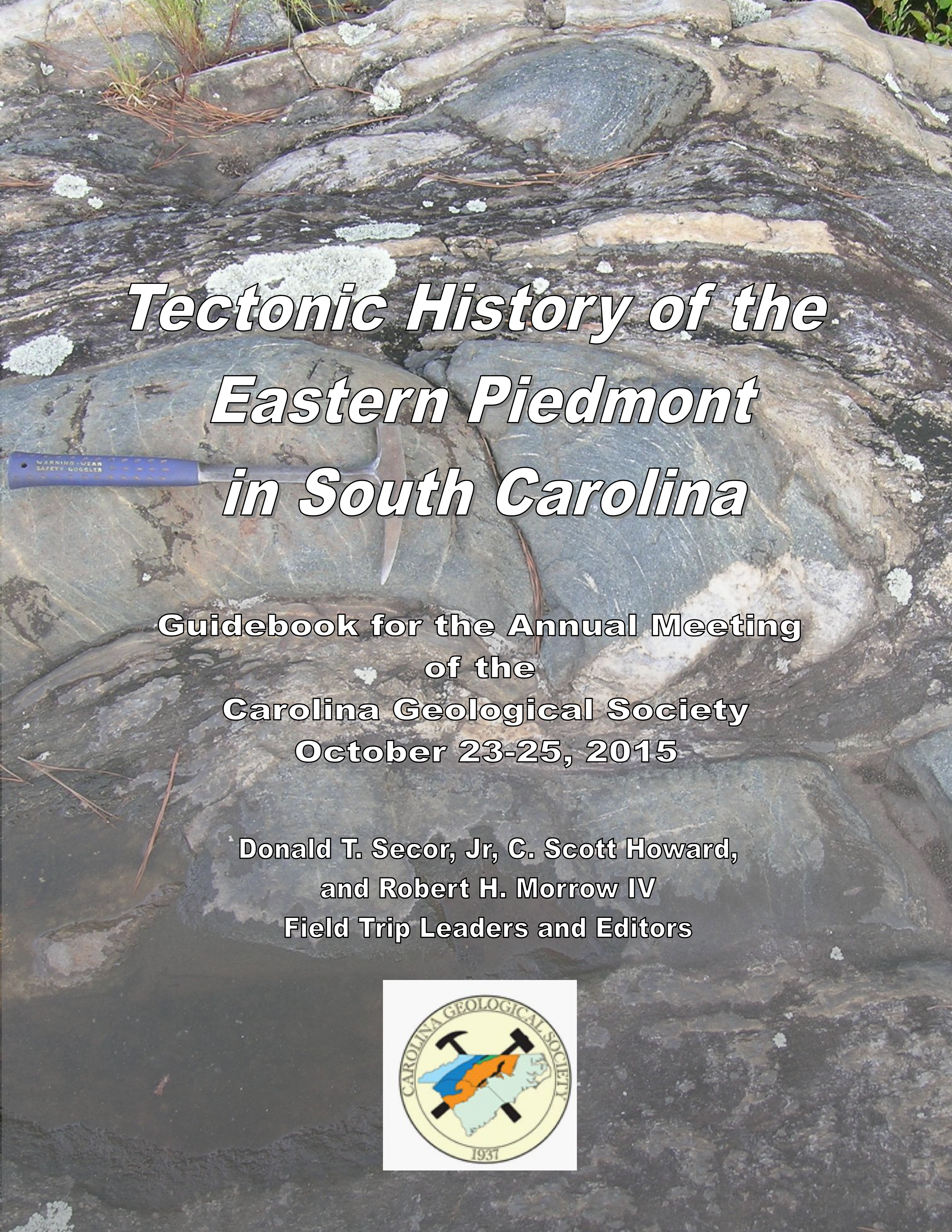

Tectonic History of the Eastern Piedmont in South Carolina

Guidebook for the Annual Meeting
of the
Carolina Geological Society
October 23-25, 2015

Donald T. Secor, Jr, C. Scott Howard,
and Robert H. Morrow IV
Field Trip Leaders and Editors

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October 24-25, 2015

Tectonic History of the Eastern Piedmont in South Carolina

Donald T. Secor, Jr

C. Scott Howard

Robert H. Morrow, IV

South Carolina Department of Natural Resources
Geological Survey
5 Geology Rd,
Columbia, South Carolina, 29212

INTRODUCTION

Beginning in the 1960's, a great deal of effort was expended to work out the plate tectonic history of the Appalachians. Many workers were inclined to extrapolate the then known depositional and tectonic history of the Appalachian foreland to understand the more complex history of the eastern hinterland. This approach yielded some successes, but there remained points of disagreement concerning correlation with hinterland geology. For example, the discovery that parts of the eastern Piedmont had undergone late Paleozoic ductile deformation and amphibolite facies regional metamorphism was originally thought to indicate affinities with the European Hercynian orogeny rather than the Alleghanian orogeny in the Appalachian foreland (Snoke and others, 1980). Ultimately, it became clear from regional geophysical and geological studies (Cook and others, 1983; Secor and others, 1986a, 1986b) that the eastern Piedmont and the foreland were also connected via the regional Appalachian decollement. In recent decades it has become clear that parts of the hinterland record events that were originally remote from the foreland in both time and space. The realization by Wilson (1966) that the presence of Atlantic province trilobites in eastern New England and Canada indicated episodes of continental collision and later

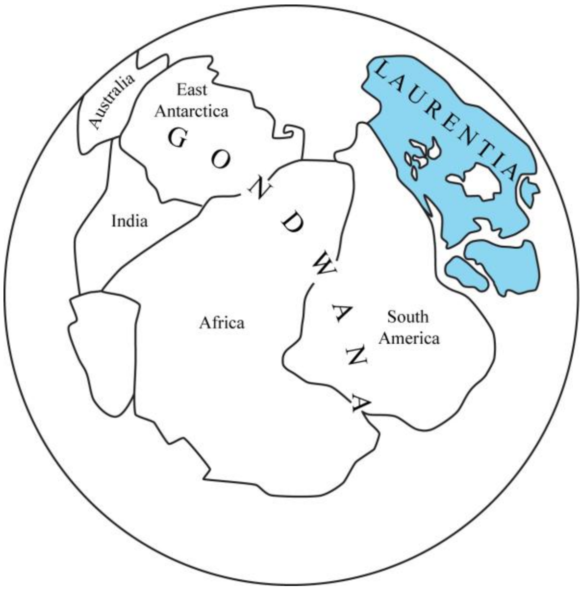


Figure 1. Hypothetical location of Laurentia at about 545Ma before its complete separation from Gondwana. Modified from Dalziel (2014).

Figure 2. Hypothetical location of the Carolina terrane relative to Gondwana at about 530 Ma just prior to its departure from Gondwana and following the rotational separation of Laurentia from Gondwana. Configuration of continents modified from Dalziel (2014). Position of the Paraguan craton, which was a presumed source of detrital zircons in the Carolina terrane, from Dennis (2014). The contrasts between Atlantic province trilobites that developed on Gondwana and Pacific province trilobites that developed on Laurentia may be a consequence of the isolation of Laurentia that developed between 545 Ma and 530 Ma (Dalziel, 2014).

separation that left an exotic sliver of Gondwana, or peri-Gondwana (Figures 1, 2), attached to Laurentia. Subsequently, the discovery of Atlantic province trilobites in the Asbill Pond Formation (Figures 3, 4) near Batesburg in South Carolina (Secor, and others, 1983; Samson and others, 1990) was similarly interpreted to indicate an exotic peri-Gondwanan Carolina terrane in the eastern Piedmont of the southern Appalachians. To make a long story even longer, the tract originally considered as comprising the Carolina terrane by Secor and others (1983) has been subdivided into several smaller terranes by more recent workers (Figure 5). In the eastern Piedmont of North and South Carolina, the name "Carolina terrane" has been retained for one of these smaller terranes characterized by low to medium-grade metavolcanic and metasedimentary rocks (Hibbard and others 2002). The name "Charlotte terrane" has been used for a terrane characterized by intrusive igneous and medium amphibolite facies metaigneous rocks (Hibbard and others, 2002). The name "Silverstreet terrane" (Dennis and others, 2012) has been used for another of the smaller terranes characterized by garnet amphibolite having a clockwise P-T-t history, starting in medium temperature eclogite facies, followed by rapid isobaric heating to high-pressure granulite facies, and then by rapid cooling and pressure reduction to retrograde amphibolite facies (Shervais and others, 2003). Finally, a small area in the Spillway of Lake Murray characterized by high-pressure rutile-garnet-staurolite-kyanite amphibolite facies metamorphism (Snoke and Frost, 1990) is now referred to as the Dreher Shoals terrane (West and others, 1995, Hibbard and others, 2002). The listing of terranes mentioned above does not include all of those present in the area of the original (1983) Carolina terrane, but the list does contain those relevant to the discussion of deformation chronology presented in this guidebook.

In 1983, the eastern Piedmont was thought to be comprised of a series of "belts" of alternating low and medium to high grade metamorphic rocks intruded by a variety of igneous and meta-igneous rocks. Two of these "belts" (the Carolina slate belt

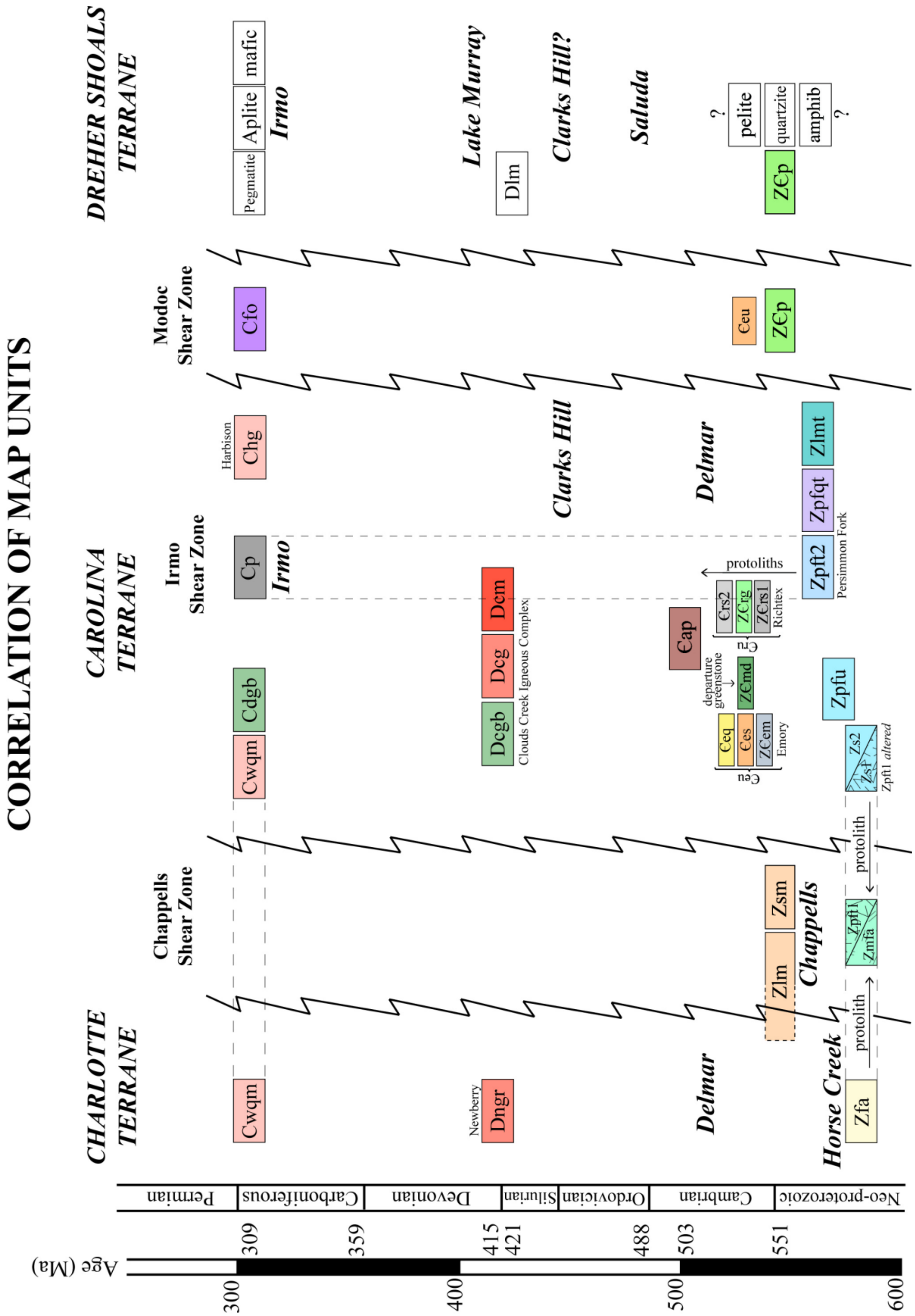


Figure 3. Correlation chart for all map units.

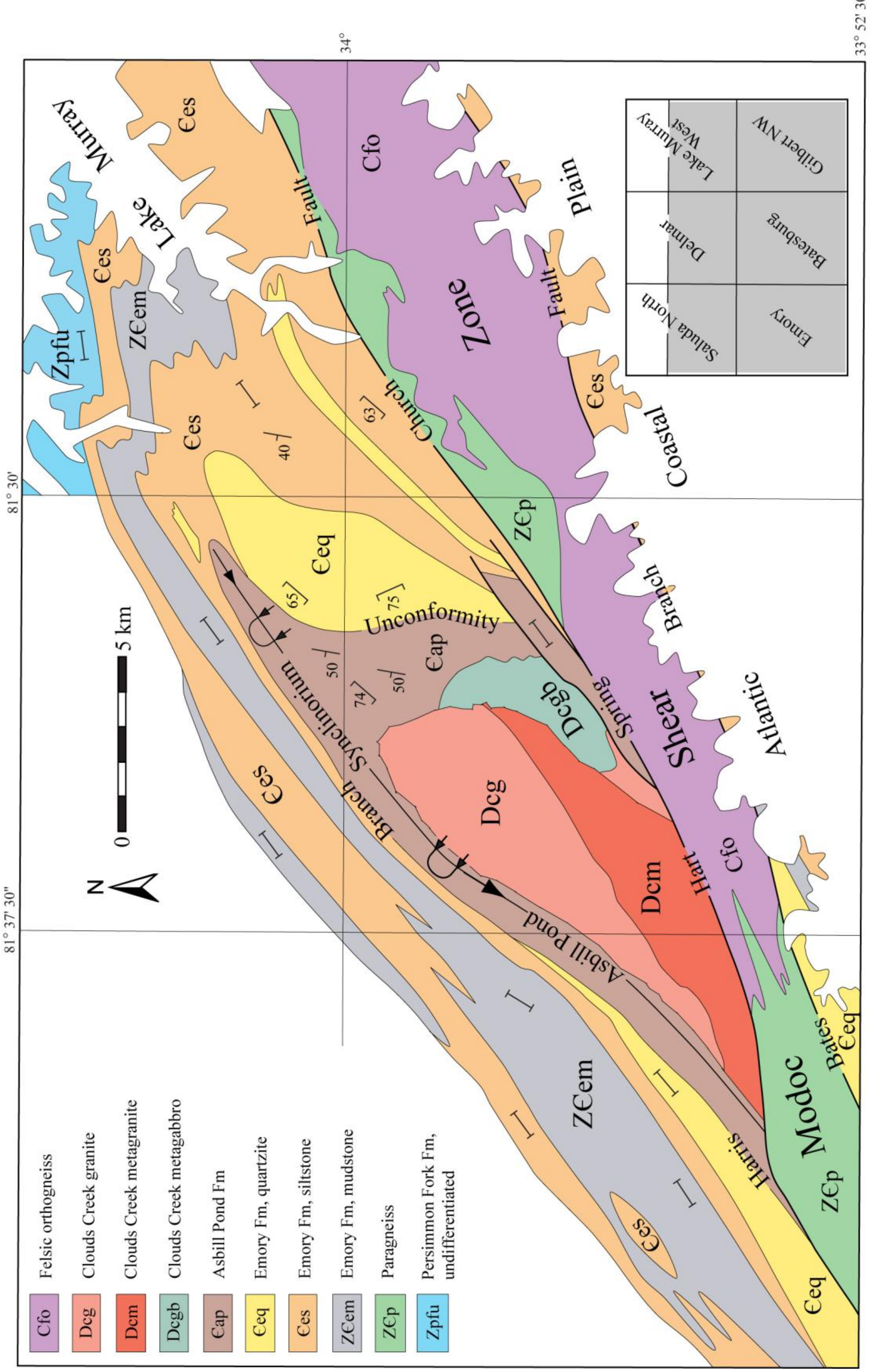


Figure 4. Geologic map of the Batesburg-Emory-Delmar region showing the location of the Asbill Pond synclinorium. Modified from Secor and others (1986a).

and the Charlotte belt) comprised much of the eastern Piedmont in North and South Carolina. The Batesburg fossils were found in the Carolina Slate belt that was then thought to have originally comprised a subduction-related volcanic suprastructure; and as a result of similarities in age and chemical composition, the Charlotte belt (adjacent on the northwest) was thought to be the corresponding infrastructure (Secor and others, 1982, 1986a; Dallmeyer and others, 1986). Because of the relationships described above, the Carolina terrane was originally defined to contain both belts (Secor and others, 1983).

More recently, several studies (Doar, 1995; Lawrence, 1995; Offield, 1995; Barker and others, 1998; Secor and others, 1998) have shown that the supposed "infrastructure" is separated from an overlying Carolina terrane volcanic "suprastructure" by the Chappells shear zone (Figures 6, 7, 8, 9). This separation, together with the discovery of relict eclogitic rocks in the interior of the supposed infrastructure (Shervais and others, 2003), led to the subdivision of the "infrastructure" into the Charlotte and Silverstreet terranes (Hibbard and others, 2002; Dennis and others, 2012), both terranes likely of peri-Gondwanan origin. The Charlotte terrane may or may not be a volcanic infrastructure of the Carolina terrane. The presence of the Chappells shear zone between the two terranes leads to this uncertainty. The complex thermal history of the Silverstreet terrane, along with the presence of relict eclogite boudins, indicates that it may have originated away from the Carolina and Charlotte terranes. Similarly, at the east end of Lake Murray, the Dreher Shoals terrane (Snoke and Frost, 1990, Samson and Secor, 2000, Hibbard and others, 2002) may have a history substantially different from that of the adjacent Carolina terrane. In this guidebook, we review the results of recent field and geochronological studies in the eastern Piedmont (Barker and others, 1998; Samson and Secor, 1999, 2000; Samson and others, 2001; Dennis and Miller, 2013; Mobley and others, 2014; Dennis 2014, 2015; Secor and Howard, in press; Secor and others, in press) that together lead to interesting speculations concerning the history of the Carolina, Charlotte, Dreher Shoals, and Silverstreet terranes from the time of their origin in a peri-Gondwana setting until their accretion to Laurentia.

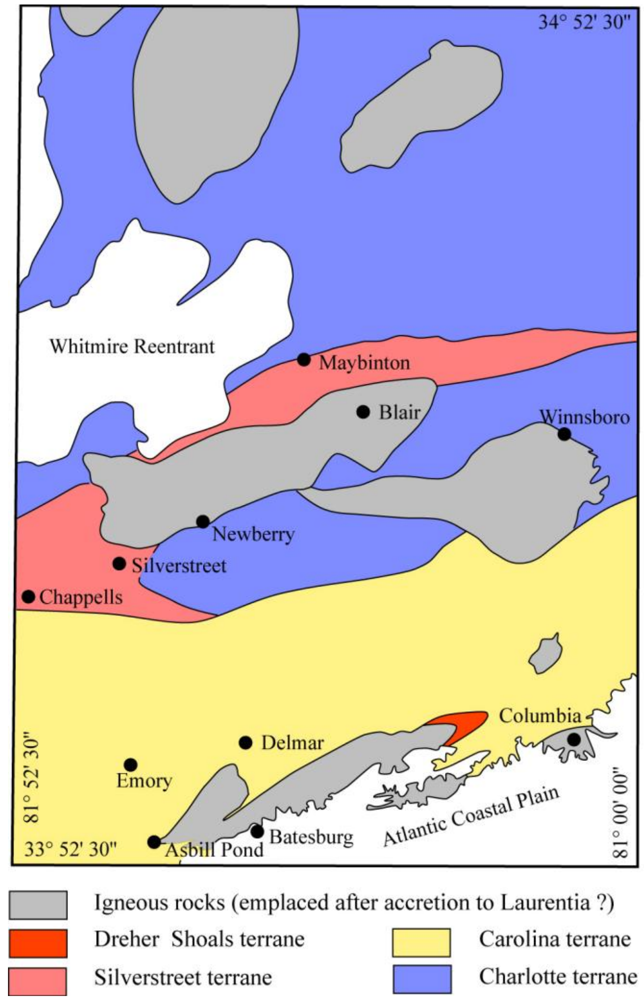


Figure 5. Current distribution of terranes in central and southeastern South Carolina. The red, yellow, blue, and orange areas were all considered to be "Carolina terrane" by Secor and others (1983). The colored subdivisions were made later by West and others (1995), Hibbard and others (2002), Shervais and others (2003), and Dennis and others (2012). Base map modified from Horton and Dickens (2001).

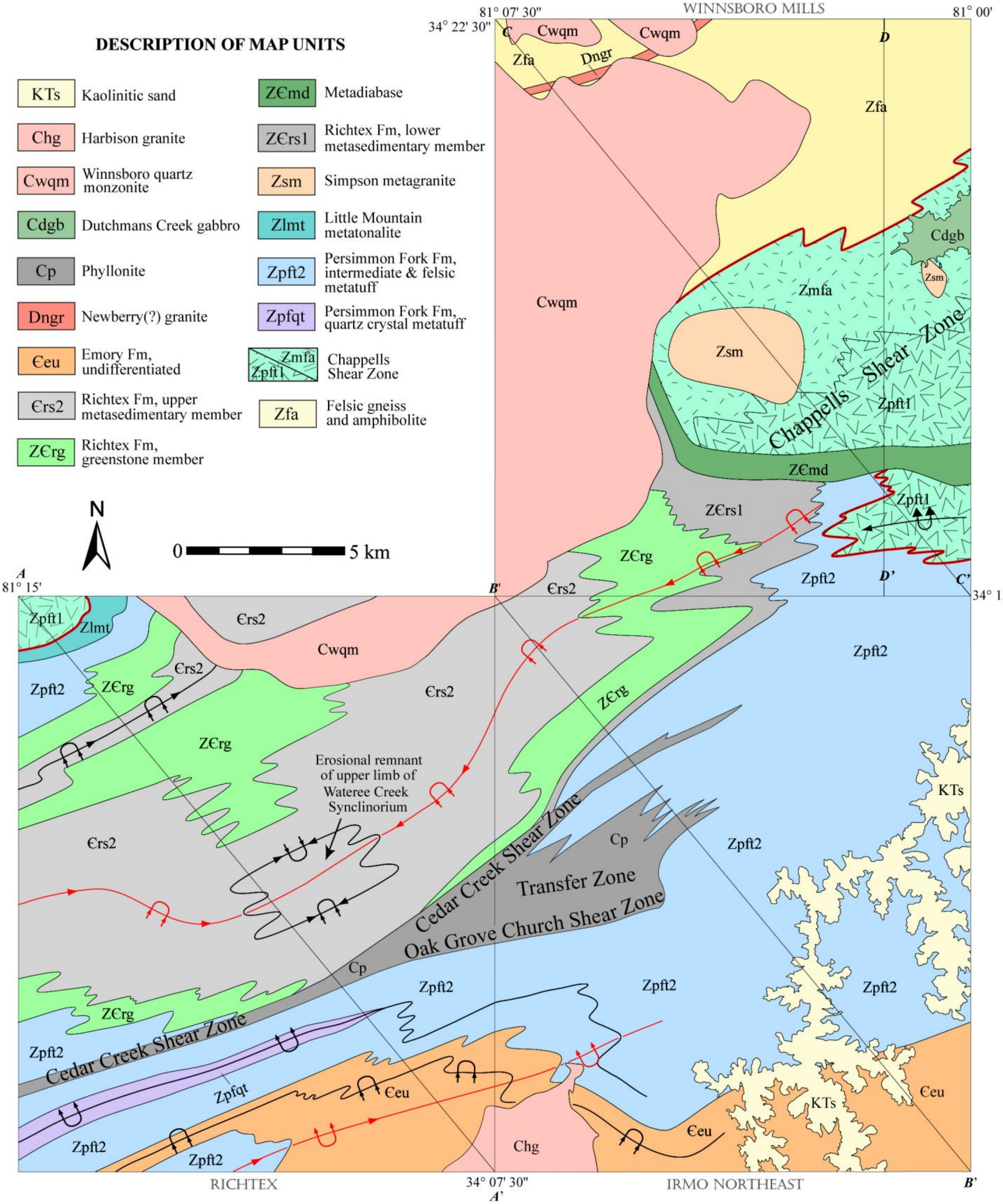


Figure 6. Geologic map of the Richtex-Irmo Northeast-Winnsboro Mills region. Modified from Secor and Howard (in press) and Secor and others (in press).

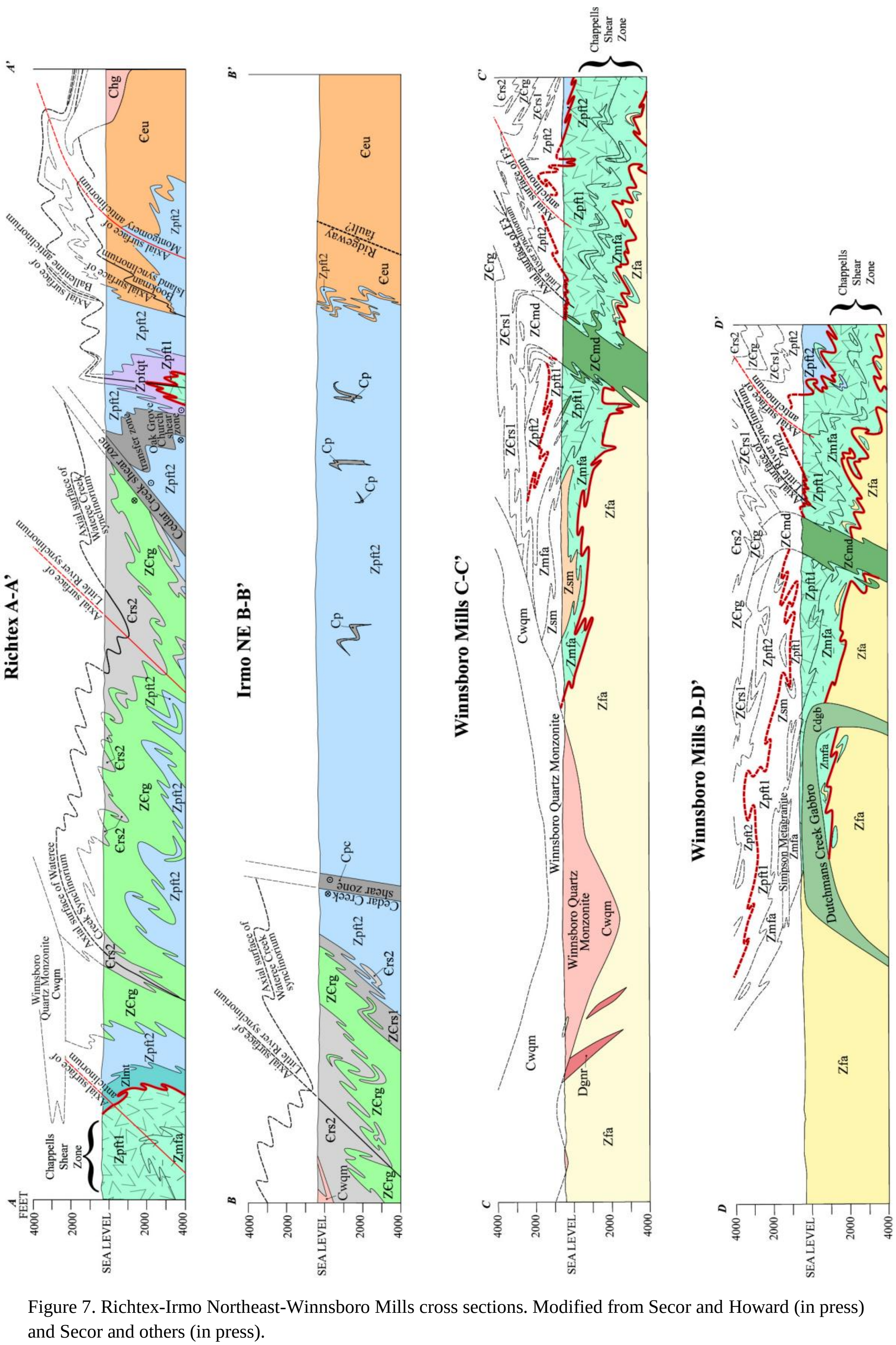


Figure 7. Richtex-Irmo Northeast-Winnsboro Mills cross sections. Modified from Secor and Howard (in press) and Secor and others (in press).

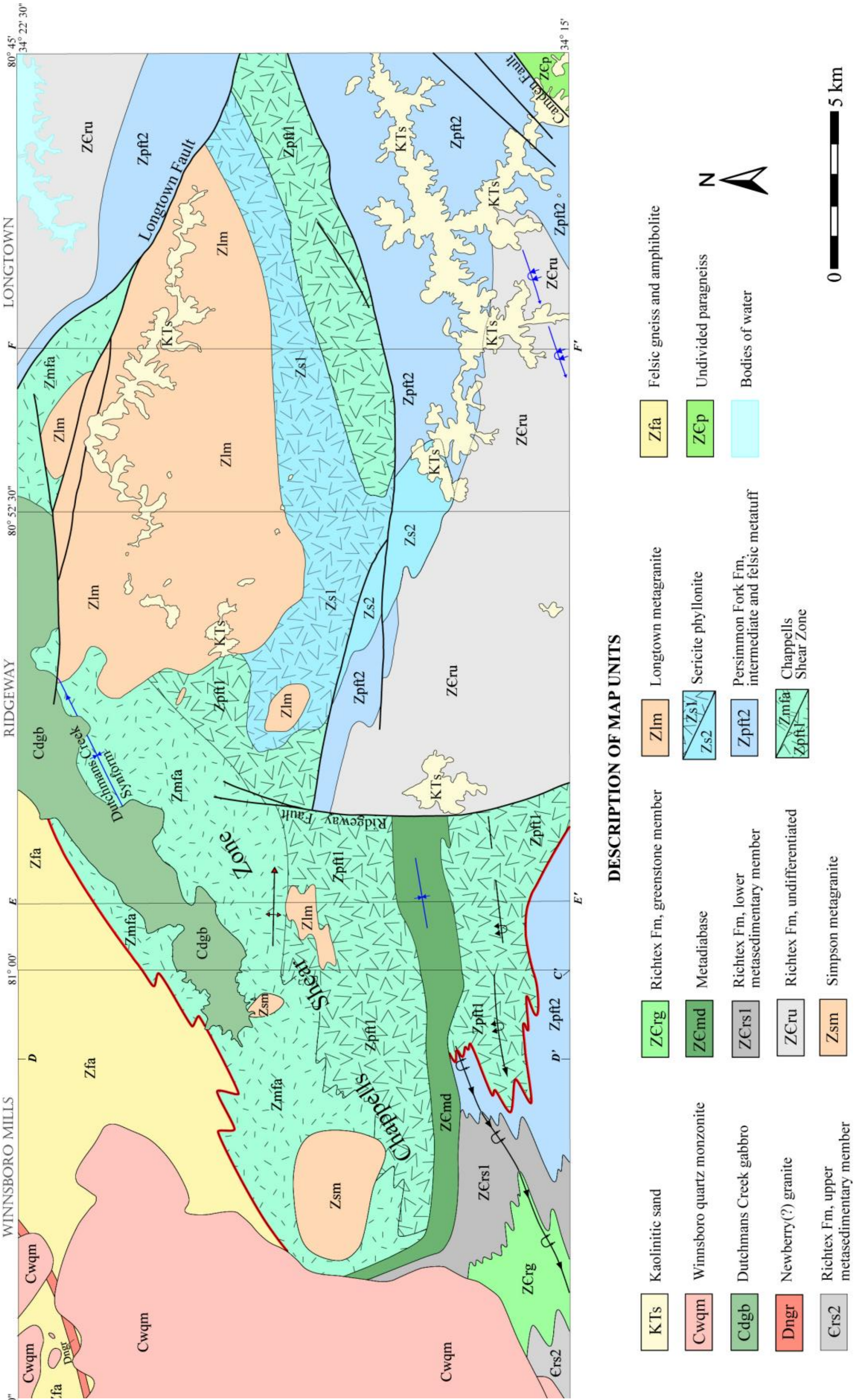


Figure 8. Geologic map of the Winnsboro Mills-Ridgeway-Longtown region. Modified from Secor and others (in press) and Barker and Secor (2005).

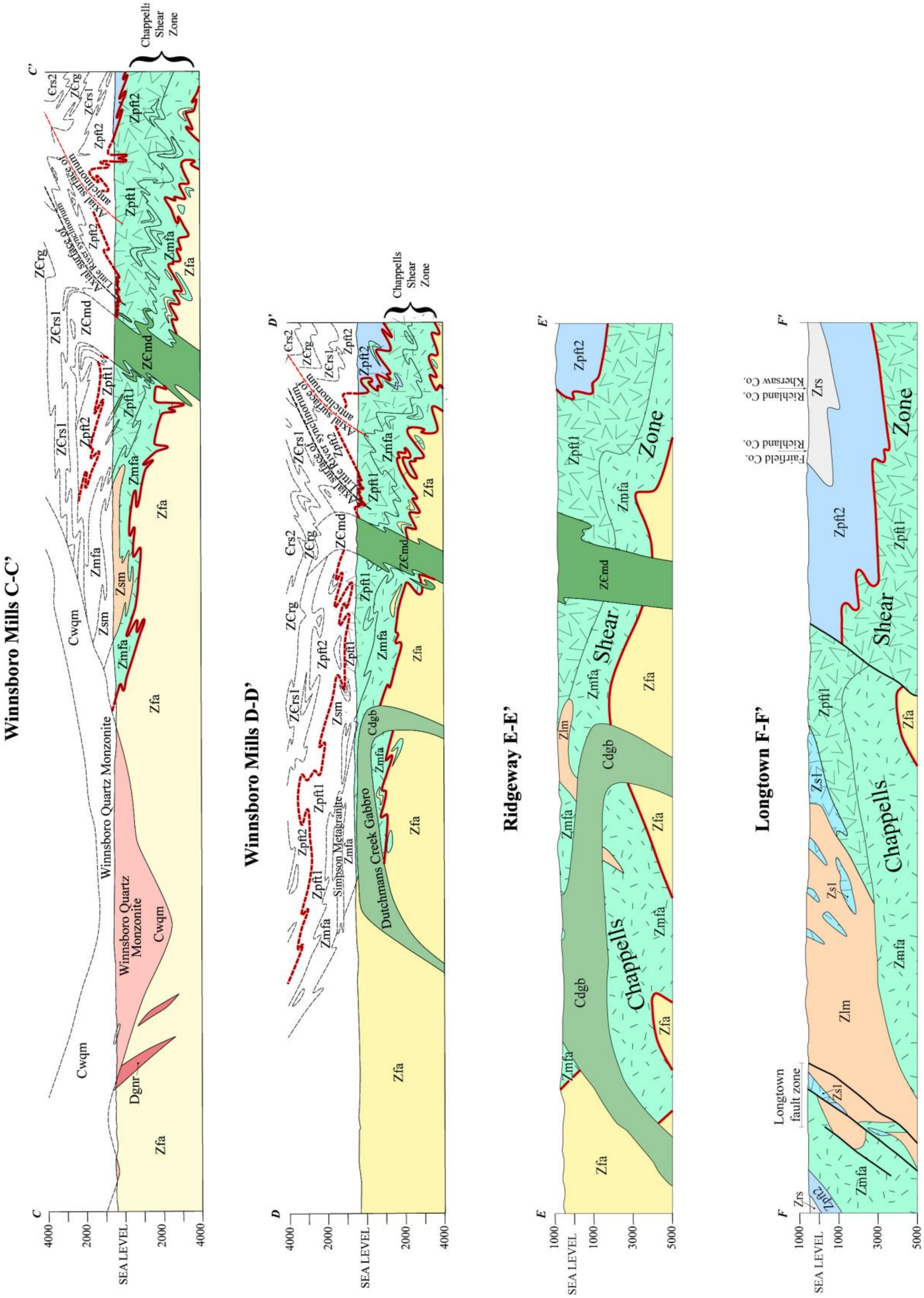


Figure 9. Winnsboro Mills-Ridgeway-Longtown Cross sections. Modified from Secor and others (in press) and Barker and Secor (2005).

DEFORMATION CHRONOLOGY

INTRODUCTION

Together, deformation in the eastern Piedmont rocks of central South Carolina is polyphase and has been affected by at least seven deformation events. These events are assigned type locality names in order to ensure that the names can be carried over, if desired, to other areas or other reports. The names of the events discussed in this guide are: Horse Creek deformation, Chappells deformation, Delmar deformation, Saluda deformation, Lake Murray deformation, Clarks Hill deformation, and Irmo deformation. Some of the above names were first used by Secor and others (1986a), although understanding of these events has evolved in the intervening time. Others are newly described in recent publications (Secor and Howard, in press; Secor and others, in press). The relative ages of these events are partially constrained by overprinting relationships; and in some cases, absolute ages have been determined from fossils and a variety of geochronological studies. Some of the information presented here, documenting the deformation history, is necessarily taken from areas outside the regions visited on this field trip.

CHARLOTTE TERRANE DEFORMATION

Geological and geochronological studies conducted by Barker and others, (1998) and Barker and Secor (2005) reveal that the Carolina and Charlotte terranes were juxtaposed during the Chappells deformation by motion along the Chappells shear zone, and that the Longtown meta-granite is a late synkinematic stitching pluton intruded into the Chappells shear zone between the Carolina and Charlotte terranes (Figures 6, 7, 8, 9). The about 551 Ma U-Pb zircon emplacement age of the Longtown meta-granite (Barker and others, 1998) also indicates that the Chappells deformation event responsible for the motion on the shear zone must have taken place prior to about 551 Ma (Figure 10). Although the rocks in the shear zone are mylonitic, pre-mylonitic precursors derived from both the Charlotte and Carolina terranes can sometimes be recognized. Precursors derived from the Carolina terrane (e.g., relict volcanic lapilli meta-tuff from the Persimmon Fork Formation) are located along the northern edge of the Carolina terrane, within mylonitic Carolina terrane rocks; whereas precursors from the Charlotte terrane (e.g., relict pegmatite and/or meta-gabbro) are located along the southern edge of the Charlotte terrane, within mylonitic Charlotte terrane rocks. The approximate location of the boundary between the Carolina and the Charlotte terranes in the Chappells shear zone can be determined from the distribution of the above relations. On the geologic map and cross sections, this boundary is located in the central part of the shear zone along the contact between the Persimmon Fork Formation felsic lapilli meta-tuff member in the Carolina terrane and the mylonitic felsic gneiss and amphibolite unit in the Charlotte terrane (Figures 7, 9). On average, the shear zone is thought to dip gently southeastward, but it has been strongly overprinted by younger folding events. Examination of stereoplots b) and f) in Figure 11, representing domains 9 and 13, indicate that poles to the Chappells mylonitic foliation in the Chappells shear zone fall along great circles oriented N 09 W 79 SW and N 01 E 79 NW respectively. These orientations, together with the contours representing the positions of poles along the great circles, indicate that the shear zone is relatively flat lying in these domains. The close grouping of the poles to the above great circles with the points representing the orientations of Chappells x Delmar intersection lineations indicate that the dispersion of poles to the Chappells mylonitic foliation on the stereoplots is a result of Delmar deformation folding, and that Delmar folds plunge gently ENE. A similar analysis of stereoplots c) and e), representing domains 10 and 12 in Figure 11, indicates that in these domains Delmar folds plunge gently WSW. Together, the above plunge directions show that the boundaries between domains 9 and 10 and similarly between domains 12 and 13 represent a regional culmination in the height of the axes of Delmar folds. Overprinting from the Clarks Hill deformation also may have substantially contributed to the effects discussed above.

Following juxtaposition of the Carolina and Charlotte terranes by motion along the Chappells shear zone, a series of late syntectonic to post-tectonic meta-granites were emplaced along the terrane boundaries.

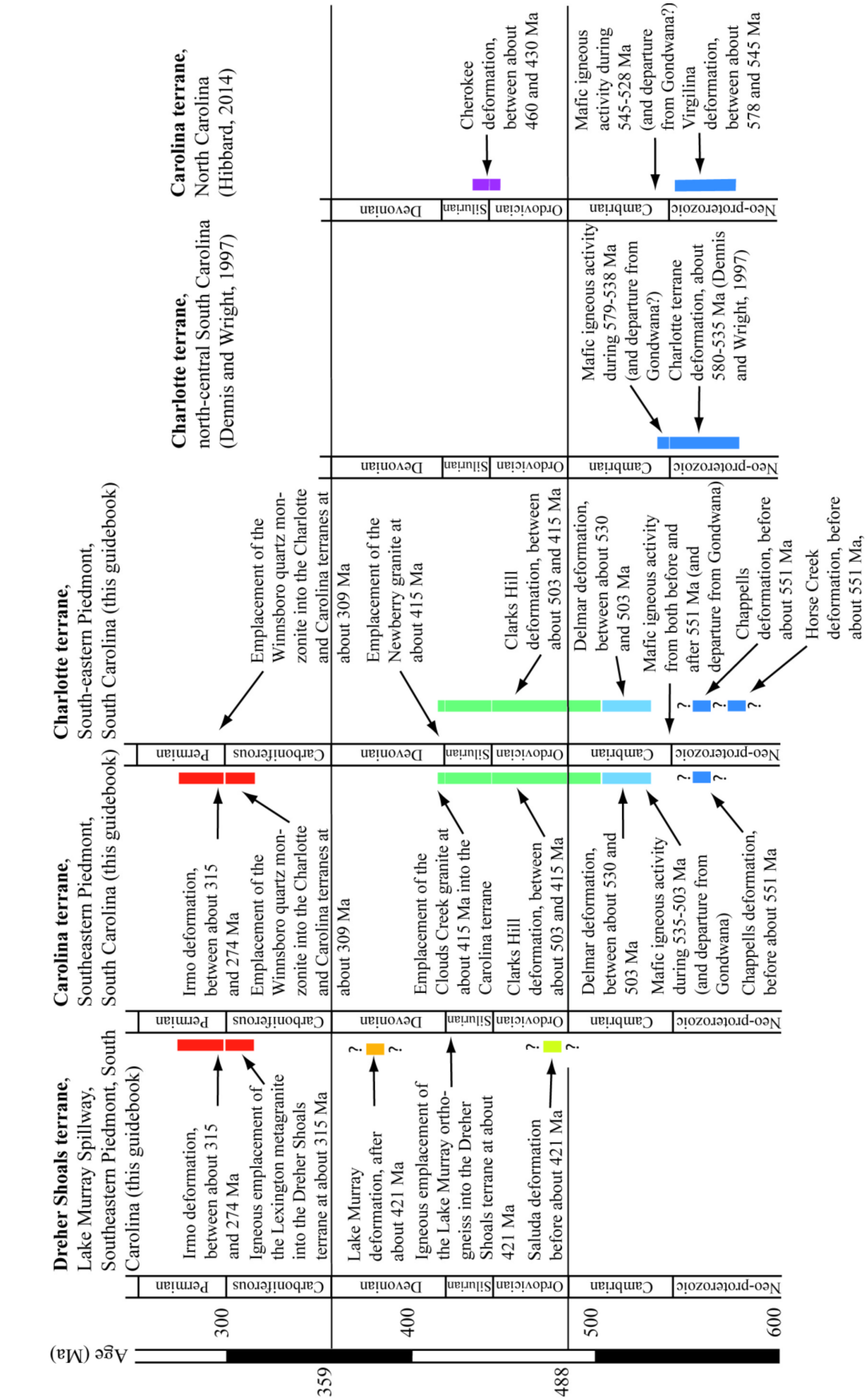
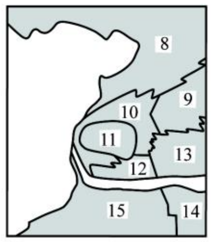
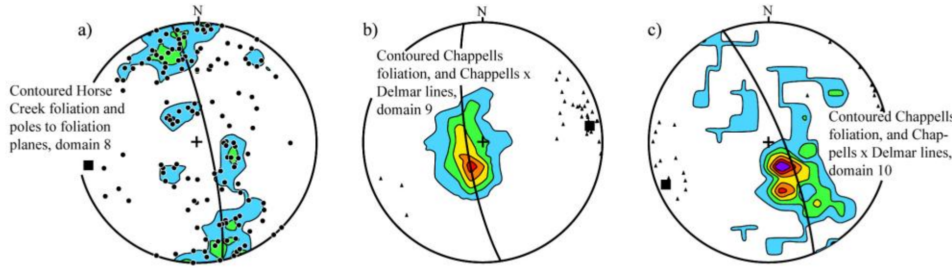


Figure 10. Deformation chronology chart.



Structural domains utilized in the Winnsboro Mills quadrangle



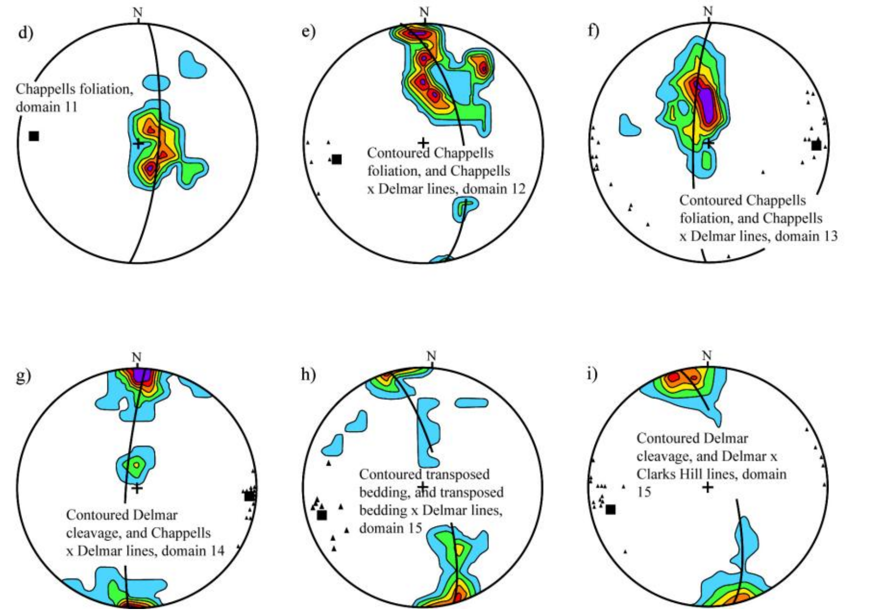


Figure 11. Equal area, lower hemisphere projections of structural data from the Winnsboro Mills quadrangle. Contoured information represents poles to planar fabric elements such as bedding, cleavages and foliations. Small black triangles represent the orientation of intersection lineations such as transposed bedding x Delmar, Chappells x Delmar, and Delmar x Clarks Hill. Small black circles represent the poles to individual Horse Creek foliation planes. The orientations of the poles to the best-fit girdles of planar data are represented by black squares. a) 144 poles to Horse Creek foliation in domain 8, contours: 2 - 4%. b) 51 poles to Chappells foliation), and 37 Chappells X Delmar intersection lineations in domain 9, contours: 2 - 6 -10 - 14 - 18%. c) 43 poles to Chappells foliation, and 20 Chappells x Delmar intersection lineations in domain 10, contours: 2, 4, 6, 8, 10, 12%. d) 20 poles to Chappells foliation in domain 11, contours: 2, 6, 10, 14, 18, 22%. e) 22 poles to Chappells foliation and 5 Chappells x Delmar intersection lineations in domain 12, contours: 2, 4, 6, 8, 10, 12%. f) 59 poles to Chappells foliation and 26 Chappells x Delmar) intersection lineations in domain 13, contours: 2 - 4 - 6 - 8 - 10 12%. g) 27 poles to Delmar cleavage, and 14 (Chappells x Delmar intersection lineations in domain 14, contours: 2, 6, 10, 14 18, 22%. h) 28 Poles to transposed bedding, and 9 transposed bedding x Delmar cleavage intersection lineations in domain 15, contours: 2, 6, 10, 14,18%. i) 75 poles to Delmar cleavage planes and 19 Delmar x Clarks Hill intersection lineations in domain 15, contours: 2, 6, 10, 14, 18%.

Two of these meta-granites [the Longtown meta-granite in the Ridgeway and Longtown quadrangles (Figure 8) and the Simpson meta-granite in the Winnsboro Mills quadrangle (Figures 6, 8)] are interpreted as stitching plutons that were emplaced at about 551 Ma following cessation of most of the relative motion between the Carolina and Charlotte terranes (Barker and others, 1998). Stereoplot a) in Figure 11, representing fabric data from domain 8 in the Charlotte terrane, and thought to be north of and beneath the Chappell shear zone, indicates a relatively weak preferred orientation of poles to the Horse Creek foliation along a great circle oriented N 12 W 82 NE. Stereoplots h) and i) in Figure 11, representing fabric elements in domain 15 in the Carolina terrane and thought to be south of and abovethe Chappells shear zone, indicate a similar, but much stronger, preferred orientation than that present in stereoplot a) in Figure 11. The intensity of the maxima in stereoplot a) are less; and consequently, the dispersion of the contoured points must be greater. Because domains 8 and 15 are both outside of the Chappells shear zone, the domains are interpreted to have been overprinted only by the Delmar and Clarks Hill deformation events. The differences in intensity noted between domains 8 and 15 are interpreted to indicate that, prior to overprinting, domain 8 was already carrying the effects of the Horse Creek deformation, whereas domain 15 was overprinted by the same deformation events acting on a previously undeformed sequence of volcanic and sedimentary rocks. The possibility that the presence of prior Horse Creek deformation in domain 8 acted to disperse the overprinting events may indicate that the Horse Creek deformation fabrics were originally similar to those of a tectonic mélange. The information in Figure 11 are interpreted to indicate that, in the Charlotte terrane, both the Horse Creek and the Chappells deformations are older than 551 Ma age for the emplacement of the Longtown meta-granite that stitches the boundary between the Carolina and Charlotte terranes (Figure 10). These data also are interpreted to indicate: 1) that P. the Horse Creek deformation is only present in the Charlotte terrane (Figure 10), 2) that the rocks along the common boundary between the Charlotte and Carolina terranes where deformed by the Chappells shear zone, and 3) that both the Charlotte and Carolina terranes were overprinted by the effects of the Delmar and possibly the Clarks Hill deformation events. The above differences in the pre-551 Ma deformation history of the Charlotte and Carolina terranes (Figure 10) may further indicate that they were originally separate terranes. Alternatively, similarities in the ages of the younger meta-igneous rocks in the Charlotte terrane with the meta-volcanic rocks in the Carolina terrane (Dallmeyer and others, 1986; Barker and others, 1998, Mobley, personal communication, 2015) may indicate that they have a common history and were both parts of the same peri-Gondwana subduction-related volcanic arc.

CAROLINA TERRANE DEFORMATION

As previously discussed, the Chappells shear zone is thought to dip gently southeastward and to have been strongly overprinted by younger deformation events. The boundary between the Carolina and Charlotte terranes is contained in the central part of the shear zone and coincides with the contact between the mylonitic felsic gneiss unit in the Charlotte terrane and the felsic lapilli meta-tuff unit in the Carolina terrane. In the Winnsboro Mills quadrangle, the effects of the Chappells deformation are thought to be primarily restricted to the boundary region between the Carolina and Charlotte terranes. Overprinting relationships, together with the 551 Ma U-Pb zircon emplacement age for the Longtown meta-granite indicates that the Chappells deformation is the earliest event to affect the Carolina terrane in the Winnsboro Mills quadrangle. Importantly, the effects of the Chappells deformation may be present in the subsurface throughout the Carolina terrane in the felsic lapilli meta-tuff member of the Persimmon Fork Formation, but the effects of the Chappells shear zone have not been observed in younger rocks in the Carolina terrane southeast of the Charlotte terrane.

Much of the following information documenting the remaining deformation history of the Carolina terrane is taken from areas outside the Winnsboro Mills quadrangle. This information is reproduced from Secor and Howard (in press) and Secor and others (in press), with some modifications. In the Batesburg, Emory, and Delmar quadrangles (Figure 4), field data and geologic map relationships (Secor and others, 1986a; Secor and Snoke, 2002, 2004) indicate that an angular unconformity (here referred to as the Harris Branch unconformity) separates the Emory Formation and the overlying Asbill Pond Formation. This unconformity is shown by discordance between the unconformity surface and bedding, Delmar cleavage, and Delmar fold axial surfaces in the underlying Emory Formation. The age of the youngest detrital zircons (Sampson and others, 2001) from the Emory Formation beneath the unconformity are ~ 530 Ma, indicating an age no older than Early Cambrian for the development of the Delmar fabric. The Asbill Pond Formation, above the unconformity, contains trilobite fossils of the *P. atavus* zone of the Drumian (Secor and others, 1983; Samson and others 1990) indicating an age no more recent than 503 Ma (Dennis, 2014) for the Delmar deformation event which is considered responsible for the angular unconformity. The above age constraints indicate that the Delmar fabrics in the Emory Formation, and likely also in the conformable underlying Persimmon Fork Formation, developed during 503-530 Ma. Elsewhere in the Carolina terrane, U-Pb zircon dating of meta-igneous rocks containing Delmar fabric (Barker and others, 1998; Ayuso and others, 2005; Mobley and others, 2014) are consistent with the pre-503 Ma age inferred for the Delmar deformation but do not serve to further constrain the time window containing the Delmar deformation. Similarly, the ages of igneous rocks in the Carolina terrane (Samson and Secor, 2000) interpreted as not containing Delmardeformation fabric also do not further constrain the time window for the Delmar deformation. Importantly, the above definition

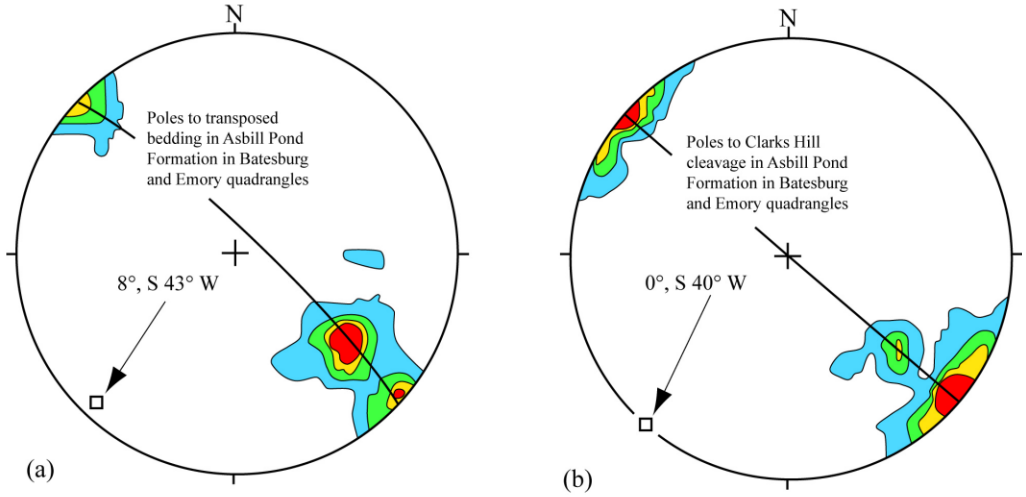


Figure 12. Lower hemisphere equal-area projections of structural data from the Asbill Pond Formation in the Batesburg and Emory quadrangles, modified from Secor and Snoke, 2002 and 2004. Open squares indicate positions of poles to great circles. (a) Poles of 45 transposed bedding planes (contours: 3% per 1 % area). The great circle is the best fit to the poles of the transposed bedding planes. (b) Poles to 81 Clarks Hill cleavage planes (contours: 3% per 1% area). The great circle is the best fit to the cleavage poles.

excludes the Delmar deformation as the event responsible for deformation fabrics in the meta-sedimentary rocks of the Asbill Pond Formation located above the Harris Branch unconformity.

Structural data (Costello and others, 1981; Secor and Snoke 2002, 2004) indicate that the Asbill Pond Formation occupies the axial region of a major, tight-southeast-verging and southwest-plunging synclinorium. Poles to both transposed bedding and cleavage from the Asbill Pond Formation [Figure 12, stereoplots a) and b)] separately fall along great circles oriented about perpendicular to the axis of the above major synclinorium. In order to explain the apparent folding of cleavage in the Asbill Pond Formation, Secor and Snoke (2002, 2004) postulated that the synclinorium had been affected by two separate but nearly coaxial deformation events; the first resulting in the development of cleavage, and a second resulting in the folding of the cleavage, as well as the dispersion of the poles to cleavage along a partial great circle.

During preparation of this guidebook, we realized that another more likely explanation for the above apparent dispersion of cleavage is possible. Rowan and Kligfield (1992) have argued that during a progressive regional simple shear deformation, folding can locally be initiated by buckling, and can then be tightened by flexural slip or flexural flow processes. When the interlimb angle reaches 90-100°, further tightening of the fold limbs can only be accomplished by passive deformation. Because the fold limbs have different orientations, cleavages develop at different rates and orientations in each limb during the operation of flexural slip and/or flexural flow processes. Following the onset of passive deformation, cleavages are rotated toward parallelism with each other and with the limbs in which they reside. Prior to the development of an isoclinal fold, the cleavages in each limb are expected to be acutely inclined to each other. We suggest that the model proposed by Rowan and Kligfield (1992) also may explain the structural relationships observed in the Asbill Pond Formation. The dispersion of poles to cleavage along a partial great circle (Figure 12), as well as the near parallelism of the great circles for both cleavage and transposed bedding (Figure 12), may indicate that a single deformation event is responsible for the fabrics discussed above.

The Asbill Pond Formation is interpreted as having been deposited in a successor basin (Kay, 1951) that developed on the Carolina terrane above the Harris Branch unconformity, starting at about 503 Ma, and which was subsequently deformed into a synclinorium by the Clarks Hill deformation events during 503 - 415 Ma (Figure 10). The above interpretations also imply that the Delmar deformation fabrics in rocks beneath the Harris

Branch unconformity may have been overprinted by Clarks Hill deformation fabrics.

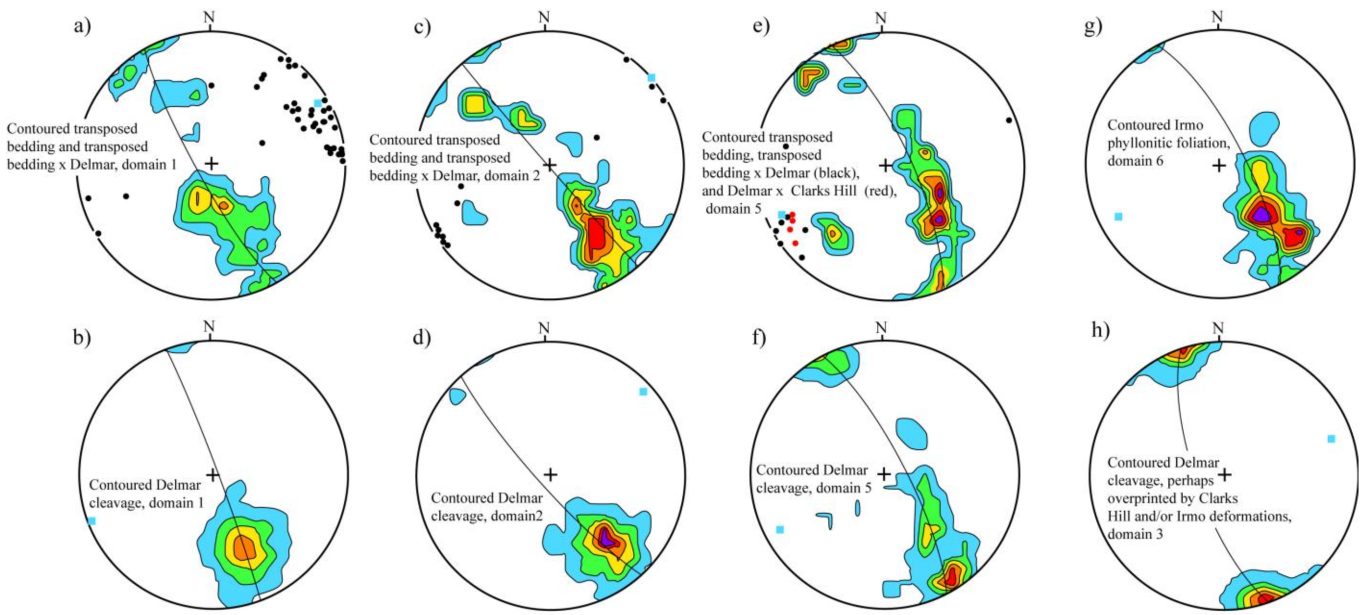
Regional studies (Snoke and Mosher, 1989) indicate that a major northeast-trending belt of Late Paleozoic (Alleghanian) ductile deformation and regional metamorphism extends along the southeastern edge of the Piedmont from central Georgia into eastern North Carolina and Virginia. The Modoc shear zone, located along the south side of Lake Murray was interpreted to be an important component of the Alleghanian deformed belt in South Carolina by Snoke and others (1980). The ages of the Lake Murray, Clarks Hill, and Irmo deformations were originally thought to be Alleghanian (Secor and others, 1986a) because the geochronological studies available at that time indicated a possible Late Paleozoic age for the Modoc shear zone orthogneisses that were interpreted to contain Lake Murray, Clarks Hill, and Irmo fabrics. Among these phases, Clarks Hill and Irmo each have distinctive characteristics (cf. Secor and others, 1986a; Dennis and Secor, 1987, 1990; Howard, 2004). The extent of the regions affected by Clarks Hill and Irmo events can, therefore, be determined in the field. Similarly, the extent of the region affected by Alleghanian regional metamorphism can be estimated from the positions of stations yielding Late Paleozoic $^{40}Ar/^{39}Ar$ cooling ages for hornblende, white mica, and biotite (Dallmeyer and others, 1986). The northern boundary of the Alleghanian regional metamorphism coincides approximately with the Cedar Creek shear zone in the Richtex quadrangle (Figure 6). These comparisons indicate that only the Irmo deformation falls completely within the area affected by Alleghanian regional metamorphism, and therefore is likely the only Alleghanian event in the map area. Based on $^{40}Ar/^{39}Ar$ cooling ages from hornblende, biotite, and white mica (Dallmeyer, 1986; Maher and others, 1994) the Irmo deformation is estimated to have taken place during about 274-315 Ma. Conversely, the Clarks Hill deformation, extends north beyond the map area and outside the region affected by Alleghanian metamorphism; therefore, as concluded previously from another line of reasoning, the Clarks Hill deformation is likely pre-Alleghanian (Figure 10).

The Irmo deformation event also is the most diverse. On a mesoscopic or outcrop-scale, Irmo deformation is expressed either by dextral shear bands or steeply plunging dextral reverse slip crenulations (Dennis and Secor, 1987, 1990). On a map scale, Irmo is manifested as northeast-trending dextral shear zones either in or outside the Modoc Shear zone (Dennis and Secor, 1990; Pray, 1997; Pray and others, 1997). The largest known Irmo structure is the Irmo shear zone which folds the Modoc shear zone in the Irmo quadrangle about a steep northeast plunging axis (Heron and Johnson, 1958; Tewhey, 1977; Secor and others, 1986a; Howard, in progress). The Irmo deformation fabrics also are present in the Richtex and Irmo Northeast quadrangles (Figures 6, 7, 13), but the fabrics have not been observed north of the Cedar Creek shear zone.

COMPARISON WITH DEFORMATION CHRONOLOGIES IN NORTH CAROLINA AND CENTRAL SOUTH CAROLINA

The Virgilina deformation (Figure 10) is the earliest known tectonic event to affect the Carolina terrane and was first identified in north-central North Carolina and Virginia by Glover and Sinha (1973). Field studies (Harris and Glover, 1988; Hibbard and Samson, 1995; Hibbard and others, 2012) have shown that the effects of the Virgilina deformation extend into south-central North Carolina. Geochronological studies (Wortman and others, 2000; Samson and others, 2001; Hibbard and others, 2013) indicate that the Virgilina deformation took place during 578-544 Ma. In central South Carolina, Dennis and Wright (1997) have shown that rocks in the Charlotte terrane were deformed during 580-535. In the southeastern Piedmont in South Carolina, the Charlotte terrane was affected by both the Horse Creek and the Chappells deformations prior to ~ 551 Ma; and in the adjacent Carolina terrane, the felsic lapilli metatuff member of the Persimmon Fork Formation also was deformed in the Chappells shear zone before ~ 551 Ma. These comparisons of the earliest deformation chronologies in North and South Carolina indicate that both the Charlotte terrane and the older part of the Carolina terrane could have been deformed at the same time as the Virgilina deformation. Although it is uncertain if the Charlotte and Carolina terranes were originally the infrastructure and suprastructure of the same subduction-related volcanic arc(s), based on both the presence of a perhaps common deformational event and the presence of ~ 550 Ma stitching plutons (Barker and others 1998; Hibbard and others, 2012), it is clear that the two terranes were together by ~ 550 Ma. Hopefully, future structural and geochronological studies will provide information enabling a decision about whether either or both the Horse Creek deformation and the Chappells deformation are equivalent to Virgilina deformation.

As stated, the age of Delmar deformation is tightly constrained to ~ 530-503 Ma by a combination of detrital zircon studies [Samson and others, 2001 (which provides the maximum age)], the presence of the Harris Branch angular unconformity separating rocks containing Delmar fabrics from those not containing Delmar fabrics (Figure 4), and an assemblage of trilobite fossils [Secor and others, 1983; Samson and others, 1990; Dennis, 2014 (which provides the minimum age)]. In the southeastern Piedmont in South Carolina, Delmar deformation in the metasedimentary rocks of the Emory and Richtex formations are characterized by slaty cleavage and mesoscale to macroscale tight to near isoclinal folds. Bedding-cleavage intersection lineations and fold axes plunge gently northeast or southwest (Figures 11, 13, 14). The intermediate to felsic metatuff member of the Persimmon Fork Formation also contains a phyllitic Delmar foliation. Typically, relict



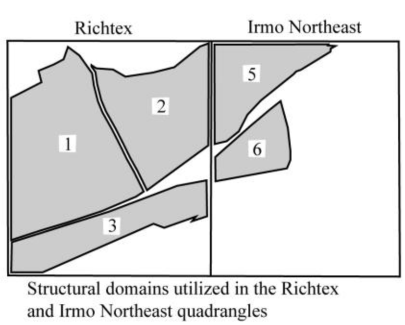


Figure 13. Equal area, lower hemisphere projections of structural data from the Richtex and Irmo Northeast quadrangles. Contoured information represents poles to planar fabric elements such as transposed bedding and cleavages (Delmar, Clarks Hill, Irmo), whereas small black circles represent the orientation of intersection lineations such as transposed bedding x Delmar and Delmar x Clarks Hill . The orientation of the poles to the best-fit girdles of planar data are represented by small blue squares. a) 86 Poles to transposed bedding and points representing transposed bedding x Delmar in domain1. Contours: 2 - 4 - 6 - 8%. b) 205 Poles to Delmar cleavage in domain1. Contours: 2 - 6 - 10 - 14%. c) 29 Poles to transposed bedding and points representing transposed bedding x Delmar in domain 2. Contours: 2 - 4 - 6 - 8 - 10%. d) 62 Poles to Delmar cleavage in domain 2. Contours: 2 - 6 - 10 - 14 - 18 - 22%. e) 22 Poles to transposed bedding and points representing transposed bedding x Delmar (black) and Delmar x Clarks Hill (red) in domain 5. Contours: 2 - 4 - 6 - 8 - 10 - 12%. f) 46 Poles to Delmar cleavage in domain 5. Contours: 2 - 6 - 10 - 14 - 18%. g) 63 Poles to Irmo phyllonitic foliation in domain 6. Contours: 2 - 4 - 6 - 8 - 10 - 12%. h) 142 Poles to Delmar cleavage in domain 3. Maybe overprinted by Clarks Hill and/or Irmo cleavages. Contours: 2 - 10 - 18 - 26 - 34%

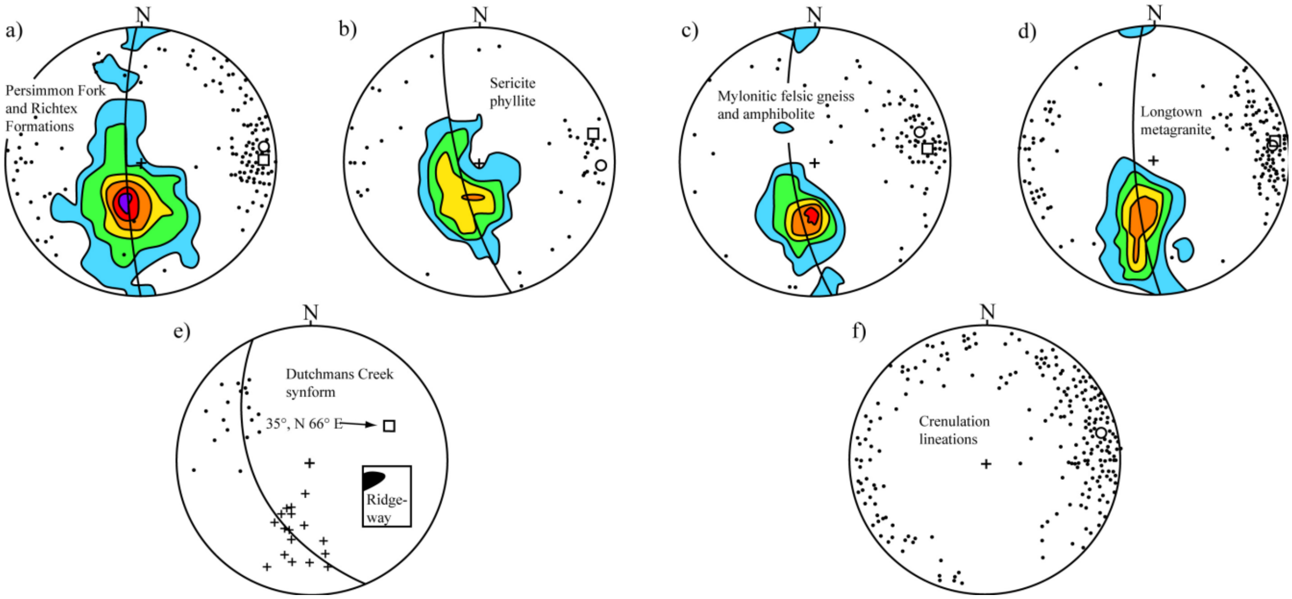


Figure 14. Lower hemisphere, equal-area projections of structural data from the Ridgeway and Longtown quadrangles (modified from Barker and others, 1998, Secor and others, 1998, and Barker and Secor, 2005). Contoured data are poles to planar fabrics. Black dots are intersection lineations in planar fabrics. Open squares indicate pole positions of best-fit great circles passing through poles of planar fabric data, and open circles indicate mean intersection lineation orientations. a) Poles to 599 Chappells and Delmar foliation planes (contours 1% per 1% area) and scatter plot of 145 Chappells x Delmar intersection lineations. b) Poles to 149 Chappells and Delmar foliation planes (contours 2% per 1% area) and scatter plot of 46 Chappells x Delmar intersection lineations. c) Poles to 229 Chappells and Delmar foliation planes (contours 2% per 1% area), and scatter plot of 99 Chappells x Delmar intersection lineations. d) Poles to 279 Chappells and Delmar foliation planes (contours 2% per 1% area), and scatter plot of 167 Chappells x Delmar intersection lineations. e) Structural data from the mylonitic felsic gneiss and amphibolite unit in the flanks of the Dutchmans Creek synform. Dots indicate poles to 20 Chappells foliation planes from the northwest flank, and plus signs indicate poles to 20 Chappells foliation planes from the southeast flank. Insert of the Ridgeway quadrangle indicates the location of the domain from which the data in this plot were taken. f) Scatter plot of 264 crenulation lineations likely resulting from the intersections of Chappells, Delmar, and perhaps Clarks Hill foliations.

metapumice lapilli in that member have been flattened into the plane of foliation (Stop 1). The older felsic lapilli metatuff member of the Persimmon Fork Formation typically carries an earlier Chappells foliation that has been overprinted by Delmar cleavage. As a result of this overprinting, flattened relict pumice lapilli in the Chappells foliation are sliced up by the Delmar cleavage to produce intersection lineations oriented parallel to NE or SW gently plunging fold axes (stop 6 and Figures 11, 14). Similarly, the Charlotte terrane rocks in the southeastern Piedmont that were deformed either by Horse Creek alone or by both Horse Creek and Chappells deformations are interpreted to have been overprinted by Delmar deformation to produce NE or SW gently plunging folds (Figure 8, 11, 14). As described, the effects of Delmar deformation in the southeastern Piedmont are characterized as having developed during a short interval of time and are characterized by a distinctive suite of structures. These characteristics together have not been described from either central South Carolina (Dennis and Wright, 1997) or North Carolina (Hibbard and others, 2012, 2013). We suggest that, although there are strong stratigraphic similarities between southeastern and central South Carolina and North Carolina, Delmar deformation seems to be unique to southeastern South Carolina. As discussed, Delmar deformation may be a consequence of a collision between the Silverstreet terrane and the conjoined Carolina-Charlotte terranes after departure from Gondwana. A better understanding of this possible event would result from a program of detailed mapping together with petrographic and geochronological studies between North Carolina and the southeastern Piedmont in South Carolina.

Cherokee deformation is best documented in the south-central Piedmont of North Carolina, where it is characterized by greenschist facies metamorphism, northwest dipping slaty cleavage, and open southeast vergent folds arranged in an en echelon pattern on either side of the NNE striking Gold Hill shear zone. The structures, together with shear sense indicators, are interpreted to indicate southeast-directed sinistral transpression (Hibbard and others, 2012, 2013). Geochronological studies (Noel and others, 1988; Offield and others, 1995; Ayuso and others, 1997; Hibbard and others, 2012) are interpreted to indicate that the Cherokee deformation took place during ~ 460-430 Ma (Hibbard and others, 2012, 2013). Structures similar to those described in North Carolina may be present in adjacent central South Carolina. Both mesoscale and macroscale southeast vergent folds similar to those described have also been observed in the Carolina terrane in quadrangles discussed in this field guide. We interpret the southeast vergent "Delmar" synclinorium (Costello and others, 1981; Secor and others, 1986a) that contains the Asbill Pond Formation in its core (Figure 4) to actually be a Clarks Hill deformation fold. In order to avoid confusion about the name of the deformation event responsible for that synclinorium, we recommend that the name "Delmar synclinorium" be abandoned, and that the name "Asbill Pond synclinorium" be used in its place (e.g. Figure 4). The age of the Clark Hill deformation is constrained only to the period 503-415 Ma by the age of the trilobite assemblage in the Asbill Pond Formation (Secor and others, 1983; Samson and others, 1990; Dennis, 2014) together with the age of the Clouds Creek granite (Samson and Secor, 2000). The structural similarities discussed are compatible with an interpretation that the Cherokee and Clarks Hill deformations events represent the same time period, but geochronological studies are needed to better constrain the age of Clarks Hill deformation in South Carolina.

The early history of research leading to the discovery that a belt of Carboniferous ductile deformation and regional amphibolite facies metamorphism extends along the Fall Line through South Carolina, is reviewed by Secor and Snoke (2002, 2004). Initially, there were uncertainties about the ages of some of the orthogneisses in the belt because the rocks apparently contained inherited zircons. Recently, a combination of field and geochronological studies (Pray, 1997; Samson and Secor, 2000) indicated that some of the orthogneisses (e.g. Lexington metagranite) were emplaced in the Carboniferous and had been deformed only once during ~ 315-274 Ma (Irmo deformation), whereas the Lake Murray gneiss in the Dreher Shoals terrane was emplaced at ~ 421 Ma and has been deformed first by the Lake Murray deformation (possibly as early as 421 Ma), and later during Irmo deformation from 315-274 Ma. If one defines a belt of amphibolite facies metamorphism containing either or both of the above deformations, the belt may extend along the Fall Line from central Georgia to southeastern Virginia (Snoke and Mosher, 1989; Pray, 1997; Sacks, 1999), but spatially the belt would be well east of the areas in central North and South Carolina studied by Dennis and Wright (1997) and Hibbard and others (2013). The Kings Mountain terrane, located immediately to the west of the Charlotte terrane in North Carolina contains the Alleghanian High Shoals gneiss that was emplaced at ~ 317 Ma (Horton and Stern, 1983;Horton and others, 1987) and was deformed in the Carboniferous. The Kings Mountain terrane may have originally been part of the Carolina terrane, but the adjacent areas to the east, now containing the Charlotte and Carolina terranes do not seem to have been affected by ductile deformation and metamorphism between 315-274.

STRUCTURE OF THE RICHTEX SYNCLINORIUM

The Richtex synclinorium is a polydeformed structure that is probably a result of the interaction of two major episodes of ductile deformation: Delmar, and Clarks Hill. It contains the Delmar Wateree Creek synclinorium and Clarks Hill Little River synclinorium, as well as many other unnamed fold structures. On the map, it is cored by the upper meta-sedimentary member of the Richtex Formation and is flanked by greenstone and lower meta-sedimentary members of the Richtex Formation, as well as by the intermediate and felsic metatuff member of the Persimmon Fork Formation. The synclinorium extends from the west-central edge of the Richtex quadrangle through the northwest corner of the Irmo Northeast quadrangle, and into the Winnsboro Mills quadrangle (Figure 7). In outcrop, the meta-sedimentary rocks of the Richtex Formation typically exhibit transposed bedding, a strong Delmar slaty cleavage, and a later Clarks Hill crenulation cleavage that is mainly expressed as a transposed bedding x Clarks Hill or Delmar x Clarks Hill intersection lineations. Less commonly, mesoscale folds (Delmar, rare intrafolial isoclines, and Clarks Hill, common, tight, upright, and southeast verging) are observed. Field data from the Richtex synclinorium are represented in Figure 13 on stereoplots a through f. The clearest representations of the fabric elements in the synclinorium are from domain 5 in stereoplots e and f. Poles to transposed bedding and Delmar slaty cleavage fall along best-fit great circles oriented N 25 W/ 75 NE and N 28 W/ 78 NE respectively. The fact that the poles fall along virtually identical great circles indicates that both have been folded at least once about fold axes that are nearly parallel. This relation, however, does not indicate that the two structures necessarily coincide in space and had simialrly oriented axial surfaces. Moreover, the observation that the poles representing transposed bedding x Delmar and transposed bedding x Clarks Hill (See stereoplot e) are closely grouped and are adjacent to the pole representing the best fit great circle to transposed-bedding poles reinforces the conclusion that Delmar and Clarks Hill fold axes are nearly parallel. This information is interpreted to indicate that in domain 5, the axis of the Delmar Wateree Creek synclinorium as well as the axes of the Clarks Hill Little River synclinorium plunge about 13 degrees to the S 64 W. Fabric elements in the western and central parts of the Richtex synclinorium (represented by domains 1 and 2) can also be analyzed as above. The results indicate that in these domains Delmar and Clarks Hill folds also are parallel, and show that in domains 1 and 2, the plunges are ~ 9 degrees to the N 60 E and 5 degrees to the N 47 E, respectively, although the data shows more scatter in these domains. These variations and direction of plunge of the Richtex synclinorium indicate that the lowest (or deepest) part of the synclinorium is located near the village of Richtex at the intersection of the Broad and Little Rivers in the east central part of the Richtex quadrangle (Figure 6). This location is interpreted to be where the Delmar Wateree Creek synclinorium and the Clarks Hill Little River synclinorium interfere positively and where the axial surface of the Delmar Wateree Creek synclinorium is folded by the Clarks Hill Little River synclinorium as well as by Clarks Hill second order folds. As shown on the map, there may be an erosional remnant of the upper limb of the Delmar Wateree Creek synclinorium near the town of Richtex. It should be noted that the geological cross sections are constructed to be compatible with the mapped surface geology. The numerous second-order structures on the cross sections and map are incorporated to illustrate the deformation style, but they are hypothetical because their exact configurations are not known.

Projections from the Irmo Northeast quadrangle show that the Richtex synclinorium continues to the northeast into the Winnsboro Mills quadrangle. In the southwest corner of the Winnsboro Mills quadrangle (Figures 6, 8), the synclinorium is cored by the upper meta-sedimentary member of Richtex Formation. Up-plunge to the northeast, in stratigraphic order, the greenstone and lower meta-sedimentary members of the Richtex Formation, and the intermediate and felsic metatuff and felsic lapilli metatuff members of the Persimmon Fork Formation wrap successively across the axis of the Richtex synclinorium. This stratigraphic sequence provides important information concerning the original depositional stratigraphy of the Carolina terrane. On the cross sections (Figures 7, 9), the major fold axis in the Winnsboro Mills quadrangle is the Clarks Hill Little River synclinorium. To the southwest, in the Irmo Northeast and Richtex quadrangles, the Delmar Wateree Creek synclinorium also is present in the Richtex synclinorium, but its axial surface is covered to the northeast by Winnsboro quartz monzonite intrusive (Secor and Howard, in press).

The most distinct fabric elements in the Richtex synclinorium in the Winnsboro Mills quadrangle are shown in Figure 11 on stereoplots h and i in domain 15. The poles to both transposed bedding and Delmar cleavage define nearly identical great circles oriented N 16 W/ 76 NE and N 13 W/ 72 NE, respectively. Those orientations again show that both features have been folded at least once about fold axes that are nearly parallel, but which do not necessarily coincide in space and which may have differently inclined axial surfaces. Moreover, the fact that the poles representing transposed bedding x Delmar and Delmar x Clarks Hill (see stereoplots h and i) are grouped and are adjacent to the pole representing the best fit great circle to transposed bedding and Delmar poles reinforces the interpretation that Delmar folds and Clarks Hill folds are nearly parallel. The above data are interpreted to indicate that in domain 15, the axis of Delmar folds, as well as the axes of Clarks Hill folds plunge ~ 16 degrees to the S 75 W.

Fabric elements in the eastern part of the Richtex synclinorium (represented by domain 14 in Figure 11) also were analyzed as above. The results indicate that in domain 14 Delmar and Clarks Hill folds also are about parallel, and show that in domains 14, the plunge is about 7 degrees to the S 86 E. Those variations in amount and direction of plunge of the Richtex synclinorium indicate that a regional culmination in the height of the axis of the Richtex synclinorium occurs about a kilometer southeast of Calvary Church, in the southeastern part of the Winnsboro Mills quadrangle (Figure 7). The location also indicates the position of a large erosional window exposing the upper surface of an outlier of the Chappells shear zone south of the large meta-diabase unit (Note cross sections and maps, Figures 7, 9, 6, 8).

THE CEDAR CREEK STRIKE-SLIP DUPLEX STRUCTURE

Taken together, the Oak Grove Church and Cedar Creek shear zones appear to exhibit the structural style of a dextral strike-slip duplex (Figure 6). If this interpretation is correct, the Oak Grove Church shear-zone would be the older of the two; inactivity on that shear zone would necessitate the observed change in direction and progressive counter-clockwise rotation of the Cedar Creek shear-zone in the region east of the Broad River. These changes would be facilitated by the development of a phyllonite zone between the two, enabling gradual transfer of slip from the Oak Grove Church shear-zone to the Cedar Creek shear-zone. Field data from the transfer zone is shown on stereoplot g, Figure 13). The correspondence between the observed and predicted geometries, as well as the presence of dextral strike-slip indicators in both shear-zones is the best evidence for the model. The inferred Irmo deformation age for the duplex is based on the assumption that the Cedar Creek shear-zone is a splay off the north side of the Irmo shear-zone, which coincides with the older Modoc shear zone to the south of Lake Murray.

THE BALLENTINE ANTICLINORIUM

The Ballentine anticlinorium is inferred to extend from the southwest corner of the Richtex quadrangle into the southwestern part of the Irmo Northeast quadrangle (Figure 6). In the Richtex quadrangle, the anticlinorium is in the central part of domain 3 (Figure 13). The inferred outcrop of the axial surface follows a band of the Persimmon Fork quartz crystal-metatuff member and is flanked on either side by the younger Persimmon Fork intermediate and felsic metatuff member. Both the Ballentine anticlinorium and domain 3 are separated from the Richtex synclinorium by the Cedar Creek shear-zone. Field data from the Ballentine anticlinorium in the Richtex quadrangle are shown in Figure 13 on stereoplot h, and indicate that the anticlinorium is practically isoclinal. However, near its eastern end, the anticlinorium appears to have been refolded by tight mesoscale to macroscale Clarks Hill and Irmo folds. The described relationship suggest that the Ballentine anticlinorium has a deformation history similar to that of the Richtex synclinorium and may have originated as a Delmar structure that was overprinted by more recent deformation events.

**METTA-GABBRO,META-DIABASE, GREENSTONE:
DEPARTURE FROM GONDWANA?**

Stratigraphy may have important implications concerning the separation of the Carolina terrane from Gondwana. Dennis and Shervais (1991) described thick sequences of both intrusive and extrusive mafic meta-igneous rocks along the northwestern edge of what was then considered to be the Carolina terrane adjacent to the central Piedmont shear zone in South Carolina. From U-Pb zircon dating, Dennis and Wright (1997) showed that the mafic rocks were emplaced between 579-538 Ma and were subsequently deformed. Those authors also described an undeformed dike with a U-Pb zircon age of ~ 535 Ma that intruded the above mafic complex;

the date implies, that deformation in the western Carolina terrane took place during ~ 579-535 Ma. Dennis and Shervais (1991), Shervais and others (1996), and Dennis and Wright (1997) suggested both the mafic rocks in an intra-arc rift basin resulting from separation of the Carolina terrane from its peri-Gondwana setting, and the greenstones in the Richtex Formation in the eastern Piedmont may have formed under similar conditions at about the same time.

Pollock and Hibbard (2010) and Hibbard and others (2013) have described mafic meta-igneous rocks similar to those described that are intrusive into all of the Albemarle arc rocks in the Carolina terrane of North Carolina and suggested an intra-arc rift basin origin. DeDecker and others (2013) have obtained a U-Pb zircon age of ~ 545 Ma for the Stony Mountain gabbro that intrudes the Tillery Formation near Ashboro, North Carolina. The mafic igneous activity in North Carolina must have continued until at least ~ 528 Ma, because mafic rocks also intrude units as young as the Yadkin Formation at the top of the Albemarle group (DeDecker and others, 2013). The described data further indicates that the mafic rocks in both North Carolina and in central South Carolina, just east of the central Piedmont shear zone, were chemically similar and formed at approximately the same time.

The southern part of the Winnsboro Mills quadrangle contains a variety of mafic meta-igneous rocks, some or all of which may have the same origin as those just discussed. Shervais and others (1996) analyzed several samples of the Richtex Formation greenstone member from the Irmo Northeast and Chapin quadrangles and found a close chemical similarity to the mafic rocks from central South Carolina studied by Dennis and Shervais (1991). The greenstone member in the Richtex Formation is estimated to have been extruded between ~ 551-535 Ma because it is stratigraphically above the 551 Ma rocks in the Persimmon Fork Formation dated by Barker and others (1998). However, the greenstone is probably stratigraphically below the part of the Richtex Formation containing the youngest 535 Ma zircons dated by Samson and others (2001). This age range also is consistent with the ~ 530-503 Ma-age range of Delmar deformation that deformed the greenstone unit. A similar age is estimated for the meta-diabase sheets that intrude the lower meta-sedimentary member of the Richtex Formation, as well as the intermediate and felsic metatuff member of the Persimmon Fork Formation in the south-central part of the Winnsboro Mills quadrangle. Although additional geochemical and geochronological studies would be desirable, the above comparisons imply that the greenstone unit in the Richtex formation and the mafic rocks adjacent to the central Piedmont shear zone in South Carolina, studied by Dennis and Shervais (1991) and Dennis and Wright (1997), have similar ages and geometry; and may both represent the separation of the Carolina terrane from Gondwana.

A comparison of the Charlotte terrane rocks from the northern part of the Winnsboro Mills quadrangle, that contain some variably deformed meta-gabbro sheets and plugs, with the Charlotte terrane rocks near the central Piedmont shear zone, that contain the mafic rocks studied by Dennis and Shervais (1991), and Dennis and Wright (1997), brings to light age differences. As noted in the Winnsboro Mills quadrangle, the Carolina and Charlotte terranes are juxtaposed by the Chappells shear zone, and the nearby Longtown meta-granite acts as a stitching pluton between the two terranes. The ~ 551 Ma emplacement age of the Longtown meta-granite must indicate that most or all of the motion along the Chappells shear zone took place prior to 551 Ma. In that relict boudins of meta-gabbro from the Charlotte terrane have been recognized in the Chappells shear zone, it seems that at least some of the meta-gabbro is older than ~ 551 Ma. However, this age is within the limits determined by Dennis and Wright (1997). Here also, additional studies need to be undertaken on the mafic rocks in Charlotte terrane in the Winnsboro Mills quadrangle to determine if a single mafic suite is present in all of the regions discussed, and if the suite is clearly indicative of the opening of the Rheic ocean.

COLLISION WITH THE SILVERSTREET TERRANE

As well as possibly containing stratigraphic evidence of the departure of the Carolina terrane from Gondwana, the Richtex Formation also contains a full suite of Delmar fabric elements. If true, Delmar deformation must have developed after from Gondwana, which negates Delmar was the result of collision with Gondwana. The Silverstreet terrane may furnish an explanation.

The Silverstreet terrane is located west and northwest of the Richtex and Irmo Northeast quadrangles and extends northeastward from the vicinity of Silverstreet to the Maybinton area, which was originally considered to be in the middle of the Charlotte terrane (Figure 5). The Silverstreet terrane was defined (Hibbard and others, 2002; Shervais and others, 2003; Dennis and others, 2012) to contain a tract characterized by strongly deformed to mylonitic felsic and mafic gneisses, as well as relict boudins of garnet amphibolites. The boudins can be up to a few meters in diameter, are coarser grained, and apparently much less strongly deformed than the enclosing felsic gneisses. The chemical and petrographic characteristics of the garnet amphibolite boudins provide clues concerning their origin. The boudins have symplectic texture that indicates chemical disequilibrium during rapid changes in P-T conditions from eclogite facies, to granulite facies, and then to middle amphibolite facies (Shervais and others, 2003). The only place in the earth's lithosphere where an equilibrium assemblage of middle eclogite facies minerals can form is in the descending slab of a subduction zone, that was moving rapidly enough to substantially depress isothermal surfaces. The only way that eclogite facies mineral assemblages, or symplectic textures implying the former presence of eclogite assemblages can be preserved and returned to the earth's surface is by rapid exhumation which greatly retards the rate of thermal recrystallization. This requirement implies collision of two sialic plates followed by break-off and sinking of the mafic part of the descending plate and consequent rapid isostatic return of the sialic part of the formerly descending plate out of the subduction channel to the earth's surface. The mafic boudins in the Silverstreet terrane are thought to be fragments of former mafic dikes that were first converted to eclogite in the rapidly descending slab and then, after break-off, were brought back to the surface at plate tectonic rates in the return flow (Shervais and others, 2003). The 501-530 Ma Delmar deformation event in the Carolina Terrane (Figure 10) may be a consequence of a mid-ocean collision between the Carolina and the Silverstreet terranes as described.

ACCRETION TO LAURENTIA

A possible Alleghanian age for the accretion of the Carolina terrane to Laurentia was suggested by Barker and others (1998), West (1998), and Secor and Snoke (2002, 2004) because of the apparent absence in the southeastern Piedmont of deformational events that might indicate an earlier linkage between the Carolina terrane and Laurentia. Now, with the realization that Clarks Hill is not Alleghanian; but instead is constrained to the period 503-415 Ma, it seems that such a linkage may have been found. These data support the suggestion of Hibbard (2000) and Hibbard and others (2012, 2013) that both the Tuscarora unconformity in the Appalachian Valley and Ridge Province and also a suite of structures (the Cherokee orogeny) in central North Carolina may record the initial accretion of the Carolina terrane to Laurentia. Clarks Hill deformation may be the outboard equivalent of Tuscarora unconformity and Cherokee orogeny. The possible subsequent outboard collision of other terranes during the middle and/or late Paleozoic may have resulted in additional lateral and/or landward motion of the Carolina terrane relative to Laurentia.

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The Haile Gold Mine, South Carolina, USA

James M. Berry[1], Reid M. Mobley[1], Kenneth A. Gillon[1], Gene M. Yogodzinski[2], C. Cole Bates[1]

[1]Oceanagold Exploration, 6988 Snowy Owl Road, Kershaw, South Carolina 29067

[2]Department of Earth and Ocean Sciences, University of South Carolina, 701 Sumter St., EWSC617, Columbia, South Carolina 29209

INTRODUCTION AND REGIONAL SETTING

The Haile property is located 5km northeast of the town of Kershaw in southern Lancaster County. The Haile gold mine was recently acquired by Oceanagold Corporation and is currently under construction. The Ridgeway mine is located 40km southwest of Haile and the Brewer mine is located 16km to the northeast. Both of these mines produced gold during the 1980's and 1990's but are now closed. Gold was discovered in a tributary of the Little Lynches on land belonging to Benjamin Haile II in 1827 (Jack Morris, personal communication). The Haile gold mine had four periods of significant production and is estimated to have produced 360,000 ounces (Speer and Maddry, 1993; Maddry and Kilbey, 1995). The mine produced 85,000 ounces of gold from 1985 to 1992 by open pit, heap leach mining. Romarco Minerals, Inc. acquired the property in 2007, leading to the current operation. The Haile mine is situated within the Carolina terrane (Figure 1), one of several Neoproterozoic to Cambrian age arcs of peri-Gondwanan affinity (i.e., African tectonic plate) that run the length of the Appalachian orogen (Pollock et al., 2015). These fossil arcs, which were accreted to North American in the Paleozoic, are known to host gold mineralization from Georgia to Newfoundland (3,700km). Their complex geologic history has proved challenging to exploration geologists working in the Appalachians. The Carolina terrane, which was formerly referred to as the Carolina slate belt, formed during the late Neoproterozoic to lower Cambrian and is bounded by the Charlotte terrane to the northwest and the Augusta-Dreher Shoals terrane to the southeast. All of these terranes are part of the Carolina superterrane or Carolinia (Hatcher et al., 2007; Hibbard et al., 2007). The Carolina terrane consists of greenschist grade volcanic and volcaniclastic rocks, as well as related intrusives and sedimentary units that accumulated on older arc material or thinned continental crust (Shelley, 1988; Ayuso et al., 2005; Hibbard et al., 2013).

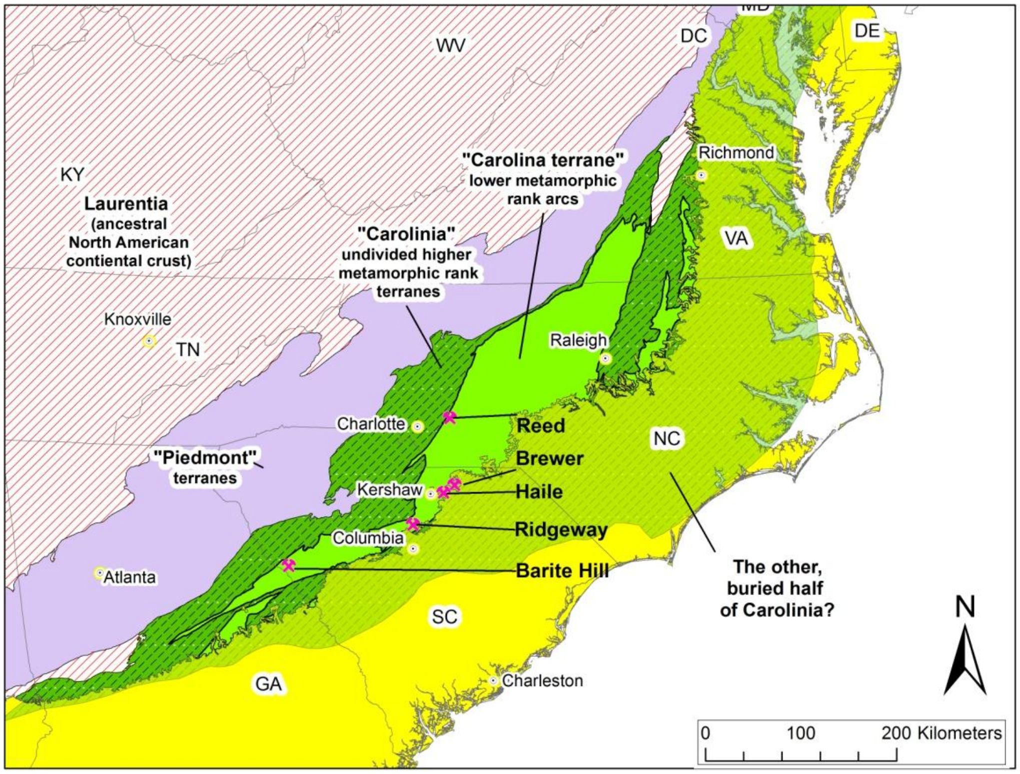

Figure 1: Map of the southeastern US showing major tectonic terranes in this portion of the Appalachians mountain chain orogen. Of the 5 gold mines shown on this map, the Reed mine, NC, was the scene of the first US gold rush in 1799. The only recently active gold mines to operate in the eastern US were Barite Hill, Ridgeway, Haile, and Brewer, all located in the lower metamorphic rank volcanic arc rocks of the Carolina terrane (modified after Hibbard, 2006; Hatcher, et. al., 2007; and HGM's own in-house mapping and compilation).

MINE AREA GEOLOGY

The Neoproterozoic units exposed in the mine area consist of metamorphosed crystal bearing felsic volcanics and possibly shallow level intrusives, lapilli bearing volcaniclastics, transitional coarse grained epiclastics, greywackes, mudstones and thinly bedded siltstones. The volcanic-rock dominated sequence is known as the Persimmon Fork Formation and the sedimentary sequence is the Richtex Formation (Secor et al., 1983). The Persimmon Fork Formation consists of felsic to intermediate volcanic and volcaniclastic rocks that are rhyodacitic to andesitic in composition. The unit is typically buff, gray or green in color and is distinctive due to the lack of bedding and the presence of feldspar crystals o lapilli as shown in Figure 2a. The unit contains albite, quartz, white mica, biotite, chlorite and epidote. Overprinting of primary textures by alteration, metamorphism and weathering has made interpretation of the original lithologies difficult, but pyroclasitc deposits and reworked epiclastic units, combined with, lava flows and shallow intrusives were likely the original rock types. Uranium-lead weighted ages for zircons from the Persimmon Fork Fm. have yielded crystallization ages of 553$\pm$2 Ma (Ayuso et al., 2005). Detrital grains of zircon from the Richtex sediments from drill core beneath the metavolcanic rocks have yielded an age of 518 Ma (Mobley et al. 2014), or lower Cambrian age. The younger age of the zircons in the metasediments located beneath older metavolcanics indicates the stratigraphic section at Haile is overturned.The Richtex Formation, which is the primary host of hydrothermal alteration and gold mineralization, is characterized by thin, alternating rhythmic bands of clay, silt and sand. The unmineralized Richtex is composed of quartz, white mica, feldspar, chlorite and calcite (see Figure 2b). Late, unfoliated biotite phenocrysts are occasionally present and have been dated by $^{40}Ar/^{39}Ar$ techniques. One sample yielded a plateau age of 390$\pm$1 Ma and another sample yielded a total fusion age of 388±1 Ma (Mobley et al. 2014). These ages may represent a Devonian metamorphic event or may reflect a non-geologic age due to slow cooling or local thermal disturbance. Fine grained garnets are also rarely present within the Richtex. Beds of greywacke, sandstone and conglomerate are found within the Richtex Fm. containing clasts of volcanic rock or siltstone. The coarser clastic units are poorly sorted and contacts with the volcanic Persimmon Fork are usually gradational but can locally be sharp.

thinner dikes. The diabase dikes are related to the breakup of Pangea during the Mesozoic. Less common in the mine are narrower (<2m in wide) alkaline dikes. These contain medium to fine grained biotite, plagioclase, chlorite, carbonate and clay that vary in texture from porphyritic, mottled to spheroidal. Some of the alkaline dikes contain distinctive biotite phenocrysts, are lamprophyric in composition and yield weighted plateau $^{40}Ar/^{39}Ar$ ages of 311.0±1.5 Ma and 311.3±3 Ma (Mobley et al., 2014) These ages suggest they are to other Alleghanian-age plutons that are found in the region.

Figure 2: Photographs of core samples collected from the Persimmon Fork (upper panel A) and Richtex (lower panel B) formations at the Haile Gold Mine. The Richtex formation host gold mineralization at the Haile deposit. Pictured in the lower panel B is an unmineralized form of thes Richtex Formation.

The Persimmon Fork and Richtex formations are cut by northwest trending, magnetic, diabasic dikes that vary in thickness from a few centimeters to 40m in thickness. Locally, as observed in core, the contacts also parallel the northeast-striking foliation and the dikes are present as single dikes or in dike swarms. Gold mineralization appears to have not been offset by the dikes, although displacement remains a possibility. The dikes are typically coarse grained, but exhibit finer-grained textures where occurring as

The pre-Cretaceous units have been highly weathered producing regionally extensive saprolite above the bedrock. The weathering front is transitional and the oxide – sulfide boundary does not always correspond to the clay alteration boundary. A southeastward-thickening wedge of poorly consolidated Coastal Plain sediments unconformably overlies the saprolite and weathered basement rocks, and consists of poorly sorted gravels, sands, and clays. The Coastal Plain sediments have been eroded away in the larger drainages but are up to 23m thick in the upper elevated areas of the mine area.

The Persimmon Fork and Richtex formations are deformed and metamorphosed to greenschist conditions. The units contain faint to well-developed foliation, tight to isoclinal folding and local shearing. The foliation tends to be better developed in more micaceous units such as the well bedded phyllites. More massive units such as the Persimmon Fork and well mineralized Richtex are less foliated but micas within them are generally aligned. The foliation as mapped in the area and taken from oriented drill core generally strikes east to northeast and dips moderately to the north or northwest. Bedding is more variably oriented but commonly strikes east-northeast and dips to the north-northwest. Tight toisoclinal folds are present at the thin section, outcrop and map scale. Most of the mapped fold axes have shallow to moderate plunges towards the northeast or north. Many of the folds are asymmetric with moderately dipping northwest limbs and steep to overturned southeastern limbs. Shear textures have been observed in outcrop, drill core and thin section and they may be present at map scale. Observed shear textures include pressure shadows, passive slip planes, ribbon quartz along slip planes, mica fish and anastomosing foliation surfaces. These features indicate ductile shearing but only minor offsets have been observed to date. Brittle offsets are present in the folded units and are generally parallel to the axial planar foliation. Large scale offsets along the brittle or ductile zones have yet to be identified. Lithologic contacts from drilling and mapping indicate the deposit is situated within an antiform that plunges shallowly to the northeast (see Figure 3). The general pattern is possibly complicated by lateral facies changes and interbedding of lithologies. The 3D model integration of stratigraphic and structural data obtained from logging of drill core as well as the recent zircon ages (Mobley, et al., 2014) indicates an overturned and refolded isoclinals fold. Thrust faulting and latter folding could also generate this configuration, although southeast verging thrusts have yet to be identified and gradational contacts imply an absence of thrust faults. To date, major shear offsets and large scale shear zones have not been noted.

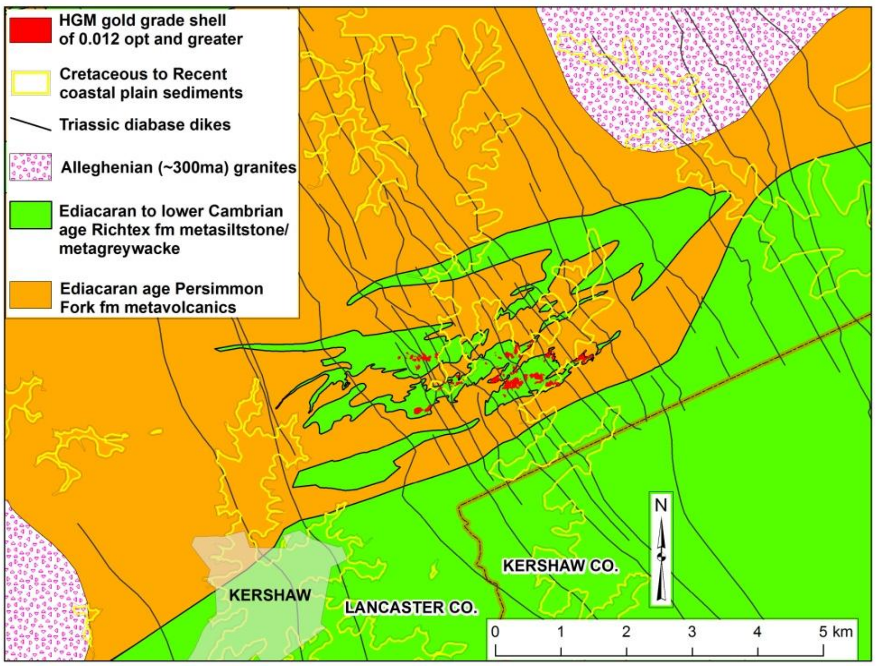

Figure 3: Geologic map of the Haile mine area that shows some of the detailed relationships in the rock units of this portion of the Carolina terrane, as well as drilled concentrations of gold mineralization.

MINERALIZATION

Gold mineralization at the Haile property occurs along a trend of moderately to steeply-dipping ore bodies within a 3.4km long and 1km wide corridor which runs from the west-southwest (WSW) to the east-northeast (ENE). Gold bearing zones, which are restricted to the laminated metasiltstone of the Richtex formation, have variable dips across the deposit and can be as thick as 150m. The mineralization within the laminated metasediments can vary in distance from the metavolcanic contact and can be at different stratigraphic levels. The gold mineralization is disseminated and occurs in silica-rich, pyrite-pyrrhotite bearing metasediments. Alteration in the mineralized zones consists of intense quartz-pyrite-sericite with occasional potassium feldspar, that grades outward to weak quartz-sericite-pyrite. The unaltered metasediments consist of pyrite bearing, sericite-quartz-chlorite-carbonate phyllites. Within the mineralized zones, quartz is dominant (greater than 80 percent), pyrite is subordinate (generally 3 to 10 percent), and sericite is variable. Moving away from the center of a mineralized zone, quartz and pyrite decrease while sericite increases in abundance. Massive sulfide lenses consisting of pyrite are occasionally present and gold grades do not always correlate with the amount of pyrite. Multiple silicification events have occurred in the mineralized zones where the earliest silicification is massive and penetrative, and later silicification appears as re-healed broken angular rock fragments (breccias) followed by a scattered wormy stringer veinlet phase. Quartz veins are present within the mineralized and unmineralized portions of the deposit. Quartz veins are rarely mineralized but notable exceptions do exist. Higher gold grades are generally associated with the hydrothermal breccia zones and examples of themineralization are shown in Figure 4.

Gold mineralization is associated with pyrite, pyrrhotite, and molybdenite mineralization. Detailed ore microscopy and scanning electron microscope mapping indicate that the gold is found as native gold, electrum, and within gold bearing tellurides (Honea, 1990 and Thompson, 2009). These minerals are found as inclusions and along fractures within pyrite. The pyrite is usually present as either disseminated euhedral to subhedral grains or as euhedral to subhedral aggregates. The pyrrhotite usually occurs as medium grained anhedral lenses that are often aligned with the foliation. Arsenopyrite, chalcopyrite, galena, and sphalerite are also associated with the mineralization. Molybdenite occurs either on foliation surfaces or as dispersed fine-grained aggregates in silicified zones. The Haile molybdenite was initially dated by Re-Os isotopes at 553.8 $\pm$ 9 and 586.6 $\pm$ 3.6 Ma (Stein et al., 1997). The first Re-Os age closely approximates the zircon crystallization age of 553 $\pm$ 2 Ma reported by Ayuso et al. (2005) indicating that molybdenite mineralization was concurrent with Persimmon Fork volcanism. Seven recent Re-Os molybdenite ages from Haile (Mobley et al., 2014) yield ages ranging from 529 to 564 Ma. Four of these samples yield a

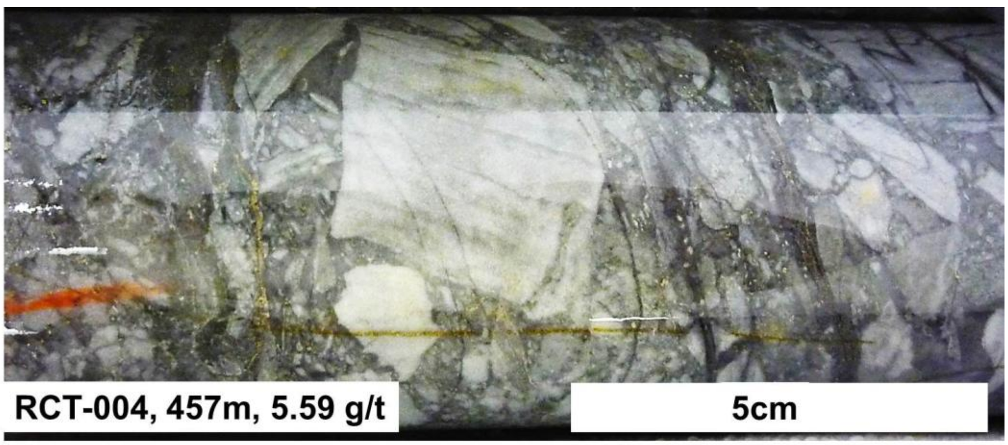

Figure 4: A hydrothermal breccia containing clasts of mineralized sediments

proper isochron that gives a weighted age of 548.7 ± 2 Ma, indicating that the gold mineralization is closely linked to the Neoproterozoic volcanism.

CONCLUSION

Genesis of the Haile deposit has been assigned to sedimentary, seafloor exhalative (Spence et al., 1980; Kiff and Spence, 1987; Feiss et al., 1993; Foley et al, 2001), structurally controlled shear hosted orogenic (Tomkinson, 1988), orogenic fold controlled (Hayward 1992), and syntectonic-epithermal (Gillon and Duckett, 1988) processes. Factors such as post-mineralization deformation, extensive surface weathering and poor exposures have led to these diverse interpretations. The hydrothermal breccia textures, alteration fronts cross-cutting bedding and sulfide-quartz veinlets indicate that the mineralization post-dates deposition. Folded mineralized veins, pressure shadows around pyrite grains and the recent molybdenite ages (Mobley et al., 2014) support pre-deformational mineralization. Although the timing and association of mineralization indicate an epithermal deposit, Haile does not exhibit characteristics of classic low-sulfidation or high-sulfidation deposits as proposed by White and Hedenquist (1990). The majority of the ore at Haile is disseminated, indicating a high-sulphidation style whereas the presence of k-spar indicates a low-sulfidation system. The absence of pyrophyllite and alunite at Haile support a low-sulfidation deposit although these are found at the nearby Brewer mine. Enrichment of Mo and Te indicate a high-sulfidation system. Haile also lacks the high Ag/Au ratios common in low-sulfidation systems. Haile is not enriched in Cu, common for high-sulfidation systems.

CURRENT MINING

In November 2014, an updated feasibility study (Snider et al., 2014) for the Haile was completed after receiving the necessary permits for the project. The mine is currently under construction and pre-production has started at the Mill zone pit. The completion of the mill and the first gold pour is scheduled to be during the fourth quarter of 2016. The proposed mine consists of 8 open pits that will mine sulfide ore to be processed in a 6,350 metric tonnes per day mill. The mine and mill layout is shown in Figure 5. The mill is designed to crush and grind the ore. The ground ore will then pass through a flotation circuit to remove the pyrite. Subsequently, the pyrite will be finely ground to 13 microns. Both the finely ground and primary ground material will run through a carbon in leach circuit that utilizes a weak cyanide solution to extract the gold. The precious metals will be removed from the loaded solution by electrowinning. Gold and silver dore will be the final plant product. A cyanide destruction circuit is located at the mill in order to keep cyanide levels at the tailings storage facility below those considered harmful to wildlife. The mine tailings will be stored in a facility that is north of the mine site. The composite lined (low permeability soil and 60-mil high density polyethelyne) tailings facility is designed to withstand a probable maximum precipitation event of 1.2m, a hurricane, and a 7.38 magnitude earthquake simultaneously. The mine is projected to produce 1,681,500 ounces of gold over a 14 year mine life.

The deposit will be mined by conventional open pit methods. The mining process will consist of blasting, loading, and hauling. Mining of 6m benches will be done in order to minimize dilution of the ore. Blast holes will be sampled for gold, total sulfur and total carbon. This information will be used to route material to the mill, to facilities designed for storage of potentially acid generating (PAG) overburden, for pit backfill, or to non-PAG overburden stockpiles. The deepest pit will extend to 262m below the current surface. The overall pit slopes will vary from 27 to 49 degrees and have been designed to account for material competency and fracture orientations. The north side of the pits will have steeper walls where foliation dips into the pit wall whereas the pit slopes on the south walls will dip with the foliation in order to prevent undercutting the slope toe (Golder report, 2010). Annual higher-grade ore production from the mine is 2.3 million tonnes and total material moved averages 57,000 tonnes per day. An estimated 4.4 million tonnes of lower grade material will be stockpiled from pre-production through year 7 that will be processed at the end of the mine life. The overall ratio of overburden to ore is 7.2 to 1.

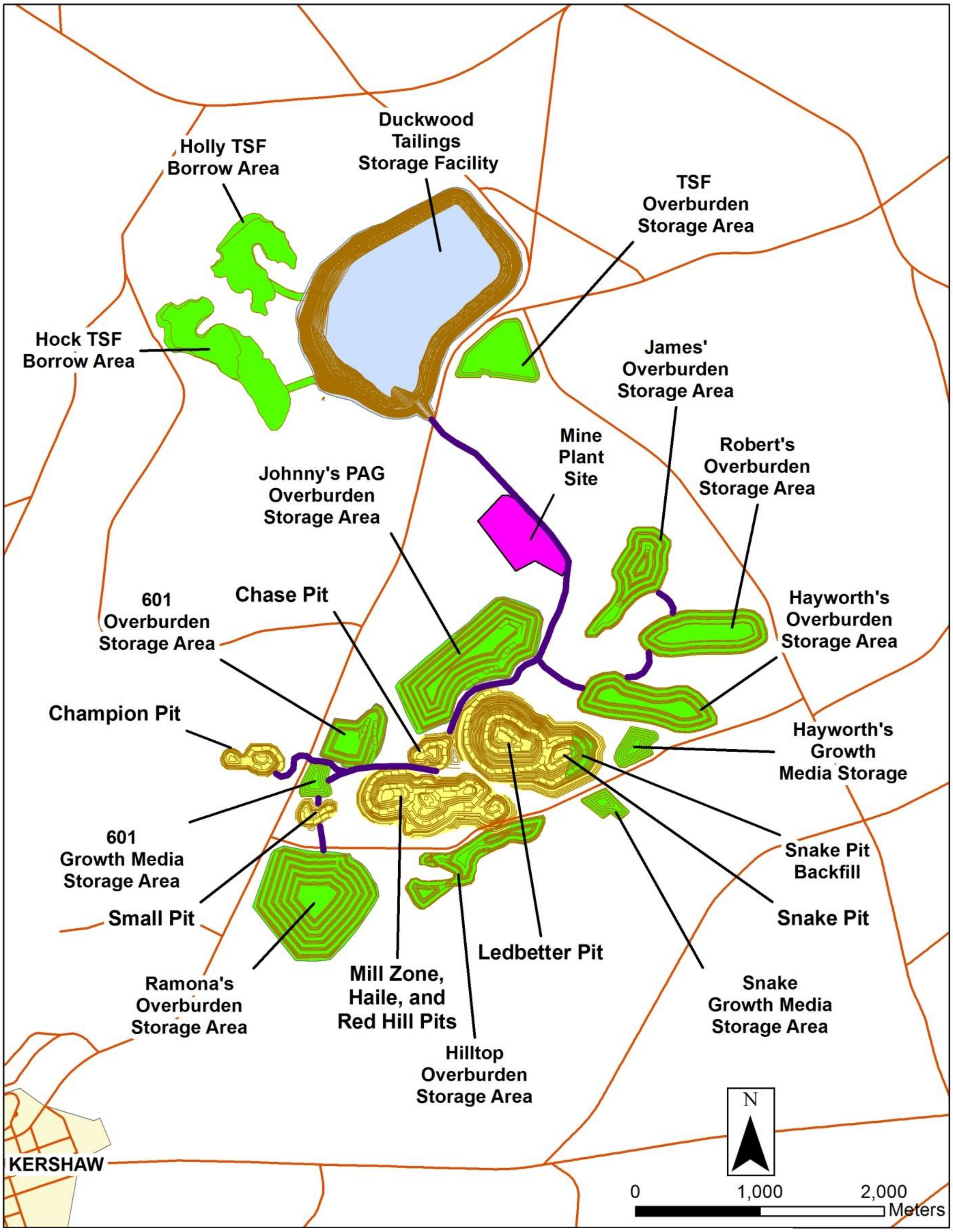

Figure 5: Haile Gold Mine general layout

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An Introduction to Lake Murray Spillway

Modified from Secor and Snoke, 2004

The Spillway to Lake Murray is by far the most spectacular rock exposure in central South Carolina. It is an emergency overflow channel for Lake Murray that was excavated in the early 20^{th} century. It has been an important stop location for many field trips, both formal and informal. The results of early research on Spillway geology were summarized in Secor and Snoke (1978). During the last twenty-five years, several additional important investigations have been made. Recently, the stability of the old Dreher Shoals earth-fill dam in response to seismic shaking was questioned, and as a result, a major construction project to strengthen the dam was undertaken. During this construction, an extensive excavation was made down to fresh bedrock on the downstream side of the old earth fill dam revealing a plethora of Irmo structures and later brittle structures.

At the east end of Lake Murray, the Modoc shear zone has been folded about the nose of a major northeast plunging antiform (the Irmo antiform). The Spillway is located in the southeast limb of this antiform. Two major map-scale rock units are present in the Spillway. The oldest is a heterogeneous assemblage of schist (Figure 1), paragneiss (Figure 2), quartzite, and amphibolite (Figure 3). The youngest is the Lake Murray orthogneiss (Figure 4), which is interpreted from contact relations. Figure 5 shows enclaves of the gneiss enveloped by pelitic schist which are interpreted as xenoliths.

Both of these units contain a strong deformation fabric (Lake Murray) that may deform one or two tight to isoclinal fold phases. Finally, there is a younger deformation (Irmo) with dextral structures (folds, duplex systems, rotated tension gashes). The dextral folds mostly plunge steeply north-northeast. Both of the above map-scale units are cut by a variety of dikes, some that predate most or all of the deformation, others that are metamorphosed but only weakly deformed, and some that are unmetamorphosed and likely emplaced in the Mesozoic.

Dallmeyer and others (1986) conducted $^{40}Ar/^{39}Ar$ studies of hornblende and biotite from metamorphic rock samples collected in the Irmo antiform and yielded plateau ages that represented cooling during 275 to 300 Ma following a late Paleozoic (Alleghanian) thermal event. Snoke and Frost (1990) conducted a petrologic study of the schist, paragneiss quartzite, and amphibolite sequence and concluded that the mineral assemblage (quartz-plagioclase-muscovite-biotite-garnet-kyanite-staurolite-rutile-ilmenite) formed at a temperature of 645°C to 695°C and at a pressure of 7.2 to 8.2 kb. They suggested that the rocks in the Irmo antiform must be separated from those in the nearby Carolina terrane by a major crustal detachment fault (extending around the nose of the antiform), because a nearby Alleghanian pluton (Harbison) in the Carolina terrane was emplaced at much lower pressures (Vyhnal and McSween, 1990). Samson and Secor (2000) determined a U-Pb zircon age of 421 +4/-2.9 Ma (Late Silurian or Early Devonian) for the Lake Murray orthogneiss. The above geochronological data constrain the age of the deformation and peak metamorphism in the Spillway to be more recent than ~420 Ma and earlier than ~300 Ma. The unique lithology and metamorphism of the rocks in the Spillway has been interpreted to represent a small terrane (the Dreher Shoals terrane) that may be exotic relative to the nearby Carolina and Savannah River terranes (Hibbard and others, 2002). However, the fabric elements in the Spillway are geometrically similar to those found elsewhere in the Modoc shear zone, and if the Dreher Shoals terrane is a separate entity, it is entirely contained in the Alleghanian Modoc shear zone and is overprinted by Alleghanian deformation fabrics.

Figure 1. Pelitic schist in Lake Murray Spillway.

Figure 2. Paragneiss with isoclinal quartzite layers.

Figure 3. Folded amphibolite in pelitic matrix.

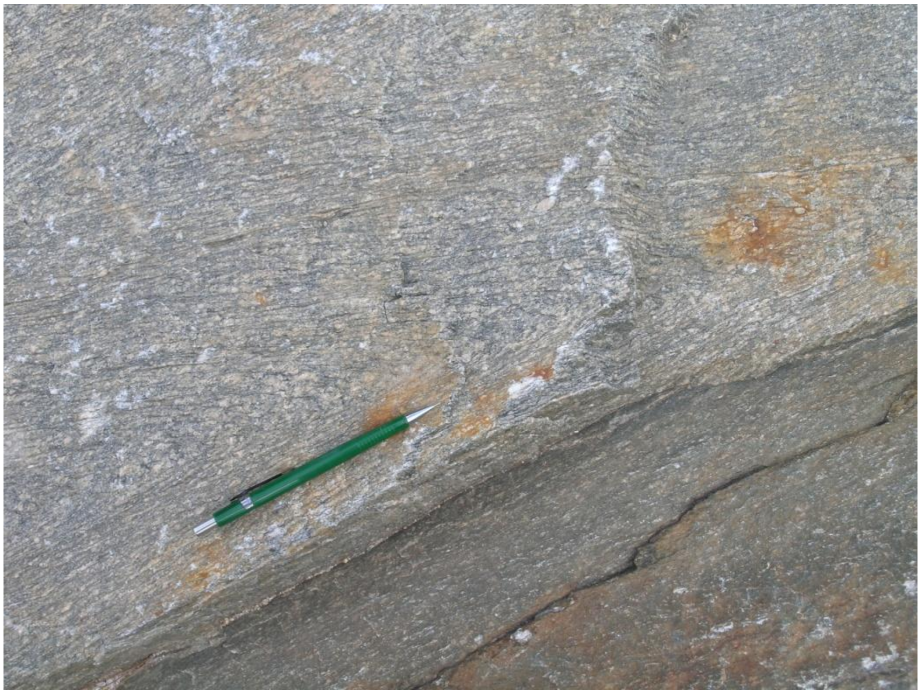

Figure 4. Lake Murray orthogneiss. Mylonitic foliation parallel to pencil.

Figure 5. Enclaves of Lake Murray orthogneiss in pelitic schist.

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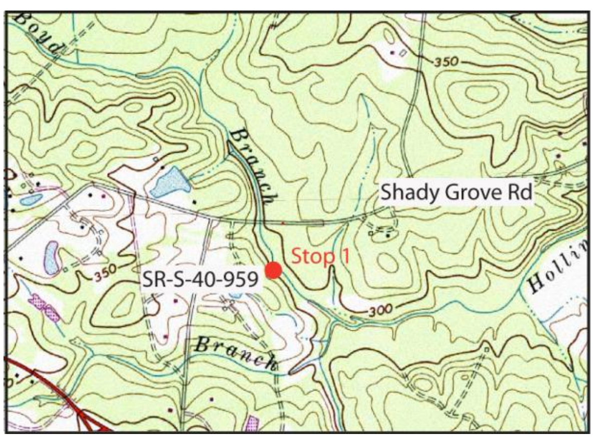
SATURDAY, OCTOBER 24, 2015

START: Embassy Suites
200 Stoneridge Dr, Columbia, SC 29210

1. Turn right out of the hotel parking lot onto Stoneridge Dr toward Greystone Blvd. (0.05 mi)
2. Turn right onto Greystone Blvd. (0.08 mi)
3. Merge onto US-76 W toward Spartanburg. (8.3 mi)
4. Stay straight on I-26 W/James F Byrnes Expy W. (4.7 mi)
5. Take the US-176 exit, EXIT 97, toward Peak. (0.2 mi)
6. Turn right onto Julius Richardson Rd. (0.6 mi)
7. Turn right onto W Shady Grove Rd. (0.2 mi)

Park along the left side of the road. Outcrop is exposed in the Creek along the sewer line.

STOP 1: Crystal-Lapilli Tuff
Persimmon Fork Formation
Shady Grove Road, Irmo, SC
Richtex 7.5' Quadrangle
(34.15314 N, 81.23172 W)



Our field excursion begins at the volcanic base of the Carolina terrane in South Carolina, the Persimmon Fork Formation (Fig. 1). The rocks here comprise the upper portion of the Persimmon Fork Formation and are classified as metamorphosed quartz and plagioclase porphyritic crystal-lapilli tuff. The volcanic character of the protolith is determined on the basis of relict phenocrysts, pumice lapilli, and other lithic fragments (Fig. 2).

Persimmon Fork rocks are variably subaerially and subqueously deposited, intermediate to felsic, ash and pyroclastic flow tuffs. They locally contain epiclastic sequences of conglomerate, diamictite, and volcanic wacke.

Available U-Pb zircon analyses indicate an age of approximately 552 Ma for Persimmon Fork volcanism (Dallmeyer and others, 1986; Barker and others, 1998; Mobley and others, 2014).

Figure 1. The Persimmon Fork Formation is an interlayered sequence of intermediate to felsic ash-flow tuffs. Hammer is 43 cm in length.

The original thickness of the Persimmon Fork Formation is uncertain because of successive deformation, but likely was on the order of several kilometers. The phyllitic cleavage and greenschist facies mineral assemblage in this outcrop are the result of Delmar deformation and metamorphism (~530–503 Ma). At this outcrop, note that the lapilli are flattened into the plane of the phyllitic cleavage.

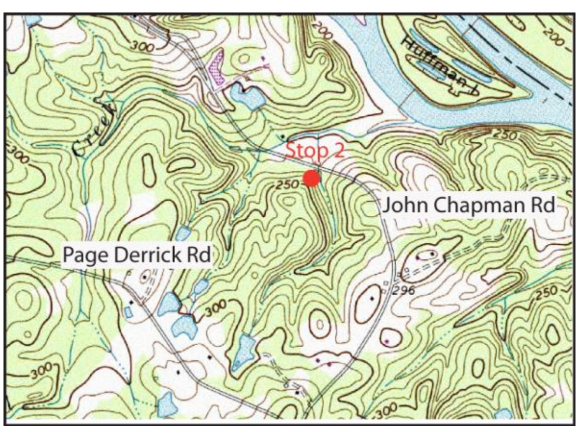
Figure 2. Flattened lapilli (L) in the crystal-lapilli tuffs range from mm to several cm in diameter. Magnet is 12 cm in length.

To Stop 2:

1. Continue west on Shady Grove Rd. (1.0 mi)
2. Turn right onto Broad River Rd/US-176 W. (0.9 mi)
3. Take the 3rd right onto Hopewell Church Rd. (1.0 mi)
4. Turn right onto Kennerly Rd. (2.2 mi)
5. Turn left onto Page Derrick Rd. (0.2 mi)
6. Turn slight right onto John Chapman Rd. (0.8mi)

Park on the right side of the road. Outcrops are on both sides of the road.

<u>STOP 2:</u> Metasiltstone
Richtex Formation
John Chapman Road, Irmo, SC
Richtex 7.5' Quadrangle
(34.18333 N, 81.20989 W)



The Richtex Formation conformably overlies the Persimmon Fork volcanic rocks. The outcrop along John Chapman Road consists of thinly-layered, locally phyllitic, quartz metasiltstone and constitutes the upper member of the Richtex Formation (Fig. 3). It was deposited as a thinly bedded sequence of graded siltstone and mudstone.

Figure 3. The upper member of the Richtex Formation is a quartz-rich metasiltstone. Magnet is 12 cm in length.

Individual beds of siltstone are laterally continuous, and are typically 1 to 10 mm thick. Bedsets of metasiltstone are sparsely interlayered with thickly bedded, graded wacke. On the basis of available relict sedimentary structures (i.e. graded bedding and cross stratification) these rocks are interpreted to represent a distal turbidite sequence deposited in relatively quiet water. Occasional episodes of rapid flow are presumed responsible for the emplacement of coarse-grained, graded wacke beds. A minimum age of 535 Ma is reported for the upper member of the Richtex Formation (Samson and others, 2001).

At this locality, Delmar deformation and metamorphism produce a phyllitic cleavage and a greenschist facies mineral assemblage in the metasiltstone. Regionally, the Richtex Formation contains a second, later Clarks Hill (~503–415 Ma) cleavage and a Delmar x Clarks Hill intersection lineation; however, these fabric elements have not been recognized here.

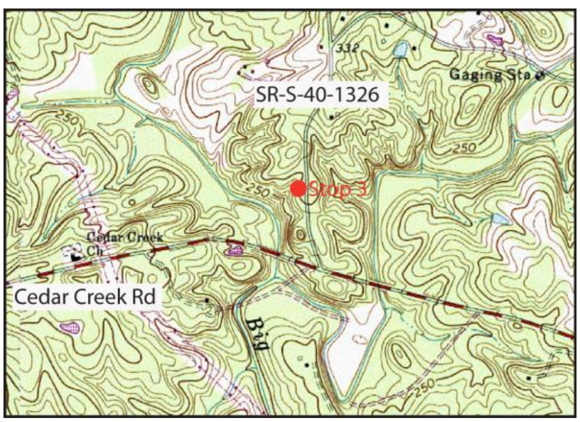
To Stop 3:

1. Start out going west on John Chapman Rd toward Watersong Ln. (1.4 mi)
2. Turn slight left onto Freshly Mill Rd. (1.3 mi)
3. Turn right onto Kennerly Rd. (2.5 mi)
4. Turn left onto Freshly Mill Rd. (0.06 mi)

5. Take the 1st right onto Broad River Rd/US-176 W. (4.4 mi)
6. Turn slight right onto R Stoudemayer Rd. (1.8 mi)
7. R Stoudemayer Rd becomes Church St. (0.08 mi)
8. Turn left onto Peak Byp. (0.3 mi)
9. Turn right onto Mayer Rd. (0.3 mi)
10. Mayer Rd becomes Broad River Rd. (0.5 mi)
11. Turn right onto SC-213/Parr Rd. Continue to follow SC-213. (3.4 mi)
12. Turn right onto Monticello Rd/SC-215. (11.4 mi)
13. Turn left onto Cedar Creek Rd. (1.2 mi)
14. Turn left onto Blume Rd. (0.05 mi)

Park on the side of the road. Outcrops are exposed on both sides of the road.

STOP 3: Phyllonite
Oak Grove Church Transfer Zone
Blume Road, Blythewood, SC
Irmo NE 7.5' Quadrangle
(34.18974 N, 81.11346 W)



The rocks exposed here are the phyllonitic equivalents of the Persimmon Fork, Richtex, and perhaps Emory Formations (Fig. 4). Locally, relict sedimentary and volcanic structures can be documented such that their protoliths are identifiable. More commonly, lithologic characteristics that define protolith relationships are obliterated by high shear strain and metamorphic recrystallization.

The deformation observed in these rocks is the result of their incorporation into the Oak Grove Church transfer zone, a region of high strain located east of the Oak Grove Church and Cedar Creek shear zones. It appears that during its later stages of development, the Oak Grove Church shear zone became inactive at its northeast end. As deformation progressed, strain accumulated within the transfer zone and displacement was transferred northward to the Cedar Creek shear zone.

Figure 4. Rocks in the Oak Grove Church transfer zone consist of phyllonitic equivalents of the Richtex, Persimmon Fork, and/or Emory Formations. Hammer is 43 cm in length.

Dextral shear sense indicators, such as asymmetric folds and porphyroclasts, have been identified in both the Oak Church Grove and Cedar Creek shear zones.

The preponderance of dextral shear sense indicators and the map pattern of shear zones suggest they are part of a macroscale dextral strike-slip duplex structure formed during Irmo deformation (See Fig. 6 of Secor, this guidebook). This outcrop displays parasitic folds and mesoscale faults, but no readily identifiable dextral shear sense indicators (Fig. 5).

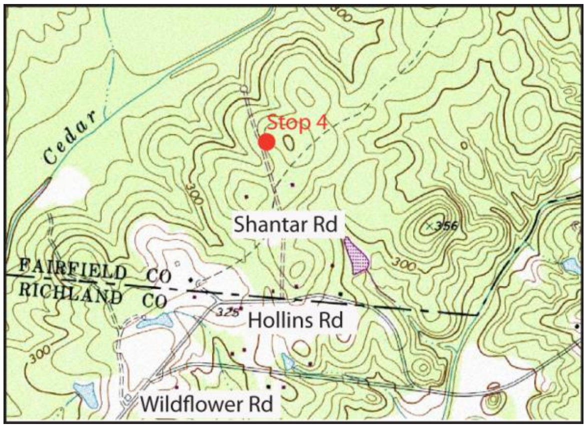
Figure 5. Parasitic folding of phyllonitic foliation within the Oak Grove Church transfer zone. Penny is 19 mm in diameter.

To Stop 4:

1. Continue north on Blume Rd toward Jordan Rd. (0.7 mi)
2. Blume Rd becomes Wildflower Rd. (0.9 mi)
3. Stay straight onto Hollins Rd. (0.3 mi)
4. Left on Shantar Rd. (0.2 mi)

Park along the side of the road. Outcrop is exposed in road cuts on both sides of the road and as float boulders in the woods.

STOP 4: Greenstone sequence
Richtex Formation
Shantar Road, Blythewood, SC
Irmo NE 7.5' Quadrangle
(34.21792 N, 81.10463 W)



The greenstone member of the Richtex Formation is thought to be the result of a periodic influx of mafic subaqueous (?) amygdaloidal lava flows and mafic turbiditic(?) tuffs and wacke (Fig. 6). These volcanic and volcanogenic sedimentary rocks are interpreted to have been deposited in an environment similar to that of the overlying and underlying siltstones and mudstones. Regional greenschist facies metamorphism produced a mineral assemblage containing quartz, albite, epidote, chlorite, actinolite, white mica, and opaque minerals.

Figure 6. Greenstone member of the Richtex Formation containing quartz amygdules (?). Penny is 19 cm in diameter.

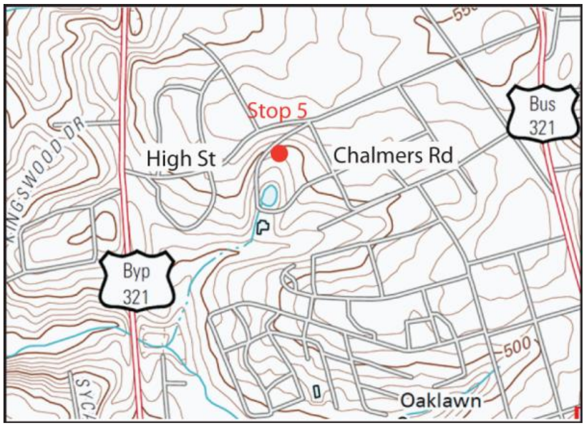
In this outcrop, the greenstone develops a Delmar disjunctive cleavage. Locally, the Delmar fabric is crosscut by a later Clarks Hill disjunctive cleavage, producing a Delmar x Clarks Hill intersection lineation.

Intrusive and extrusive mafic rocks have been identified in other parts of the Carolina terrane in North and South Carolina, and are interpreted to mark the departure of the Carolina terrane from Gondwana (Hibbard and others, 2013; Dennis and others, 2014). Although absolute age dating has not been completed on the greenstone, the ages of the overlying Richtex and underlying Persimmon Fork Formations suggest that their emplacement occurs between 552–535 Ma. These age relationships are correlative with mafic magmatism in other portions of the terrane (Dallmeyer and others, 1986; Barker and others, 1998; Samson and others, 2001; Hibbard and others, 2013; Dennis and others, 2014; Mobley and others, 2014).

To Stop 5:

1. Turn around at the cul-de-sac and go south on Shantar Rd. (0.6 mi)
2. Left on Hollins Rd. (0.5 mi)
3. Turn slight left onto Wildflower Rd. (2.0 mi)
4. Turn left onto Winnsboro Rd/US-321 N. Continue to follow US-321 N. (12.1 mi)
5. Turn right onto W High St. (0.4 mi)
6. Turn right onto Park St. (0.1 mi)
7. Turn right onto Chalmers St. (0.2 mi)
8. End at Gazebo.

<u>STOP 5:</u> Haile Gold Mine Core and Poster Presentation and Lunch
Park Woods Recreation Facility
Winnsboro, SC
Winnsboro Mills 7.5' Quadrangle
(34.38566 N, 81.09680 W)



The purpose for this stop is to provide an overview of the lithology, structure, and gold mineralization at the Haile gold mine located in Lancaster County, SC. The stop will also provide an overview of the current construction at Haile and a description of the proposed project. In addition to a poster summarizing the deposit and mine, core from three drill holes (DDH-334, DDH-379 and RCT-0199) will be available for viewing (Fig. 7). DDH-334 is located at the central Ledbetter deposit and DDH-379 is located at the eastern Horseshoe deposit. RCT-0199 is from the deeper Palomino deposit. Drill core is placed in the boxes for transport, logging and storage (Fig. 8).

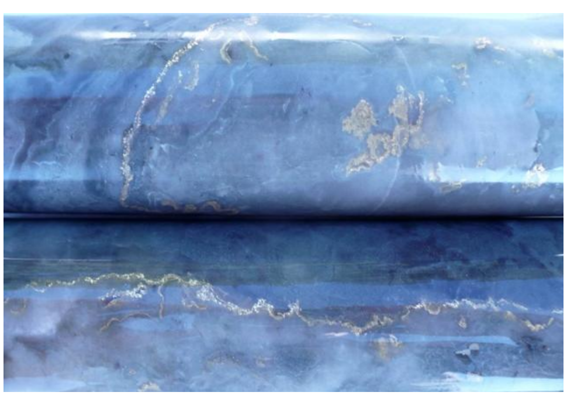


Figure 7. Gold core from the Haile Gold mine will be available to view at Stop 5. Gold at the Haile mine is found in quartz veins, brecciated zones, and is disseminated in pyrite/pyrrotite rich horizons (Berry and others, this guidebook).

Each 10-foot core box has five, two-foot rows. Within each box, the upper portion of the hole is in the upper left and the lower part is in the lower right. The core is 'read' from left to right down the hole and the core is organized like words in a paragraph. Core chocks show the drill-hole depth in engineering feet (tenths instead of inches). When inspecting the core, please try to place the core back in the correct location of the box if it is removed. A good trick is to place an identifiable object such as a pencil or scale at the location of the piece of core you remove for closer inspection.

Figure 8. Section of core from the Horseshoe deposit, Haile Gold Mine, Lancaster County, SC. Core is "read" from upper left to bottom right.

To Stop 6:

1. Take the 1st right onto Park St. (0.1 mi)
2. Turn left onto W High St. (0.4 mi)
3. Turn left onto US Highway 321 Byp N/US-321 S/SC-34. Continue to follow US-321 S. (6.0 mi)
4. Turn left onto Gumsprings Rd. (0.4 mi)

Park at the sign that reads "End of State Maintenance". Walk to end of the road to view pavement outcrop.

STOP 6: **Simpson metagranite**
Gumsprings Road, Winnsboro, SC
Winnsboro Mills 7.5' Quadrangle
(34.3039 N, 81.0744 W)

Exposed along Gumsprings Road is a pavement outcrop of metamorphosed granite. In the Ridgeway and Longtown Quadrangles, located east of the Winnsboro Mills Quadrangle, Barker and Secor (2005) mapped several variably foliated metagranite plutons in a NE-SW trending belt. The largest of these, the Longtown metagranite, is described as being variably deformed and containing mesoscale and macroscale anastomosing ductile shear zones. These plutons locally contain xenoliths of surrounding wall rock, as well as distinctive clots of fine-grained biotite and chlorite that are interpreted to mark the positions of original biotite and/or amphibole crystals in the magma.

Located at the southwest end of the belt near the village of Simpson, the metagranite exposed here is the largest metagranite pluton in Winnsboro Mills quadrangle, and is referred to as the "Simpson metagranite" (Fig. 9). It intrudes and stitches the mylonitic equivalents of the Persimmon Fork Formation and Charlotte terrane that are deformed within the Chappells shear zone.

It is important to note that the granitic plutons do not exhibit nearly the same intensity of deformation as the rocks they intrude. Comparison of the fabrics in the metagranites with the mylonitic fabrics contained in both xenoliths in the granite and in the wall rocks surrounding the granite led Barker and others (1998) and Barker and Secor (2005) to conclude that the metagranites were emplaced either late synkinematically or post-kinematically with respect to the development of the mylonitic fabric in the surrounding rocks. The relationships described above, together with U-Pb zircon ages for the emplacement of the Persimmon Fork Formation (550.5 ± 5.9 Ma) and the Longtown metagranite (551.2 ± 2.6 Ma) are interpreted to indicate the stitching of the Carolina and Charlotte terranes during Late Proterozoic and/or Early Cambrian Chappells deformation (Barker and others, 1998).

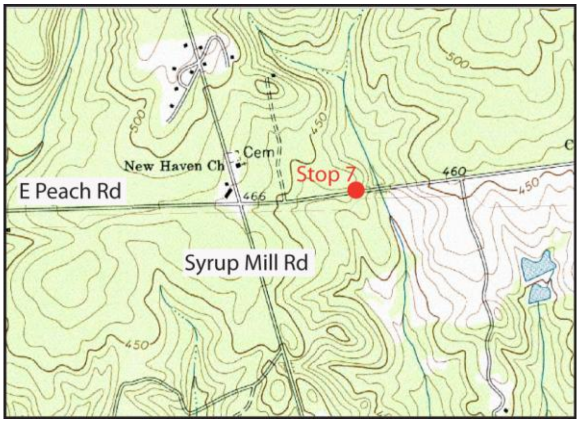
Figure 9. Boulder of metagranite from the Simpson metagranite, the stitching pluton between the Charlotte and Carolina terranes in the Chappells shear zone. Here, the granite is typically equigranular and weakly deformed. Penny is 19 mm in diameter.

To Stop 7:

1. Start out going southwest on Gumsprings Rd toward US Highway 321 S/US-321 S/US-321 N (Portions unpaved). (0.2 mi)
2. Turn left onto US Highway 321 S/US-321 S. (2.1 mi)
3. Turn left onto E Peach Rd. (2.1 mi)

Park at the Sheriff Sub-Station on left. Outcrops exposed along left and right side of E Peach Rd.

<u>STOP 7:</u> Metadiabase
E. Peach Road, Ridgeway, SC
Winnsboro Mills 7.5' Quadrangle
(34.27718 N, 81.03785 W)



The unit exposed here along E. Peach Road, referred to as metadiabase, was originally interpreted as a sequence of mafic metavolcanic flows and/or flow breccias resting with angular unconformity on the underlying Richtex Formation (Fig.10; Barker and Secor, 2005). Later, it became apparent that this unit more likely represents a series of dikes that served as feeders to coeval mafic lava flows in the greenstone member of the Richtex Formation (Stop 4).

Although the southern border of the large east-west trending metadiabase superficially resembles an angular unconformity between the metadiabase and underlying rocks, the field relationships can be equally well interpreted as an intrusive contact (See map in this guidebook). The presence of several small, scattered dikelets of metadiabase are significant features that support the intrusive hypothesis and are difficult to incorporate in the angular unconformity hypothesis.

Furthermore, the apparent absence of relict amygdaloidal texture in the metadiabase suggests an origin in a pressurized magma chamber rather than in a surficial lava flow. The absence of both stratification and interlayered metasedimentary sequences in the metadiabase also support the intrusive hypothesis.

The diabase has been metamorphosed to the greenschist and lower amphibolites facies, and is predominantly overprinted by a Delmar disjunctive cleavage. Locally, a Clarks Hill disjunctive cleavage develops in the metadiabase, crosscutting the earlier planar fabric elements and producing a Delmar x Clarks Hill intersection lineation.

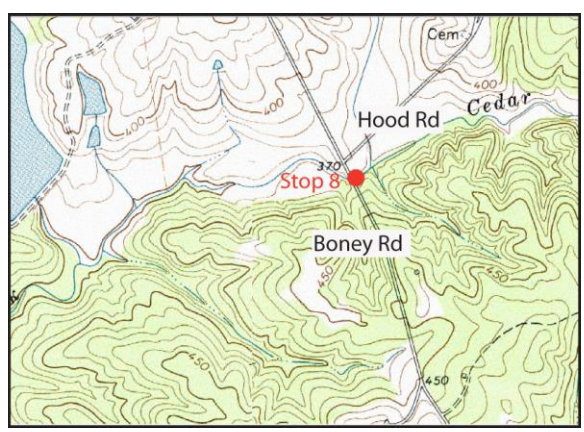
Figure 10. Metadiabase was emplaced as a series of feeder dikes to the greenstone lava flows at Stop 4. The prominent fabric here is Delmar disjunctive cleavage. Penny is 19 mm in diameter.

To Stop 8:

1. Start out going east on E Peach Rd. (2.9 mi)
2. Turn right on Stark Rd. (0.40 mi)
3. Turn right onto Hood Rd. (0.7 mi)
4. Turn left onto Boney Rd. (0.08 mi)

Park along the side of the road. Outcrop is below bridge on Boney Rd along Cedar Creek.

<u>STOP 8:</u> Popsicle Sticks
Persimmon Fork Formation
Boney Road, Ridgeway, SC
Richland 7.5' Quadrangle
(34.26998 N, 80.99536 W)



The rocks in Cedar Creek beneath Boney Road represent a portion of the lower member of the

Persimmon Fork Formation, and are classified as metamorphosed felsic crystal-lapilli tuffs. Quartz is the predominant phenocryst phase, and pumice lapilli comprise the majority of lithic fragments. Felsic tuff is commonly interlayered with intermediate tuff and epiclastic volcanogenic wacke. Like the upper member of the Persimmon Fork, they are thought to have originated as alternating sequences of subaerial to subaqueous ash-falls and pyroclastic flows that are metamorphosed to the upper greenschist and lower amphibolite facies.

The importance of this stop is to highlight the manifestation of, and interaction between, the Chappell and Delmar fabrics. The first to develop is a strong mylonitic Chappells foliation (Pre-551 Ma). Chappells deformation smeared the pumice lapilli into "pancake-shape" clasts. Subsequent Delmar deformation (530-503 Ma) produced a second cleavage that dissected the pumice lapilli and generated a Chappells x Delmar intersection lineation that is characterized by the distinct "popsicle stick" shape of the volcanic lapilli (Fig. 11).

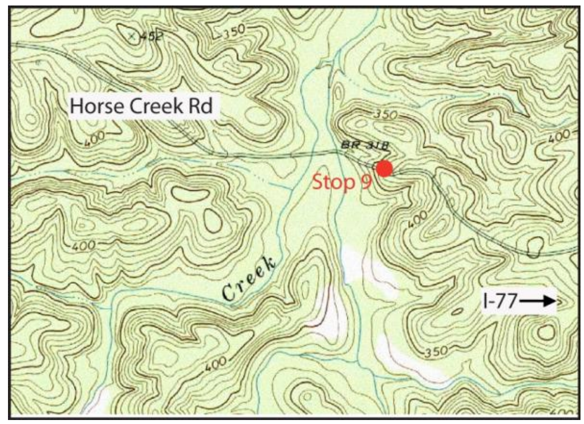
Figure 11. Crystal-lapilli tuff at Stop 8 contains flattened and diced "popsicle stick" lapilli fragments (white streaks). Penny is 19 mm in diameter.

To Stop 9:

1. Start out going northwest on Boney Rd toward Hood Rd. (0.08 mi)
2. Take the 1st right onto Hood Rd. (3.1 mi)
3. Turn left on Stark Rd. (0.4 mi)
4. Turn right on E. Peach Rd. (2.3 mi)
5. Turn right on N. Coleman St. (0.2 mi)
6. Turn left onto W. Church St. (0.2 mi)
7. Turn left onto N. US 21/ N. Palmer St. (7.0 mi)
8. Sharp left on Old River Rd. (0.6 mi)
9. Turn left onto Hope Rd. (3.5 mi)
10. Turn right onto Old 21/ Old Camden Rd. (3.8 mi)

Park on the side of the road. This outcrop is exposed in roadside ditches on the right side of the road (Fig. 12).

<u>STOP 9:</u> Felsic Gneiss and Amphibolite, Charlotte Terrane
Horse Creek Road, Ridgeway, SC
Winnsboro Mills 7.5' Quadrangle
(34.36389 N, 81.01896 W)



Rock types observed along Horse Creek Road include felsic gneiss, amphibolite, granite, gabbro, granite pegmatite, and leucogranite of the Charlotte terrane (Fig. 12). The protoliths for the felsic gneiss and amphibolite unit were predominantly intrusive igneous rocks, and have yielded a U-Pb zircon age of approximately 570 Ma (Dennis and Wright, 1997).

Figure 12. Rocks of the Charlotte terrane at Stop 9 in Horse Creek, Winnsboro Mills 7.5-minute quadrangle. Hammer is 28 cm in length.

Horse Creek deformation (Pre-551 Ma) produces the penetrative gneissosity observed in this outcrop.

Geometric analyses of the fabric suggest that the Horse Creek deformation is similar to what is observed in a tectonic mélange. The gneiss and amphibolite are later intruded by sheets and lenses of granite, gabbro, granite pegmatite, and leucogranite having U-Pb zircon ages of 538-532 Ma (Gilbert and others, 1982; Dennis and Wright, 1997). More recent age dating on rocks at this outcrop suggest that felsic plutonism was active as early as 550 Ma (Fig. 13; Mobley, personal communication, 2015).

Figure 13. Mafic gneiss (G) and amphibolite (A) of the Charlotte terrane intruded by pegmatitic granite (P). Hammer is 28 cm in length.

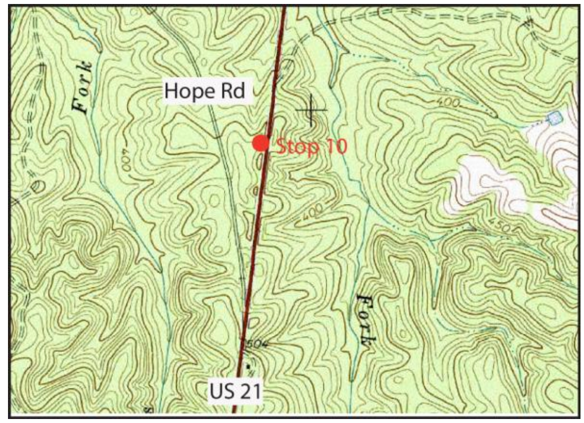
A weak orientation manifested in the Horse Creek fabric is a product of successive deformation that overprints younger intrusive rocks (See stereoplot in Fig. 11a, Secor, this guidebook).

To Stop 10:

1. Turn around.
2. Drive East on Old 21/ Old Camden Rd. (3.8 mi)
3. Turn left onto Hope Rd. (3.5 mi)
4. Turn right onto Old River Rd. (0.6 mi)
5. Turn sharp right onto US Highway 21 N/US-21 S. (5.3 mi)

Park on the side of the road. Outcrops are exposed in road cuts on both sides of the highway.

<u>STOP 10:</u> Chappells Shear Zone, Charlotte terrane
US 21 N, Ridgeway, SC
Ridgeland 7.5' Quadrangle
(34.33054 N, 80.96026 W)



The exposures along this portion of US 21 are the mylonitic, amphibolite facies equivalents of the Charlotte terrane rocks observed at Stop 9 (Fig. 14; Secor and Snoke, 2002). The intensity of mylonitization gradually increases from northwest to southeast between Stops 9 and 10.

Figure 14. SE-dipping mylonitic foliation (dashed red lines) in metamorphosed mafic and felsic igneous rocks of the Charlotte terrane within the Chappells shear zone along US 21 at Stop 10. Matt Henderson, SCGS, is 1.7 meters in height.

The mylonitization is the result of the incorporation of the Charlotte terrane into the lower and northwestern portion of the Chappells shear zone. This high strain zone juxtaposes the Carolina and Charlotte terranes in central South Carolina at approximately 551 Ma (Barker and others, 1998; Secor and Snoke, 2002).

A feature to note at this outcrop is the boudinage of leucocratic layering within the amphibolite (Fig. 15). Additional fabric elements that you might expect to see in ductile shear zones, such as mineral elongation lineation, asymmetric clasts, and other shear sense indicators are present in other parts of the Chappells shear zone, but are not readily observable in this outcrop.

Figure 15. Boudinage of felsic layering (L) within the mafic gneiss and amphibolite of Charlotte terrane located within the Chappells shear zone. Hammer is 28 cm in length.

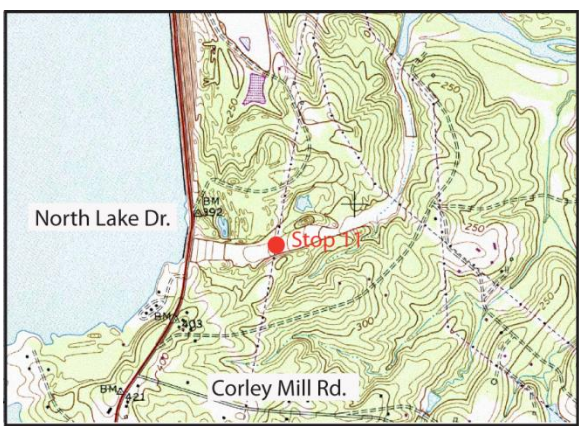
This concludes the road log for Saturday, 24 October, 2015. Buses will proceed back to the Embassy Suites. We hope you enjoyed today's trip through the Carolina and Charlotte terrane!

SUNDAY, OCTOBER 25, 2015

<u>START:</u> Embassy Suites
200 Stoneridge Dr, Columbia, SC 29210

Start out going east on Stoneridge Dr toward Greystone Blvd. (0.08 mi)
2. Take the 1st right onto Greystone Blvd. (0.08 mi)
3. Turn right onto I-126 W/US-76 W toward Spartanburg (0.2 mi)
4. Continue onto US-76 W (0.4 mi)
5. Merge onto I-26 W/ US-76 W (5.4 mi)
6. Merge onto SC-60 W/Lake Murray Blvd via EXIT 102A toward Irmo. (2.84 mi)
7. Lake Murray Blvd/SC-60 becomes SC-6/N Lake Dr (2.00 mi)
8. Entrance to Spillway access is left at the light, before the spillway.

<u>STOP 11:</u> Dreher Shoals terrane
Lake Murray Spillway, Lexington, SC
Irmo 7.5' Quadrangle
(34.03990 N, 81.21235 W)



The spillway is an emergency overflow channel that diverts water from Lake Murray into the Saluda River. It has provided us with one of the most spectacular exposures of geology.

Rocks exposed in the Lake Murray spillway are collectively referred to as the Dreher Shoals terrane and are incorporated into the late Paleozoic Modoc shear zone (West and others, 1995, Hibbard and others, 2002).

Figure 16. View east of the spillway exposure.

Lithologies include porphyroblastic rutile-garnet-staurolite-kyanite schist, amphibolite, quartzite, biotite schist and gneiss, granitic orthogneiss, and mafic and granitic intrusive rocks that texturally range from aplitic to pegmatitic.

Currently, the porphyroblastic schist is considered the oldest unit in the spillway. It contains thin lenses of amphibolite, quartzite, biotite schist and biotite gneiss. The metamorphic mineral assemblage of the schist indicates that this package of rocks experienced high-pressure amphibolite facies metamorphism (Snoke and Frost, 1990). It is thought that these rocks have a similar age to the rest of the Carolina terrane; however, there is no published geochronology to confirm this relationship. Consequently, they may have a tectonic history vastly different from the Carolina terrane.

A mylonitic granitic gneiss, termed the Lake Murray gneiss, was emplaced approximately 421 Ma (Samson and Secor, 2000). The contact between the Lake Murray gneiss and the porphyroblastic schist sequence is sharp, and has traditionally been thought of as an intrusive contact. Both the gneiss and the schist-quartzite-amphibolite package are intruded by felsic and mafic dikes.

The Dreher Shoals terrane contains structures related to Saluda (?), Lake Murray (?), Modoc shear, and Irmo deformation. Each of these episodes has its own characteristic structural style that can be identified in outcrop (Fig. 17). The spillway exposes the overprinting relationships among these deformations, making this the perfect location for structural analysis.

Saluda (?) deformation (Pre-421 Ma) produced tight to isoclinal folding, now expressed as rootless folds whose limbs are locally distended during later deformation. The strong S-C mylonitic fabric in the gneiss and schistose units is manifestation of Lake Murray (?) deformation (~421 Ma). A second period of mylonitization formed during dextral shear in the Modoc shear zone and likely transposed earlier fabrics and structures (Figs. 18, 19).

The latest event, the Irmo deformation (315-274 Ma), is characterized by steeply NE-plunging dextral z-shaped folds, reverse–slip crenulation and dextral C' shear bands that offset the earlier fabrics (Fig. 17; Secor and Snoke, 2002). Other observable structures in the Spillway include boudins and brittle faults (Fig. 18).

Structures that comprise individual deformation events are commonly obliterated by later tectonism; however, vestiges of these events are locally preserved. Can you identify the different fabric elements and structures that comprise each individual event?

Figure 17. Mesoscale dextral fault breaking a folded layer of amphibolite. Magnet is 12 cm in length.

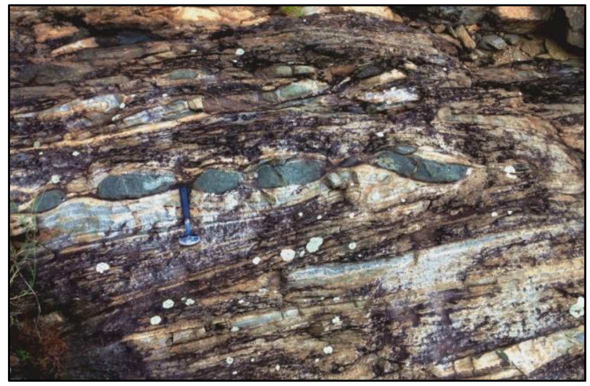


Figure 18. Asymmetric folds, boudinage, and mesoscopic faulting in the Dreher Shoals terrane. Hammer is 28 cm in length.

Figure 19. Asymmetric folds in an amphibolite layer. Magnet is 12 cm in length.

This is the end of the road log for Sunday, 25 October, 2015. Thank you for joining us for the 78th annual Carolina Geological Society Meeting and Fieldtrip

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CORRELATION OF MAP UNITS