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PALEOZOIC-MESOZOIC TECTONIC HISTORY OF THE WESTERN INNER PIEDMONT BASED ON SUPERIMPOSED STRUCTURAL RELATIONSHIPS, SOUTH CAROLINA AND NEARBY NORTH CAROLINA, SOUTHERN APPALACHIANS

John M. Garihan

Bulletin 42
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Geological Survey
2018

Cover Photo. West-southwest verging, overturned folds in saprolitic gray Table Rock gneiss and brown amphibolite, Jim Timmerman Natural Resources Area, southeast Eastatoe Gap quadrangle. Left of the scale, a discordant mafic dike intruded across a fold in gneiss and then was deformed by continued folding.

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ABSTRACT

Interpretation of new structural relationships, as well as re-examination of published regional relationships, provides the basis for a proposed deformation sequence of Paleozoic and Mesozoic events in the western Inner Piedmont, upstate South Carolina and adjacent North Carolina, of the southern Appalachians. The events of this proposed deformation sequence were identified primarily by first and second pass mapping of the region. The deformation sequence consists 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 backthrusting and folding; and 7) Mesozoic brittle faulting and diabase dike intrusion, associated with systematic changes in regional extension direction.

INTRODUCTION

The focus of this report is the description and interpretation of regional structural relationships mapped in the western Inner Piedmont (IP) of northwestern South Carolina and adjacent North Carolina in the southern Appalachians. Earlier geologic reports and geologic maps for 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, 1997, 1998). Geologic maps also have been published by the S.C. Geological Survey and have been periodically updated as newer mapping became available. The updated versions, particularly for the Mountain Bridge area, provide significant additional information relevant to regional structure development. The Mountain Bridge area, however, represents only part of the writer's mapping in the western IP (Figure 1).

"First pass" mapping of Cleveland, Table Rock, and Standingstone Mountain 7.5-minute quadrangles (Garihan, 2005a; Garihan and Ranson, 2003, 2007; Figure 1) was undertaken subsequent to a project that delineated silicified cataclastic zones across the IP of the Carolinas (Garihan and others, 1988; Garihan and Ranson, 1992, and references therein). From 1995 to the present, with the participation of the S.C. Geological Survey, "first pass" mapping also has been completed between Salem and Chesnee quadrangles, South Carolina, as well as adjacent portions of North Carolina in Standingstone Mountain and Zirconia quadrangles. Observations of structures from those mapped quadrangles also are given and interpreted to support observations made in Cleveland, Table Rock, and Standingstone Mountain quadrangles.

To provide background information, "first pass" mapping of Cleveland, Table Rock, and Standingstone Mountain quadrangles done by the writer is described first (Figure 1). "Second pass" mapping of Cleveland and eastern Table Rock quadrangles was undertaken by the writer when geologic work in the Saluda quadrangle (Garihan and others, 2010) demonstrated that significantly more structural detail could be gained by simple subdivision of the Tallulah Falls Formation into two map units: a lower gneiss and an upper schist (Figure 2a). By using this subdivision, the emphasis of "second pass" mapping focused on tracing lithologic and fault contacts (See Compton and Garihan, 2013).

The development of the various structural events places them into a Paleozoic-Mesozoic deformation sequence. It is necessary to describe the structural characteristics of those events so that interpretations of a number of new features are based on documented observations. Specific relationships also are discussed to help the reader understand how the new features fit into the proposed deformational sequence.

FIRST PASS MAPPING

"First pass" 1:24,000-scale mapping of Cleveland, Table Rock, and Standingstone Mountain quadrangles established the following geologic information (Garihan, 2005a; Garihan and Ranson, 2003, 2007; Figure 1):

a) Detailed descriptions of individual metamorphic map units were provided on each map. A tectono-stratigraphic summary of those schist, gneiss, or amphibolite map units is given in Figure 2a.

b) The general distribution of Walhalla thrust sheet (largely Late Ordovician Table Rock quartzo-feldspathic orthogneisses) and overlying Six Mile thrust sheet rocks (Poor Mountain and Tallulah Falls Formations) was established (Figure 2a). Meso-scale details of the Seneca fault at the base of the Six Mile thrust sheet were described.

c) Scattered klippen of Six Mile thrust sheet rocks were defined generally.

d) The map patterns of polyphase macro-scale fold sets on both thrust sheets were outlined.

e) The pattern of regional NE- and E-striking brittle fault sets was traced, with the two laterally separate fault sets merging in central Cleveland quadrangle.

f) The distribution of NE- and E-striking silicified cataclastic zones was delineated.

g) The distribution of NW-striking Mesozoic diabase dikes in eastern Cleveland

quadrangle was established. Mapping showed sinistral offset of a diabase dike by a brittle NE-striking fault, which had been described by Snipes and others (1984).

It should be noted that the described relationships were used in subsequent "first pass" mapping of the western IP.

Second Pass Mapping

"Second-pass" mapping produced the following observations and interpretations:

a) The alternating NE and E-W, zig-zag pattern of belts of Six Mile rocks represent first order synforms that were offset by subsequent faulting (Figure 2a). The synformal belts are represented by continuous outcrop areas and separated klippen of Six Mile thrust sheet rocks bound at their margins by the trace of the Seneca fault or by brittle faults of various strikes. In the case that the Walhalla-Six Mile contact is linear, the contact was interpreted as a steep fault; if sinuous across the topography, the contact was interpreted as the gently-dipping Seneca fault. Normally the contact is not exposed, and the juxtaposition of Walhalla and Six Mile rocks was used to infer the contact (Figure 2a).

b) A regional macro-scale Type-1 superposed fold pattern was recognized (Garihan, 2015) after back-stripping younger fault offsets. The current alternating NE- and E-W-striking, zig-zag pattern of the synforms originated as part of a Type-1 (orthogonal) superposed macro-scale fold system. The fold system was strongly modified by oblique movements along N-S-, NE-, and particularly E-W-striking fault sets (Figure 2a).

c) A significantly more complex fault pattern was recognized than originally mapped. Sinistral and dextral oblique-slip faults strike E-W, NW, ~ N-S, NE, and ENE. Movements along several oblique-slip faults were interpreted as more dip-slip than strike-slip, and this fault style was identified as an important part of the IP brittle fault network.

d) A variety of ductile shear zones and fabrics was recognized in the Walhalla-Six Mile thrust stack. Those features formed after thrust stacking and primarily indicate a top-to-the-SW sense of shear. The Mine Mountain ductile shear zone and other shear zones were re-examined, and kinematic indicators also show dominant top-to-the-SW movement. Their occurrence after thrust stacking is considered evidence of a period of gravitational collapse.

e) Northwest-directed thrusting in Standingstone Mountain quadrangle and associated hinterland-directed backthrusting in Cleveland and Table Rock quadrangles were recognized.

f) The tectonic setting of the Slicking Gap fault, a major normal fault in the western IP, was interpreted as either the result of relaxation of Alleghanian compression or as the result of Mesozoic extensional events.

Early Orogenesis

During Taconic orogenesis, A-subduction accreted the oceanic and arc assemblages of the Cowrock, Cartoogechaye, and Tugaloo Terranes onto the Laurentian margin in the southern Appalachians (Hatcher, 2005). Merschat (2009) proposed IP and Blue Ridge suspect terranes of peri-Laurentian, mixed Laurentian, and peri-Gondwanan origins as accreted to the Laurentian margin during the Taconic, (465–450 Ma) and Neoacadian (365–340 Ma) orogenies. Dennis (2007, his Figure 4) describes a tectonic model involving: 1) Ordovician closing of the Rheic Ocean, with accretion of Carolinia to the IP Tuguloo terrane and associated plutonism, followed by 2) opening of the Cat Square basin, with transtensional granites, and ultimately the re-accretion of Carolinia to Laurentia before early Pennsylvanian time.

The Table Rock Igneous Suite

A recognized stratigraphy of late Proterozoic and early Paleozoic metasedimentary and

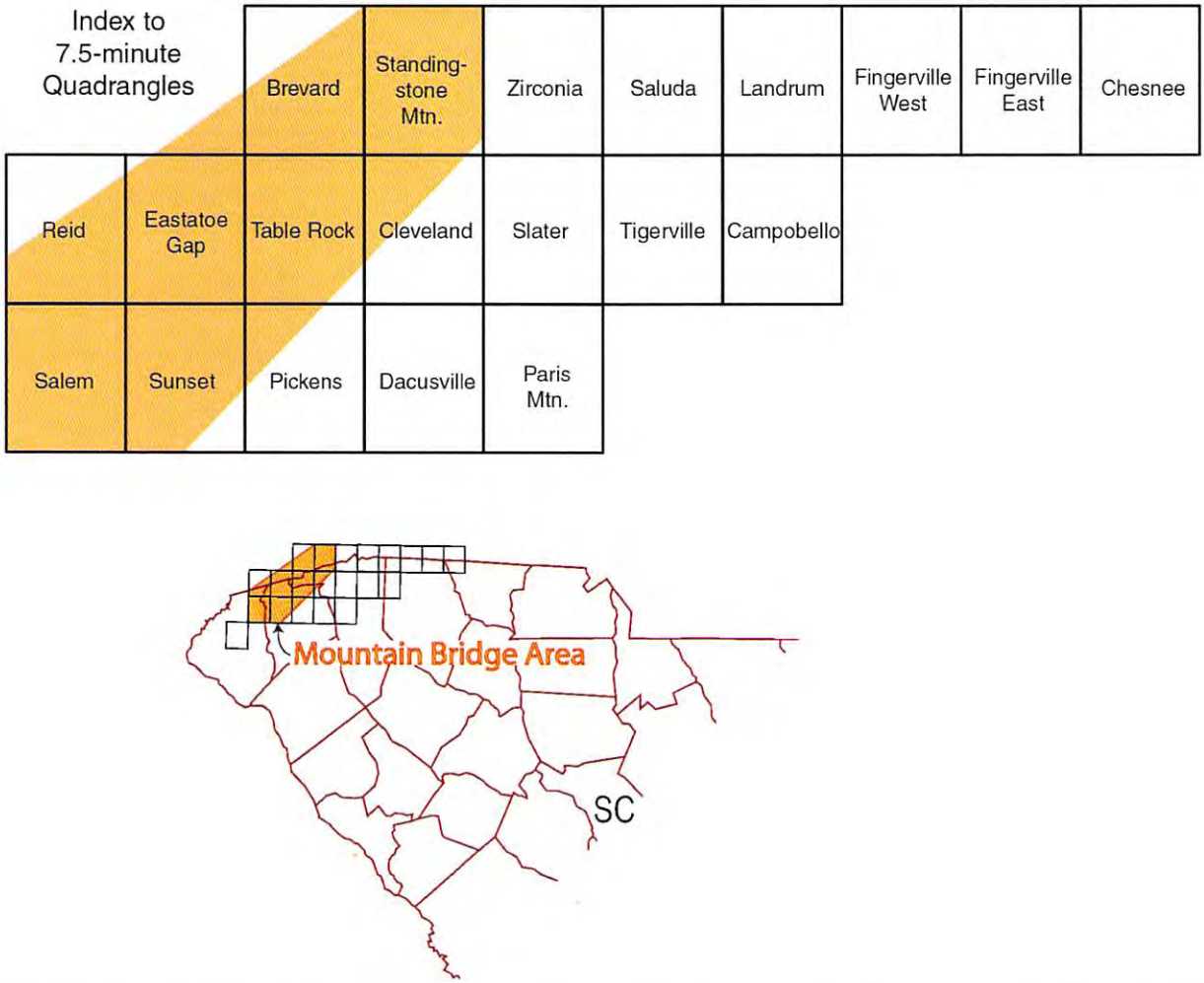


Figure 1. Index to 7.5-minute quadrangles in the Mountain Bridge area and those mapped farther east, South Carolina and adjacent North Carolina.

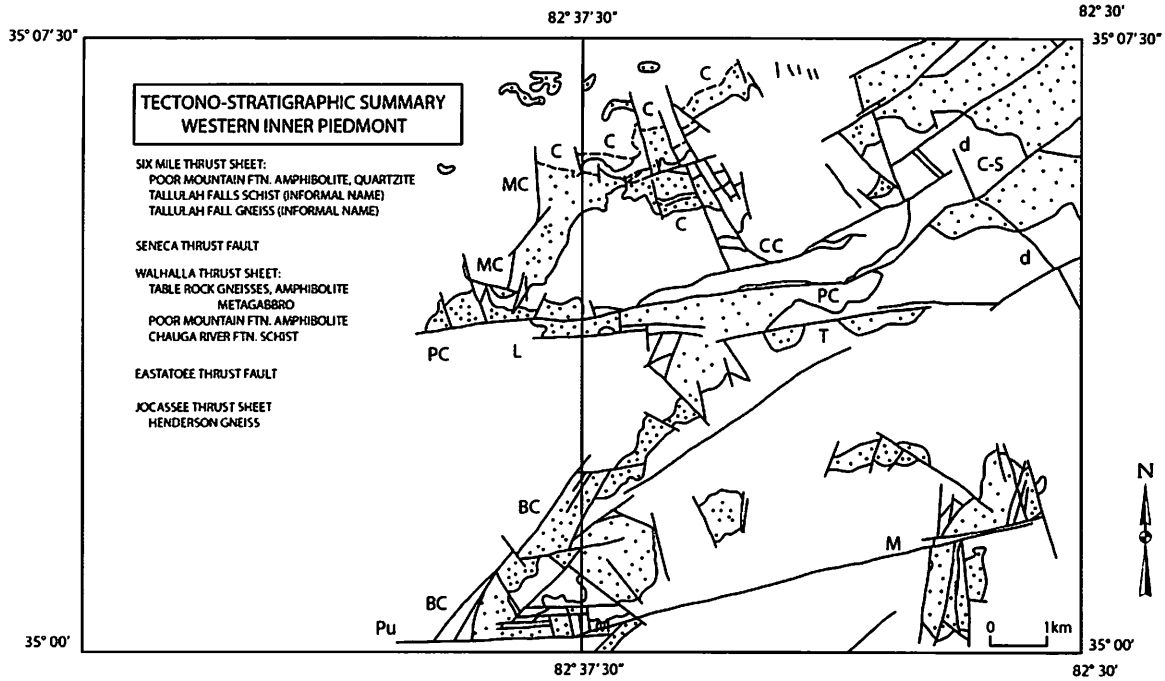


FIGURE 2a. Generalized geologic map of Cleveland (right) and eastern Table Rock (left) quadrangles, with faults. Six Mile thrust sheet- dotted area. Walhalla thrust sheet- blank area. Labeled faults: Burgess Creek- BC, Caesars Head fault system- C, Civitan Camp- CC, Cox Creek-Short Branch- C-S, Lakemont- L, Marietta- M, Matthews Creek- MC, Palmetto Cove- PC, Pumpkintown- Pu, Tall Pines Lake- T. diabase dike- d. Tectono-stratigraphic summary of the western Inner Piedmont shows the thrust stack sequence.

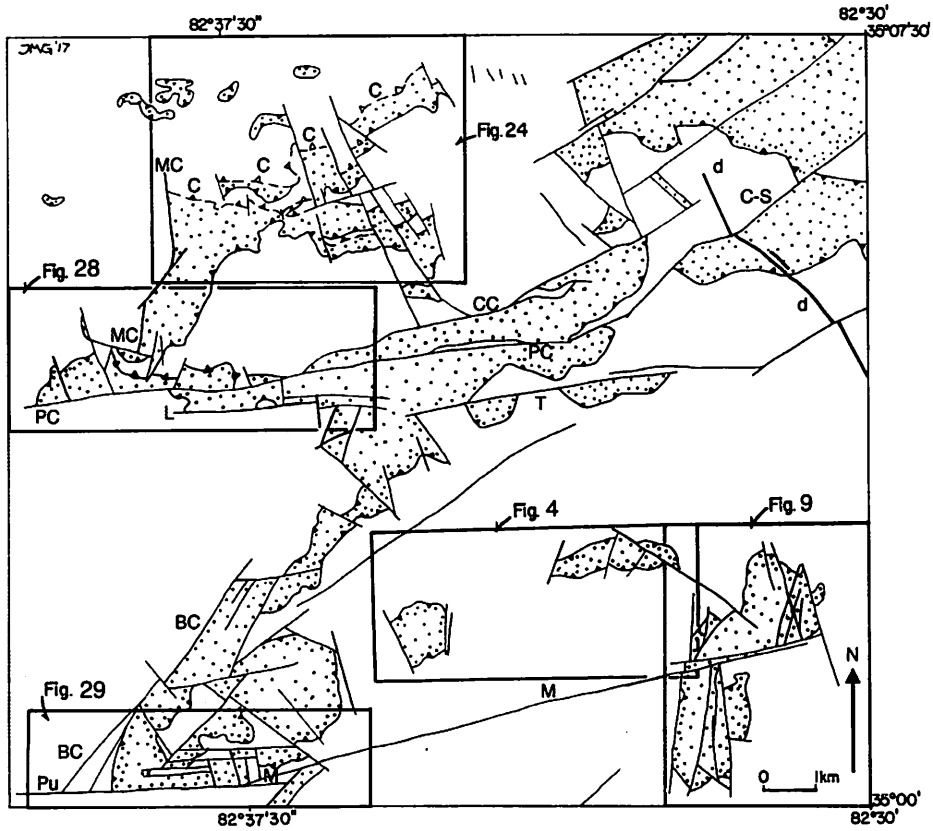


FIGURE 2b. Location index for the geologic map portions referred to in the text. Seneca fault- sawtooth line; Caesars Head fault- open sawtooth line. Labeled faults: Burgess Creek- BC, Caesars Head fault system- C, Civitan Camp- CC, Cox Creek-Short Branch- C-S, Lakemont- L, Marietta- M, Matthews Creek- MC, Palmetto Cove- PC, Pumpkintown- Pu, Tall Pines Lake- T. diabase dike- d.

metavolcanic protoliths is present in the Tuguloo terrane (Figure 2a). These protoliths are represented by a variety of schists, gneisses, amphibolites, and quartzites. Details of amphibolite-grade metamorphism affecting the IP are given in the literature (for example, Hatcher, 1993, 2002, and references therein) and are not described here.

Intrusive into the Tuguloo terrane of the western IP, the Table Rock Igneous Suite (TG) of biotite microcline augen gneiss (oldest phase), finer-crystalline biotite quartzo-feldspathic gneiss, discordant coarser-crystalline biotite granitoid gneiss (youngest phase), and lesser amphibolite (as basic sills and dikes, locally transposed into foliation) compose the bulk of the Walhalla thrust sheet. This batholith-scale gneiss, previously called the Caesars Head Granite (Horton and McConnell, 1991), includes metamorphosed granitic rocks and multiple intrusive felsic phases (both syn- and post-kinematic).

The older augen gneiss has been dated at 450.2±4.5 Ma, Late Ordovician (Ranson and others (1999). Hibbard (2000) related this granitic magmatism (ca. 460-440 Ma) to a supra-subduction zone setting, with sinistral transpressive docking and accretion of the Carolina terrane with Laurentia. Hibbard's (2000) tectonic model is adopted here to explain the genesis of the TG.

Several features of TG may be associated with TG intrusion, for example deformation of multi-stage pegmatites and complex felsic vein networks. Other features possibly associated with emplacement are irregular passive folds deforming the vein networks and some meso-scale ductile shear zones.

Thrust Stacking

Griffin (1971, 1974), Nelson and others (1987, 1998), Davis (1993a), Hatcher (2002, and references therein), Dennis and Wright (1997), Dennis (2007), and Bream (2002, and references therein) have summarized aspects of IP structure, tectonic history, and geochronology. It is not always possible to assign an orogenic age with certainty to the structures mapped, particularly as geochronologic data are sparse for the western IP.

The stacking of the high-grade Walhalla-Six Mile thrust sheets (Nelson and others, 1986) has been interpreted as the result of Acadian collision of the Carolina Terrane with the IP (Hatcher, 2010). This interpretation was corroborated by a thermal metamorphic peak in the IP occurring at 355–365 Ma (Late Devonian-Early Mississippian; Dennis, 2007). Hibbard (2017, oral communication), however, regards the tectonic framework of the Devonian as a time of dextral strike-slip faulting with partial exhumation and isotopic ages representing mineral cooling. The docking of the Tugaloo terrane in the Early or Middle Ordovician also adds uncertainty to the timing of the thrust stacking event. In the eastern Blue Ridge, Trupe and others (2009) indicate that Taconic deformation and regional high-grade metamorphism may be difficult to discriminate from high-grade Silurian-Devonian (Acadian) fabrics.

The Seneca fault. The Seneca fault lies at the base of the Six Mile thrust sheet and separates kyanite-grade rocks of the Walhalla thrust sheet from the overlying, higher sillimanite-muscovite-grade rocks of the Six Mile sheet (Griffin, 1977, 1978; Nelson and others, 1987, 1998). The fault is mapped at the sharp contact above a zone of grain-size reduced, recrystallized TG gneiss (Garihan, 2001).

The Seneca fault is a prominent regional structure that was initially described as a 'tectonic slide' by Griffin (1974). The fault emplaced Six Mile thrust sheet rocks to the northwest over footwall Walhalla thrust sheet rocks (Griffin, 1971). Griffin (1974) regarded the thrust sheets as infrastructural fold nappes (his Figure 13); that is, as large transported nappes with the underlying limb thinned and stretched out. Hatcher and Hooper (1992), however, regarded the migmatitic, crystalline Six Mile and Walhalla thrust sheets as plastically deforming sheets in a gently dipping stack of nappe-thrusts. Hopson and Hatcher (1988) considered the Seneca fault to be out-of-sequence and possibly equivalent to the Toccoa-Shorts Mill thrust at the base of the Alto Allochthon that lies farther southwest in the IP.

Garihan (2001, and references therein) described and illustrated Seneca fault occurrences in the Mountain Bridge area (Figure 1). The Seneca

fault cuts upsection from southeast to northwest in the western IP. In southern Cleveland quadrangle, Tallulah Falls gneiss and schist lie in the fault's immediate hanging wall (Figure 1); in Standingstone Mountain quadrangle, Poor Mountain Formation amphibolite lies in the immediate hanging wall.

At Camp Greenville in southern Standingstone Mountain quadrangle, one of the best exposures of the Seneca fault anywhere in the western IP can be seen. In that exposure, a duplex several meters thick of interleaved Poor Mountain Formation amphibolite (hanging wall) and TG (footwall) (Figure 3a, B) defines the Seneca fault. The fault is mapped at the sharp contact above a zone of gray, grain-size reduced, recrystallized TG that is in contact with discordant, red-black amphibolite hanging wall, with or without an intervening thickened schist zone (Figure 3b, panel F, c).

The Seneca fault is regarded as an important structural marker because of its structural style and because fold sets both pre-date and post-date its emplacement. The Seneca fault trace truncates earlier NE-striking, NW-vergent, overturned folds and later E-W–striking, upright-inclined folds of Six Mile rocks in SE Sunset quadrangle (Garihan, 2005b). Elsewhere, the Seneca fault truncates earlier NW-striking, SW-vergent, overturned folds cored by Tallulah Falls gneiss or schist in several isolated Six Mile klippen in Cleveland quadrangle (Figure 4). In the exposure at Camp Greenville, the Seneca fault is deformed by meso-scale SW-vergent folds (Figure 3d); and on Glassy Mountain (Saluda quadrangle) it also is deformed by a SW-vergent fold (C. W. Clendenin, oral communication).

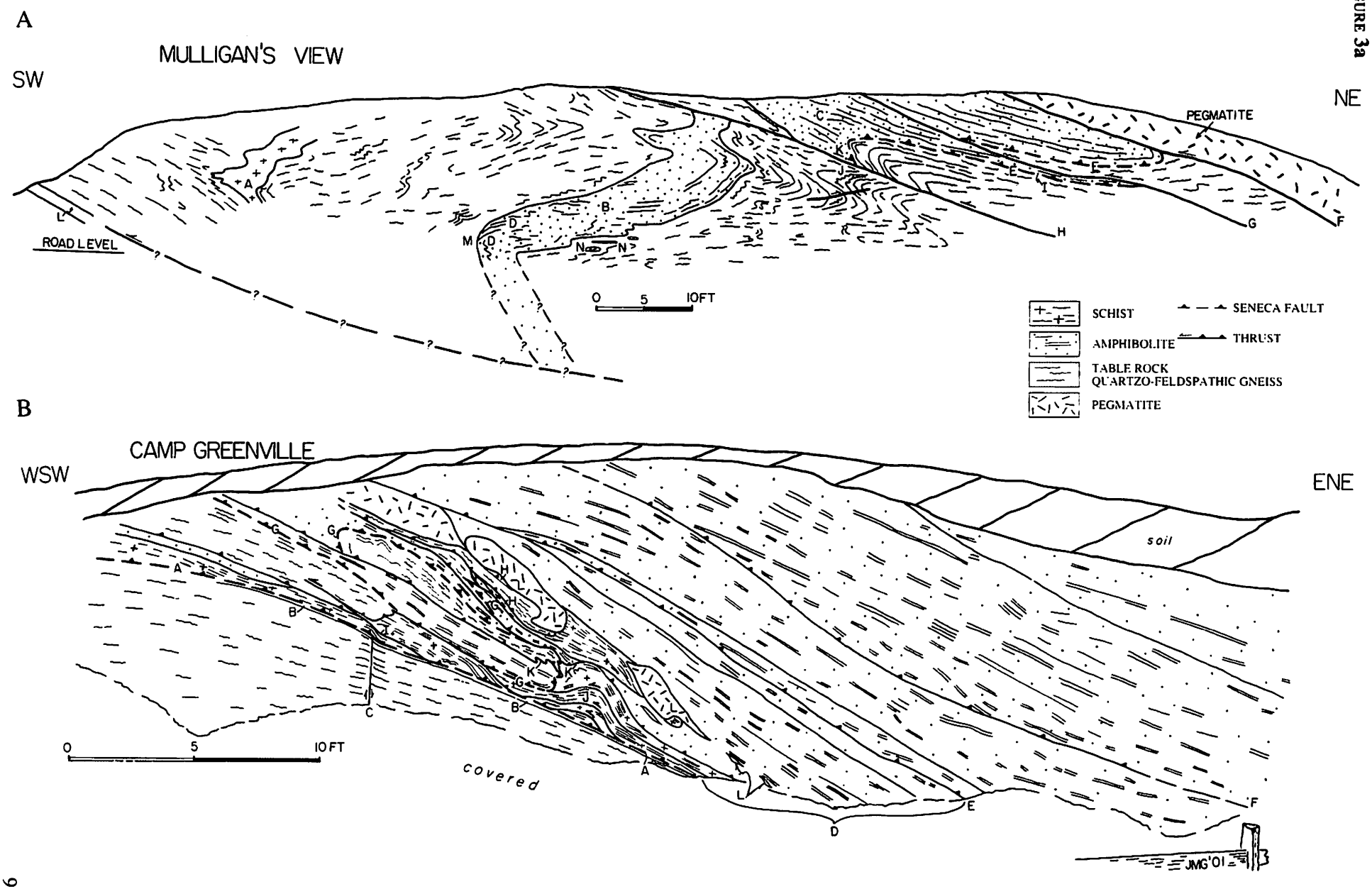
The Eastatoee fault. After being recognized in Sunset quadrangle (Figure 1), the Eastatoee fault was formally described by Garihan and Clendenin (2007). The fault lies at the base of the Walhalla thrust sheet, with grain-size reduced Henderson Gneiss in its footwall upward to a sharp contact. Throughout the region, the fault carries Chauga River Formation rocks in the immediate hanging wall (Figure 5a). The Eastatoee fault is interpreted here as being emplaced in a more foreland position than the Seneca fault. It should be noted that TG was syn- to post-kinematic with respect to the emplacement of the Eastatoee fault.

The fault has been traced northeastward between southwestern Salem quadrangle (Clendenin and Garihan, 2007a) and the northern edge of Standingstone Mountain quadrangle (Figures 1, 6). Cattanach and Bozdog (2011) traced it across the intervening Brevard quadrangle in North Carolina. Three-point calculations along its sinuous topographic trace indicate a gentle southeast dip (~25°).

At Sharp Top Mountain in extreme northern Sunset quadrangle, the Eastatoee fault contact is duplicated in zone a few meters thick by shallow, west-directed thrusts. Interpreted as a small duplex (Figure 7), the faulting is analogous to the imbricate zone along the Seneca fault exposed at Camp Greenville. At Horse Mountain in Eastatoe Gap quadrangle (Figure 1), the Eastatoee fault has been offset by a younger, NW-directed thrust fault (Garihan and others, 2005b; See their cross section A-A').

In northern Standingstone Mountain quadrangle (Figure 1), a narrow (0.2-0.7 km wide), NE-striking belt of Chauga River Formation rocks with Henderson Gneiss on both sides was initially interpreted as a NW-vergent, overturned synform which folded the Eastatoee fault (Garihan and Ranson, 2007). The Eastatoee fault clearly bounds its northwest margin. However, a NE-striking thrust, interpreted here as Alleghanian, bounds the southeast side of this Chauga River exposure belt. The tectonic significance of this Alleghanian thrust is considered below.

Where originally recognized in Sunset quadrangle, the Eastatoee fault surface does not appear to be folded. However, to the southwest near Lake Jocassee in Salem quadrangle (Figure 1), the Eastatoee fault surface, its overlying Chauga River Formation rocks, and Henderson Gneiss footwall are folded into narrow, NE-striking, NW-vergent, overturned synforms (Clendenin and Garihan, 2007a, 2007b). Ten kilometers northwest of its apparently simple sinuous trace in Sunset quadrangle, the Eastatoee fault has been repeatedly duplicated by later imbricate thrusting related to Brevard zone deformation (Clendenin and Garihan, 2008, 2012).


A
MULLIGAN'S VIEW
SW
NE
PEGMATITE
ROAD LEVEL
0 5 10FT
SCHIST
AMPHIBOLITE
TABLE ROCK QUARTZO-FELDSPATHIC GNEISS
PEGMATITE
SENECA FAULT
THRUST
B
CAMP GREENVILLE
WSW
ENE
soil
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0 5 10FT
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FIGURE 3a

FIGURE 3b

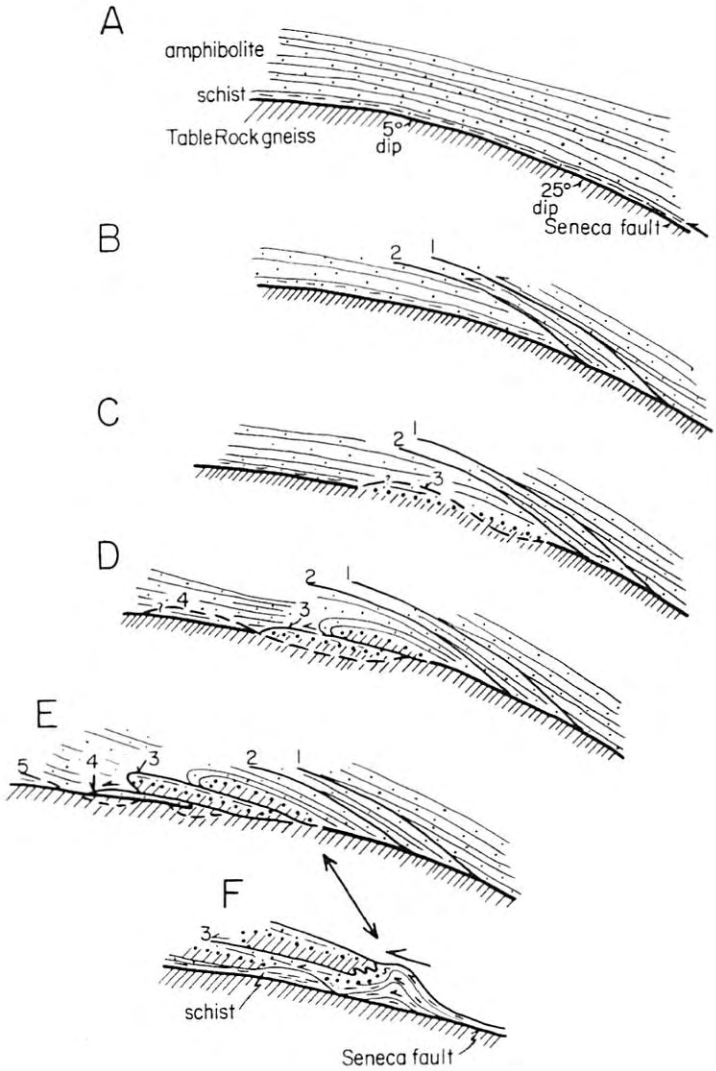

FIGURE 3c

FIGURE 3d

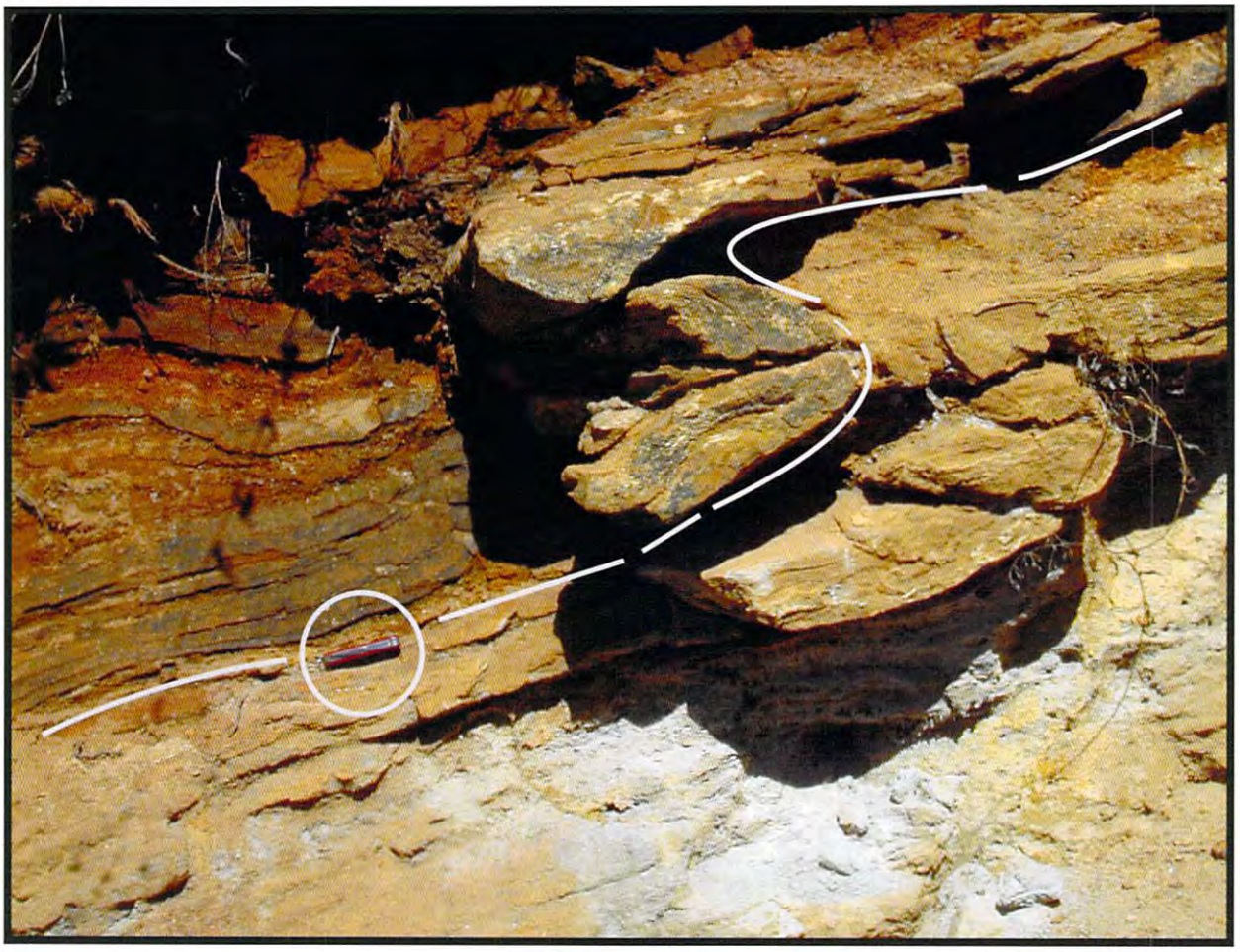

FIGURE 3. **a.** A. Geologic cross section sketch of the roadcut at Mulligan's View, Camp Greenville Road, southern Standingstone Mountain quadrangle. The dashed sawtooth line is the folded Seneca fault, cut by younger thrusts. Amphibolite (dotted) occurs in the hanging wall of the Seneca fault, distinct from amphibolite in Table Rock gneiss footwall (dashes). 3 **a.** B. Geologic cross section sketch of the Seneca fault (dashed sawtooth line) and related duplex (labeled D), Camp Greenville, southern Standingstone Mountain quadrangle. Rock units labeled for A and B. Garihan (2001) gives explanations for the individual labeled features on both cross sections. **b.** Sequential sections, showing interpreted development of the duplex above a ramp of the basal Seneca fault, Camp Greenville. Seneca fault: portions are shown by a solid line, dashed line, and dotted line at various development stages. Rock units labeled. From Garihan (2001). **c.** Detail of the duplex at Camp Greenville. Basal Seneca fault lies at the thin, white quartz zone above the hammer. Table Rock gneiss is sandy-weathering, light gray, and planar layered; Poor Mountain amphibolite is red (limonite-weathered) and black. Duplex shows complex interleaving and folding of Table Rock gneiss, amphibolite, and Seneca fault in several horses. Hammer is 40 cm. **d.** Folded Seneca fault surface, Camp Greenville Road, immediately west of the Figure 3**c** location. The fault lies at the position of the pocket knife (circled), and it is traced by the dashed lines through a SW-vergent, overturned S-fold. Black-red Poor Mountain amphibolite lies above the Seneca thrust, and sandy-weathering, light gray Table Rock gneiss lies below it. View is to the northwest. Pocket knife is 8 cm.

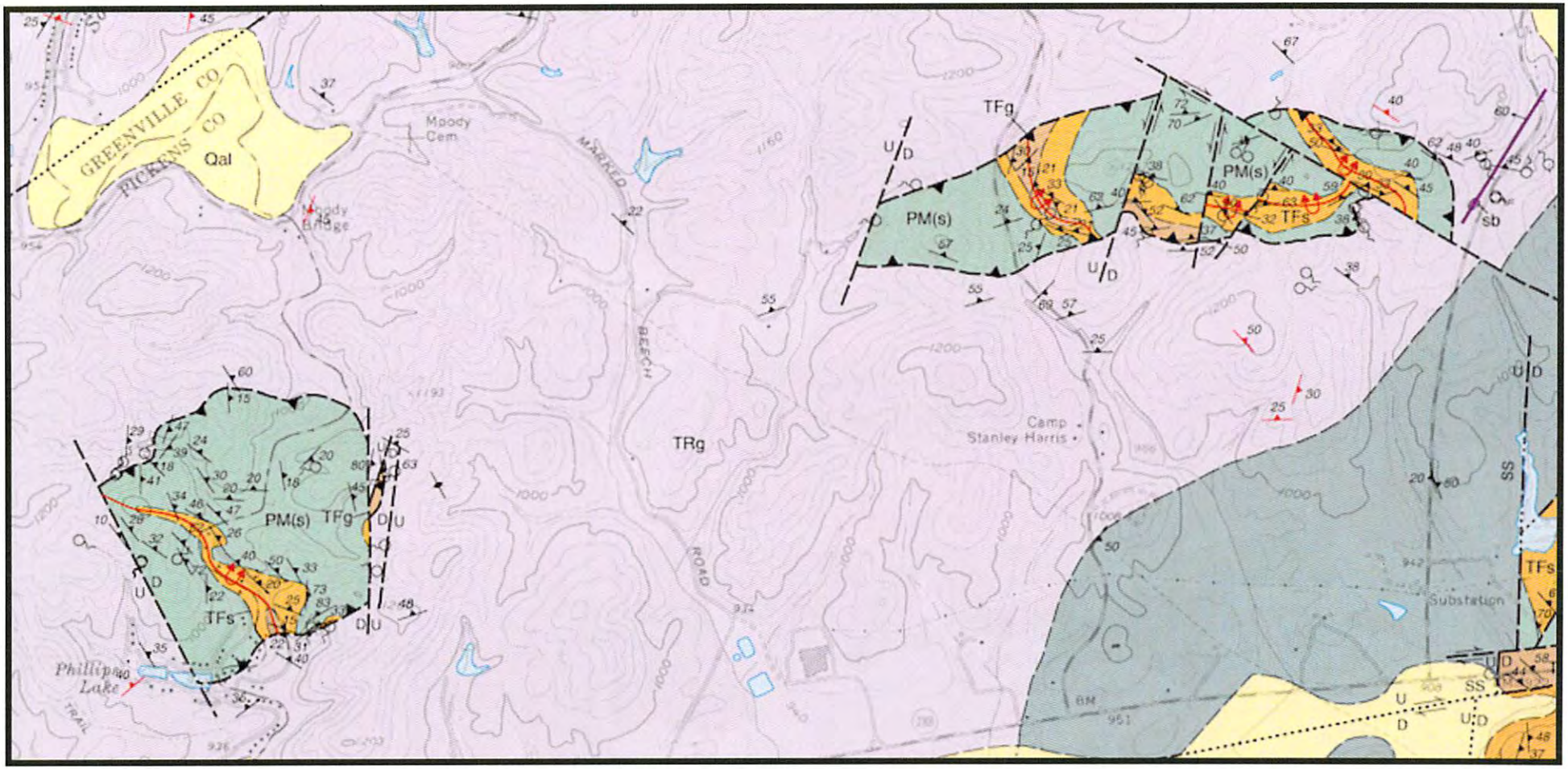

Figure 4. Two small klippen of Six Mile thrust sheet rocks, bound by the Seneca fault (sawtooth line) and brittle faults, SE Cleveland quadrangle. Separate NW-striking, SW-vergent, overturned antiforms (fold symbol in red), cored by TFs in each klippe, are truncated laterally by the Seneca fault. Table Rock gneiss- TRg. Otherwise same labels as Figure 9. Open circles on all geologic maps are springs. Located on Figure 2b.

Discussion

A complicated structural history is indicated by the reported observations of the two faults. A narrow (<2.5 km wide), tight-isoclinal, overturned fold system is present in the immediate hanging wall of the Eastatoee fault in SE Eastatoe Gap quadrangle (Garihan and others, 2005b, cross section A-A'). This fold system involves Chauga River Formation, Poor Mountain amphibolite, and TG, the latter as a discordant, felsic intrusive body of Late Ordovician age caught up in the deformation. The fold system is inferred to have resulted from compression related to the northwest thrust-sheet emplacement. A potential factor may have been resistance to the thrust's advance by the thick body of Henderson Gneiss in the footwall, regardless of its apparent plastic rheology.

If the Eastatoee fault and adjacent hanging-wall fold system are indeed related, two further inferences can be drawn based on relationships in SE Eastatoe Gap quadrangle: 1) the Eastatoee fault is a Taconic (Late Ordovician) rather than an Acadian structure; and 2) if a klippe of the map unit Mhgs, sitting directly on the Eastatoee hanging wall folds, is in fact a Six Mile outlier (Garihan and others, 2005b), then the Seneca, farther from the foreland than the Eastatoee, is an out-of-sequence thrust which emplaced Six Mile rocks onto the hanging wall NW-vergent, tight-isoclinal, overturned fold system. As mentioned, Hopson and Hatcher (1988) proposed the Seneca fault to be out-of-sequence.

Across Sunset quadrangle, deformation associated with emplacement of the Eastatoee fault resulted in numerous NE-striking, NW-vergent, overturned macro-scale folds across the exposed width of the Walhalla thrust sheet (Garihan, 2005b; See cross section A-A'). The NW-vergent folds in the Eastatoee hanging wall span a distance at least nine kilometers southeast of the thrust trace. In contrast to an apparent out-of-sequence structural relationship in SE Eastatoe Gap quadrangle, based on relationships in SE Sunset quadrangle, regional compression produced an elongate, NE-striking, NW-vergent, overturned antiformal structural window through the Six Mile sheet and the Seneca fault. At this location, the Seneca fault appears to pre-date folding deformation related to Eastatoee fault emplacement, and the Eastatoee is the later, in-sequence thrust.

An explanation to the apparent out-of-sequence/in-sequence contradiction is that the two significant IP thrusts are essentially contemporary features, overlapping in time of their movement. If true, one result was development of the wide swath of folding deformation between the two advancing thrusts, as intense regional compression caused overlapping northwest transport of both thrust sheets. Both pre-Seneca folding of its hanging wall rocks (Six Mile) and post-Seneca folding relationships across the Walhalla thrust sheet below it were mapped in Sunset quadrangle (Garihan, 2005b; See cross section A-A'), and those relationships support the interpretation that the thrusts are contemporary features.

Folding

As stated, the Seneca fault is a prominent regional structure in the IP because of its structural style, and many structures throughout the rest of this section are referenced to it because of the uncertainty tied to orogenic age. Immediately to the north of the Mountain Bridge area in the vicinity of Hendersonville, North Carolina, Lemmon (1982) envisioned Seneca thrusting during Acadian D_2 deformation, which post-dated earlier D_1 (Taconic?) isoclinal folding, amphibolite grade metamorphism (M_1), and dominant S_1 foliation development. Lemmon's D_2 also involved progressive metamorphism (M_2), a second isoclinal folding event (F_2) nearly coaxial and coplanar to F_1, NE-SW-oriented subhorizontal rodding of augen in Henderson Gneiss, S_2 foliation development, and Seneca thrusting that truncates S_1. Lemmon's D_1 deformational event is recognized in the study area immediately to the south.

According to Hatcher (1993) and Hatcher and others (2005) the prominent penetrative metamorphic foliation present throughout the IP is an S_2 foliation that developed under peak metamorphic, upper amphibolite facies conditions during 'Neoacadian' D_2 deformation. Transposed compositional layering and migmatitic layering parallel to S_2 are axial planar to isoclinal-tight, gently plunging folds (Hatcher and others, 2011) and to the schistosity of matted sillimanite (Clarke, 1981). Merschat and others (2005, Table 1)

FIGURE 5a

FIGURE 5b

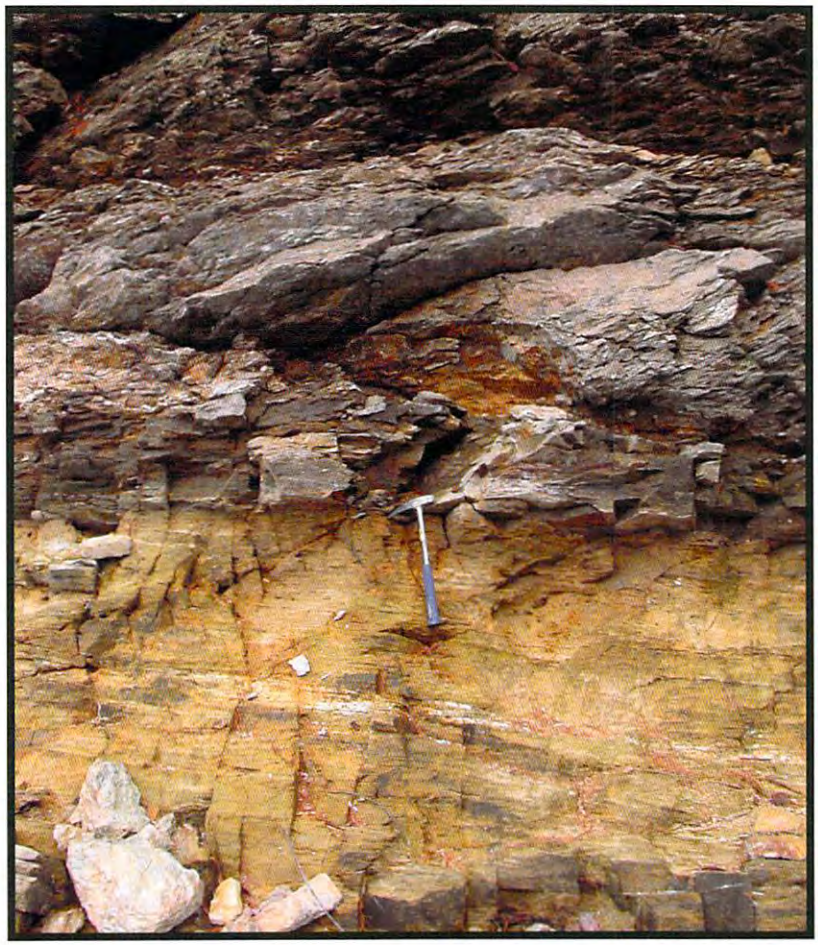

FIGURE 5. a. Eastatoee fault, northwest side of Horse Mountain above Reedy Cove, SE Eastatoe Gap quadrangle. Brown metasiltstone and schist of Chauga River Formation is separated by a sharp contact from light gray, grain-size reduced Henderson Gneiss. The pegmatite bodies just below the fault surface are not foliated or sheared, suggesting they are younger than the ductile deformation accompanying the faulting. View is to the southwest. Hammer is 40 cm. **b.** Eastatoee fault in the Brevard zone: the sharp contact at hammer point marks the fault surface separating Chauga River Formation phyllonite ledge above from tan, grain-size reduced Henderson Gneiss below. View is to the southeast in Whitewater River, Salem quadrangle. Hammer is 40 cm. (From Clendenin and Garihan, 2008, their Figure 2, p. 33).

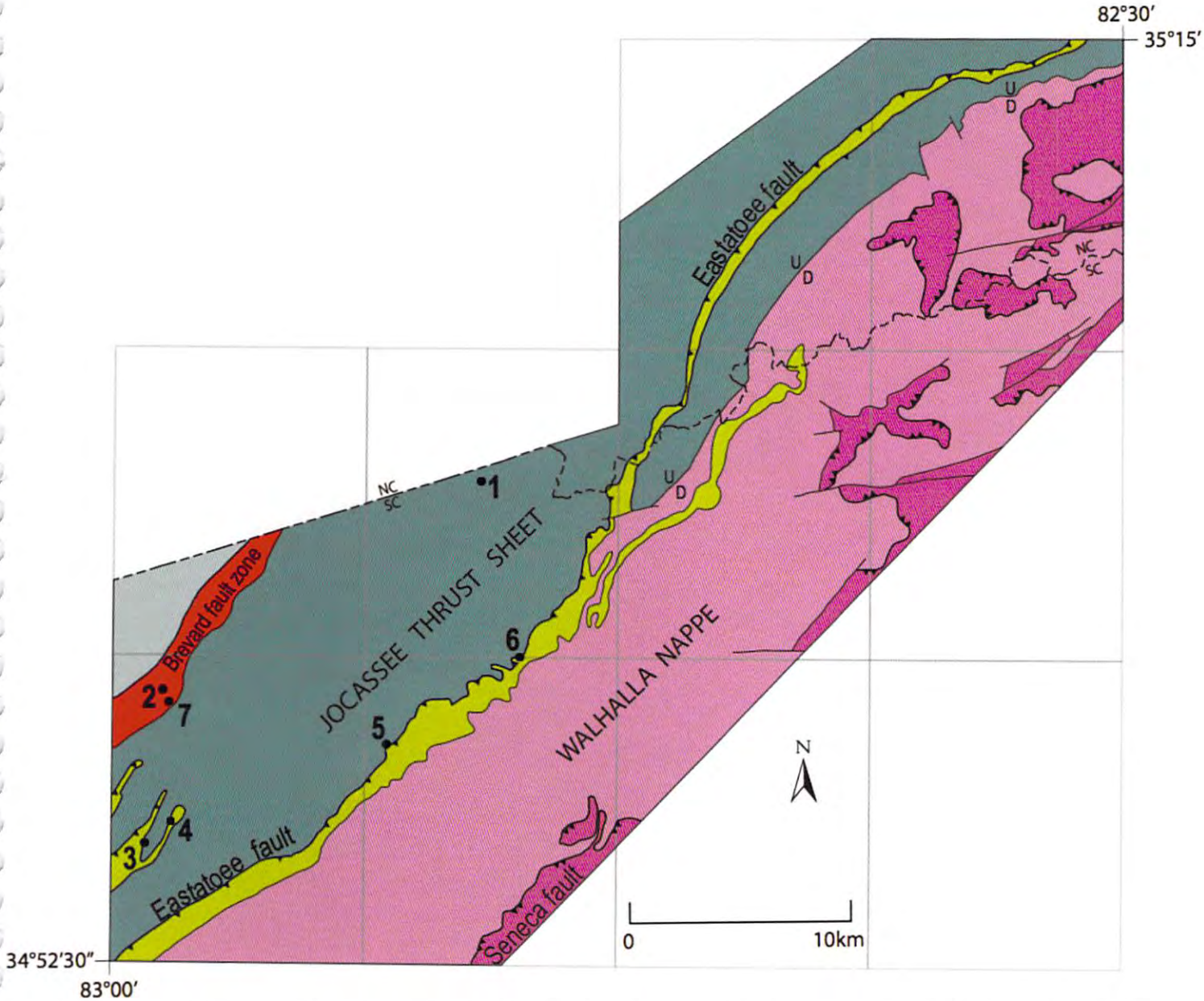

Figure 6. Generalized geology of Mountain Bridge area, the shaded portion of Figure 1. The Brevard zone and three thrust sheets, stacked vertically upward northwest to southeast, are labeled. Henderson Gneiss is forest green. The Eastatoee fault (single sawtooth line) lies at the base of the Walhalla thrust sheet. Chauga River Formation is light green. The Seneca fault (double sawtooth line) lies at the base of the Six Mile thrust sheet (darker rose color). Numbered locations are features described in Garihan and Clendenin (2007).

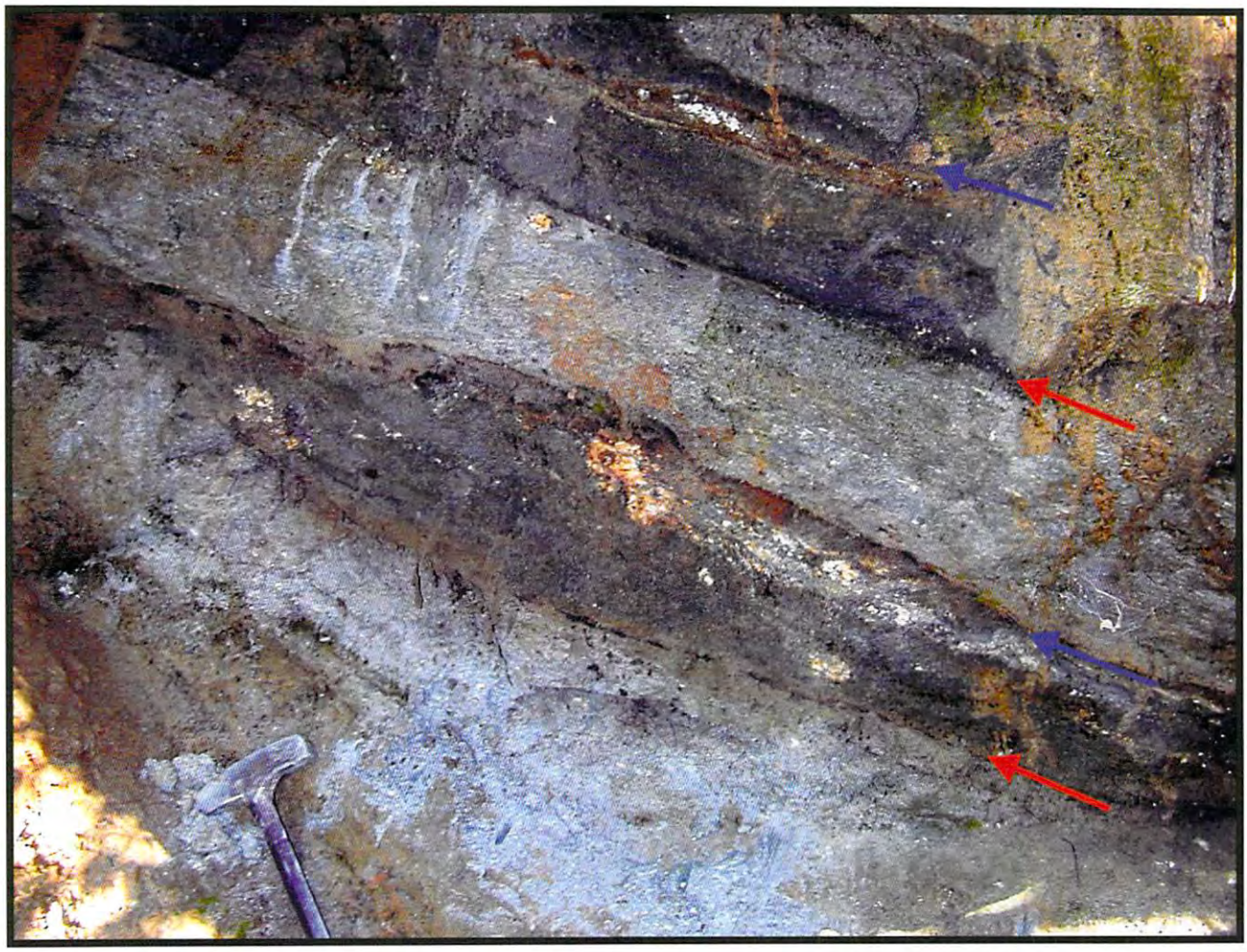

Figure 7. Small Eastatoee fault duplex at Sharp Top Mountain, extreme northern Sunset quadrangle. Mylonitic Henderson Gneiss is gray; Chauga River Formation is brown. The Eastatoee fault is at the red arrow positions. The duplex faults are at the blue arrow positions, truncating the base of Henderson layers. View is to the northeast. Hammer portion is ~25 cm.

describe structures and present a tectonic summary for the northern IP region, North Carolina. In that summary, Merschat and others (2005, correlate various fabrics, fold generations, and faults, metamorphic conditions, and regional events with orogenic timing, particularly in relation to the 'Neoacadian' and Alleghanian orogenies. Trupe and others' (2009) statement about the difficulty of discriminating between Taconic and Acadian metamorphic fabrics, however, should be kept in mind.

Macro- and Meso-scale Folds

Macro-scale (generally map-scale) and meso-scale (outcrop-scale) folds formed during multiple fold phases, with their axial traces currently striking NE-SW, N-S, NW-SE, and E-W. Particularly common on both the Walhalla and Six Mile thrust sheets are macro-scale NE-striking, NW-vergent, overturned folds and NW-striking, SW-vergent, overturned folds. Folds which are inclined, but not overturned, strike mainly N and NE. Well-exposed sets of gently plunging, NW- and SW-vergent, overturned, tight to isoclinal, passive and flexural-flow folds occur, for example, on The Stool and Table Rock exfoliation dome (Table Rock quadrangle; Figures 1; 8a, b, c).

Macro-scale Folds Truncated by the Seneca Fault

Macro-scale folding poses a problem in developing a fold event sequence because many map-scale folds are either pre- or syn-emplacement of the Seneca fault and the Six Mile thrust sheet. In Six Mile rocks, the axial trace strikes of the NE-SW, N-S, NW-SE, and E-W map-scale fold phases are truncated along the Seneca fault. In SE Sunset quadrangle, the Seneca fault trace truncates earlier NE-striking, NW-vergent, overturned folds and later E-W–striking, upright-inclined folds of Six Mile rocks (Garihan, 2005b). In Cleveland quadrangle, the Seneca fault truncates earlier NW-striking, SW-vergent, overturned folds cored by Tallulah Falls gneiss or schist in several isolated Six Mile klippen (Figure 4). At two places in a large faulted klippe in SE Cleveland quadrangle, Tallulah Falls gneiss and schist were thrust westward over younger Poor Mountain Formation amphibolite (Figure 9). Both of these local thrusts were folded by west-vergent, overturned antiforms, exposing younger Poor Mountain amphibolite in their cores. At the southern occurrence, south of the Marietta faults shown in Figure 2a, the thrust surface is upright on the eastern antiform limb and can be traced directly around the fold nose to an overturned position on the western limb. At the northern occurrence, north of the Marietta faults, the Seneca fault truncates the earlier local thrust. These pre-Seneca, folded-thrust relationships were not seen elsewhere on the Six Mile sheet. This is true fault truncation and not an effect of topography.

Regional Interference Folding

After emplacement of the Six Mile-Walhalla thrust stack, a Type-1 (egg-carton) interference-fold pattern developed at meso- and macro-scale in the Six Mile and Walhalla thrust sheets (Garihan, 2015). The interference pattern has been recognized between Sunset and Campobello quadrangles (Figure 1). The pattern involves gentle, upright folds of NE and NW strike (respectively, Set I and Set II). One can recognize this pattern of macro-scale synformal downwarps after back stripping the offsets of younger E-W-striking faults. The relationship is shown on Figure 10. On that schematic, Six Mile rocks are blue areas; blank areas on the figure are footwall-cored antiforms exposing Walhalla gneisses. Several structural basin (B) and culmination (C) positions are indicated. Fold Sets I and II are interpreted to have been initially orthogonal. As a result of their gentle, upright geometries, it is not possible to establish the developmental sequence of these NE and NW gentle folds. Meso-scale examples of this Type-1 interference pattern were recognized by Chan Soo and others (2011) in pavement and quarry exposures in Campobello quadrangle.

A Set I antiform-synform-antiform fold triplet encompass much of the presently exposed width of the Walhalla thrust sheet. Set I folds strike ~N45°E, and antiformal crest-crest wavelength is ca. 12-13 km. An intervening Set I synformal downwarp of Six Mile paragneisses and schist has a current erosional width of ca.10 km.

Discussion

A review of IP fold chronologies based on regional studies shows that not all workers recognize an early D_1 deformational event that is defined by rootless F_1 intrafolial folds and isoclinal folding of an early S_1 foliation preserved in isolated amphibolite and calc-silicate boudins (Nelson, 1986; Davis, 1993b). The timing assigned to D_1 is Taconic? to early Acadian (Merschat and others, 2005). Beyond the D_1 event agreement by different workers, polyphase fold numbering assigned to deformational phases differs in older studies. Table 1 provides a compilation of fold phases by various IP mappers

Examination of Table 1 indicates that assignment of each progressive fold phase laterally to the F_1 through F_6 scheme of Merschat and others (2005, Table 1) involves inconsistencies; for example, some earlier workers did not recognize the D_1 phase of rootless F_1 intrafolial folds. Thus, one worker's F_1 is another's F_2. Moreover, any particular area may not display all fold phases regionally present, adding more inconsistency to the attempt to place each 'local' fold scheme into a regional chronology.

One is likely to distinguish two or three distinct macro- or meso-scale fold phases in any good exposure in the western IP, even if saprolitic, but the distinct fold phases represent only a fold event sequence for that particular exposure. Common field examples are isoclinal folds that have been folded by a close-tight, inclined fold set, or isoclinal folds warped by upright, gentle folds (Figure 8d). It should be noted that only rarely isoclines are seen to refold isoclines.

Another problem across the western IP is that fold orientations have been rotated to various degrees from their original orientations by subsequent folding and faulting events. Thus, there is difficulty in assigning with confidence an age or generation to an individual meso-scale fold seen in the field based solely on its fold style or hinge orientation. Moreover, based on macro- and meso-scale examples of refolded folds, there are similarities in fold style of the different generations (Table 1).

A third problem is the map-scale folds and interference folding reported here. Map-scale folds are recognized to be pre- or syn-emplacement of the Seneca fault, whereas interference folding is post-emplacement of the Six Mile-Walhalla thrust stack. It is noted that these observations should be considered significant in the fold event sequence. Therefore, no attempt is made here to "pigeonhole" the fold generations into traditional F-series categories.

Ductile Shear Zones

In the Mountain Bridge area after thrust sheet emplacement, a variety of ductile features developed in the Walhalla-Six Mile thrust stack, and those features primarily indicate a top-to-the-SW sense of shear. The ductile features are: 1) small-scale ductile normal faults, 2) S-C' and S-C-C' 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, TG, Poor Mountain Formation amphibolite, and Tallulah Falls Formation paragneiss and schist (Figure 2a). The presence of these features at all structural levels in the thrust stack (Figure 11a-e) and their occurrence after thrust stacking are considered evidence of a period of gravitational collapse.

Retrograde shear zones of ductile muscovite-quartz schist (generally up to a few meters thick) and fine biotite-coarser muscovite quartzo-feldspathic TG also are inferred to have formed as a result of gravitational collapse. Muscovite formed at the expense of K-feldspar under greenschist facies conditions. It should be noted that muscovite in TG typically is up to five modal percent of the rock and fine-crystalline. However, in the retrograde shear zones, coarser muscovite comprises up to forty modal percent. Mica growth is interpreted to have been facilitated by fluids moving through the gneiss. The migration of fluids along widespread fracture networks also has produced bleach zones a few centimeters wide in TG.

Mine Mountain Shear zone

Mine Mountain is located in SW Standingstone Mountain quadrangle (Figure 1), in an area underlain by TG (Figure 12, A). A

FIGURE 8a

FIGURE 8b

FIGURE 8c

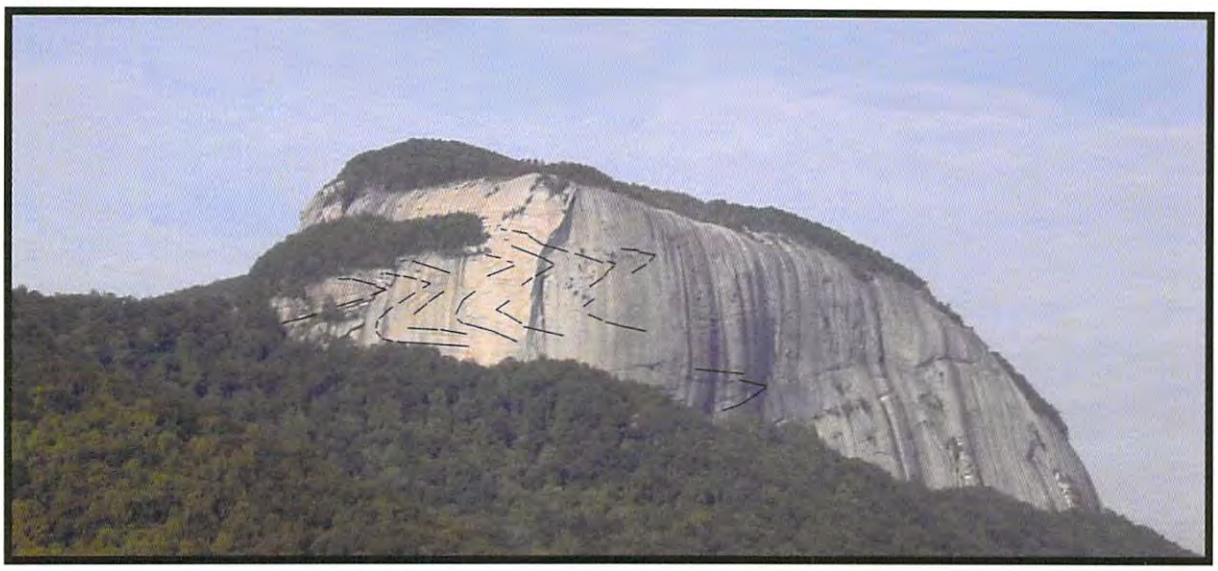

FIGURE 8d

FIGURE 8. Folds in Table Rock quadrangle. **a.** Gently NE-plunging, SW-vergent isoclinal folds in Table Rock gneiss and amphibolite, east face of The Stool. Black, iron-stained, differentially weathered rock surface. Lateral distance at base about 4 m. **b.** Detail of gently NE-plunging, SW-vergent isoclinal Z-fold in Table Rock gneiss and amphibolite (dark, recessed area), east face of The Stool. Hammer portion is ~ 30 cm. **c.** Near-recumbent, NW-vergent, overturned folds (outlined) on the north face of the Table Rock exfoliation dome. View is to the southwest. About 0.8 km of the rock face is shown. **d.** Isoclinal folds in maroon weathering mica schist, Pickens quadrangle. Pencil is parallel to the axial surface of an isocline. The schistosity and axial surfaces have been warped by broad folding. View is to the west. Pencil is 16 cm.

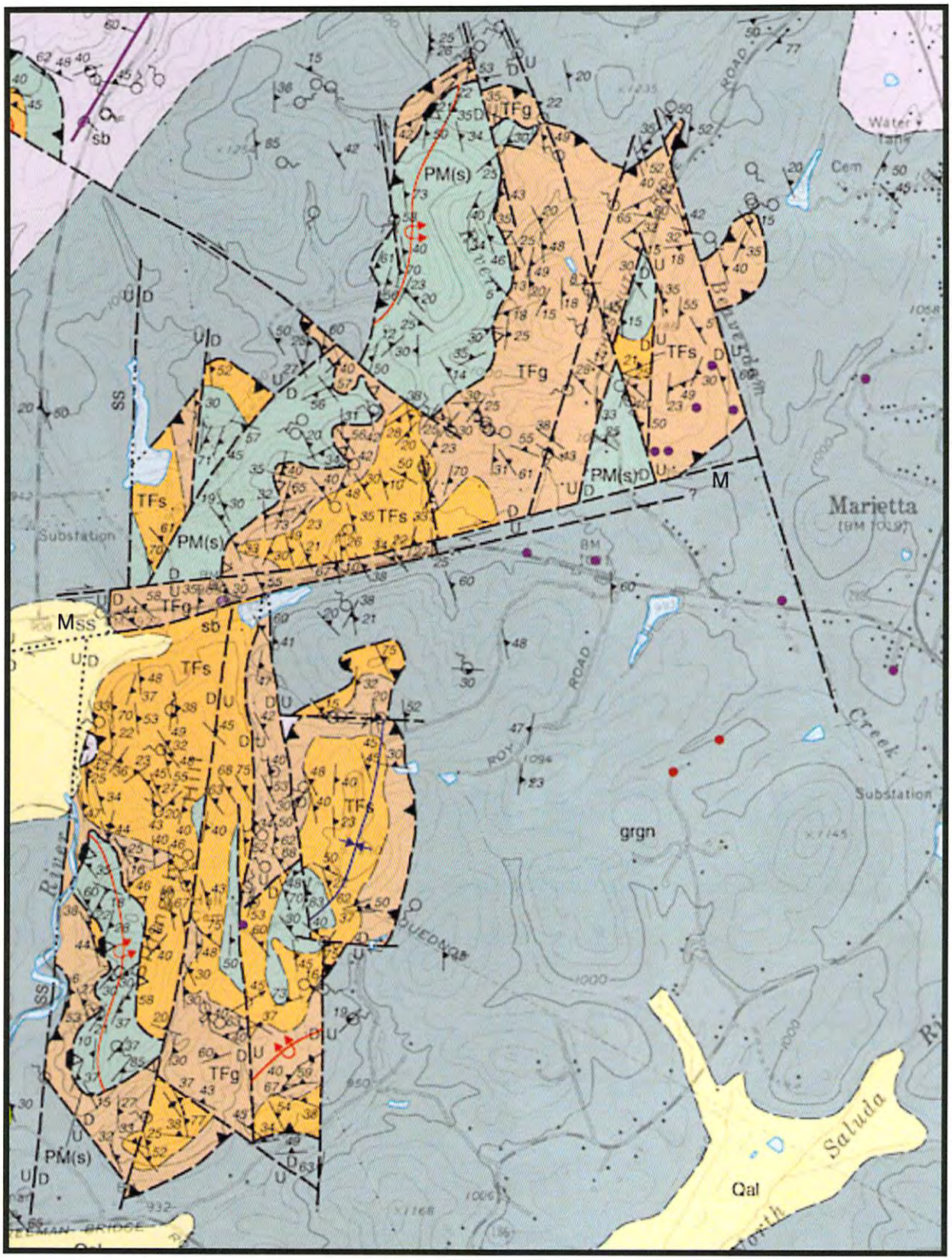

Figure 9. Faulted klippe, SE Cleveland quadrangle. Tallulah Falls gneiss- TFg, brown; Tallulah Falls schist- TRs, orange; Poor Mountain amphibolite- PM(s), green; Table Rock granitoid gneiss- grgn, blue-green and pink. Seneca fault- sawtooth line; pre-Seneca thrust- open sawtooth line, overturned on the west side of an overturned antiform cored by PM(s). Marietta faults- two ENE dextral faults, labeled M; silicified cataclastic zone- purple sb line, dots. Located on Figure 2b.

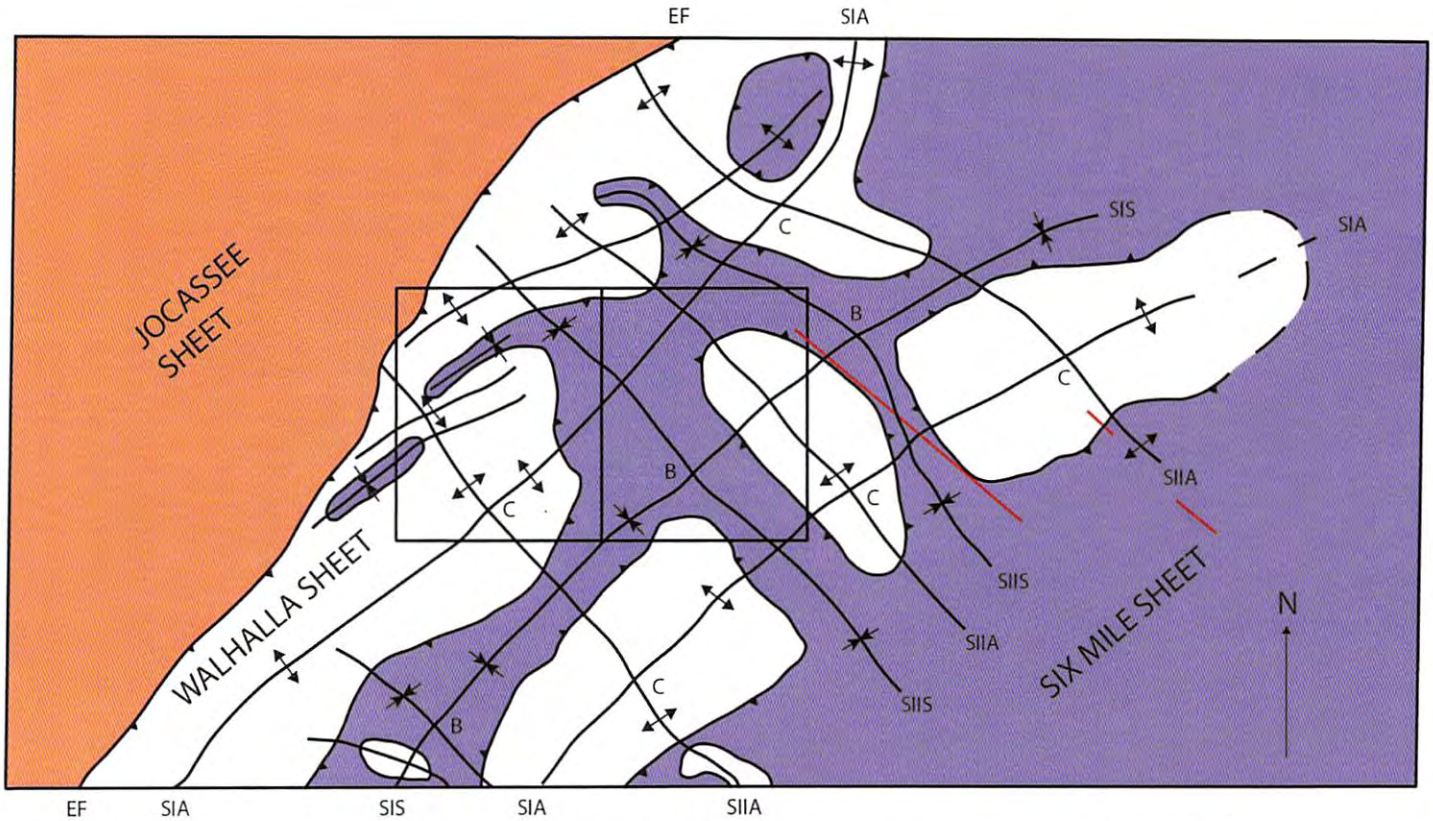

Figure 10. Schematic diagram of the macro-scale Type-1 interference-fold pattern, after back-stripping younger fault offsets. Six Mile thrust sheet- blue; Walhalla thrust sheet- blank; Jocassee thrust sheet of Henderson Gneiss- red. Eastatoee fault- EF. Seneca fault- sawtooth line between Six Mile and Walhalla thrust sheets. Fold Set I, NE strike; fold Set II, NW strike. SIA, SIIA- fold Set I and Set II antiforms; SIS, SIIS- fold Set I and Set II synforms. Culminations- C, basins- B. Diabase dike locations- red lines. Table Rock (left) and Cleveland (right) quadrangles are outlined.

FIGURE 11a

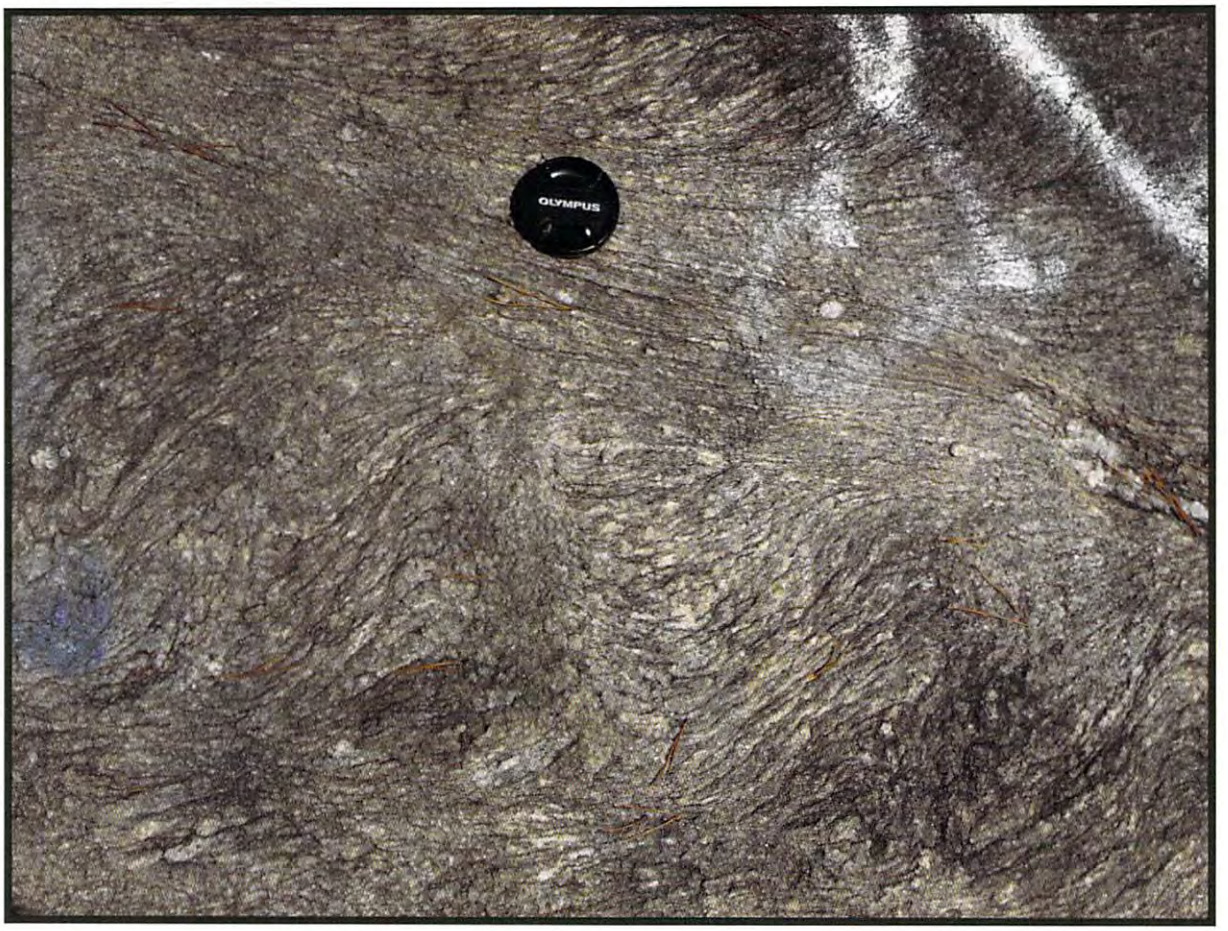

FIGURE 11b

FIGURE 11c

FIGURE 11d

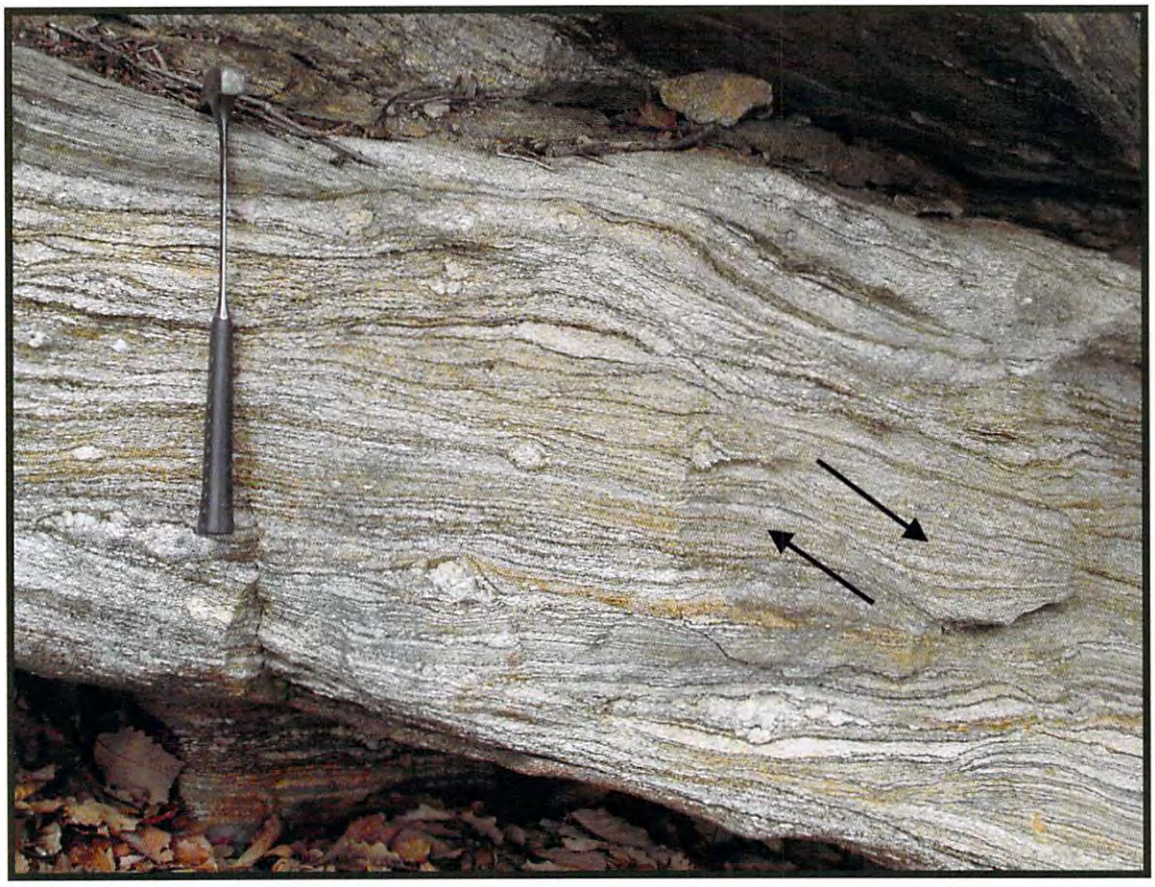

FIGURE 11e

FIGURE 11. Shear sense features. **a.** Ductile shear zone in Table Rock augen gneiss, Bald Rock, Cleveland quadrangle. Shear zone is at base of the lens cap, with its transposing foliation. View is to the southeast. Top-to-right, normal shear sense is shown by curved, reoriented augen gneiss foliation adjacent to the thin shear zone. Lens cap is 6 cm. **b.** A small ductile shear in Table Rock granitoid gneiss, right of centimeter scale, Saluda quadrangle. View is to the east; top-to-right normal shear sense. **c.** S-C-C' in Table Rock gneiss, Cleveland quadrangle. S surfaces (gneiss foliation) dip gently right, C surfaces are horizontal, C' surfaces are parallel to the pencil. Lower scale in cm. View is to the west; top-to-left shear sense. **d.** Small ductile shear in mylonitic Tallulah Falls gneiss, Bailey Ridge, Saluda quadrangle. View is to the northeast; top-to-right normal shear sense. Hammer is 40 cm. **e.** Asymmetric quartzo-feldspathic lenses in Tallulah Falls schist, Cleveland quadrangle. View is to the northwest; top-to-left shear sense (arrows). Hammer is 40 cm.

Article	Merschat *et al.* (2005)	Clendenin and Garihan (2004)	MacLean and Blackwell (2001)	Garihan and Ranson (1997)	Nelson (1986)	Clarke (1981)	Wetmore and Griffin (1977)	Griffin (1974)	Griffin (1967)
F_1	Intrafolial folds and isoclinal folds preserved in boudins	Isoclinal folding	Rootless isoclinal intrafolial folds		Rootless recumbent to reclined isoclinal folds	Folds axial planar to schistosity of matted sil.	Recumbent-reclined folds trend NE-SW & NW-SE	Isoclines and tight to isoclinal chevrons	Upright concentric and isoclinal folds
F_2	Inclined to recumbent, tight to isoclinal passive and flexural folds, and sheath folds; curving pattern trends NE-SW, E-W, & NW-SE	Gentle to moderately inclined NNW trending closed folds	Upright to recumbent tight to isoclinal folds (chevron style)		Steep to recumbent isoclinal folds post peak metamorphism (rare F2 axial planar foliation)	Steep to vertical axes (upright) fold schistosity of F1	Upright low amplitude refolding of F1 limbs	Low amplitude upright isoclinal E-W trending folds and Upright isoclinal NNW trending folds	Overturned isoclinal folds to the NW
F_3	Inclined to upright, closed to open folds, trend NNE-SSW, N, & NW	Kink folding	Open upright folds trending N-S		Upright to slightly inclined conjugate fold sets that trend NE & NW (crenulation cleavage late metamorphic)	Refolds F2 to folds with horizontal axes and trend N10E			Secondary undulations of gentle folding
F_4	Upright, open folds, trends NW-SE, & NE; crenulations plunge SE, & NE		Open upright folds trending E-W	2-4 mi in wavelength trending N-S, near recumbent (?)	Post F3 folding about E-W & N-N-E axes	Chevron folding in schist			Break up into boudins
F_5	Regional broad, open folds, most trend NE & NW		Macroscopic fold that refolds the mesoscopic folds – E plunging hinges	0.25-1.5 mi trending E-W to WNW (?)					
F_6	Regional broad, open folds, trend NE		Macroscopic fold that refolds the mesoscopic folds – N plunging hinges						

Table 1. Compilation of various authors, indicating fold characteristics and associated fold chronology assignment, based on individual Inner Piedmont field studies.

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 after it. Schistosity is deflected locally around meter-scale lenses of quartz-feldspar pegmatite. The shear zone is more resistant than the surrounding saprolitic gneiss and generally forms low 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. No sulfides, other than pyrite, were noted. Shear zone thickness is variable along strike, estimated to be a few meters to tens of meters. In a few places, there are several parallel shear zones, separated by TG. The shear zone is truncated to the north by a NE-striking fault.

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 a schistose, wavy, S-C' fabric (Figure 13). This fabric resembles a strongly flattened honeycomb geometry, with cell walls being the schistose micas. Millimeter- to centimeter-scale chevron folding of schistosity is locally present.

The shear zone has been folded, with map-scale synforms showing arcuate axial traces (Figure 12, A). An S-C' fabric is well developed, particularly along both limbs of the eastern synform (Figure 14a, b). On the western limb of the eastern synform, the orientation of C' shear bands indicate top-to-the-SW movement. On the eastern limb the sense of shear is reversed as a result of the folding, indicating top-to-the-NE (Figure 14c).

Pinnacle Mountain Trail Shear Zone

The Pinnacle Mountain trail crosses another shear zone on an E-W ridge of Table Rock gneiss south of Caesars Head in northwest Cleveland quadrangle (Figure 1). At its south end, the shear zone (Figure 12, B) is truncated by a younger thrust of the Caesars Head fault system that will be discussed later. The shear zone 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. S-C-C' structures are present, but poorly developed, in this shear zone.

The texture of this shear zone is similar to that at Mine Mountain. However, sillimanite occurs as moderately- to well-aligned needles on thin, satiny (fine-crystalline) muscovite-quartz schistosity surfaces (Figure 15a). Thin lenses and discontinuous layers of clear, glassy, fine-crystalline, equigranular quartz a few millimeters wide are enveloped by schistose, anastomosing S-C' tapered buttons of fine- to medium-crystalline muscovite and scattered limonite after euhedral pyrite. Euhedral garnet (generally 1-2 mm) grew in the quartzose lenses and schistosity.

Tight-close chevron folds up to a few centimeters across deform aligned sillimanite needles on the dominant schistosity surfaces (Figure 15b). That is, at the chevron fold crests and troughs (fold noses), the sillimanite needles are sharply bent. In places a set of thin (1-2 mm), wavy, secondary schistosity surfaces, with or without aligned sillimanite needles, disrupts the chevron fold limbs that folds the earlier dominant schistosity. This second schistosity lies parallel to chevron fold axial surfaces and is a locally-developed discrete crenulation cleavage. Where laterally continuous and better developed, these secondary micaceous schistosity surfaces envelop the individual chevrons. In addition, the dominant schistosity is warped by younger gentle, upright folds.

Near its northern terminus, sheared textures are developed outside the main Pinnacle Mountain trail shear zone (Figure 12, B). Isolated aggregates of fine- to coarse-crystalline, ragged muscovite form dark gray buttons 1-2 mm thick (Figure 15c) in TG away from the zone. Observations suggest that movements along strike were distributed across a wider zone in the enclosing gneiss and migmatitic biotite schists at its northern end. These exposures show foliated biotite quartzo-feldspathic gneiss layers a few centimeters wide alternating with thin, wavy schistose zones (a few millimeters to a centimeter thick) composed of garnet, lineated sillimanite, muscovite, and quartz. The alternating schist zones are interpreted as narrow zones of movement localized within TG.

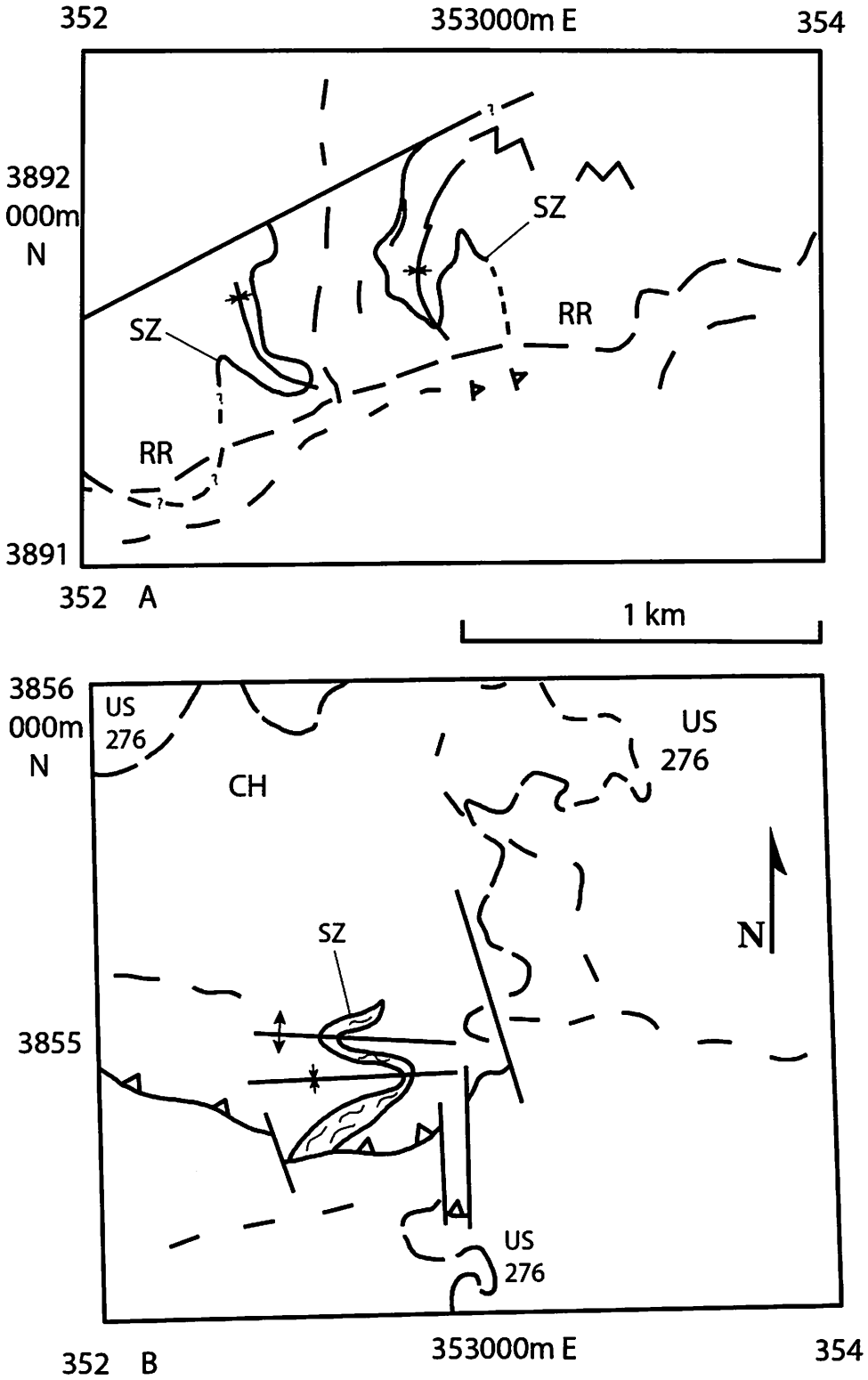

Figure 12. A, B. Geologic sketch maps of two shear zones. UTM coordinates shown. A. Folded Mine Mountain shear zone, Standingstone Mountain quadrangle. Mine Mountain- MM; Reasonover Road- RR; shear zone- SZ. Fault (motion sense unknown) truncates the shear zone to the north. Drainages are shown as unlabeled, wider-spaced, dashed lines. B. Folded Pinnacle Mountain trail shear zone, Cleveland quadrangle. Caesars Head community- CH; shear zone- SZ; Caesars Head fault- open sawtooth line. US 276 labeled. Drainages shown as unlabeled, wider-spaced, dashed lines.

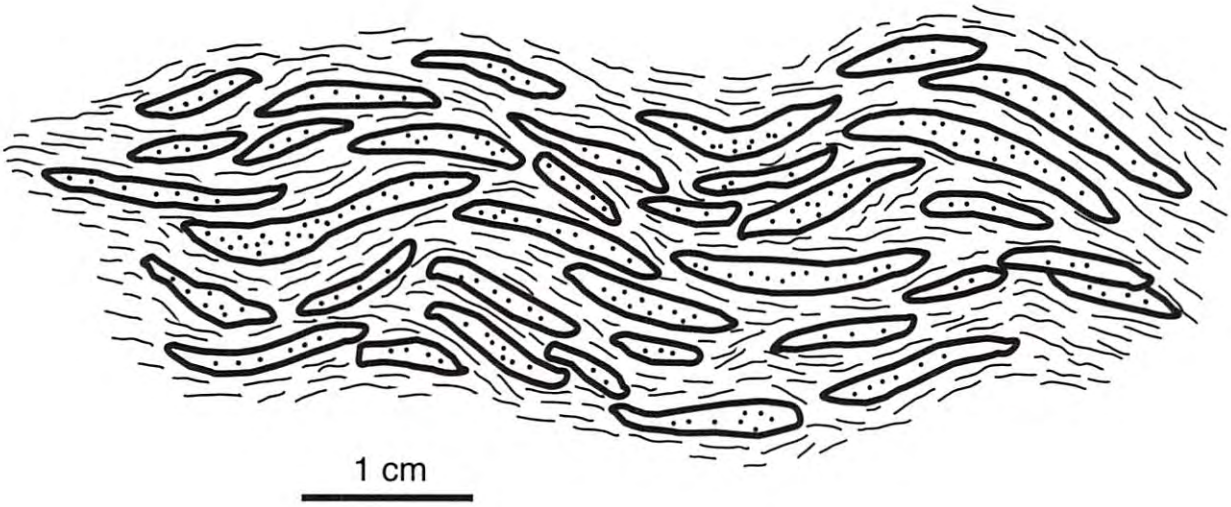

Figure 13. Sketch of typical shear zone texture, muscovite-quartz schist. Fine-crystalline, equigranular quartz forms lenses; aligned muscovite is represented by lines.

Figure 14a

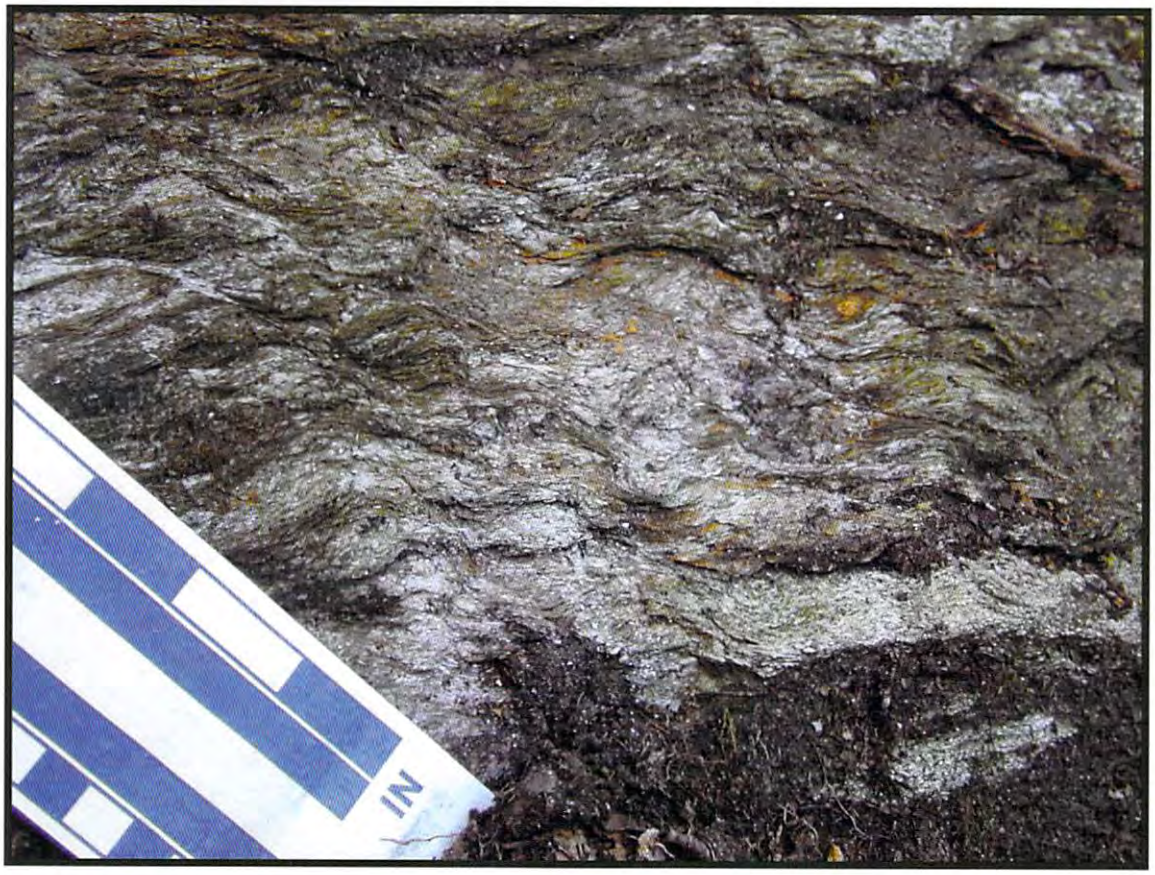

FIGURE 14b

FIGURE 14c

FIGURE 14. Shear fabrics in muscovite-quartz schist, Mine Mountain shear zone. **a.** S-C' fabric, west limb of eastern syncline of Figure 12, A. S surfaces dip gently left. C' surfaces parallel to edge of scale. View is to the southeast; top-to-right shear sense. Scale is in inches. **b.** S-C' fabric with interpretation, west limb of the same eastern syncline as in **a.** S surfaces dip gently to left. C' surfaces parallel to pencil. View is to the southeast; top-to-right shear sense. Coin is 2.6 cm. **c.** S-C-C' fabric, east limb of eastern syncline of Figure 12, A. Prominent 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 shear sense. Folding reverses the shear sense direction between **a.** and **b.**, and this view.

Muscovite-biotite TR gneiss is interlayered with muscovite-quartz schist at the wider, southern end of the Pinnacle Mountain trail shear zone. A meso-scale normal fault at this position is shown in Figure 15d.

Minor Ductile Shear Zones

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. An example is a pavement 1.5 km northeast of Table Rock Reservoir along Gitomo Road in Table Rock quadrangle. The S-C fabric produces wavy mica buttons that weather out and litter the ground (Figure 16).

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. This occurrence lies in the immediate hanging wall of the younger Caesars Head fault system, as does the Pinnacle Mountain trail shear zone.

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.

Farther southwest in Salem quadrangle (Figure 1), resistant, fine- to medium-crystalline, muscovite-quartz schist, locally with garnet, forms discontinuous zones up to several meters wide and 200 meters long (Clendenin and Garihan, 2007b). The zones occur intraformationally and along fault contacts of Chauga River Formation, Poor Mountain Formation, and TG. Some leucocratic biotite quartzo-feldspathic gneiss interlayers within Poor Mountain Formation amphibolite show ductile deformation. The schist also is derived from localized shearing of fine-crystalline muscovite-quartz-feldspar gneiss in TG. Several anastomosing schistosities are present in some hand specimens and are characterized by millimeter-thick schistose layers of muscovite surround lenticular aggregates of fine-crystalline, equigranular quartz. Textures resemble the anastomosing muscovite-quartz, strongly flattened honeycomb textures of the Mine Mountain and Pinnacle Mountain shear zones. Millimeter-scale chevron folds are present.

Several of ductile shear zones along the west shore of Lake Keowee in Salem quadrangle, one less than 0.3 meters thick, display S-C structure indicating top-to-the-SW movement. These zones lie along one thrust contact (Chauga River Formation over Poor Mountain Formation amphibolite) or otherwise lie in metamorphic units in the general area of a set of NW-directed thrusts. The shear zones may be earlier ductile zones preserved in rock slices between later thrusts, or they may represent polyphase compression-extension episodes produced during the thrusting.

Howard (2001) describes a cycle of progressive development of transposition structures in TG augen gneiss in southern Saluda quadrangle (Figure 1). The latest transposition structure recognized is an S-C' fabric with a top-to-the-SE movement sense (See Howard, 2001, his Figure 10). He suggests that the fabric developed in footwall mylonitic rocks during NW emplacement of overlying Six Mile sheet rocks, with episodic compression and extension. Alternately, these extensional features in TG augen gneiss may have formed during the period of gravitational collapse described here.

Secondary Fabrics in the Chauga River Formation

In the western IP, Chauga River Formation garnet schist and garnet metasiltstone in the hanging wall of the Eastatoee fault forms a continuous belt of resistant rocks that was mapped across five quadrangles between Salem and Standingstone Mountain quadrangles (Figures 1, 6). S-C' fabric, folds, and boudinage are common in ledge and cliff exposures. Foliation and schistosity in Chauga River Formation rocks is a secondary foliation,

FIGURE 15a

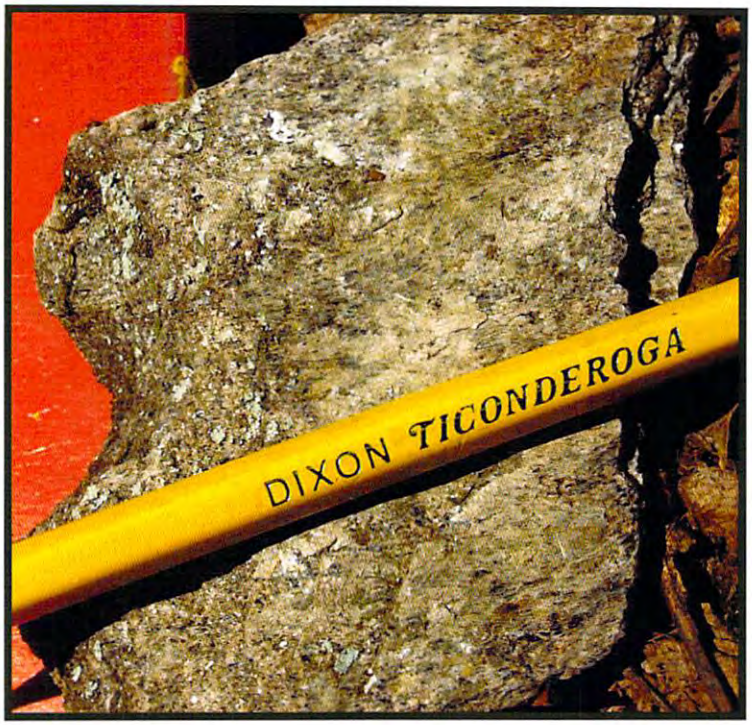

FIGURE 15b

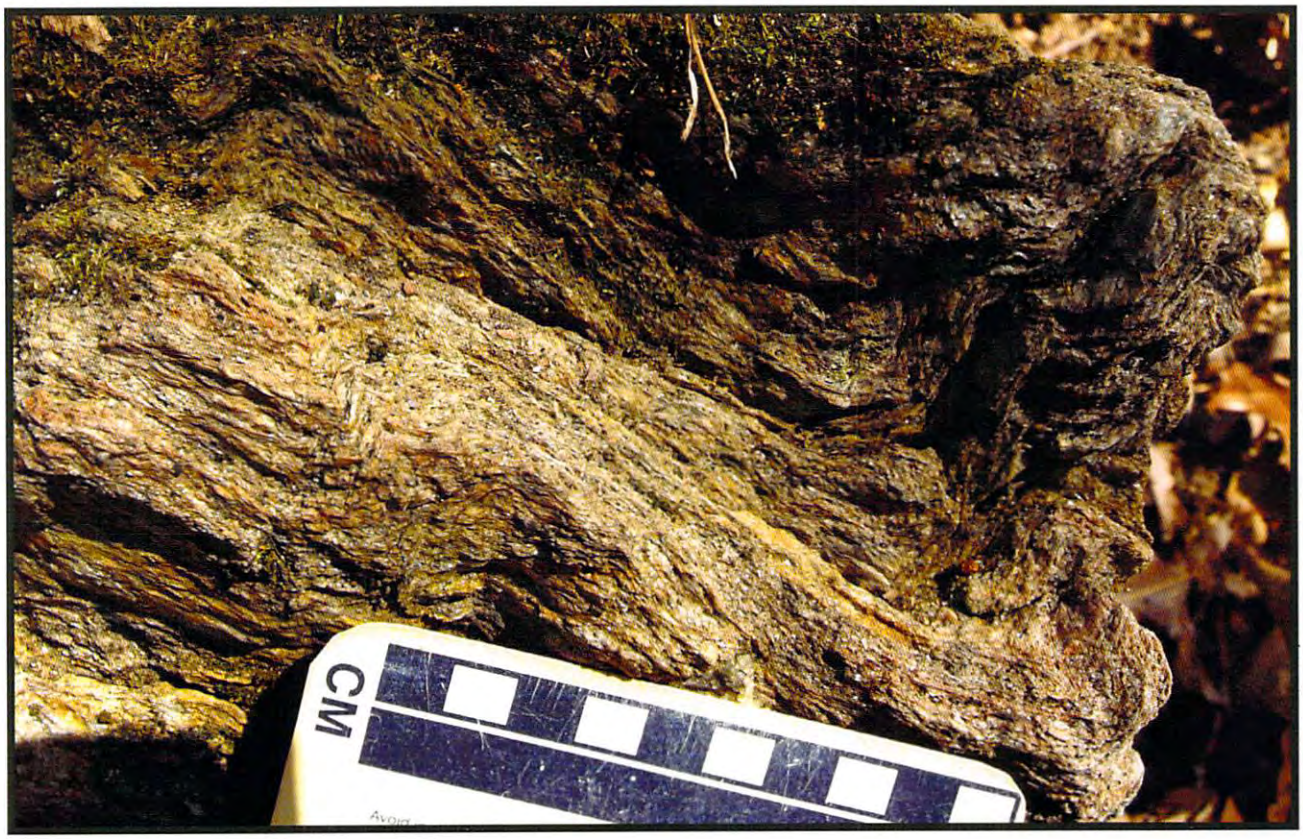

FIGURE 15c

FIGURE 15d

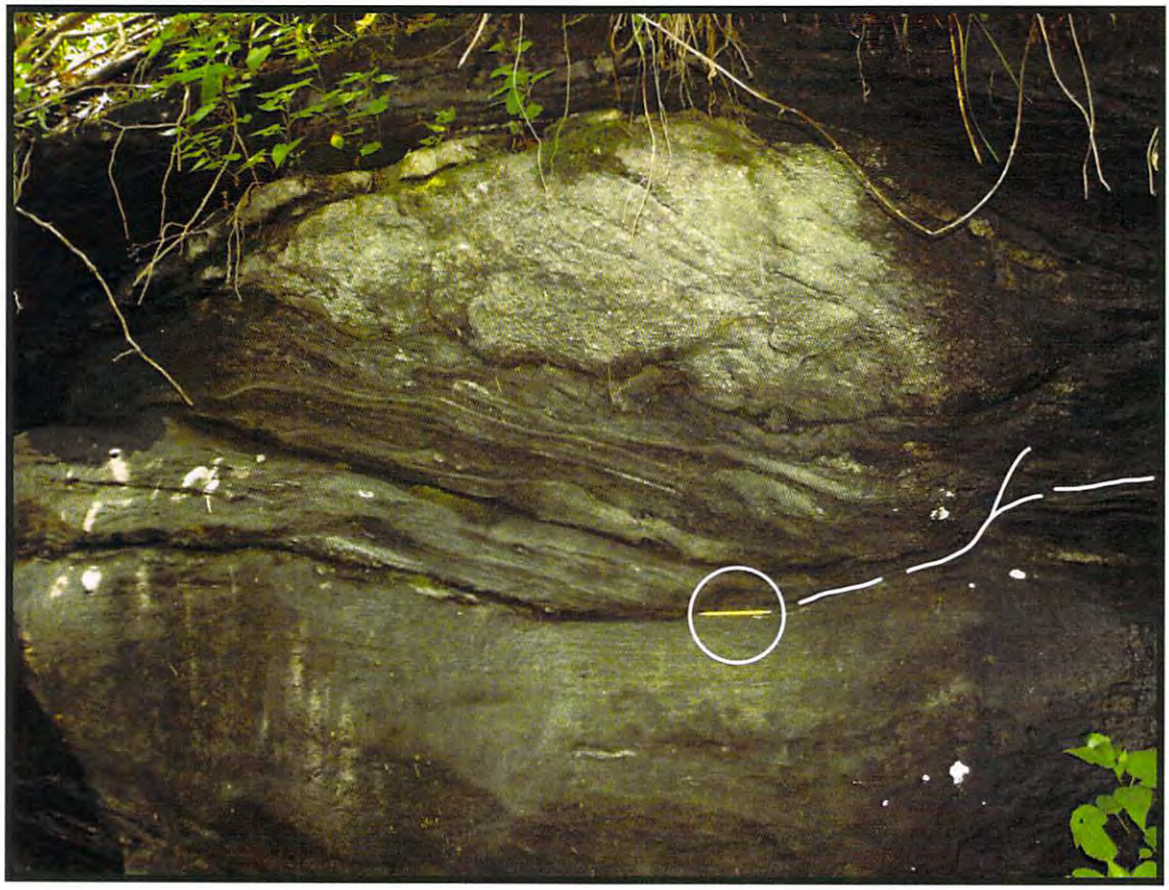

FIGURE 15. Fabrics in sillimanite-muscovite-quartz schist, Pinnacle Mountain trail shear zone, Cleveland quadrangle. **a.** Moderately- to well-aligned, prismatic sillimanite needles (parallel to pencil) on schistosity surface. Pencil length ~7 cm. **b.** Chevron folding of schistosity and prismatic sillimanite bundles (small white lenses). Float block. Scale in cm. **c.** Dark buttons composed of ragged muscovite aggregates, Table Rock gneiss, outside but near the northern end of the shear zone. Mica aggregates generally strike northeast-southwest (top to bottom). View is down. Scale is in cm. **d.** Small normal fault in Table Rock muscovite-biotite gneiss, Pinnacle Mountain trail shear zone. Pencil (circled) lies on the fault, with its steeper portion to the right marked by dashed lines. An oblique view of the curved fault surface is to the north-northwest. A pegmatite lens with scalloped margins lies in the fault hanging wall. Movement is down-to-left, approximately to the west. Pencil is 15 cm.

Figure 16. Gitomo Road shear zone pavement, Table Rock quadrangle. Thin (1-2 mm), anastomosing mica schistosity surfaces wrap around lenses of fine-crystalline, clear, equigranular quartz. Schistosities generally strike N20°W (upper left - lower right). Pegmatite lens is right of the pencil. Total shear zone thickness is about 5 m, of which 0.5 m is shown. View is down. Pencil is 15 cm.

as indicated by intrafolial folds and lenticular amphibolite enclaves internally preserving isoclines with foliation truncated at their margins (Figure 17). Those folds clearly belong to the D_1 deformation (Table 1).

Two end-member lithologies, on occasion interlayered (Figure 18a), make up the range in compositional variation. The first end-member 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.

An S-C' fabric is developed in this schist throughout the outcrop belt, but particularly in Sunset, Eastatoe Gap, Salem, and Standingstone Mountain quadrangles (Figure 1). The S-C' fabric consists of coarse muscovite flakes or aggregates of finer muscovite that form conspicuous buttons in a groundmass of fine-crystalline biotite (Figure 18b, c, d, e). Buttons litter the ground in the proximity of the schist. The schistose rocks may contain resistant layers and pods of medium- to coarse-crystalline granitoid material and pegmatite, which is locally foliated and sheared (Figure 18f).

'Block-in-Schist' Shear Zones

Two greenschist-grade shear zones occur in western Table Rock quadrangle along the South Saluda River below the dam of Table Rock Reservoir (Figure 19). Their origin is controversial because their features are unique. The 'block-in-schist' character of these shear zones, described by Garihan and Ranson (2014), has not been observed elsewhere in the western IP (Figure 20a).

The two shear zones contain abundant dismembered, lenticular- and spindle-shaped fragments and irregular blocks of Table Rock gneiss, with fewer amphibolite and biotite gneiss pieces, floating in a medium- to coarse-crystalline pyrite (2-3%)-garnet-muscovite schist matrix. In the exposures, schistosity in places is generally planar and elsewhere 'swirled'. The southern shear zone is ten to eleven meters wide; whereas the northern one is thinner, about three meters. The difference in thicknesses suggests two separate shear zones, rather than one folded back on itself.

Blocks and fragments are 2-50 cm in length. The long axes generally are parallel, or at a low angle, to the schistosity of enveloping schist. In a few places, alignment of separate, isolated gneiss pieces appears to be the result of disruption of originally more continuous gneissic layers (Figure 20b). If true, the original gneiss layers apparently were boudinaged and then subsequently folded in the shear zone. This type of sequential deformation – boudinage followed by folding – requires two periods of deformation.

Internal compositional layering may be truncated abruptly by external schistosity at the margins of individual blocks; internal gneissic layering may lie at any angle to external schistosity (Figure 20c). Variably oriented isoclinal folds of compositional layers are preserved *in* individual gneissic fragments. Tight and isoclinal folds are common regionally in Table Rock gneiss. In addition, some gneissic fragments have *individual* tight or isoclinal fold shapes (and even refolded folds), with well-preserved fold noses and transposed limbs (Figure 20d). These folds may have been transposed in gneiss developed prior to shearing in the schist and delicately preserved within it. Alternatively, these isolated tight-isoclinal folds were produced by intra-schist shearing deformation of originally spindle-shaped pieces.

In a few places, centers of these curved, antler-like shapes show a micaceous axial planar schistosity of the matrix consistent with flattening during shearing deformation (sub-simple shear; Figure 20e). At the margins of some irregular, partly disrupted blocks, delicate, finger-like projections of gneiss into schist were contorted during shearing and flattening (Figure 20f). Internal mafic compositional layers in places also appear to have been utilized to assist in peeling apart and fragmenting some larger individual blocks. One elongated gneiss piece appears to have been rotated >180° into a crude circular structure.

Along the creek between the two shear zones and also north of the thinner one, TG exposures do not have the 'block-in-schist' fabric. At

Figure 17. Lenticular enclave of folded amphibolite encased in Chauga River Formation schist, northwest slope of Horse Mountain, SE Eastatoe Gap quadrangle. S_1 foliation preserved in the enclave is folded by D_1, the oldest regional IP deformation (See Table 1). S_1 foliation is truncated at the enclave margin by a younger schist foliation, parallel to the pencil. View is to the southwest. Pencil is 15 cm.

Figure 18a

FIGURE 18b

FIGURE 18c

FIGURE 18d

FIGURE 18e

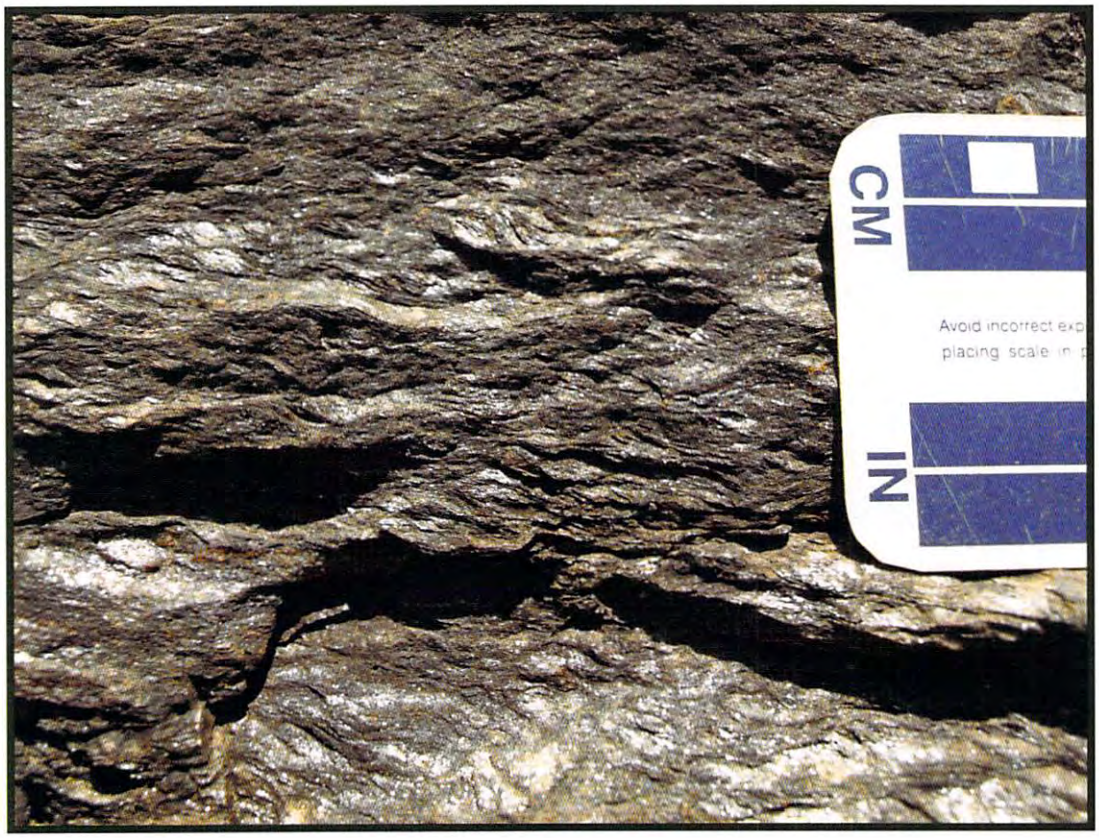

FIGURE 18f

FIGURE 18. Chauga River Formation fabrics. **a.** Oblique view of interlayered metasiltstone and button schist (reflective mica surfaces), Sunset quadrangle. View is to the southwest. Notebook is 19 cm. **b.** S-C' fabric in 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. **c.** S-C' fabric in garnet button schist, northern Standingstone Mountain quadrangle. 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. **d.** S-C' fabric in garnet button schist, Eastatoe Gap quadrangle. S surfaces dip gently left, C' surfaces dip steeply upper left to lower right. View is to the southeast; top-to-right shear sense. Pencil portion is 6 cm. **e.** S-C-C' fabric in Chauga River Formation schist, roadcut north side of Highway 11, Salem quadrangle. 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. **f.** Asymmetric quartzo-feldspathic lenses in saprolitic schist. View is to the northwest; top-to-left shear sense. Hammer is 40 cm.

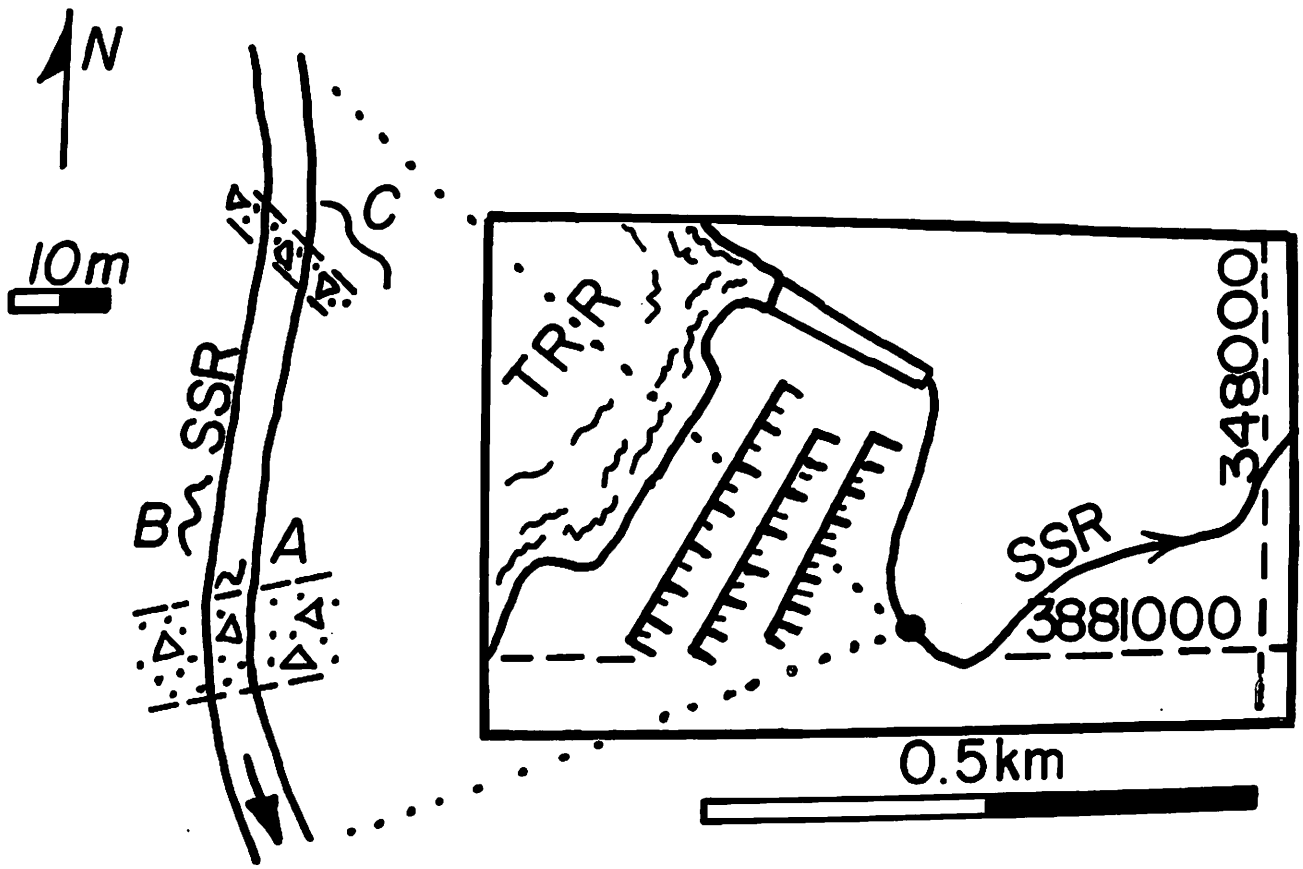

FIGURE 19. Location of two 'block-in-schist' zones, South Saluda River below Table Rock Reservoir dam, Table Rock quadrangle. Table Rock gneiss is blank; brittle-ductile shear zones are dot and triangle pattern. Southern zone is 10-11m thick; northern zone is 3-4m thick. Fold data: location A- upright folds, hinges plunge 56° in the direction S64°E (56°/S64°E); location B- upright-inclined folds, hinges plunge 6°/N55°W; location C- broad foliation warps, hinges plunge 20°/east (see Figure 20g). Table Rock Reservoir- TRR; South Saluda River- SSR. Northing (3881000) and easting (348000) of UTM grid. Access is restricted by the Greenville Water System.

these locations (Figure 19, A, B, and C), several generations of folds are well developed. Contacts between the southern shear zone and adjacent typical TG are not well enough exposed to know whether the folding at locations A and B has deformed the adjacent shear zone.

Discussion

In the western IP, 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-compressional 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.

Greenschist-grade features such as ductile normal faults, S-C' and S-C-C' fabrics, and sheared, 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 western IP, 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 – in weak Chauga River schist, with more rigid Poor Mountain amphibolite above, and also at levels in the crystalline thrust stack. In alpine Corsica, Jolivet and others (1990) describe extensional deformation distributed throughout the "nappe stack" and importantly along thrust contacts which served to localize the strain. Catalan and others (2003) also describe the synorogenic timing of contractional and major extensional zones during emplacement of a crystalline thrust sheet-nappe in NW Spain. In Spain, extension parallel to the contemporaneous shortening direction took place under conditions involving major rheological heterogeneities in the orogenic pile, heat accumulation at depth, and deep-seated viscous flow.

A difficulty in the western IP is correlating observed structures with different orogenic events because many structures show top-to-the-SW movement. A key is the direct linkages that exist between older features formed initially outside the Brevard zone in the western IP and their later incorporation into the Brevard zone. Those structures are: 1) the Eastatoee ductile thrust, which had been incorporated into the Brevard zone and duplicated by later imbricate thrusting within it (Figure 5b), and 2) the distinctive top-to-the-SW S-C' fabric marking Chauga River Formation horse blocks. Bobyarchick (1988, See his Figure 30) recognized that 'early' thrusts had been incorporated into the Brevard zone from outside it, including the Eastatoee fault and thrusts that placed Henderson Gneiss *onto* Chauga River Formation rocks. As reported here, the top-to-the-SW S-C' fabric is found in the Chauga River Formation throughout the western IP, and the regional occurrence of the fabric negates it being unique to the Brevard Zone (Clendenin and Garihan, in prep).

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 relatively 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 western IP were part of Taconic orogenesis. This explanation is supported by the interpretation that Acadian deformation involved NE-striking, dextral strike-slip faulting in the Eastern Blue Ridge and IP of the Carolinas (Ferrill and Thomas, 1988; Dennis, 2007; Hibbard

and Waldron, 2009; Trupe and others 2009), which did not include thrust stacking.

Henderson Gneiss in the footwall of the Eastatoee fault is mylonitic wherever 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. 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. Here the Henderson Gneiss (at least in part) and Chauga River dextral fabrics are considered older than the Alleghanian and possibly older than the Acadian. If the explanation offered here is true, the extensional fabrics were developed initially during top-to-the-SW gravitational collapse of the western IP thrust stack. It should be noted that deformation prior to the Brevard Zone does not preclude later reactivation or displacement by the Acadian or Alleghanian events.

At least two possibilities exist for the greenschist 'block-in-schist'shear zones along the South Saluda River in western Table Rock quadrangle (Figure 19). First, the shear zones are not folded. These two 'block-in-schist' occurrences lie approximately along strike and are several kilometers west of the mapped position of the steep Lakemont fault (Figure 2a). Hence, the fabric may have resulted from brecciation along deeper portions of this fault zone. Dismemberment of brittle gneiss blocks in a ductile greenschist matrix indicates conditions in the crust near the brittle-ductile transition. Second, the shear zone contacts do not appear to be straight and, therefore, are probably not steep. One gets the impression, for example, that the northern contact of the thinner shear zone dips gently beneath overlying TG and is parallel to its compositional layering (Figure 20g). If indeed the shear zones are folded by NW-striking fold sets, as TG is at adjacent locations A and B, and are similar to the shear zone at Mine Mountain (Figure 12, A), these shear zones may represent an unusual gravitational collapse occurrence. Both shear zones have a similar pyrite-garnet-muscovite schist mineralogy similar to the Mine Mountain shear zone. As corroboration, a crude fabric is locally visible as layers of gneiss spindles are flexed (Figure 20h), resembling C' fabric. Shear-sense indication is top-to-south motion.

Dextral Transpression

In the Eastern Blue Ridge and IP of the Carolinas, Acadian deformation involved northeast-striking, dextral strike-slip faulting (Ferrill and Thomas, 1988; Dennis, 2007; Hibbard and Waldron, 2009; Trupe and others 2009). Although evidence in the immediate study area is circumstantial, Acadian regional dextral transpression may have been responsible for the development of several NW-striking structural windows exposing footwall gneiss beneath the Six Mile sheet. Partitioned transpressive shortening would have produced folding and thrust deformation, while being ineffective at producing strike-slip movement (cf. Tikoff and Teyssier, 1994).

These macro-scale windows formed in northeast Standingstone Mountain (Garihan and Ranson, 2007) and northwest Zirconia (Garihan and Ranson, 2008) quadrangles. The structural windows are SW-vergent, overturned antiforms that deform the Seneca fault and adjacent rocks. At several locations on the overturned, southwest limb of these antiforms, there are meso-scale exposures where TG is juxtaposed above Six Mile rocks. These oval map areas which expose footwall gneiss surrounded by Six Mile rocks are antiformal culminations whose positions lie at the intersection of earlier NE- and these later NW-striking macro-scale overturned antiforms. The NW-striking folding of the nearby Mine Mountain ductile schist zone also may have occurred at this time. In terms of the development of the SW-vergent, overturned antiformal windows in Standingstone Mountain and Zirconia quadrangles, fold development also might be related to the earlier episode of regional post-Seneca, NW-striking folding, developed prior to regional Type-1 interference folding.

Curved Lineations

The orientations of the curving array of lineations on TG foliation surfaces in the western IP measured by the writer is shown in Figure 21. To the east, the lineations strike E-W; farther west they

FIGURE 20a

FIGURE 20b

FIGURE 20c

FIGURE 20d

FIGURE 20e

FIGURE 20f

FIGURE 20g

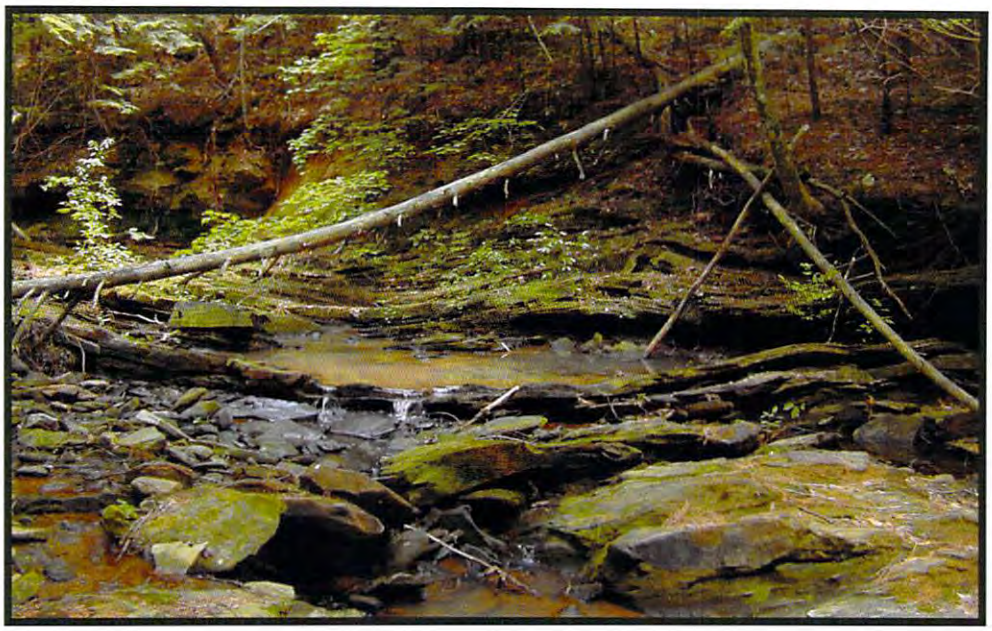

FIGURE 20h

FIGURE 20. **a.** Typical exposure of 'block-in-schist' character. Separated, irregular blocks and lenticular fragments dominantly of Table Rock gneiss, with lesser amphibolite and biotite gneiss, are enveloped by a medium- to coarse-crystalline pyrite (2-3%)-garnet-muscovite schist matrix. View to the south, downstream. **b.** The line traces an interpreted boudinaged and folded layer of gneiss, southern shear zone. Matrix schistosity also is folded within the fold outline. Lower scale is in cm. **c.** Irregular gneiss block, with internal contorted compositional layering. Layering is truncated at the block margin. Circled is a block of amphibolite. **d.** Isolated isoclinal fold in gneiss, in dark gray schist matrix. Schistosity is parallel to the hammerhead. Hammer is 40 cm. **e.** Circle: antler-like fold fragment; oval: 'Z fold' fragment, with an axial plane schistosity in its fold cores, suggesting dextral shearing and flattening. View is to the north. Upper scale is in cm. **f.** Finger-like projections of gneiss into schist (circled area). Lens cap is 2.6 cm. **g.** Thinner (northern) shear zone, visible in the foreground on the right side. C location folds or warps plunge gently east. Note vertical stacking discordance between warps in upper (distant ground) and lower (middle ground) layers of TG. Lateral shifting along gneissic foliation has occurred between upper and lower warps. This may represent an incipient stage of 'block-in-schist' development. View is to the northeast, upstream. **h.** Crudely developed S-C' fabric in gneiss-rich layer, southern shear zone. C' surfaces are upper left to lower right, indicating dextral movement. Clockwise rotation of some gneiss spindle shapes. View is to the east. Upper scale is in cm.

strike NE-SW. The curved array differs markedly from Griffin's (1971) northwest transport of the Six Mile sheet.

Discussion

The pattern of curving lineations in the IP has been interpreted in several ways. Goldsmith (1981) recognized the curved lineation pattern as defined by fold hinges and mineral lineations on the Charlotte 1°X 2° sheet. Davis (1993a), Merschat and others (2005), and Hatcher and Merschat, (2006, their Figure 14) suggested that the development of regional curving mineral stretching lineations (quartz, feldspars, mica) tracked the flow of plastic fold-thrust sheets and sheath folds in the IP. Hatcher and Merschat, (2006) placed the lineations in a D_2 Neoacadian event. L_2 was interpreted as resulting from the NW to SW "deflected" displacements of ductile thrust sheets bearing meso- and macro-scale sheath folds along an interpreted orogenic channel, floored by the Brevard zone below and capped above by the overthrust Carolina terrane. Plastic flow in this channel was envisioned as "constricted" within a narrow 1-3 km zone (Hatcher and Merschat, 2006). Dennis (2007) describes the pattern in terms of older structures transposed into parallelism with the adjacent Brevard zone in a shear zone no less than 20 km in width. If this is true, the entire western IP adjacent to the Brevard zone is a mylonite zone (Davis, 1993b).

The tectonic significance of this well-established regional lineation array also has been explained in a number of other possible ways. Among the possibilities are: The footwall lineations indicate the Six Mile sheet moved southwest with its TG footwall, consistent with the kinematic thrust sheet-tracking model of Merschat and others (2005), but not necessarily related to flow in an interpreted orogenic channel (Hatcher and Merschat, 2006). Alternately, the ductile Seneca fault may have served as a high-strain detachment zone, with footwall plastic TG moving southwest, as shown by sheath fold orientations (Figure 22a-d) and stretching lineations (Figure 21), relative to a somewhat less mobile (?), detached, more NW-emplaced Six Mile sheet. In this scenario, stretching would have affected the weaker, mobile, plastic quartzo-feldspathic gneisses more pervasively than the rheologically stiffer Six Mile cover rocks (compositionally diverse paragneisses, amphibolite). The result was sheath folds and widespread lineation development on foliation surfaces in footwall rocks.

A slightly different interpretation is proposed here on the basis of a finite strain pattern of diverse L_2 mineral stretching lineations in the high-pressure Malpica Tui Complex of northwestern Iberia. In Iberia, Fernandez and Catalan (2012) described a case of early stretching lineation orientations that were heterogeneously reoriented by subsequent thrusting, transpressional fold-nappe tectonics, ductile shearing accompanying extensional collapse, and later strike-slip movements reorienting earlier lineations orientations toward their shear planes. Although more complex, their interpretation is similar to Dennis (2007), who described the curving pattern in terms of older structures reoriented into parallelism with the adjacent Brevard zone.

Backthrusting and Attendant Folding

In Cleveland, Table Rock, Standingstone Mountain, and Zirconia quadrangles (Figures 1, 23), "second pass" mapping recognized a backthrust system which is interpreted to be Alleghanian age. In those quadrangles, a broadly arcuate system of brittle thrusts emplaced 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. Those thrusts are referred to here as the Caesars Head fault system and are indicated by the blue arrows on Figure 24.

The eastern-most Caesars Head system fault is preserved as a klippe on Hyde Mountain in southern Zirconia quadrangle and adjoining northern Slater quadrangle (Garihan and others, 2005a). On Hyde Mountain, Caesars Head thrusting is defined by TG augen gneiss resting on Tallulah Falls Formation rocks of the Six Mile thrust sheet.

This isolated klippe is ~7 km southeast of the nearest erosional trace of a Caesars Head fault, located across a NE-striking zone of complex oblique-slip faulting (Figure 23).

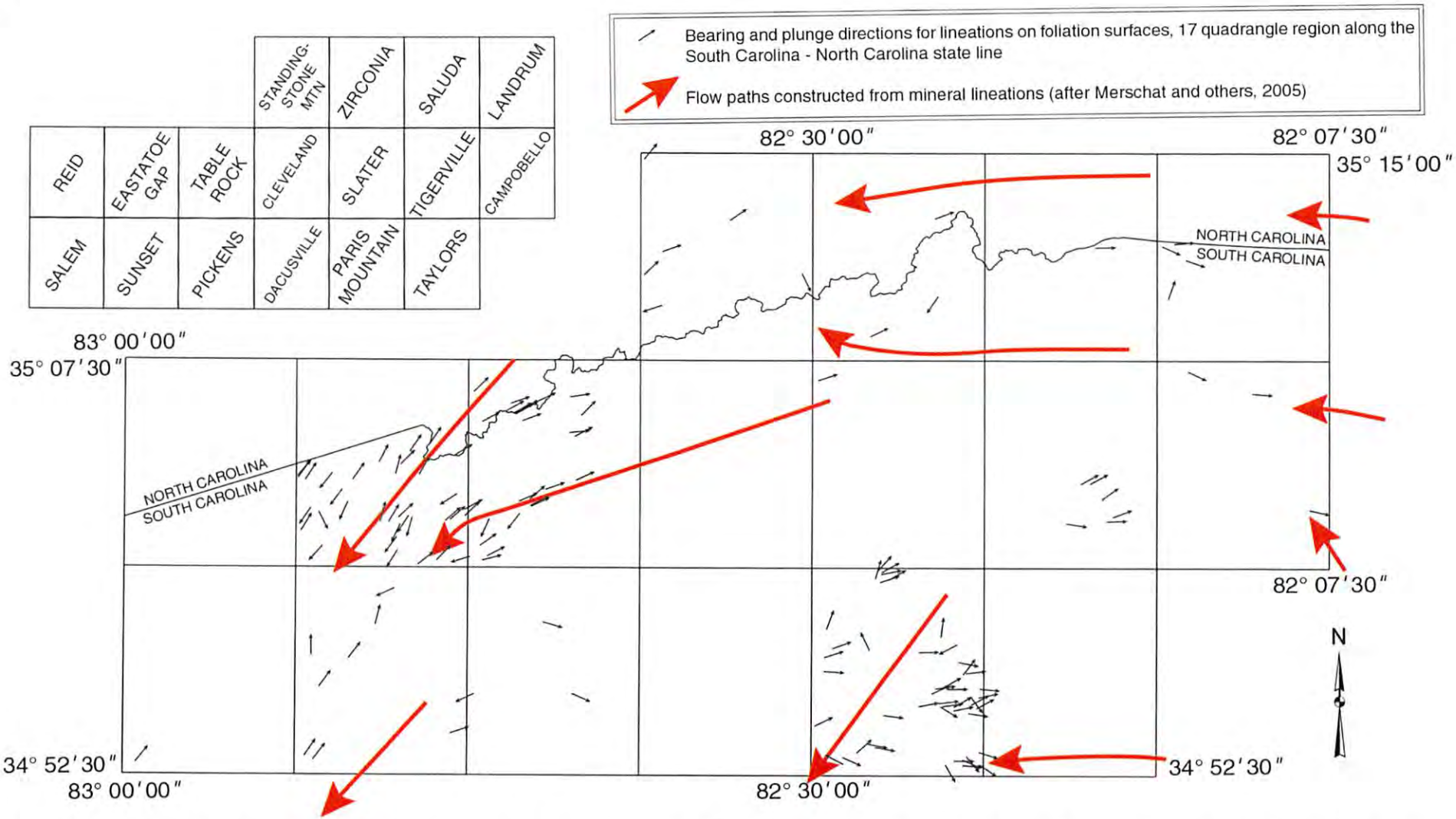

Figure 21. Pattern of stretching lineations (small plunging arrows) on Table Rock gneiss foliation surfaces, South Carolina and adjacent North Carolina quadrangles. Data collected by the writer. Movement paths after Merschat and others (2005, Figure 2) are shown by red arrows.

FIGURE 22a

FIGURE 22b

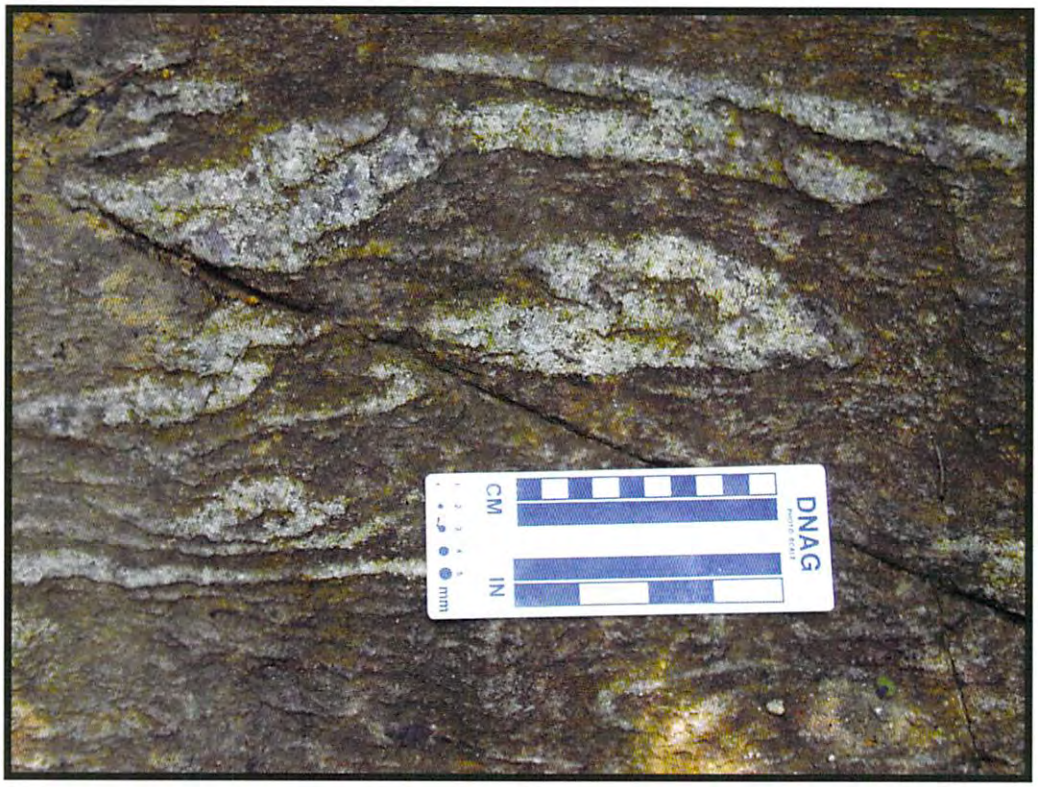

FIGURE 22c

FIGURE 22d

FIGURE 22. Sheath folds. **a.** Sheath fold, cut by a small granitic intrusion (bottom right), Jim Timmerman Natural Resources Area, southeast Eastatoe Gap quadrangle. Amphibolite is red; Table Rock gneiss is gray. In the gneiss core the lower sheath limb is flattened and extended. All rocks are saprolitic. View is to the north. Upper scale is in cm. **b.** Small sheath folds in Table Rock gneiss, outlined by quartose layers. Upper scale is in cm. **c.** Sheath fold in Table Rock gneiss, southeast end of Chapman Mountain, Pickens quadrangle. An "S fold" geometry occurs on the left side of the sheath (below the scale), and a "Z fold" geometry is on the right. View is to the northwest. Upper scale is in cm. **d.** Sheath fold in Poor Mountain amphibolite, outlined by thin quartzite layers, south side Campbell Mountain, Cleveland quadrangle. Float block. Lens cap is 6 cm.

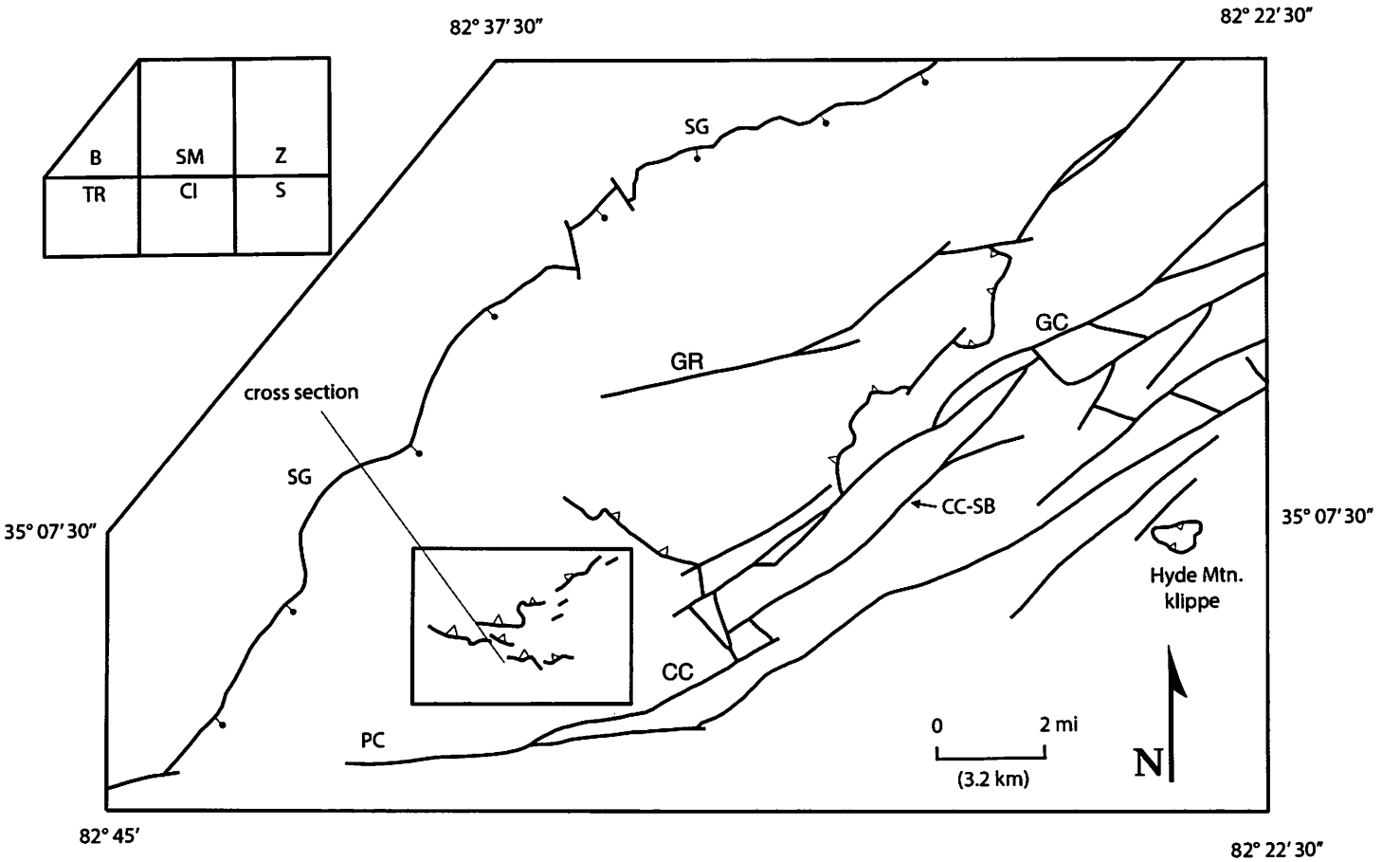

FIGURE 23. Generalized fault map. Quadrangles: Brevard- B; Standingstone Mountain- SM; Zirconia- Z; Slater- S; Cleveland- Cl; Table Rock- TR. Major faults: Civitan Camp fault- CC; Cox Creek-Short Branch fault- CC-SB; Gap Creek fault- GC: Green River fault- GR; Palmetto Cove fault- PC; Slicking Gap normal fault, with bar and ball on the downthrown side- SG; Caesars Head system faults- open sawtooth lines. Location of Hyde Mountain klippe is shown. Rectangle is the location of Figure 24. Cross section location is for Figure 27.

Immediately south of Caesars Head community in Cleveland quadrangle, the Seneca fault and Six Mile hanging wall rocks have been antiformally folded and overturned to the southwest. This post-Seneca structural window exposes TG in its core. An E-striking, N-dipping Caesars Head thrust has partly overridden this older NW-striking antiformal window (Figure 24).

Backthrusting has deformed their 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 24).

At the Mulligan's View exposure west of Camp Greenville in Standingstone Mountain quadrangle (Figure 1), the Seneca fault is truncated by several SW-directed brittle thrusts of the Caesars Head fault system (Figure 3a, A). Elsewhere, a well-exposed Caesars Head fault exposure is present in Standingstone Mountain quadrangle along the trail leading down from Camp Greenville to Rainbow Falls on Cox Camp Creek. The SW-directed thrust has emplaced TG over Poor Mountain Formation amphibolite. Shear zones up to 1 m thick in the hanging wall of that fault have muscovite lineations (Figure 25a) related to older top-to-the-SW movement. A boudinaged, slightly discordant pegmatite in TG and older protomylonite lie in the fault's immediate hanging wall (Figure 25b, c). Brittle fracturing has occurred along the TG pegmatite - Poor Mountain Formation amphibolite contact; a small conjugate fold in amphibolite has been truncated by fault movement (Figure 25d). Within 0.5 meter below the fault in the footwall, thin green epidote layers in the amphibolite are strongly boudinaged (Figure 25d), which is interpreted as the effect of vertical loading by the overlying thrust sheet. A combination of movement and flattening associated with this Caesars Head fault also has produced, in its hanging wall, small-scale offsets by slippage along interlayered TG-amphibolite contacts (Figure 25e).

In the vicinity of several Caesars Head faults, axial-plane orientation and fold-plunge data were collected from overturned folds located in immediate hanging wall TG and footwall Poor Mountain Formation amphibolite (Figure 26a, b). These data indicate southwest movements, interpreted as a result of Caesars Head faulting. Alternately, some of the folds may belong to an older inclined-overturned, NW-striking fold set. Those observations once again emphasize the point that top-to-the-SW structures are ubiquitous features of the western IP and that discrimination among them is challenging.

Discussion

The array of Caesars Head hinterland-directed backthrusts is shown in Figures 23 and 24. An interpretative cross section, Figure 27, shows their structural relationship to the NW-directed thrust in Standingstone Mountain quadrangle, that is interpreted here to be Alleghanian age. The Henderson Gneiss, Eastatoee thrust, and Chauga River Formation have been duplicated at the apparent leading edge of that thrust (Figure 27, Dismal Creek location). The Caesars Head backthrusts emplaced Walhalla thrust sheet TG generally southward over Six Mile thrust sheet rocks. In places older ductile shear zones and strain-softened muscovite-rich zones in TG may have localized the position of these later brittle thrust faults.

A number of interpretations have been described as causing backthrusting in mountain belts. Ferrill and Dunne (1989) indicate backthrusts, 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 backthrusts form at or near the base of a thrust ramp when a rigid unit encounters resistance during foreland motion. If the mass of unlayered, rigid TG made it difficult to nucleate more NW-directed thrusts, backthrusts might develop at higher structural levels nearer to the Seneca thrust and its rheologically weaker Six Mile hanging wall rocks. In that case, the thrusts also might be positioned to utilize older strain softened zones in TG and form near older, weaker ductile shear zones.

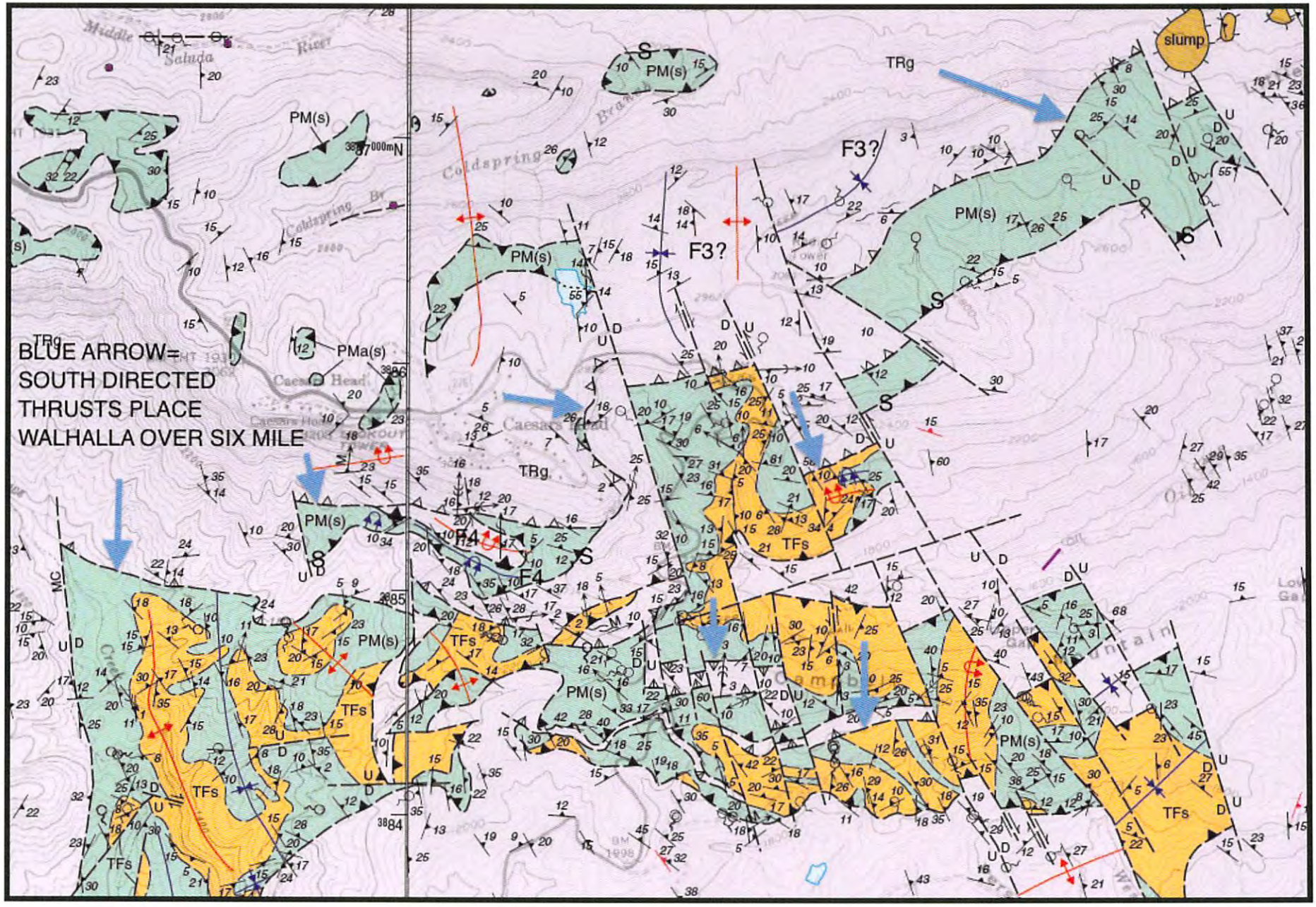

FIGURE 24. Caesars Head system faults- open sawtooth lines, blue arrows; Seneca fault- closed sawtooth lines, labeled S. Eastern Table Rock (left) and western Cleveland (right) quadrangles. Walhalla gneisses- pink; otherwise same labels as Figure 9. Located on Figures 2b, 23.

FIGURE 25a

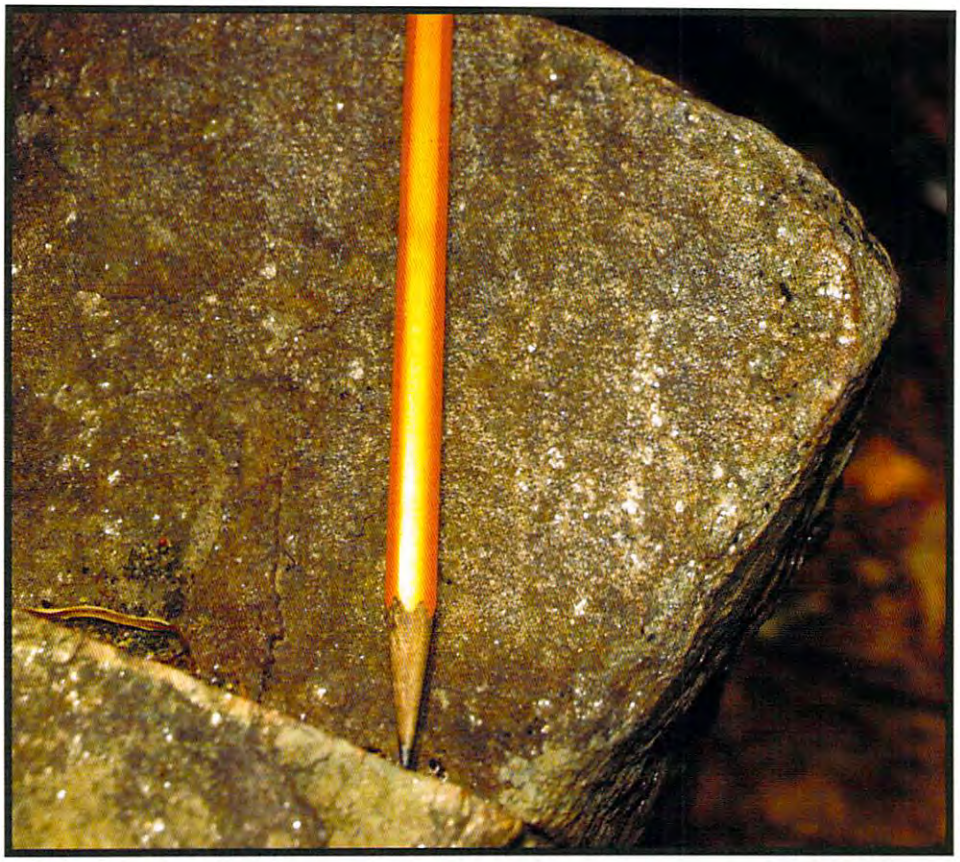

FIGURE 25b

FIGURE 25c

FIGURE 25d

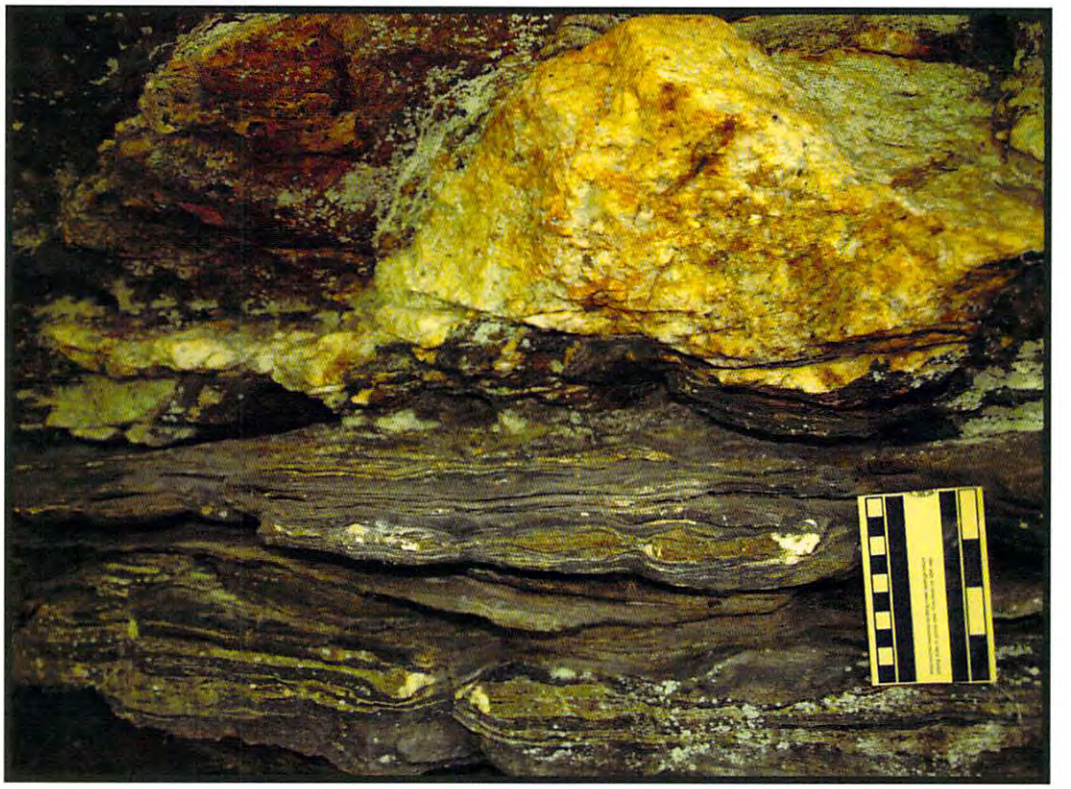

FIGURE 25e

FIGURE 25. Exposures along Rainbow Falls trail, south of Camp Greenville, Standingstone Mountain quadrangle. **a.** Reflective muscovite mineral stretching lineations (parallel to the pencil) on Table Rock gneiss schistose foliation surfaces. They plunge 13° in the direction N35°E, indicating southwest movement on a collapse-related shear zone. Pencil is 10 cm. **b.** Caesars Head system fault, at the base of a boudinaged pegmatite in Table Rock gneiss. Arrow (far right) marks the fault position. Below the fault is Poor Mountain Formation amphibolite, on which a hammer (circled) lies. View is to the southeast. **c.** Same Caesars Head fault, looking toward the position shown in b. Fault is located at the hammer position (circled). Amphibolite compositional layering below the fault is essentially horizontal. View is to the northwest. Hammer is 40 cm. **d.** Close up of boudinaged, equigranular, green epidote layers in amphibolite footwall. Broken quartz fillings occur at boudin ends. The fault below the pegmatite has fractured and truncated a small conjugate fold. View to the north. Left scale is in cm. **e.** In the hanging wall above the fault in **c.** and **d.**, contacts between interlayered TG (gray) and amphibolite (black) have experienced top-to-left (west) slippage. Thin felsic dikes are left offset in the circled areas. A thin amphibolite is left offset between the arrows. View is to the north. Hand lens is the scale.

FIGURE 26a

FIGURE 26b

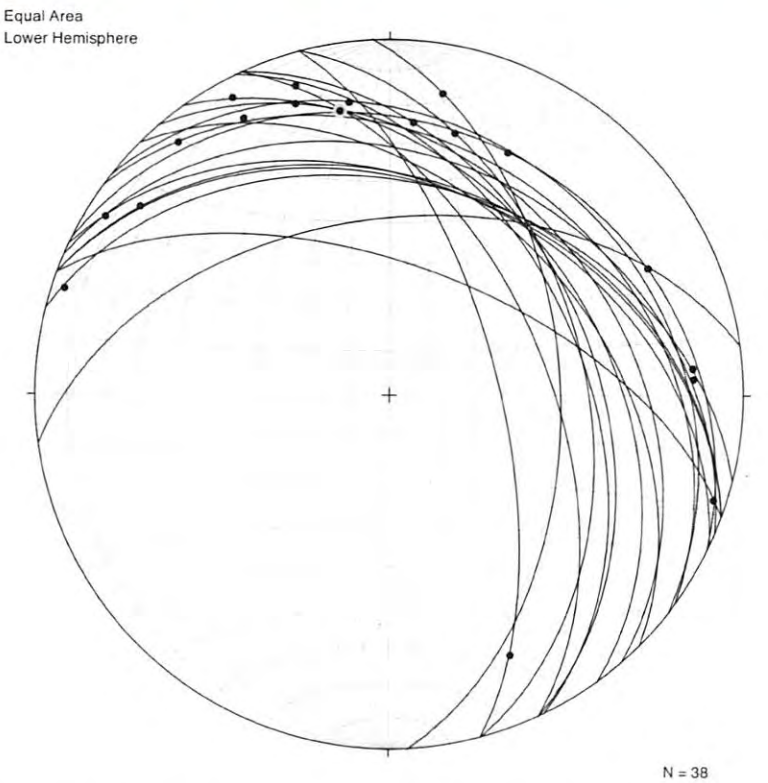

FIGURE 26. a. SW-vergent fold in Poor Mountain Formation amphibolite, Cleveland quadrangle. Fold plunges 4°/N74°W, parallel to the pencil. **b.** Southern hemisphere, equal area projection of data for folds in the vicinity of several Caesars Head faults, Standingstone Mountain, Cleveland, and Table Rock quadrangles. Fold axial planes- great circles; attitude of fold hinge, lying on each fold's axial plane- black dot. Hinge orientations are highly dispersed. NE-dipping axial planes are interpreted to represent the effect of SW-directed Caesars Head faulting on adjacent rocks. Some older fold attitudes may be included in the data set.

The Pinnacle Mountain trail shear zone was folded along an E-W strike and truncated by a Caesars Head thrust (Figure 12, B). The addition of sillimanite only in Pinnacle Mountain trail rocks suggests that the Caesars Head thrust fault beneath and truncating it brought up a 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, positioned well north of any known Caesars Head backthrusts, suggests its contemporaneous development occurred at a shallower, cooler position in the thrust stack.

Mesozoic Brittle Faulting-Diabase Intrusion

All older macro-scale fold and fault patterns were disrupted and offset by later sets of NW-, N-, NE-, and E-striking oblique-slip to more nearly normal oblique-slip faults and NE-striking cataclastic zones. Riedel relationships are believed to exist on some of these fault sets. These cataclastic zones and brittle faults are considered to be Mesozoic in age (Garihan and Ranson, 1992, and references therein).

In the Tigerville-Landrum-Campobello quadrangles to the east (Figure 1), siliceous cataclastic zones are considered the oldest phase of brittle deformation (Garihan, 2012). Right-stepping, en echelon cataclastic zones at Pax Mountain (Tigerville quadrangle) (Garihan and others, 2009) indicate sinistral faulting. Clendenin and Garihan (2001) recognized that the cataclastic zones commonly have faults developed along their margins; these faults are marked by uncemented damage zones and gouge. In Tigerville-Landrum-Campobello quadrangles, based on truncation relationships, the general order of fault development is: 1) sinistral movements on NE-striking faults and related cataclastic zones, 2) northerly faults, 3) NW-striking, near-normal oblique-slip faults, and 4) recurrent dextral movements along at least several earlier NE-striking faults.

Discontinuous cataclastic zones are present along four NE-striking fault zones in northeast Cleveland quadrangle, as well as along the NE-striking Burgess Creek fault in Table Rock and adjacent Pickens quadrangles (Garihan and others, 2007; Figure 1). In the Cleveland-Table Rock area, sinistral movements also preceded dextral movements on NE-striking faults. A noteworthy difference, however, is the presence of major E-W-striking faults and their absence in the Tigerville-Landrum-Campobello area 40 km to the east. Fault truncation relationships indicate the E-W-striking fault zones are the youngest fault structures in the western IP, area, offsetting earlier structural features.

In the Cleveland-Table Rock area, NE- and E-W-striking fault sets disrupt the regional interference fold pattern (Figure 10). The synformal belts of Six Mile rocks were offset obliquely along two separate zones of major E-W-striking faults. Each of the two major fault zones is made up of several faults and is described separately below.

One possible interpretation of these E-W-striking fault zones is that the NE strikes of Six Mile rocks immediately adjacent to each of these two high-angle fault zones were rotated or dragged into more easterly orientations. The result was two separate fault-localized, E-W-striking belts within the regional setting of NE-striking foliation for Six Mile rocks. Together the alternating NE- and E-W-striking belts produce the regional zig-zag pattern of Six Mile exposures across the area (Figure 2a).

Palmetto Cove-Lakemont-Tall Pine Lakes Fault Zone

In the Cleveland and Table Rock quadrangles, the northern E-W-striking fault zone comprises the Palmetto Cove, Lakemont, Civitan Camp, and Tall Pine Lakes faults (Figure 2a). A significant component of oblique-slip along the Palmetto Cove fault produced 2.5 km of sinistral offset of the Seneca fault (Figure 28). Immediately to the south, oblique-slip along the parallel Lakemont fault also produced ~2.5 km of sinistral offset of the Seneca fault.

To the east, the Palmetto Cove fault and two parallel ones (Civitan Camp and Tall Pine Lakes faults; Figure 2a) have more of a dip-slip component of movement. Each of the faults is down-to-the-south, preserving Six Mile rocks and the Seneca

fault in the hanging wall and exposing TG in the up thrown footwall. The change from oblique-slip to more dip-slip occurs where those three E-W-striking faults merge with the NE-striking regional fault system. The overlap intersection geometry of E-W-striking faults and NE-striking, oblique-slip faults is consistent with the oblique rifting models of McClay and others (2002) and with the development of a graben.

Pumpkintown-Marietta Fault Zone

The southern E-W-striking fault zone in the Cleveland and Table Rock quadrangles comprises the Pumpkintown fault and the Marietta faults (Figures 2a, 29). The E-W-striking Pumpkintown fault sinistrally offsets the NE-striking Burgess Creek fault ~ 1.2 km. To the east, the Pumpkintown fault overlaps the western extension of the Marietta fault zone. This geometry is similar to the intersection relation of the northern E-W-striking fault zone described above.

In southeast Cleveland quadrangle, a relatively large, elongate klippe of Six Mile rocks (~5.3 km^2) was dextrally offset by two parallel ENE-striking faults of the Marietta fault zone (Figure 9). Prior to that movement, this klippe was deformed into a complex graben structure resulting from bounding and numerous internal N-S-striking normal faults. As stated, pre-Seneca emplacement folds and thrusts are preserved in the graben. The NW-striking dextral fault that offsets the NW margin of this klippe and an adjacent klippe to the west (Figures 2a, 9 upper left) is interpreted as a Riedel shear associated with the dextral Marietta fault zone.

Formation of E-W-striking folds in Narrow Grabens

E-W-striking folds confined to narrow grabens, ~ 0.5 km wide, are unusual occurrences in the western IP. An E-W-striking antiform in Six Mile rocks is preserved in a narrow graben between the Palmetto Cove and Lakemont faults (Figure 28). To the south, the Pumpkintown fault and four parallel faults north of it form a complex graben structure. An east-plunging, E-W-striking synform in Six Mile rocks is preserved in the graben structure and repeatedly segmented by NNW-striking faults (Figure 29).

The folds preserved in these narrow grabens may have formed several different ways: 1) The folds are earlier NE-striking structures on the Six Mile sheet that were rotated up to ~65° clockwise by the S-directed compression that emplaced the Caesars Head faults to the north. 2) The folds are E-W folds produced directly by the S-directed compression that emplaced the Caesars Head faults to the north. 3) The folds are rotated earlier NW Set II interference folds, modified in orientation by sinistral movements along the two major E-W-striking fault zones.

Oblique-slip to Normal Dip-slip Faults

Faults ranging from near-normal oblique-slip to normal dip-slip have a wide range of strikes: NW, NNW, N, NNE, and NE. In general, the throw on any fault is unknown, with one exception: the N-striking Matthews Creek fault in Table Rock quadrangle (Figure 2a, labeled MC) has at least 425 m of throw, based on topographic difference in elevation of Poor Mountain Formation amphibolite across it. Map patterns also suggest that the NE-striking Burgess Creek fault, northwest of Pumpkintown, South Carolina, has a significant component of dip-slip; however, its throw is unknown. The NE-striking Burgess Creek fault is sinistrally offset ~1.2 km by the younger Pumpkintown fault and extends southward into the Pickens quadrangle.

NW-, N-, and NE-striking faults of this structural style locally bound and internally dissect belts and isolated klippen of Six Mile rocks. Commonly the NW- and N-striking faults are cut by NE- and E-W-striking faults. This truncation relation may not imply a significant timing sequence of faulting episodes; some NW- and N-striking faults may be contemporaneous with NE- and latest ENE-striking faults as associated minor Riedel faults.

Slicking Gap Fault

The NE-striking Slicking Gap fault crosses Table Rock, Brevard, and Standingstone Mountain quadrangles (Figures 1, 23) and is the most extensive normal fault known in the western IP.

Henderson Gneiss lies in its footwall and TG in its hanging wall, with movement down-to-the-southeast. The fault is offset in several places by minor NW-striking faults.

In Brevard quadrangle, Cattanach and Bozdog (2011) mapped a local "mixed unit" (TG intruded into Henderson Gneiss) in the immediate footwall of this fault, which was interpreted as a thrust (dipping 15° SE in their A-A' cross section). Although TG did intrude Henderson Gneiss locally, their mapped Henderson-TG fault contact is a smoothly curving surface trace, with no intrusive irregularities. Older, pre-mylonitization ages for the Henderson Gneiss composite pluton in the footwall are generally Cambrian (Horton and McConnell, 1991, and references therein). A more recent ~447 Ma age (Late Ordovician) by Moecher and others (2011) is based on monazites and zircons from modern alluvial materials. In general, footwall Henderson Gneiss ages are older than the hanging wall TG, with the oldest augen phase dated at 450.2±4.5 Ma, Late Ordovician (Ranson and others, 1999). Age relations across the structure, therefore, are consistent with a down-to-the-southeast, normal fault.

An interpreted Alleghanian thrust bounds the SE margin of the exposed belt of Chauga River Formation rocks across Table Rock, Brevard, and Standingstone Mountain quadrangles (Figures 1, 6). The Slicking Gap fault lies in its hanging wall, is within 1-3 km of its surface trace, and closely parallels the thrust. At the surface, the Slicking Gap fault dips gently southeast at 25°-30° (based on 3-point solutions of its map trace). In the subsurface, it may be listric and merge with the interpreted Alleghanian thrust (Figure 27).

Mesozoic Diabase Dikes and the Cox Creek-Short Branch Fault

In eastern Cleveland quadrangle, a NW-striking, Mesozoic diabase dike was emplaced under NE-SW extension. The dike then was offset sinistrally along the NE-striking Cox Creek-Short Branch fault (Figure 2a). The same fault to the northeast, however, dextrally offsets the Seneca fault some 3 kilometers. This displacement is interpreted to represent reactivated dextral movement along the Cox Creek-Short Branch fault. Moreover, in Slater quadrangle even farther northeast, the Cox Creek-Short Branch fault is cut by a different NW-striking Mesozoic diabase dike which crosses the fault trace without interruption.

Discussion

Brittle faults at the surface and in the subsurface across the Carolinas generally are ascribed to Late Triassic-Early Jurassic continental rifting events associated with the breakup of Pangaea and opening of the Atlantic Ocean (Marzoli and others, 2011; Clendenin, 2013; Clendenin and others, 2016, and references therein). In the central Georgia IP, Huebner and Hatcher (2011) interpret map-scale, pod- and rhomb-shaped cataclastic zone occurrences, with associated boxwork and veining features, as having formed in dilational step-overs of sinistral strike-slip fault systems. Along these NE-striking brittle faults, sinistral offsets are marked by displacements of 200 Ma diabase dikes (See their Figure 13). The cataclastic zones in Cleveland and Table Rock quadrangles in the study area are interpreted as associated with the oldest sinistral-oblique movements along the NE-striking brittle faults that displaced Walhalla and Six Mile rocks (Garihan, 2012).

An approximate age of brittle faulting in the western IP is proposed based on geologic observations reported here. As stated in eastern Cleveland quadrangle, a NW-striking Mesozoic diabase dike is offset sinistrally by the Cox Creek-Short Branch fault (Figure 2a). Another NW-striking dike crosses the same fault without offset ~2 km to the east in Slater quadrangle. The relationships in Slater quadrangle indicate that diabase emplacement continued after sinistral movements. These relations imply that fault movements and Mesozoic diabase intrusion were roughly coeval events (Garihan and others, 1993).

Hatcher (2006) describes a strain regime affecting the Carolinas Piedmont and Coastal Plain wherein sets of NW-striking diabase dikes (190-170 Ma) and siliceous cataclastic zones "formed at about the same time". The range of orientations (NW, NNW, N and NE) and movements of oblique-slip faults in the western IP, however, is consistent with changing stress-field directions. Earlier studies of fracture and syntaxial quartz

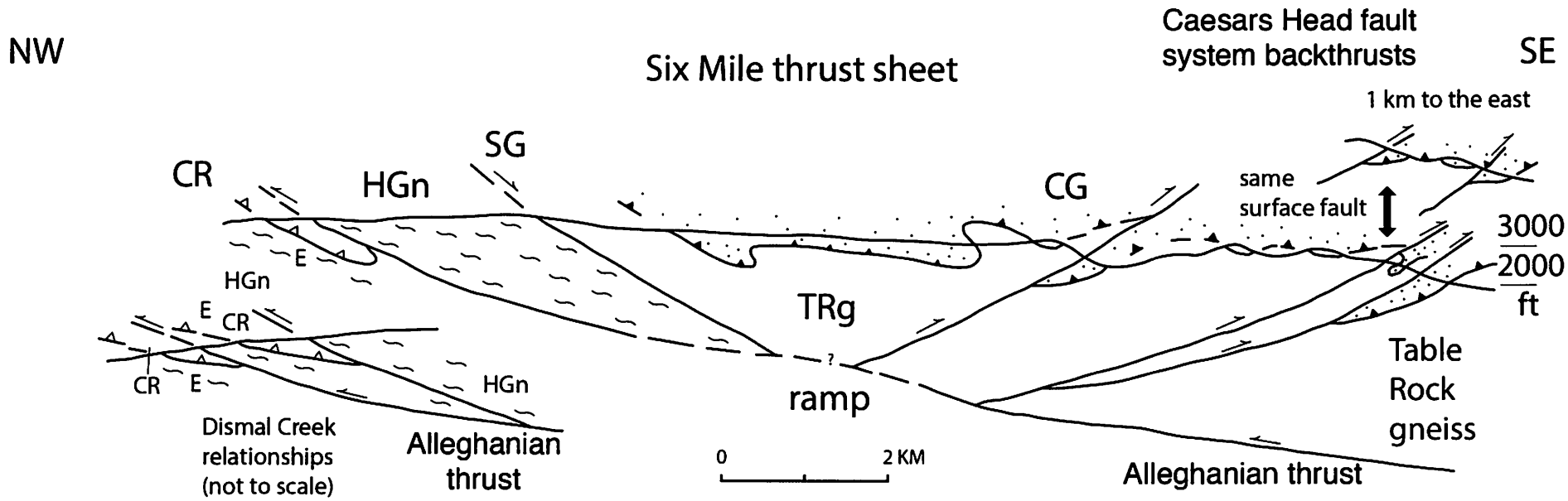

Figure 27. Interpretive cross section across Standingstone Mountain and Cleveland quadrangles. Location is shown on Figure 23. The Eastatoee thrust, E (open sawteeth), has Chauga River Formation, CR, and Henderson Gneiss, HGn, in its hanging wall and footwall, respectively. The main NW-directed thrust, interpreted to be Alleghanian age, cuts the Eastatoee fault, and it duplicates the Eastatoee fault at Dismal Creek in northern Standingstone Mountain quadrangle. Shown is the relationship of this main thrust to the hinterland-directed Caesars Head fault system backthrusts. Ramp is hypothetical. The Slicking Gap normal fault, SG, is conjectured to merge with the Alleghanian thrust at depth, locally reactivating motion along it. 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 backthrust southeast of CG is shown in Figure 25**b** and **c.**

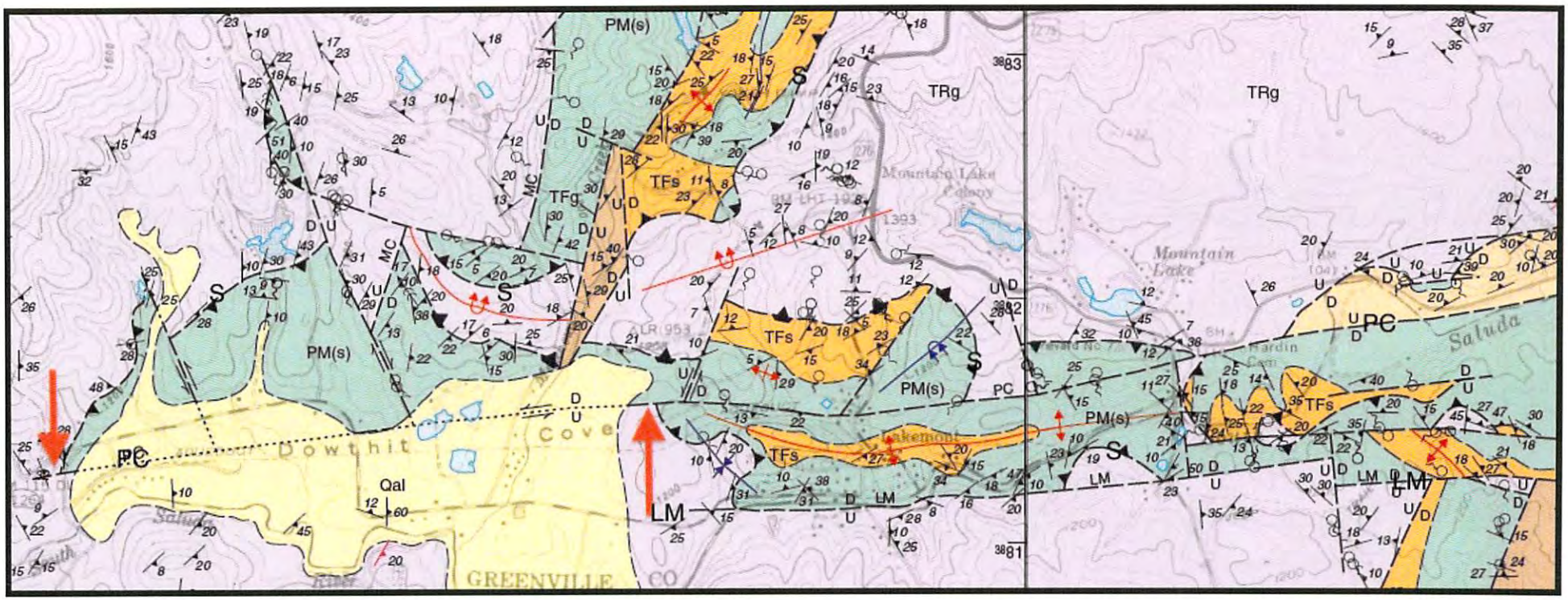

Figure 28. Sinistral offsets of Six Mile thrust sheet rocks along both the Palmetto Cove fault (PC), between the red arrows, and the Lakemont fault (LM) to the south. Eastern Table Rock and western Cleveland quadrangles. Total sinistral offset along the east-west fault zones is 5 km. A narrow, east-striking antiform, cored by Tallulah Falls schist (TFs), is present between the Palmetto Cove and Lakemont faults. Table Rock gneiss- TRg. Otherwise same labels as Figure 9. Seneca fault-sawtooth line, labeled S, is locally overturned. Located on Figure 2b.

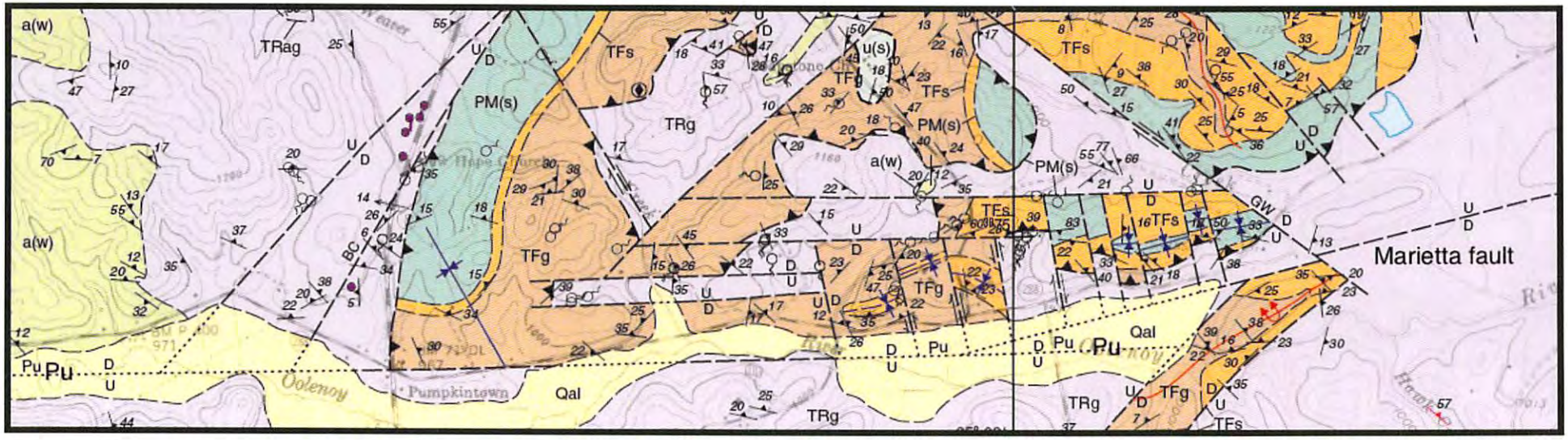

Figure 29. East-west fault zone near Pumpkintown, South Carolina. NNW-striking faults offset an east-striking synform in a graben north of the Pumpkintown fault (Pu). This gently east-plunging synform, segmented along strike by a horst block of Table Rock gneiss (TRg), is cored to the west by Tallulah Falls schist (TFs) and to the east by Poor Mountain amphibolite PM(s). Labeled faults: Burgess Creek fault and adjacent silicified cataclastic rocks- BC and purple dots; Gowens Creek fault- GW. Marietta fault is labeled to the right. Seneca fault- sawtooth lines. Ultramafic rock- u(s); amphibolite within Walhalla gneisses- a(w). Otherwise same labels as Figure 9. Located on Figure 2b.

vein networks in siliceous cataclastic rocks of the Piedmont of the Carolinas indicated that significant rotation of extensional stress orientations affected the fracture and syntaxial vein networks over time, from earlier NW-SE extension to later NE-SW extension (Garihan and others, 1990, 1993). Based on aeromagnetic imaging, Clendenin and others (2016) also described a model of changing regional extension directions operating at this time and related those changes to dike emplacement directions.

Sinistral oblique-slip movements on NE-striking faults are interpreted to have occurred during regional Mesozoic NW-SE extension. Sinistral offsets on both the Palmetto Cove-Lakemont-Tall Pine Lakes fault zone and along the Pumpkintown fault to the south, occurred during this phase of extension. Younger, dextral oblique-slip movements on some of the same NE-striking faults are interpreted to have occurred during subsequent regional NE-SW extension. Dextral displacement along the Marietta faults and an associated Riedel (Figure 9) occurred at that time. Mesozoic NW-striking diabase dikes developed during the regional NE-SW extensional regime (Ragland and others, 1983; Clendenin and others, 2016).

E-W extension also has modified a Six Mile klippe in SE Cleveland quadrangle (Figures 2a, 9). This klippe, initially ringed by the Seneca fault, was modified by a complex graben structure along bounding and numerous internal N-S normal faults. These faults were subsequently dextrally offset by the Marietta fault zone.

As indicated by Late Triassic-Early Jurassic diabase dike offsets and brittle fault orientations and movement directions, a systematic rotation of regional extensional stress directions occurred, changing with time from NW-SE (earlier) to E-W to NE-SW (later). As stated, based on intersecting syntaxial vein set data from siliceous cataclastic zones measured across the Carolinas, Garihan and others (1993) documented changing regional stress directions from NW-SE extension (S40°E) to NE-SW extension (N40°-45°E). Clendenin and others (2016) used styles of rifting, changes in dike directions, and data summarized from the literature to show that systematic changes in extensional stress directions clearly took place during Triassic time and that the changes occurred over a relatively short time period.

Proposed Deformational Sequence

Paleozoic faulting and metamorphism accompanied the Taconic, Acadian, and Alleghanian orogenies in the Southern Appalachians (Hatcher and Odom, 1980). Interpretations of Southern Appalachian tectonics in terms of collisional-subduction episodes and strike-slip episodes were described by Ferril and Thomas (1988), Hatcher and Merschat (2006), Hibbard (2000), Hibbard and Waldron (2009), Hibbard and others (2012), Dennis (2007), Trupe and others (2009), Hatcher (2010, and references therein), and others. Numerous workers describe structures in the Brevard fault zone (notably Bobyarchick and others, 1988, and references therein; Hatcher, 2001; Clendenin and Garihan, 2008; 2012). The recognition of the presence and significance of brittle faulting in the western IP of South Carolina and adjacent North Carolina is based on geologic quadrangle mapping since 1995 (Garihan, 2008, 2012).

Mapping in the western IP area and remapping in Cleveland, Table Rock, and parts of other quadrangles provide another look at the complex Paleozoic-Mesozoic structural relationships of northwest South Carolina and adjacent North Carolina in the southern Appalachians. The progressive development of those structural relationships defines the proposed deformational sequence. Sequentially, this proposed deformational sequence consists of the following: supra-subduction zone Ordovician granitic magmatism, polyphase folding episodes, Ordovician ductile thrust stacking, post-ductile thrust polyphase folding (particularly with NW-striking, SW-vergent attitudes), regional Type-1 interference folding, SW-directed gravitational collapse at various structural levels within a thickened thrust stack, possible effects of regional dextral strike-slip faulting, south-directed brittle backthrusting related to an interpreted Alleghanian thrust, and, finally, contemporary Mesozoic brittle faulting-diabase intrusion.

The TG, with other Late Ordovician supra-subduction zone intrusions and associated

magmatic and ductile features, was emplaced into metasedimentary and metavolcanic rocks of the Tugaloo terrane. In Early-Mid Paleozoic time, under amphibolite facies conditions, with migmatization, regional NE-, E-W-, and NW-striking, inclined and overturned folds developed in rocks which were to become parts of the Six Mile and Walhalla thrust sheets. Under amphibolite facies conditions, Taconic collision emplaced the Walhalla thrust sheet with the Eastatoee ductile fault at its base and the Six Mile thrust sheet with the Seneca ductile fault at its base; both thrust sheets advanced simultaneously to the northwest. Movement was accompanied by mylonitization and local transposition. NE-striking, inclined-overturned folding produced antiformal structural windows through the Six Mile sheet. Subsequent deformation developed a regional Type-1 interference pattern of NE- and NW-striking, upright, gentle folds at macro- and meso-scale.

Under greenschist facies conditions, top-to-the-SW gravitational collapse occurred following development of an over-steepened Walhalla-Six Mile thrust stack. Resultant extensional structures developed in the Chauga River Formation near the base of the stack, internally in Six Mile Tallulah Falls gneiss and schist units, and along numerous garnet-muscovite-quartz ductile shear zones, particularly within Walhalla TG and locally in Poor Mountain Formation amphibolite. Two unusual 'block-in-schist' shear zones are inferred to be related to this event.

Regional Acadian deformation involved NE-striking, dextral transpressional strike-slip faulting. In NE Standingstone Mountain and NW Zirconia quadrangles, related transpression may be responsible for several SW-vergent, overturned antiformal structural windows through the Six Mile sheet at antiformal culmination positions of intersecting earlier NE- and the NW-striking macro-scale folds. Nearby, the Mine Mountain ductile shear zone may have been folded about a northwest strike at this time. The dextral movements also may have affected the curved lineations in the Walhalla footwall gneiss by reorienting them into parallelism with the adjacent Brevard zone to the northwest.

NW-directed thrusting, interpreted here as Alleghanian, was accompanied farther south and east by backthrusts of the Caesars Head brittle fault system. During this thrusting event, Walhalla thrust sheet rocks were backthrust to the southwest, south, and southeast over Six Mile thrust sheet rocks. Some backthrusts appear to be localized near older ductile shear zones and strain-softened zones in TG. Macro-scale E-W folding associated with backthrusting affected Six Mile sheet rocks and the Pinnacle Mountain trail ductile shear zone.

Steep Mesozoic brittle faults, cataclastic rocks, and diabase dike intrusions, related to a systematic rotation of regional extensional stress directions, further modified earlier structures. With the changing stress regimes, in structural order, left-lateral oblique-slip, near normal oblique-slip or normal dip-slip, and finally right-lateral oblique-slip faults developed. The Slicking Gap normal fault either formed during relaxation of Alleghanian compression or during Mesozoic extension.

Understanding the Inner Piedmont continues to be a formidable task, in spite of so much fieldwork done by so many for so long. The point to emphasize in IP mapping is the strong potential for completely different, often unrelated tectonic features to be preserved in close proximity. A case is made here for a certain degree of awareness of the polyphase events that are present regionally when focusing one's attentions and expectations on a new exposure. At all scales IP rocks are palimpsest.

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