones, coarser muscovite ductile fish ('buttons') with finer biotite inclusions are visible on schistosity surfaces. Sense of shear is top-to-SW (left) (Figure 19).

Figure 19. Dupont Road exposure, west of Shoal Creek. Chauga River Formation (location Figure 4a) S-C' fabric in garnet button schist. Schistosity within gold-weathering mica buttons dips gently right. C' surfaces dip gently upper right to lower left. View is to the west; top-to-left shear sense. Scale is in inches.

Stop 1-5. Triple Falls. (35.1995, -82.6169). From Cedar Mountain, NC follow Cascade Lakes Road. Turn east (right) onto Staton Road (in Transylvania Co.) continuing northeast. Park at the Hooker Falls Access Parking Lot, Dupont State Forest, NC. Traveling from Shoal Creek stop 1-4, follow south (left) on Dupont Road (in Henderson County) to the Hooker Falls Access Parking Lot (on the right). Stop location is indicated on Figure 4a).

From the parking lot (35.202140, -82.620194) follow Trail 27 southeast and cross the bridge over Little River with its pavements of jointed Henderson Gneiss. Continue east until you reach the intersection on the trail between the lower and middle cascades of the Triple Falls. At the trail intersection, a large flight of wooden stairs descend on the left to water-worn pavement exposures of the Henderson Gneiss at the base of the middle cascade (Figure 20a; Guidebook cover). The water descends on cascade faces defined by joints that trend N50^{O}E and are cut by another set of joints that trend N50^{O}W (Figure 20b, sometimes under water). The Henderson augen Gneiss at this location is mylonitic, and textures are best seen on wet pavement surfaces. **Careful: wet pavement <u>will</u> be slippery!!**

Figure 20a. Henderson Gneiss, middle cascade of Triple Falls, Little River (location Figure 4a). Dupont State Forest. Triple Falls, guidebook cover.

Figure 20b. Henderson Gneiss pavement at the base of middle cascade, Triple Falls. Lines are traces of northwest-striking joints. View downriver to the northwest.

Second Day Field Trip Stops

Sunday – Trip Group A.

Follow US Rt. 276 north past Caesars Head State Park, with its scenic views of Table Rock exfoliation dome, Table Rock reservoir, and the Inner Piedmont landscape. A Mountain Bridge Wilderness Area trail map is available at Caesars Head State Park headquarters. At the state line, the eastern Continental Divide (2910 ft), turn east (right) onto Camp Greenville Road (S-23-15), which immediately becomes Solomon Jones Road (SR 1559). Proceed 3.4 miles to Mulligan's View exposure, southern Standingstone Mountain quadrangle (SM), Greenville County.

Stop 2A-1. Mulligan's View. (UTM: 354246, 3888858).

At the Mulligan's View exposure west of Camp Greenville (Figure 21, at MV), the Seneca fault separates black hanging wall Poor Mountain amphibolite (Six Mile sheet) from footwall grey TG (Walhalla sheet). The Seneca fault in turn is folded and truncated by several SW-directed brittle thrusts of the Caesars Head fault system (Figure 22). Several are exposed in the cut (Figures 23a, 23b). This is an outstanding teaching outcrop for students to observe structural relationships!

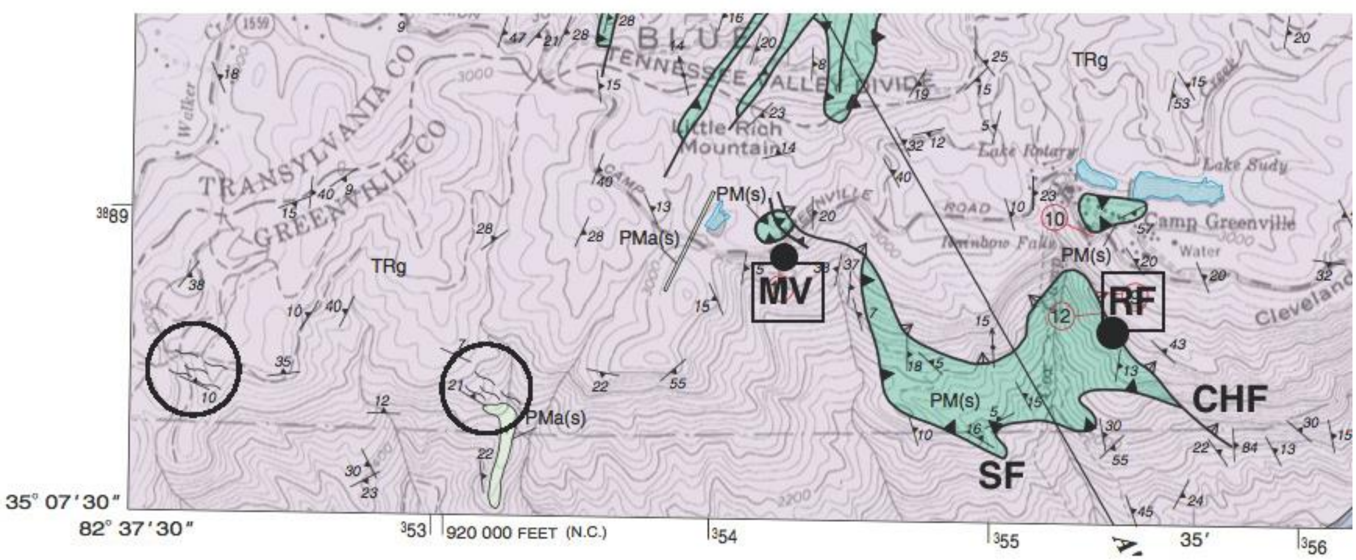

Figure 21. Geology of southwest corner of Standingstone Mountain quadrangle. Caesars Head fault- CHF, overrides Seneca fault- SF. Mulligan's View stop- MV, black dot; Rainbow Falls stop- RF, black dot. Poor Mountain Formation amphibolite- PM(s), green; Table Rock gneiss- TRg, pink. Collapse-related micaceous shear zones in TG- circled areas. 40 ft contours.

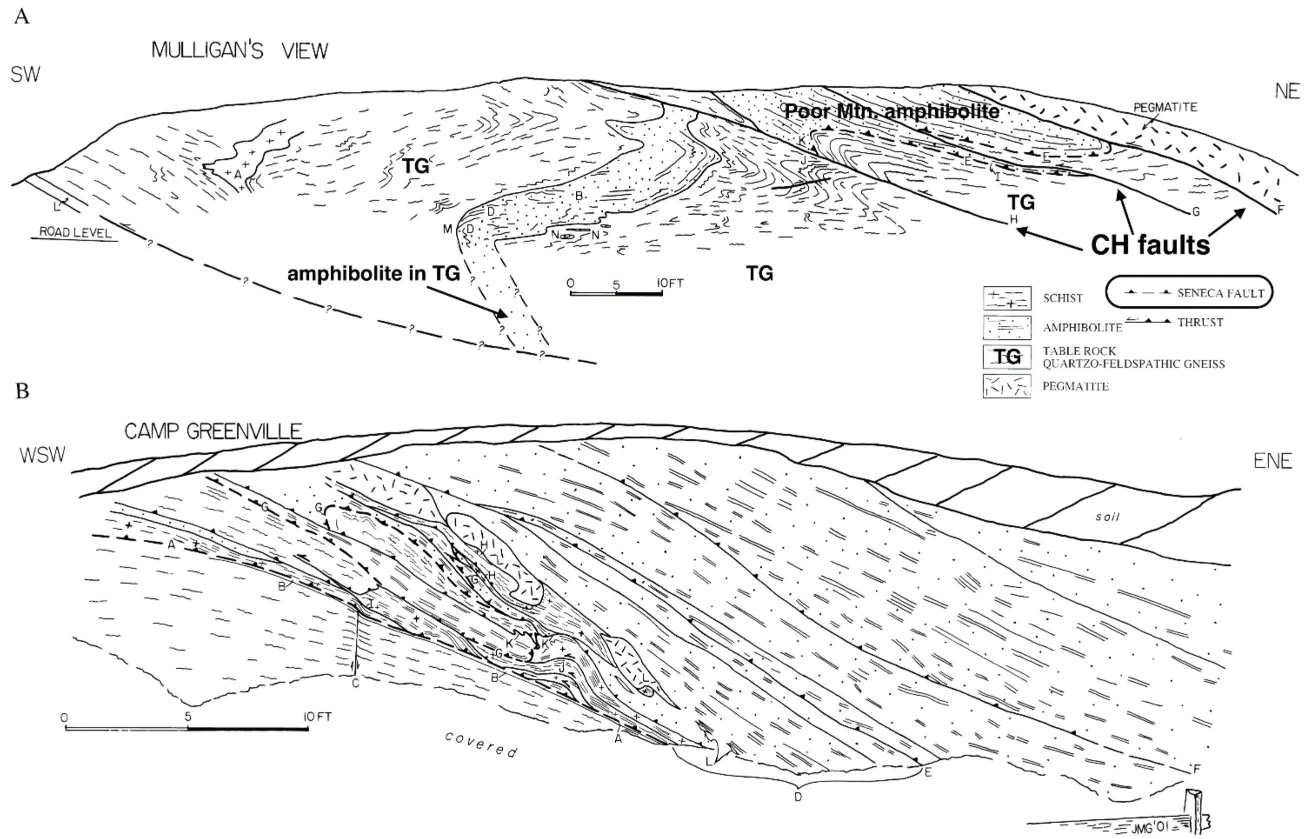

Figure 22. **A.** Mulligan's View, cross section sketch. SW-directed Caesars Head faults truncate folded Seneca fault. **B.** Camp Greenville cross section sketch; duplex above Seneca fault interleaves Table Rock gneiss and Poor Mountain amphibolite. Details of both cross sections (the letters) are given in Garihan (2001, CGS Guidebook).

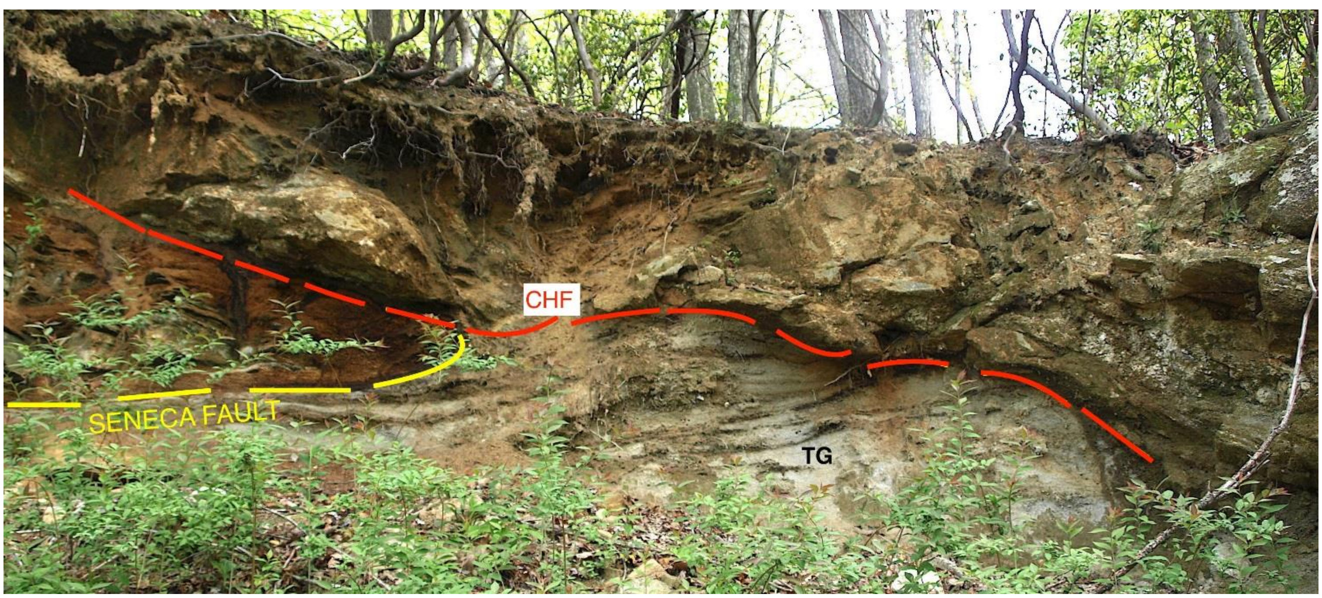

Figure 23a. Mulligan's View exposure. Caesars Head fault (CHF, red) overrides Table Rock gneiss- TG and folded Seneca fault (yellow). View northeast.

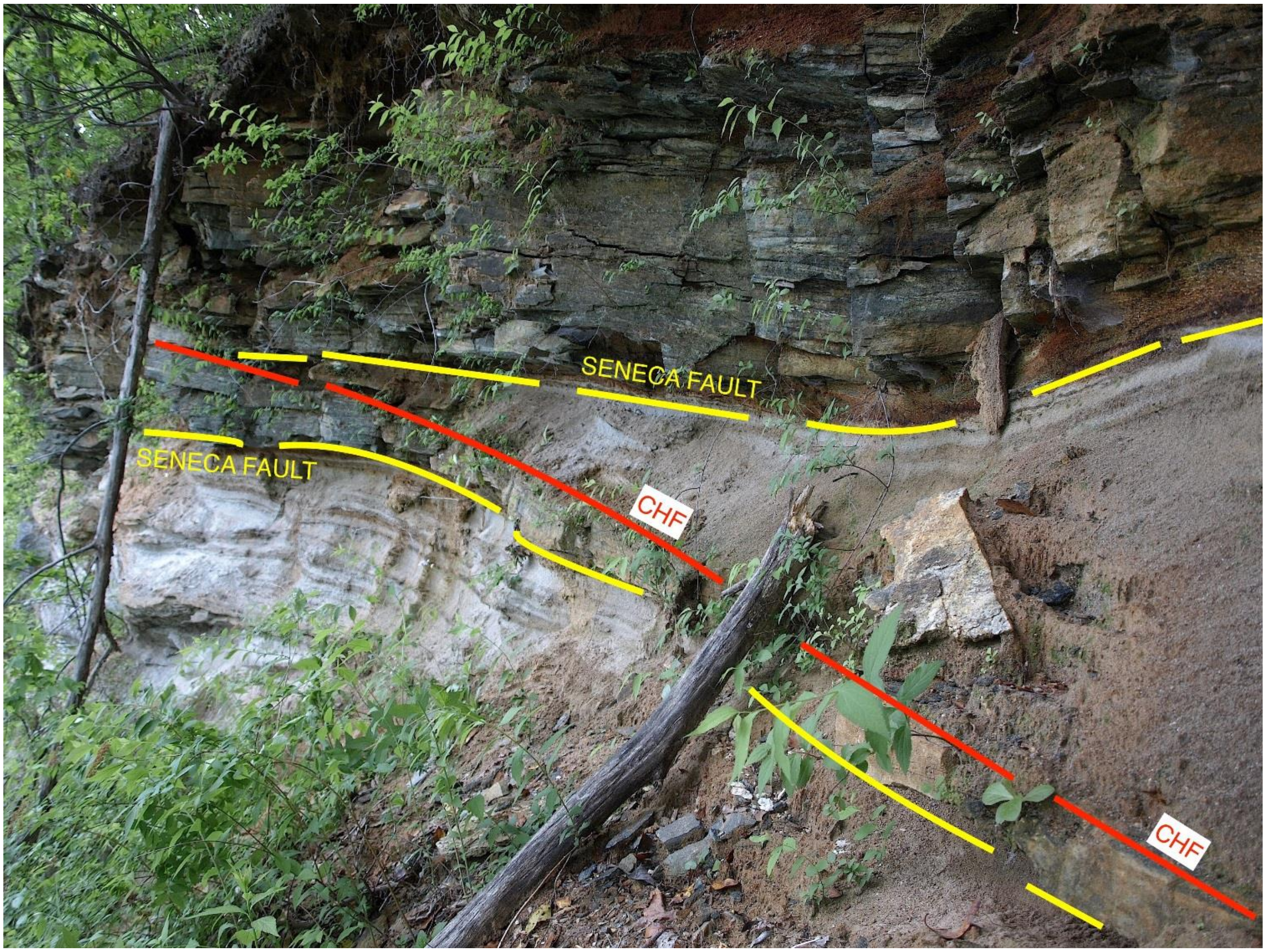

Figure 23b. Mulligan's View exposure. Seneca fault (yellow) below black Poor Mountain amphibolite is truncated by a Caesars Head system fault (CHF, red). Gray saprolite is Table Rock gneiss. Laterally CHF is intraformational to the amphibolite and difficult to recognize.

Continue east to Camp Greenville, southern SM.

Stop 2A-2. Rainbow Falls Trail. Through public access on the road is permitted *only* to Symme's Chapel; otherwise Camp Greenville is private property and permission *must* be obtained in advance to make stops within Camp property. Pass the Camp Greenville exposure of the Seneca fault (Figure 22 B), which has degraded since our 2001 CGS trip visit. Park at the Camp Greenville Office; walk west to trailhead, past exposures of weathered Table Rock gneiss. A Caesars Head system fault is exposed along the trail leading to Rainbow Falls on Cox Camp Creek (Figure 21, at RF). **Please be careful. Five sets of wooden stairs await. THIS STEEP, ROUGH TRAIL IS FOR EXPERIENCED HIKERS! Please stay in single file – you'll see why!**

As you move downhill, watch for an exposure where TG appears thrust discordantly onto TG. Farther down below the stairs, there are unusual meso-scale features to observe along a rock face of TG: an asymmetric amphibolite lens with internal folds; offset thin, sill-like amphibolite layers; and offset discordant felsic dikes. These features (Figure 24a) indicate small-scale brittle movements (left slips) have occurred along lithologic breaks, foliation surfaces, and along fractures at shallow angles to TG foliation. A quartz vein with bleached margins is tightly folded into chevrons. A poorly foliated quartz-feldspar lens is deformed into a Z fold with southeast vergence (Figure 24b); it is truncated below by a break with sinistral offset of its tapered end. Above the Z fold is a brown alteration zone; it is coated in places by a white mineral crust. This alteration zone is a fault and/or a water-flow conduit in otherwise fresh crystalline rock.

Figure 24a. Rainbow Falls trail. Interlayered TG (gray) and amphibolite (black) have experienced west (left) slippage along their contacts and along discordant fractures. Thin felsic dikes are left offset in the circled areas. A thin amphibolite layer is left offset between the arrows. Chevron-folded quartz vein below. View is to the northeast. Hand lens is scale.

Figure 24b. Rainbow Falls trail. Poorly layered quartz-feldspar lens in TG has been deformed into a Z fold with southeast vergence. The lens is left offset. Red alteration zone at the top. View is to the northeast. Pen is scale

At the end of our traverse (UTM: 355394, 3888622), well before Rainbow Falls is reached, a SW-directed Caesars Head back thrust has emplaced TG over Poor Mountain Formation amphibolite. A boudinaged pegmatite in TG and older protomylonite lie in the fault's immediate hanging wall (Figure 25a, 25b). Brittle fracturing has occurred along the TG – Poor Mountain Formation amphibolite fault contact; a small conjugate fold in amphibolite has been truncated by fault movement (Figure 25c). Thin green epidote layers in the amphibolite are strongly boudinaged within 0.5 meter below the fault (Figure 25c), likely the result of vertical loading by the overthrust crystalline rocks. **End of Rainbow Falls trail traverse.** Schist with S-C' structures lies below the amphibolite further down the trail, demonstrating that indeed we are looking at Six Mile rocks *below* TG and not simply a boudinaged amphibolite layer *within* TG.

Strangely enough, going back up is easier than coming down. Anyway… mind how you go.

Figure 25a. Rainbow Falls trail. Caesars Head fault, at the base of a boudinaged pegmatite in Table Rock gneiss. Arrow at fault position. Below the fault is Poor Mountain Formation amphibolite, on which a hammer (circled) lies. View is to the southeast.

Figure 25b. Same Caesars Head fault as Figure 25a, looking back toward the position of 25a. Fault is located at the hammer position (circled). Amphibolite compositional layering below the fault is nearly horizontal. View is to the northwest. Hammer is 40 cm.

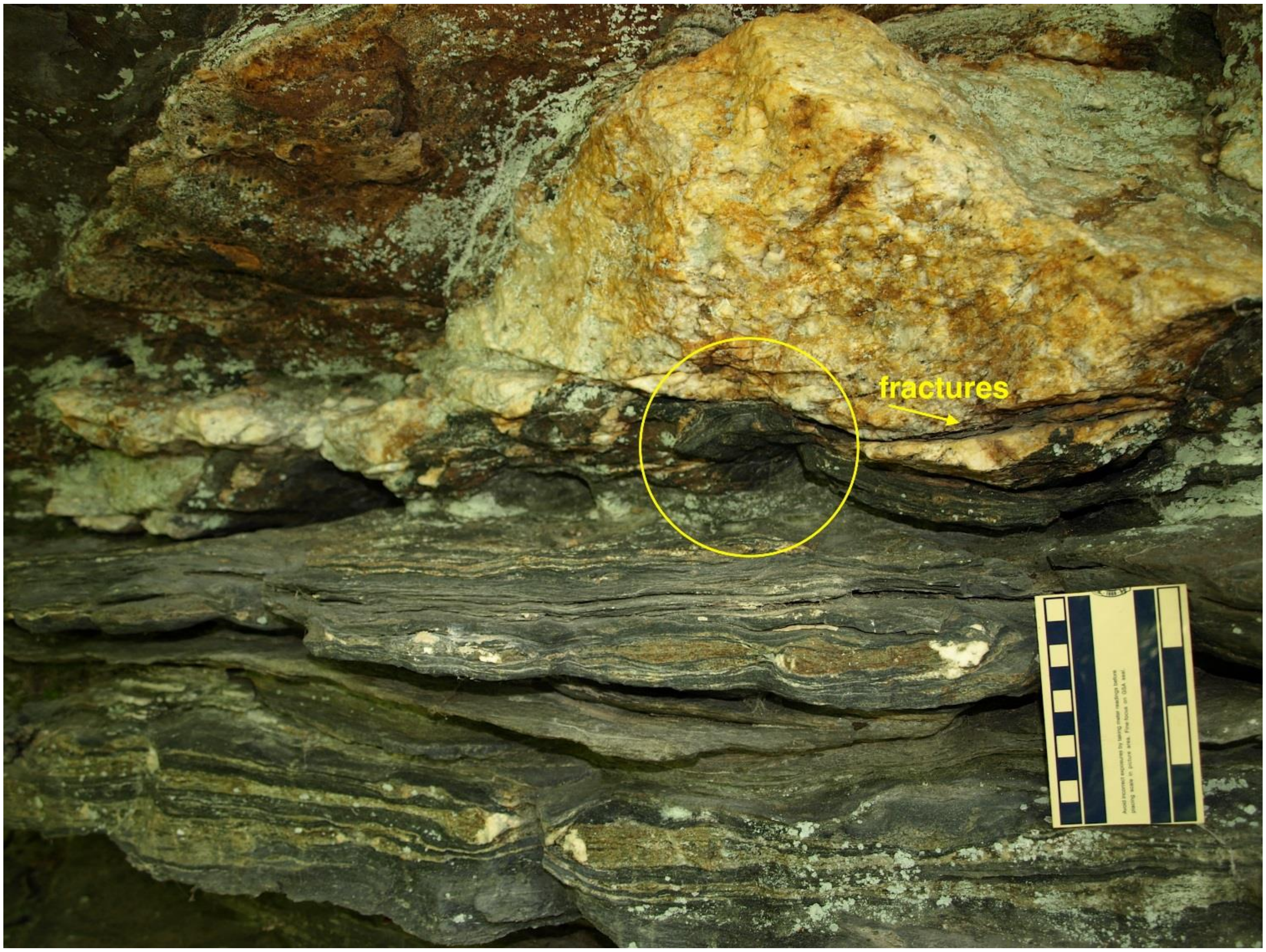

Figure 25c. Rainbow Falls trail. Close up of boudinaged, equigranular green epidote layers in amphibolite of the footwall. Broken quartz fillings occur at boudin ends. Fractures below the pegmatite have truncated a small conjugate fold (circled). View to the north. Left scale is cm.

Optional Stop 2A-3. Cliff Ridge. From Caesars Head Park Headquarters follow US Rt. 276 to the south. Park at Cliff Ridge Colony entrance (UTM: 352645, 3885989). Greenville County.

At this stop there is a relationship that, regionally speaking, is upside-down. We will take a short walk down Trail 14 from Rt. 276 and the Cliff Ridge entrance gate. The location is circled on Figure 10. The blue arrows on the figure are various Caesars Head system back thrusts. This exposure lies on a Caesars Head fault that places TG (Table Rock gneiss) southward over Poor Mountain Formation rocks. This particular back thrust can be traced laterally along strike, and it is marked on Figure 10 with blue stars.

At the exposure, exfoliated Table Rock gneiss sits on top of Poor Mountain Formation amphibolite layer (Figure 26). The amphibolite, covered by moss, lichen, and grey coatings, has been intruded along its compositional layers – and along a local, internal fault (oriented N20E°, 32°SE) – by sills of pegmatite. One prominent dike of pegmatite in amphibolite is folded into a Z-shape (a flattening effect of the overriding thrust?).

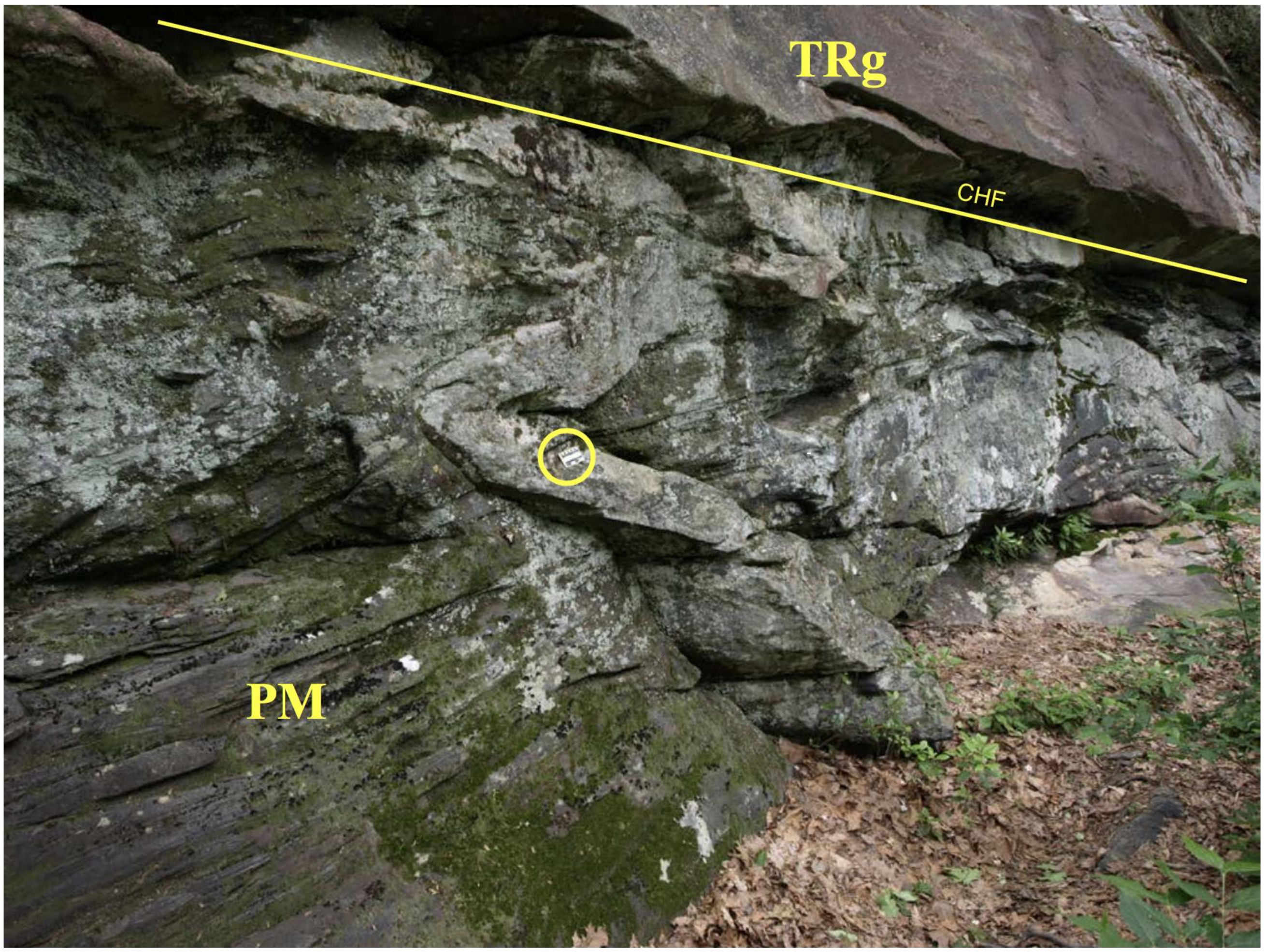

Figure 26. Trail 14 exposure, south of Cliff Ridge community. Rounded Table Rock gneiss- TRg, lies above compositionally layered Poor Mountain amphibolite- PM. Caesars Head fault- CHF, yellow line; this fault and stop location is the circled area on Figure 10. Scale (circled) sits on a folded pegmatite dike.

Optional Stop 2A-4. Pinnacle Mountain trail shear zone. Continue south on Rt. 276 to a pull off on the east (left) side of the road (UTM: 353111, 3885005). Walk south to Trail 20, then uphill.

The Pinnacle Mountain trail crosses a shear zone on an E-W ridge of Table Rock gneiss south of Caesars Head in northwest Cleveland quadrangle. At its south end the shear zone (Figure 6, B) is truncated by a back thrust of the Caesars Head fault system and is not present south of the thrust. The garnet-sillimanite-muscovite-quartz schist as a discrete zone dies out in gneiss at its north end. Shear-sense structures are present, but not well developed.

The texture of this shear zone is somewhat similar to that at Mine Mountain, but mineralogy differs. Sillimanite occurs as moderately- to well-aligned needles on thin, satiny (fine-crystalline) muscovite-quartz schistosity surfaces. Thin lenses and discontinuous layers of clear, glassy, fine-crystalline, equigranular quartz a few millimeters wide are enveloped by schistose, anastomosing buttons of fine- to medium-crystalline muscovite and scattered limonite after euhedral pyrite. Euhedral garnet (generally 1-2 mm) grew both in quartzose lenses and schistosity.

Tight-close chevron folds up to a few centimeters across deform aligned sillimanite needles on the dominant schistosity surfaces. At the chevron fold crests and troughs (fold noses), the sillimanite needles are sharply bent. The dominant schistosity is warped by younger gentle, upright folds.

The Pinnacle Mountain trail shear zone was folded along an E-W strike and truncated by a Caesars Head thrust (Figure 6, B). The addition of sillimanite in Pinnacle Mountain trail rocks suggests that the Caesars Head thrust fault beneath and truncating it brought up an older ductile shear zone in its hanging wall that initially was at sillimanite-grade temperatures consistent with greater depths in the thrust stack. The absence of sillimanite in greenschist shear zone rocks at Mine Mountain, located north of any known Caesars Head back thrusts, suggests its contemporaneous development occurred at a shallower, cooler position in the thrust stack.

Second Day Trip Stops

Sunday – <u>Trip Group B</u>.

Geology of the South Carolina portion of the Saluda quadrangle

Southern Saluda quadrangle lies across the Blue Ridge Front, southeast of the Brevard zone, in a rugged part of the IP referred to as the 'Hendersonville Bulge' (Hack, 1982) or the 'Columbus Promontory' (1993 CGS Guidebook). It is a complexly faulted region with faults dominantly of ENE, NE (N50°-70°E), and NW strikes (Garihan and others, 2010, geologic map). This brittle, oblique-slip fault system includes significant down-to-east normal faults. The sinuous trace of the gently-dipping Seneca thrust runs along the steep, south-facing slope of the Front where the Cliffs at Glassy are located (Figure 27).

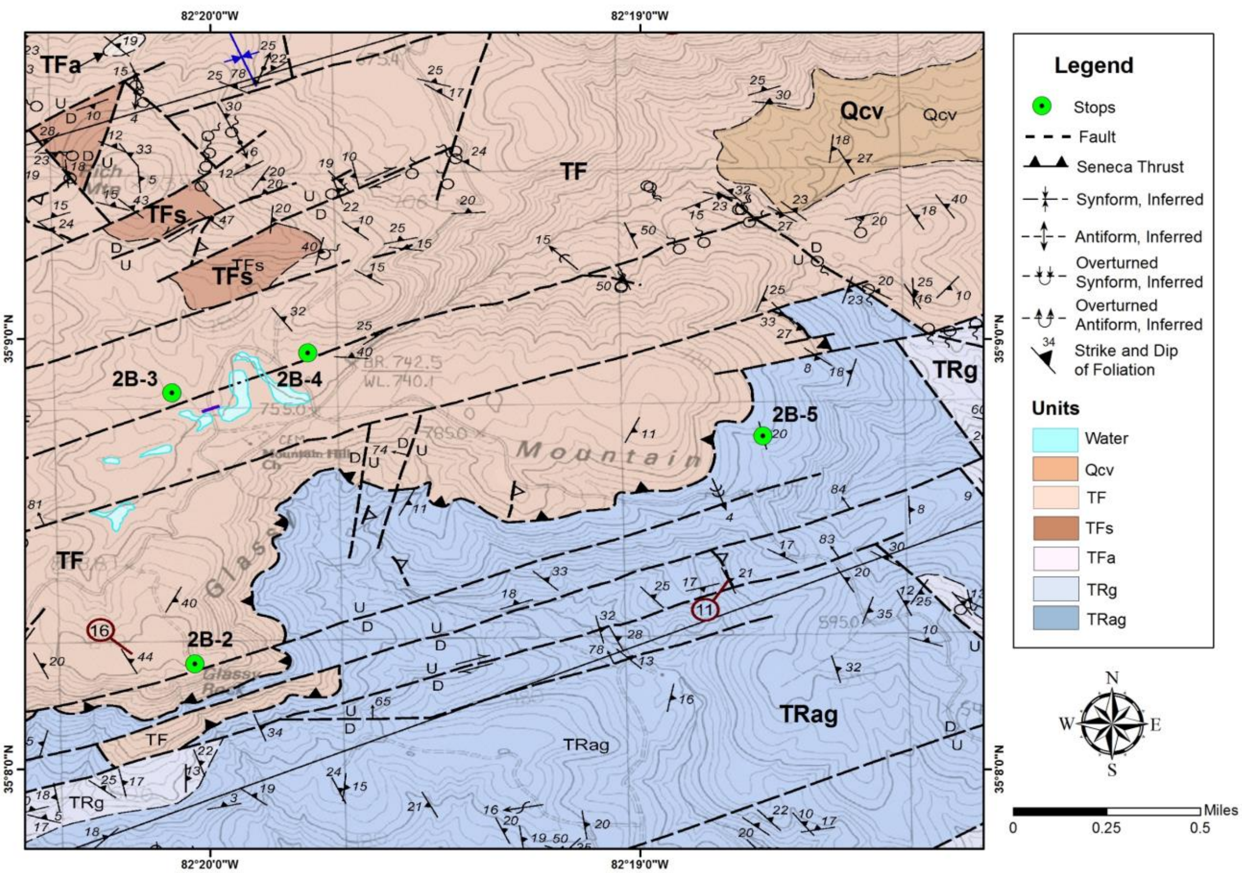

Figure 27. Geologic map of the Glassy Mountain area, showing the sinuous trace of the Seneca thrust fault on the south-facing slope and the complex brittle fault system. Trag (augen gneiss) and Trg (TG) units occur in the Seneca thrust footwall; Tf, Tfs and Tfa are hanging wall Tallulah Falls rocks that lie above the Seneca fault. Part of Saluda quadrangle.

Tallulah Falls Formation gneiss and schist, with minor amphibolite, are in the hanging wall of the Seneca fault with Table Rock gneiss and mylonitic augen gneiss as footwall rocks. The easternmost surface exposures of all regional Walhalla thrust sheet gneisses (TG and augen TG) occur in eastern Saluda quadrangle. This is the result of a prominent normal fault that drops them to depth on its east side, exposing only structurally higher Tallulah Falls rocks at the surface.

The purpose of this excursion is to see geologic and hydrologic features and conditions present at Pax Mountain and at the Cliffs at Glassy Community along US Rt. 11, west of Gowensville, SC. Permission is required to enter the property.

The Glass Mountain area lies along a scenic, rugged portion the Blue Ridge Front (locally 1500 feet of relief). Appreciable growth in the number of new homes, support services, and property values has occurred in the area in the past 30 years. A drainage divide bordering the restricted-access Greenville Watershed area lies immediately north of The Cliffs at Glassy community. West-flowing streams there south of the state line feed the Poinsett (North Saluda) Reservoir, a major regional surface water supply for the upstate. Environmental protection of this water supply resource is an on-going concern for all who utilize the surface water and ground water and hike in the area. The Heritage Trust Blue Wall Preserve has provided hiking trails in the area east of The Cliffs community, restricting further housing development. Water supply lakes for Landrum, SC also lie at the base of the Escarpment. Occasional small magnitude earthquakes (m=2+) occur in the state line area. Therefore, there is potential for seismic and accompanying landslide risk along the steep edge of the Escarpment.

Stop 2B-1: Pax Mountain.

Road sign says “Packs Mountain Road”. Tigerville quadrangle.

Pax Mountain is a steep N65°E ridge (maximum elevation 415 m) in the Tigerville quadrangle rising above the surrounding Piedmont . Numerous northeast-trending lenses of resistant siliceous cataclastic rocks (SCR) are arranged in east-northeast, right-stepping patterns and form one or two zones along the Pax ridge crest and flanks. Their geometry indicates sinistral faulting. Our experience mapping SCR indicates they normally indicate the immediate proximity of younger faults (even if these are "no see-ums"); damage zones and slickenlines related to the younger faults may deform the SCR bodies. Many springs on both sides of the ridge are present and aligned along the northeast trace of these younger faults. Spring locations are an aid in tracing the faults laterally when mapping.

The Pax Mountain fault lies between the two parallel zones of SCR bodies (Figure 28). The Walhalla nappe (grgn map unit), the Six Mile thrust sheet (TF map unit), and the intervening ductile Seneca thrust, are repeatedly offset by a dominant set of N60°-75°E faults in Tigerville quadrangle; both oblique, left- and right-lateral offsets are produced by that fault set. Groundwater exploration in fracture zones of crystalline metamorphic bedrock was described for the upstate Piedmont by Snipes (1981) and Snipes and others (1984). Geologic and hydrologic conditions associated with drilling water wells and yields at Pax Mountain were described by Snipes and others (1986). Kaolinitic clay (presumably weathered fault gouge) along fractures inhibited water flow and yield. Local people are well aware of the kaolinitic clay in their wells, and they aptly refer to it as 'mountain lard'.

This vantage point provides a spectacular view north toward the Escarpment and homes of The Cliffs at Glassy community. The conspicuous bald is Round Mountain (summit 850 m). To the right is broadly flat-topped Hogback Mountain, with its WSPA broadcast towers. Summit elevation is 3211 feet (about 975 m). Antenna height is 459 ft; a severe ice storm with high winds in February 2009 caused the older transmitter towers to collapse. Between 1926 and 1933, the developer of the "Blue Ridge Forest" built a golf course, a pond, and roads for home sites atop Hogback Mountain and the ridge to the west. Upon his death the project was abandoned, with just one lot sold to an artist (Edgar Woodfin, personal communication). We will visit Glassy Rock at the top at the flagpole.

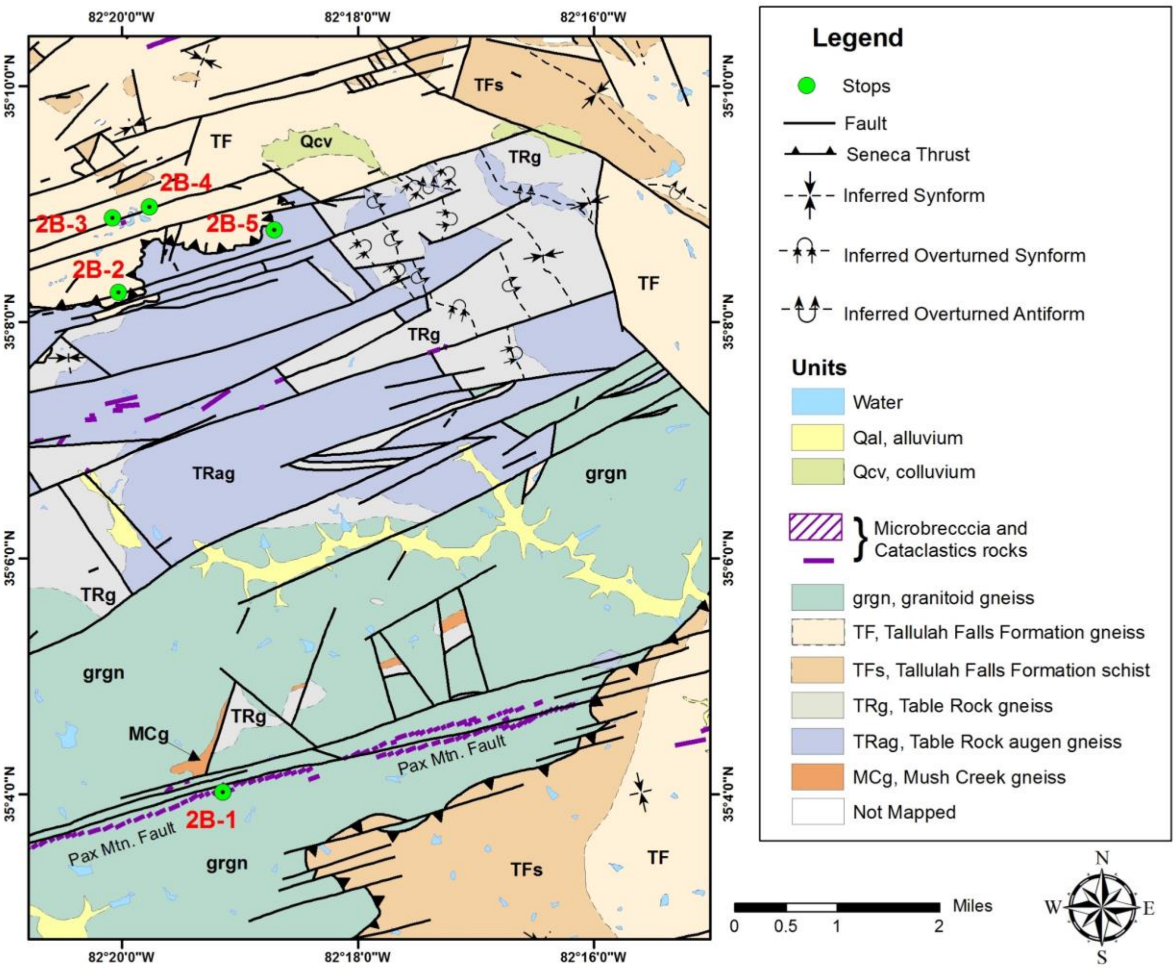

Figure 28. Geologic map with stops showing location of the Pax Mountain fault system in relation to Glassy Mountain.

Stop 2B-2. Glassy Rock overview. Flagpole and pavillion. Saluda quadrangle.

This stop is located at the top of the cliffs at an elevation of 840 m (Figure 29). Picturesque views to the south show the rolling Piedmont landscape. Pavements adjacent to the pavillion expose Tallulah Falls Formation rocks, which structurally are part of the Six Mile thrust sheet above the Seneca fault. The resistant, more homogeneous-looking, poorly layered biotite granitoid gneiss here is of igneous origin. Within it one can see scattered, lenticular and irregular xenoliths of biotite quartzo-feldspathic gneiss (Figure 30). Occasional layers of equigranular calc-silicate rock (epidote, quartz, amphibole, garnet) occur within the contorted biotite quartzo-feldspathic gneiss xenoliths. Floating, disaggregated blocks of calc-silicate rock can be observed in the biotite granitoid gneiss pavements. Calc-silicate rocks are common in the Tallulah Falls Formation regionally.

Figure 29. Tallulah Falls Formation gneiss exposures on the south face of Glassy Rock. Stop 2B-2 overlook. View to the west.

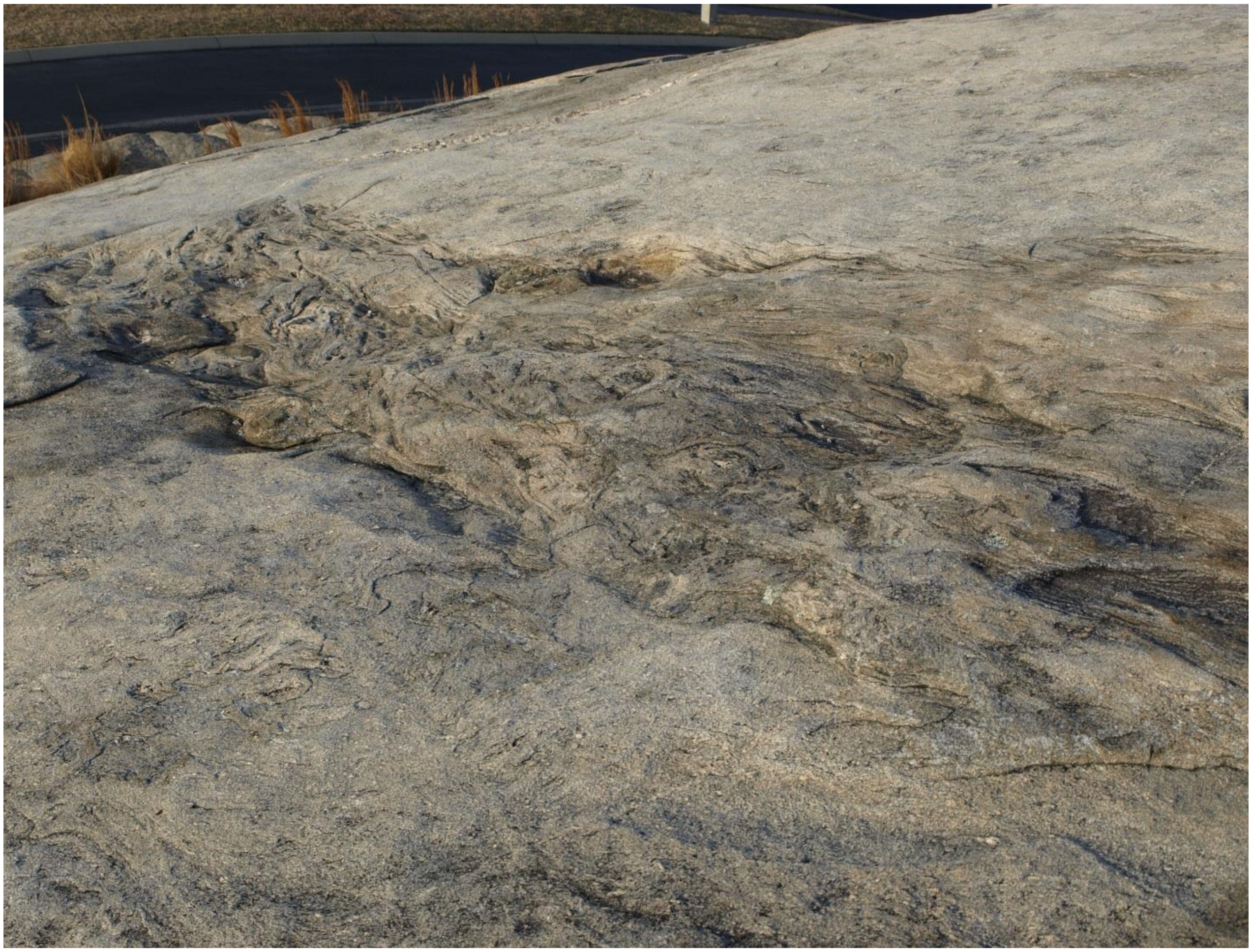

Figure 30. Glassy Rock. Large xenolith (~14 meters long) of compositionally layered biotite quartzo-feldspathic gneiss with scattered internal blocks and disrupted layers of resistant calc-silicate gneiss. The xenolith has digitated margins where in contact with surrounding intrusive biotite granitoid gneiss (left side of photo). Conspicuous pale green epidote-rich compositional layers are present in the individual blocks. The epidote-rich blocks represent stiffer calc-silicate layers in the gneiss boudinaged during deformation and intrusion of the enveloping biotite granitoid gneiss. A small pegmatite cuts the xenolith at the north end of the xenolith. View to the east.

Stop 2B-3. Golf course wells near the Clubhouse, The Cliffs at Glassy. Saluda quadrangle.

The Cliffs at Glassy Water System serves over 800 service connections as well as the golf and clubhouse facilities within The Cliffs at Glassy Development. The water system covers an area of approximately 6 square miles. The system was originally constructed by The Cliffs Communities, Inc. during the early 1990's prior to the initial development and sale of residential lots. Ownership and operation of the system was then transferred to the Blue Ridge Rural Water Company (BRRWC) of Greer, SC. Blue Ridge's "Piedmont System" serves a large portion of northern Greenville County and spans from the Greenville/Spartanburg County line to the east to U.S. 25 to the west. The steep slopes flanking The Cliffs at Glassy development preclude BRRWC from pumping water supplies from their contiguous service area at S.C. Highway 11. Consequently, BRRWC currently utilizes bedrock wells that are located within the elongated valley that is present at the top of Glassy Mountain to supply water to The Cliffs community. A total of 21 wells have been constructed within The Cliffs at Glassy wellfield, although only 11 wells are currently in service (Table 1, Figure 31). Many of the drilled wells were never developed as production wells because of low yields. The valley within which the wells are drilled trends southwest-northeast parallel to the headwaters of the South Pacolet River. This trend is also roughly parallel to the prevalent orientation of mapped faults within the Golf Course area. Relatively thick layers of regolith and saprolite (38 to 92 feet) overlie the bedrock within the wellfield and serve as important reservoirs of groundwater storage for the aquifer system atop the mountain.

The permitted capacity of the existing Cliffs at Glassy Water System is approximately 562,000 gallons per day. In recent years, The Cliffs at Glassy Mountain community's water supply has been inadequate as development has progressed and new users have been added to the system. Water usage has also increased with the proliferation of drought intolerant landscapes throughout the development. Two (Wells #1A and #1B) of the eleven wells in use have been constructed within the last few months and intersect productive bedrock fractures at depth. These wells are expected to contribute over 100,000 gallons per day of permitted capacity to the Cliffs at Glassy Water System. BRRWC has also instituted separate metering for lawn irrigation and scaled rates for water use in order to encourage conservation of their supplies.

Well Name	Depth (ft bgs)	Casing Depth (ft bgs)	Pumping Rate (gpm)	Drawdown @24 hrs (ft)	Specific Capacity (gpm/ft)
Well # 4	500	39	81	69	1.17
Well # 8	405	75	52	323	0.16
Well # 11	505	51	37	439	0.08
Well # 12	475	76	23	423	0.05
Well # 13	425	54	27	364	0.07
Well # 14	405	92	25	351	0.07
Well # 16	350	58	73	206	0.35
Well # 19	602	38	75	133	0.56
Well # 20	873	54	90	168	0.54
Well # 1A*	800	50	50*	90*	0.55*
Well # 1B*	700	50	40*	112*	0.36*

Table 1. Physical parameters derived from SC DHEC 24-hour pumping test results of the nine current production wells within The Cliffs at Glassy. Well and casing depths are from drillers' logs and are below ground surface (bgs). *The values presented for new wells, 1A and 1B, are derived from 8-hour preliminary pumping tests. The pumping tests for regulatory purposes of these wells will occur this fall.

Stop 2B-4. Water processing facility, The Cliffs at Glassy. Saluda quadrangle.

The Blue Ridge Rural Water Company has recently completed construction of a new groundwater treatment facility for The Cliffs at Glassy Water System. The treatment capacity of the new plant is over 800,000 gallons per day over the previous treatment capacity of roughly 500,000 gallons per day. Raw groundwater is directed here from BRRWC's wells for disinfection and pH adjustment prior to being pumped to finished water tanks at Rich Mountain at the northern extremity of the development. The Operations Manager for BRRWC will provide a brief tour of the new treatment facility and answer questions concerning the groundwater treatment and finished water transmission process.

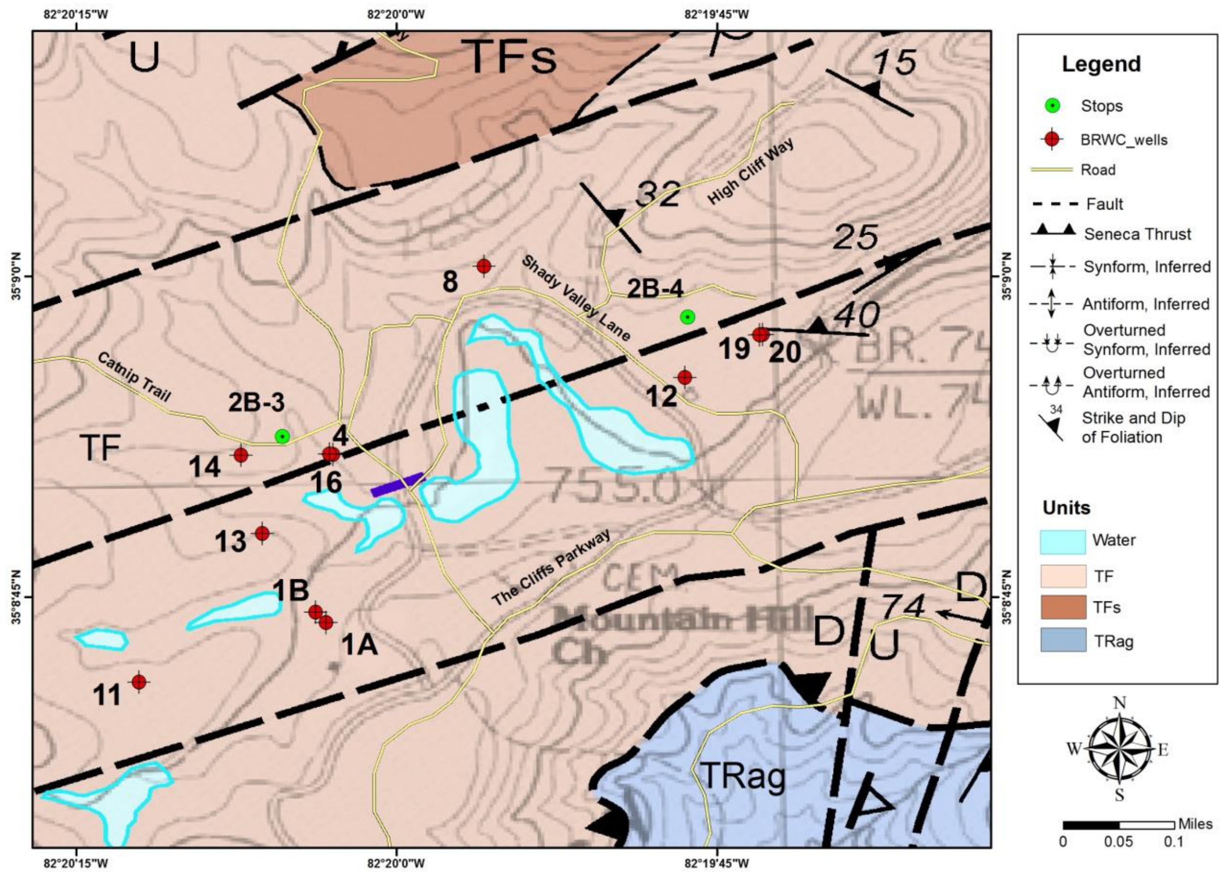

Figure 31. Locations of production wells currently in use for The Cliffs at Glassy Water System.

Stop 2B-5. Transposition structures in biotite augen gneiss, Hawk Springs Drive. Saluda quadrangle.

We have crossed the trace of the ductile Seneca fault (Figure 27) into the footwall rocks. We see here well-exposed transposition structures and extensional crenulation cleavage in biotite augen gneiss described in detail by Howard (2001). Transposition is a process that partly realigns S-surfaces (here foliation in gneiss) into similar or different orientations, forming a zone with a newer gneissic foliation. At this location the older foliation is contorted into northwest-vergent chevron folds. Their limbs are transposed or cross-cut locally by zones where a new foliation has developed. The new foliation has utilized the same fabric elements in the rock (pink feldspar augen, quartz, and biotite), and they have undergone crystal plastic deformation and recrystallization. In Figure 32, older foliation surfaces are approximately horizontal and more widely spaced. The C' shear bands cross cut transposition zones of ductile deformation. Shear sense of movement along extensional crenulation cleavages (C' shear bands) is consistently down to the south (right). The photogenic exposure has world-class ductile deformation features!

In the Glassy Mountain area, numerous exposures have zones that represent particularly intense shearing localized with sharp contacts adjacent to coarser-crystalline, less sheared mylonitic biotite augen gneiss. In the less sheared mylonite, feldspar augen with modified shapes normally are a few centimeters in long dimension. However, in the high strain zones, closely spaced, planar compositional layers occur with feldspar augen porphyroclasts that have been dynamically reduced to small lenticular crystals with high aspect ratio (length divided by width). They are less than 1 cm in length sitting in a matrix of fine-crystalline, recrystallized material. The texture of the rock locally borders on an ultramylonite (less than 10% of the original K-feldspar porphyroclasts are preserved). Therefore, within the Trag footwall unit, high-strain, planar zones exist where more intense shearing and ductile deformation has been concentrated compared to adjacent mylonitic biotite augen gneiss. One interpretation for the cause of the ductile shearing and variable mylonitization of the augen gneiss is the westward emplacement of the overriding ductile Seneca fault during Taconic or Acadian deformation of the southern Appalachian orogen. Clearly not all the movement associated with the emplacement of the ductile Seneca thrust took place in or near the thrust surface. It was distributed also into planar zones within the footwall rocks beneath it. Movement along extensional crenulation cleavages consistently down to the south may be related to collapse of a tectonically-thickened orogenic wedge at a time following ductile thrusting.

Figure 32. Transposition and extensional crenulation cleavage structures in biotite augen gneiss, Hawk Springs Drive.

Acknowledgments

Regional geologic mapping in upstate South Carolina and in the North Carolina portions of Standingstone Mountain and Zirconia quadrangles since 1995 has been a shared effort between Furman University and the South Carolina Geological Survey. Nick Patton, Groups and Education Director, YMCA Camp Greenville, gave permission to access Rainbow Fall trail. Co-leader Scott Brame constructed the maps used in the Sunday Cliffs at Glassy field trip and the map on the back cover of this guide.

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Legend for map on back cover

Map Units

Qal **Quaternary alluvium**

Rocks of the Walhalla nappe

TRg **Table Rock gneiss (Middle Ordovician)**

CRfm **Chauga River Formation metasiltstone (Cambrian-Early Ordovician)**

Rocks of the Jocassee thrust sheet

Hgn **Henderson Gneiss (Early-Middle Ordovician)**

Rocks of the Six Mile thrust sheet

PM **Poor Mountain Formation amphibolite, schist, and gneiss (Middle Ordovician)**

TF **Tallulah Falls Formation gneiss, schist, and amphibolite**

Map Symbols

Stops

Oblique slip fault

Seneca fault

Eastatoe fault

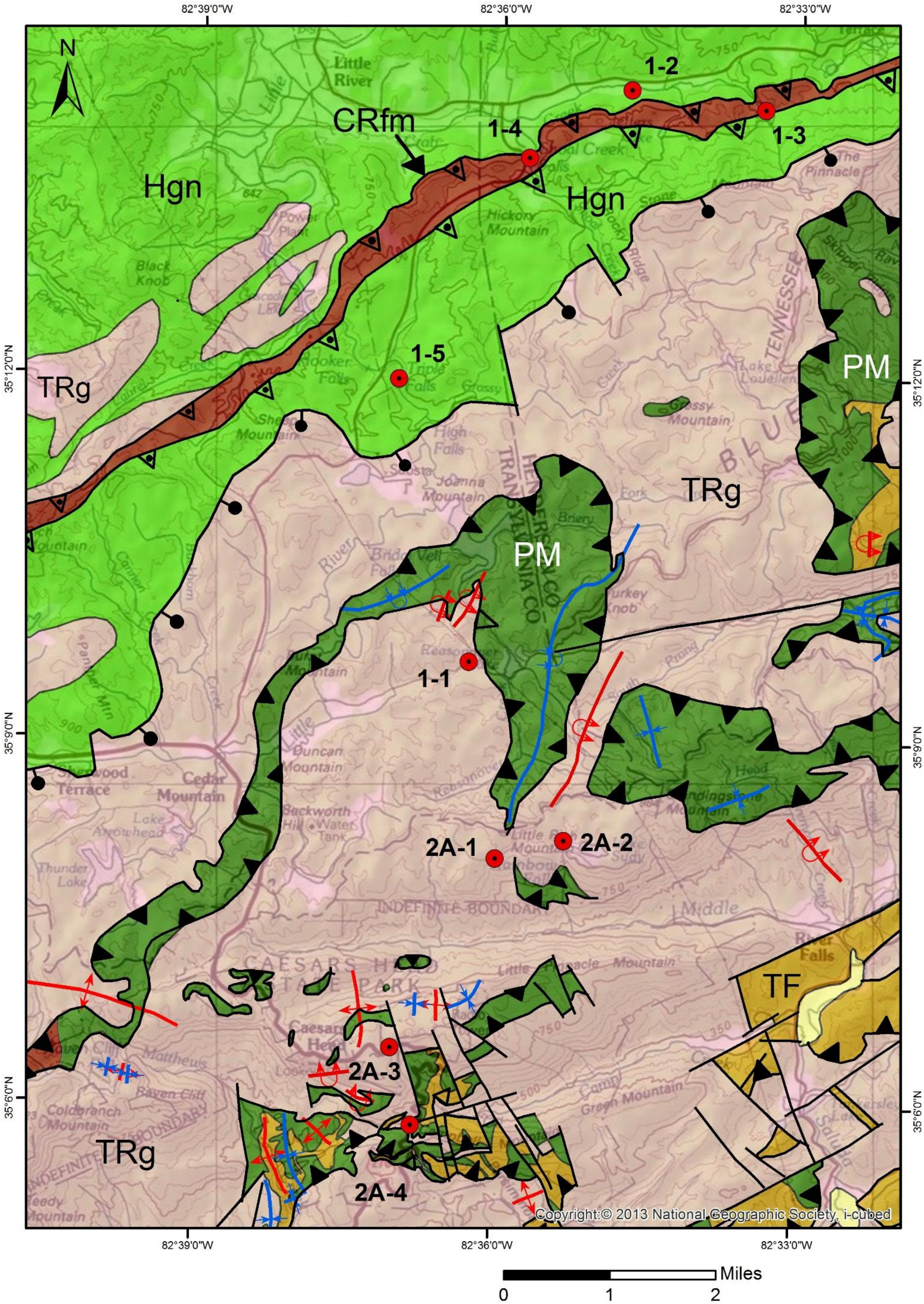
Slicking Gap normal fault, ball and bar on downthrown block

Synform

Antiform

Overturned synform

Overturned antiform



82°39'0"W
82°36'0"W
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