[AMERICAN JOURNAL OF SCIENCE, VOL. 294, APRIL, 1994, P. 428–448]

# $^{40}Ar/^{39}Ar$ CONSTRAINTS ON CHRONOLOGY OF AUGUSTA FAULT ZONE MOVEMENT AND LATE ALLEGHANIAN EXTENSION, SOUTHERN APPALACHIAN PIEDMONT, SOUTH CAROLINA AND GEORGIA

H. D. MAHER, JR.*, R. D. DALLMEYER**, D. T. SECOR, JR.***, and P. E. SACKS****

**ABSTRACT. $^{40}Ar/^{39}Ar$ ages recorded by muscovite concentrates and whole-rock phyllite samples collected along a traverse in the southern Appalachian eastern Piedmont help constrain the chronology of movement on the Augusta fault zone. Three muscovite plateau ages from the Savannah River terrane in the footwall range between 272 to 278 Ma and are similar to two muscovite plateau ages obtained from the Modoc fault zone farther to the northwest. By contrast, two whole-rock phyllite spectra from Augusta terrane rocks in the hanging wall to the southeast are characterized by intermediate-temperature plateau segments at about 310 to 320 Ma. Geologic relations and the $^{40}Ar/^{39}Ar$ cooling ages suggest that the Augusta fault juxtaposed Augusta terrane rocks from upper crustal levels against Savannah River terrane rocks from lower crustal levels at and after about 274 Ma. Late Alleghanian extension along the Augusta fault zone is consistent with gravitational collapse of an orogenic topographic front which developed during crustal shortening in early stages of the Alleghanian orogeny. Evidence exists for extensional components on other portions of the Eastern Piedmont fault system. We speculate that the role of Alleghanian extension in the Piedmont tectonothermal history could be significant.**

## INTRODUCTION

The Alleghanian orogeny of the southern Appalachians extended from 320 to 260 Ma (Dallmeyer and others, 1986) and exhibited diverse regionally extensive kinematic events. These are known to include: (1) greater than 140 km of thin-skinned contraction in the Valley and Ridge foreland (Roeder and Witherspoon, 1978) and (2) dextral transcurrence in the Piedmont hinterland (Bobyarchick, 1981, 1988; Gates, Speer, and Pratt, 1988). A third, more recently recognized, event is that of hinterland extension in the eastern Piedmont (Sacks and Secor, 1986; Maher, 1987; Sacks and Dennis, 1987; Vynhal and McSween, 1990; Snoke and Frost, 1990). Temporal correlation and position of various regional events are important for evaluation of tectonic models proposed for the orogen. For example, coeval but kinematically contrasting events might suggest strain partitioning (in other words, decoupled transpressive plate motion), whereas temporally distinct events might suggest an evolution of plate responses. Also, extension early in a collisional event could be

* Department of Geography and Geology, University of Nebraska, Omaha, Nebraska 68182-0199.
** Department of Geology, University of Georgia, Athens, Georgia 30602.
*** Department of Geological Sciences, University of South Carolina, Columbia, South Carolina 29208.
**** U.S. Geological Survey, M.S. 928, National Center, Reston, Virginia 22092.

expected with lithospheric delamination (Sacks and Secor, 1990), but extension significantly after initial crustal thickening could be in accord with gravitational collapse of an orogenic topographic front (Burchfiel and Royden, 1985).

This paper presents $^{40}Ar/^{39}Ar$ ages for 5 muscovite concentrates and 3 whole-rock phyllite samples from along the Savannah River area. These data and geologic relations are then used to help constrain the age of Augusta fault zone movement and associated extension in the Piedmont. Timing of this extension is considered in the context of various published models that explain extension within a collisional orogeny.

## GEOLOGIC SETTING

The eastern Piedmont has traditionally been described in terms of alternating high- and low-grade metamorphic belts defined by Overstreet and Bell (1965). In the context of understanding the tectonic history, this had led to a legacy of confusion, which is discussed by Horton and Zullo (1991). In response to this legacy and for purposes of description in this paper, we will use the following terms to describe geologic entities in the Eastern Piedmont along the Savannah River (fig. 1) from northwest to southeast: Carolina terrane, Modoc fault zone, Savannah River terrane, Augusta fault zone, and Augusta terrane. Equivalences between the belt terminology and that employed in this paper are given in table 1.

Metavolcanic and metasedimentary rocks of the Carolina terrane, extending from Georgia to North Carolina, are part of a late Precambrian to Cambrian composite arc terrane exotic to North America (Secor and others, 1983; Samson and others, 1990), which likely accreted sometime in the Ordovician to Devonian (Vick, Channel, and Opdyke, 1987; Noel, Spariosu, and Dallmeyer, 1988). The Modoc fault zone mainly consists of originally lower grade Carolina terrane rocks, which underwent significant granitic sheet intrusion, prograde metamorphism, and penetrative strain during the Alleghanian (Snoke and others, 1980; Secor and others, 1986; Secor, Snoke, and Dallmeyer, 1986; Secor, 1987). Associated structures and regional relationships indicate predominantly dextral motion but with a northwest side-down component, potentially related to early Alleghanian extension (Sacks and Secor, 1990). Geochronologic data indicate movement occurred between 315 to 290 Ma (Dallmeyer and others, 1986).

Rocks exposed to the southeast of the Modoc fault zone differ in lithologic and fabric characteristics from Carolina-terrane rocks and thus have been designated the Savannah River terrane (Maher, Sacks, and Secor, 1991). These rocks consist of migmatitic sillimanite-bearing schists, paragneisses, and granitic orthogneisses, and subordinate metamorphosed mafic to ultramafic rocks (such as the Burks Mtn. complex, Sacks and others, 1989). Discordant, post-metamorphic, Alleghanian intrusives are common in the Savannah River terrane and indicate migmatitic fabric development here was early or pre-Alleghanian and predates that

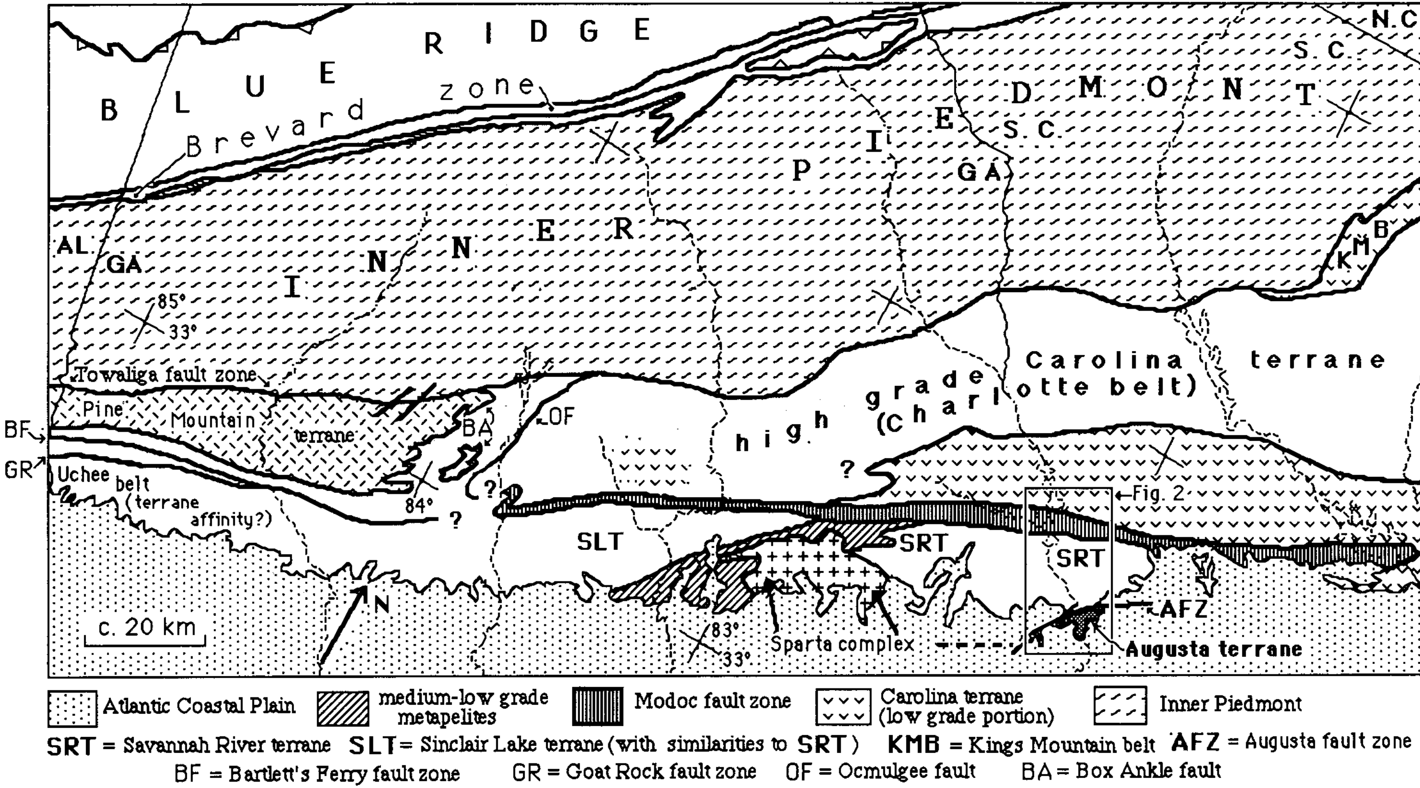


Fig. 1. Tectonic map of part of the Southern Appalachians. Location of study area shown as inset box. Compiled from Williams (1978), Secor and others (1986), Maher (1987), Steltenpohl (1988), Hooper and Hatcher (1988), and recent field work. Where terrane affinity is unknown older belt terminology is used.

TABLE 1

*Rough equivalency chart of nomenclature commonly used in previous literature and that used in this description*

| Nomenclature this paper | Nomenclature previous literature |
|---|---|
| Carolina terrane | Carolina slate belt (low grade portion of Carolina terrane) |
| Modoc fault zone | Modoc fault zone, northern part of Kiokee belt (includes abundant Carolina terrane protoliths) |
| Savannah River terrane | southern part of Kiokee belt |
| Augusta fault zone | Augusta fault zone |
| Augusta terrane | Belair belt (with strong similarities to Carolina slate belt/ Carolina terrane rocks) |

in the Modoc fault zone (Maher and others, 1992). The contact between the two terranes is obscured by and buried along the southeast edge of the Modoc fault zone.

Greenschist-facies, metavolcanic and metasedimentary rocks with characteristics similar to the Carolina-terrane rocks compose the Augusta terrane (Maher, 1979) on the southern flank of the Savannah River terrane. These are in tectonic contact along the ductile Augusta fault zone (fig. 1). A significant hanging-wall-down movement component for the Augusta fault zone is indicated by folded and discordant granitic veins, composite shear-zone fabrics, a sporadically developed lineation, and regional geologic relations (Maher, 1987). Fabric characteristics indicate that movement within the Augusta fault zone occurred during transition from ductile to brittle conditions. The age of the Augusta fault zone was previously constrained only by the assumption that the deformed granitoids were Alleghanian (Maher, 1987). Similarities between the Augusta and Modoc fault zones led to the suggestion that the two were coeval as part of an unusual metamorphic core complex (Maher, Sacks, and Secor, 1991). In this case movement would be about 315 to 290 Ma, relatively early in the Alleghanian time span.

## $^{40}$AR/$^{39}$AR SAMPLES AND ANALYTIC METHODS

Sample-site locations are depicted in figure 2. Location coordinates and sample mineralogy are given in tables 2 and 3. Samples were collected from (1) various structural levels within the Modoc fault zone, (2) near the core of the foliation arch and within the southeastern limb of the Savannah River terrane, (3) the Augusta fault zone, and (4) the Augusta terrane. The sample distribution constitutes a northwest-southeast transect (fig. 2, nos. 1-8) across the southeasternmost Piedmont. This transect represents an offset continuation of a central South Carolina geochronologic transect described by Dallmeyer and others (1986). Together, these transects provide a complete traverse across the eastern Piedmont of the southern Appalachian orogen.

Analytical methods generally follow those described in detail in Dallmeyer and Gil-Ibarguchi (1990). Variations in the neutron flux along

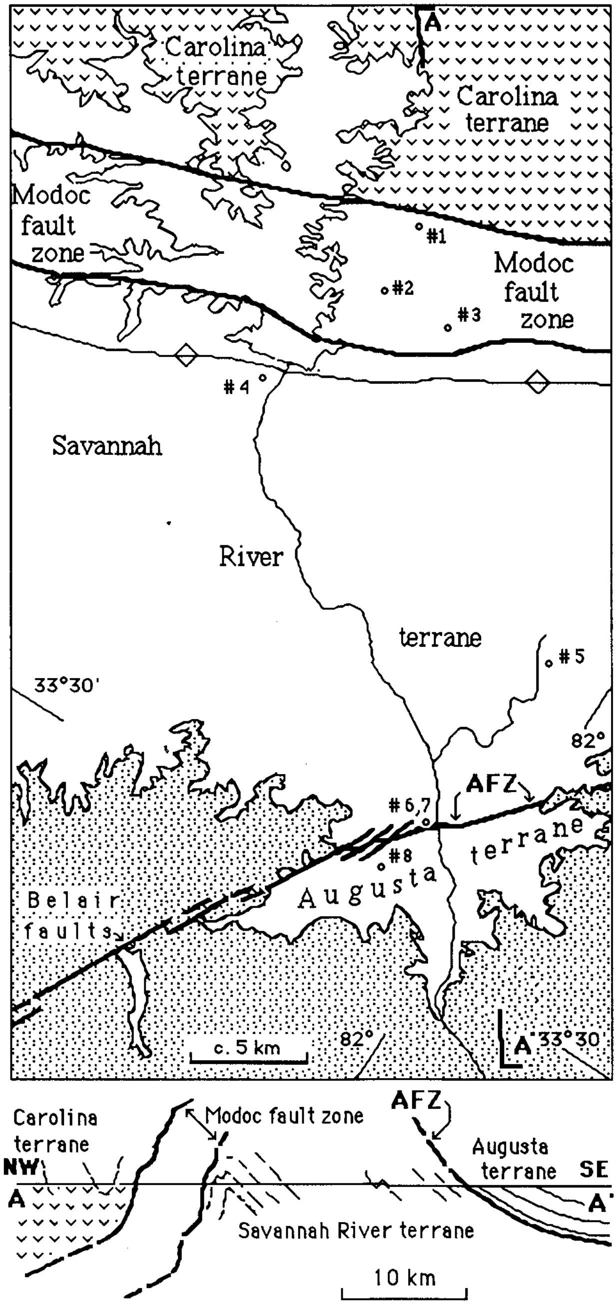


Fig. 2. Map of tectonic elements along the Savannah River around and north of Augusta, Georgia, showing sample sites (nos. 1-8), along with simplified cross section modified from Maher (1987b). AFZ=Augusta fault zone. Brittle Belair faults offset AFZ and Cretaceous Atlantic Coastal Plain (dot pattern) (Powell, 1980).

the length of the irradiation assembly were monitored with several mineral standards, including Mmhb-1 (Samson and Alexander, 1987). Measured isotopic ratios were corrected for total system blanks and the effects of mass discrimination. Interfering isotopes produced during irradiation were corrected using factors reported by Harrison and Fitzgerald (1981: Ford reactor) or Dalrymple and others (1981:TRIGA reactor). Apparent $^{40}Ar/^{39}Ar$ ages were calculated from the corrected isotopic ratios using the decay constants and isotopic-abundance ratios listed by Steiger and Jåger (1977) following methods described in Dallmeyer and Gil-Ibarguchi (1990).

Intralaboratory uncertainties are reported and have been calculated with statistical propagation of uncertainties associated with measurement of each isotopic ratio (at two standard deviations of the mean) through the age equation. Interlaboratory uncertainties are approx 1.25 to 1.5 percent of the quoted age. Analyses of the MMhb-1 monitor indicate that apparent K/Ca ratios may be calculated through the relationship: $0.518(\pm 0.005) \times {}^{39}Ar/^{37}Ar$ corrected (TRIGA reactor) or $0.505(\pm 0.003) \times {}^{39}Ar/^{37}Ar$ corrected (Ford reactor).

## RESULTS

$^{40}Ar/^{39}Ar$ analytic data are given in tables 2 and 3 and are presented as age spectra in figures 3 and 4. The five muscovite concentrates generally display internally concordant $^{40}Ar/^{39}Ar$ age spectra (fig. 3, table 2), which define plateau ages ranging between about 272 and 279 Ma. $^{36}Ar/^{40}Ar$ versus $^{39}Ar/^{40}Ar$ isotope correlation of the plateau data yields similar ages. Inverse ordinate intercepts in the correlations are similar to the $^{40}Ar/^{36}Ar$ ratio within the present-day atmosphere and provide no suggestions of extraneous argon contamination. Apparent K/Ca ratios are very large and show no significant or systematic variations throughout the mica analyses; therefore, they are not presented with the muscovite age spectra. The 272 to 279 Ma range of plateau ages are interpreted to date the last cooling through muscovite intracrystalline argon-retention temperatures. Although not fully calibrated experimentally, using the preliminary data of Robbins (ms) in the diffusion equations of Dodson (1973) indicates muscovite-closure temperatures of about 400°C. This is similar to those suggested for muscovite on the basis of empirical comparisons with other mineral isotopic systems (for example, 350°C; Wagner, Reimer, and Jåger, 1977; Jåger, 1979).

Whole-rock phyllite samples 2 and 8 display variably discordant $^{40}Ar/^{39}Ar$ age spectra (fig. 4; table 3). Small-volume increments evolved at low experimental temperatures record variable, relatively young apparent ages and are marked by fluctuating apparent K/Ca ratios. Gas fractions liberated during intermediate-temperature portions of the two experiments define contrasting plateau ages (274 Ma, sample 2; 314 Ma, sample 8) with corresponding consistently large apparent K/Ca ratios. Sample 2 fluctuations in K/Ca ratio for the plateau section are relatively small, while those of sample 8 are more notable. Gas fractions evolved

TABLE 2

*$^{40}Ar/^{39}Ar$ analytical data for incremental-heating experiments on muscovite from the eastern Piedmont, Georgia and South Carolina*

***Sample 1***: D2 synkinematic orthogneiss mylonite.
**Location:** Long 82° 10' 43", Lat. 33° 43' 52". The locality is on Key Branch Creek, just northwest of where SC-23 crosses Stevens Creek. A well marked footpath several 100 m long leads from the road to and past the outcrop.
**Mineralogy:** quartz, microcline, plagioclase (moderately sericitized), biotite, muscovite (1-3%, .05-.4 mm length), opaques, traces of epidote, chlorite.
J=0.009998

| Release T °C | ($^{40}Ar/^{39}Ar$)* | ($^{36}Ar/^{39}Ar$)* | ($^{37}Ar/^{39}Ar$)$^c$ | $^{39}Ar$ % of total | %$^{40}Ar$ + non-atmos | $^{36}Ar/Ca\%$ | Apparent age (Ma)** |
|---|---|---|---|---|---|---|---|
| 550 | 18.82 | 0.00637 | 0.060 | 3.59 | 90.00 | 0.26 | 282.4± 0.9 |
| 620 | 17.17 | 0.00165 | 0.006 | 5.33 | 97.13 | 0.09 | 278.3±0.3 |
| 665 | 17.10 | 0.00158 | 0.005 | 5.61 | 97.23 | 0.08 | 277.5±0.7 |
| 695 | 17.25 | 0.00211 | 0.005 | 14.85 | 96.36 | 0.06 | 277.4±0.5 |
| 725 | 17.24 | 0.00206 | 0.004 | 12.53 | 96.44 | 0.05 | 277.5±0.4 |
| 765 | 17.14 | 0.00179 | 0.004 | 17.40 | 96.89 | 0.07 | 277.0±0.7 |
| 805 | 17.24 | 0.00202 | 0.003 | 19.62 | 96.51 | 0.04 | 277.6±0.3 |
| 850 | 17.21 | 0.00158 | 0.004 | 12.49 | 97.26 | 0.07 | 279.2±0.4 |
| 895 | 17.12 | 0.00107 | 0.008 | 7.29 | 98.12 | 0.19 | 280.1±0.2 |
| Fusion | 17.19 | 0.00089 | 0.032 | 1.28 | 98.45 | 0.96 | 282.1±5.4 |
| Total | 17.26 | 0.00197 | 0.007 | 100 | 96.62 | 0.09 | 278.1±0.5 |
| Total without 550°C and fusion | | | | 95.13 | | | 277.9±0.4 |

***Sample 3*** Sericitic button (composite surfaces) phyllite
**Location:** Long. 82° 08' 50", Lat. 33° 42' 31". The locality is on Gundy Creek where SC-19-139 crosses it and is described as Stop 4 in Secor, 1987.
**Mineralogy:** quartz, muscovite (35%, .5-1.2 mm length), biotite, plagioclase, opaques, schorlite, garnet, staurolite, chlorite.
J=0.009881

| Release T °C | ($^{40}Ar/^{39}Ar$)* | ($^{36}Ar/^{39}Ar$)* | ($^{37}Ar/^{39}Ar$)$^c$ | $^{39}Ar$ % of total | %$^{40}Ar$ + non-atmos | $^{36}Ar/Ca\%$ | Apparent age (Ma)** |
|---|---|---|---|---|---|---|---|
| 550 | 17.40 | 0.00565 | 0.027 | 5.94 | 90.39 | 0.13 | 260.6±0.9 |
| 625 | 17.20 | 0.00137 | 0.007 | 8.09 | 97.61 | 0.13 | 276.9±0.3 |
| 665 | 17.18 | 0.00155 | 0.006 | 22.93 | 97.31 | 0.11 | 275.8±0.3 |
| 700 | 17.17 | 0.00099 | 0.005 | 19.44 | 98.27 | 0.14 | 278.1±0.4 |
| 735 | 17.36 | 0.00180 | 0.008 | 7.80 | 96.91 | 0.13 | 277.5±0.7 |
| 775 | 17.53 | 0.00218 | 0.007 | 12.96 | 96.30 | 0.09 | 278.3±0.2 |
| 815 | 17.52 | 0.00243 | 0.007 | 2.50 | 95.87 | 0.08 | 277.0±1.1 |
| 855 | 17.52 | 0.00239 | 0.015 | 3.44 | 95.95 | 0.17 | 277.2±0.6 |
| 890 | 17.53 | 0.00210 | 0.008 | 4.07 | 96.44 | 0.10 | 278.7±0.9 |
| Fusion | 17.49 | 0.00149 | 0.006 | 12.82 | 97.45 | 0.11 | 280.7±0.3 |
| Total | 17.33 | 0.00184 | 0.008 | 100.0 | 96.85 | 0.12 | 276.7±0.5 |
| Total without 550°C | | | | 94.6 | | | 277.7±0.4 |

***Sample 4***: - late-kinematic fine-grained gray granite.
**Location:** Long. 82° 39' 04", Lat. 33° 12' 30". Small quarry southwest of Clark Hill dam, produced during dam construction, marked on U.S.G.S. 7.5' Clark Hill topographic quad.
**Mineralogy:** quartz, microcline, plagioclase (notably sericitized), biotite, muscovite (.5-1% .5-1.5 mm length), opaques, traces of chlorite, zircon.
J=0.009265

| Release T °C | ($^{40}Ar/^{39}Ar$)* | ($^{36}Ar/^{39}Ar$)* | ($^{37}Ar/^{39}Ar$)$^c$ | $^{39}Ar$ % of total | %$^{40}Ar$ + non-atmos | $^{36}Ar/Ca\%$ | Apparent age (Ma)** |
|---|---|---|---|---|---|---|---|
| 550 | 20.98 | 0.00743 | 0.070 | 3.43 | 89.53 | 0.26 | 289.4±1.4 |
| 610 | 18.10 | 0.00194 | 0.038 | 5.21 | 96.81 | 0.54 | 271.5±0.6 |
| 640 | 18.31 | 0.00290 | 0.042 | 4.20 | 95.31 | 0.40 | 270.4±1.6 |
| 670 | 18.17 | 0.00229 | 0.023 | 9.58 | 96.25 | 0.27 | 270.9±1.0 |
| 700 | 18.16 | 0.00194 | 0.017 | 13.99 | 96.81 | 0.24 | 272.2±0.5 |
| 735 | 17.97 | 0.00133 | 0.010 | 13.18 | 97.78 | 0.21 | 272.1±0.7 |
| 775 | 18.09 | 0.00160 | 0.011 | 9.79 | 97.36 | 0.18 | 272.7±0.7 |
| 815 | 18.22 | 0.00231 | 0.011 | 8.42 | 96.22 | 0.13 | 271.6±0.7 |
| 855 | 18.26 | 0.00228 | 0.009 | 11.46 | 96.28 | 0.10 | 272.2±0.6 |
| 900 | 18.12 | 0.00159 | 0.011 | 12.12 | 97.37 | 0.19 | 273.2±0.7 |
| 960 | 18.27 | 0.00135 | 0.035 | 6.82 | 97.80 | 0.71 | 276.4±0.7 |
| Fusion | 18.18 | 0.00167 | 0.346 | 1.82 | 97.40 | 5.62 | 274.0±4.2 |
| Total | 18.25 | 0.00207 | 0.025 | 100.0 | 96.66 | 0.36 | 273.0±0.8 |
| Total without 550°, 960° C, and fusion | | | | 87.94 | | | 272.1±0.7 |

TABLE 2

*(continued)*

***Sample 5*** - Savannah River terrane migmatitic felsic paragneiss
**Location**: Long. 82° 01' 56", Lat. 33° 37' 22". Road cut outcrop on east side of SC 230, northeast corner of U.S.G.S. 7.5' Martinez topographic quad.
**Mineralogy**: quartz, plagioclase, K-feldspar, muscovite (5%, .5-1.5 mm length), biotite, opaques.
J=0.009591

| Release T°C | $(^{40}Ar/^{39}Ar)^*$ | $(^{36}Ar/^{39}Ar)^*$ | $(^{37}Ar/^{39}Ar)^c$ | $^{39}Ar$ % of total | $\%^{40}Ar^+$ non-atmos | $^{36}Ar/Ca\%$ | Apparent age (Ma)** |
|---|---|---|---|---|---|---|---|
| 550 | 20.36 | 0.01300 | 0.019 | 3.34 | 85.23 | 0.05 | 281.1±3.5 |
| 625 | 18.67 | 0.00390 | 0.006 | 7.05 | 93.80 | 0.04 | 280.1±1.2 |
| 675 | 18.61 | 0.00417 | 0.007 | 19.23 | 03.36 | 0.04 | 278.1±0.7 |
| 725 | 17.92 | 0.00228 | 0.006 | 30.77 | 96.20 | 0.07 | 276.0±0.4 |
| 765 | 18.44 | 0.00357 | 0.008 | 6.86 | 94.26 | 0.06 | 278.1±0.4 |
| 805 | 18.59 | 0.00402 | 0.007 | 6.02 | 93.58 | 0.05 | 278.3±0.9 |
| 845 | 18.35 | 0.00321 | 0.006 | 10.42 | 94.79 | 0.05 | 278.4±0.4 |
| 885 | 18.07 | 0.00210 | 0.006 | 14.09 | 96.54 | 0.08 | 279.1±0.3 |
| 925 | 17.97 | 0.00161 | 0.019 | 1.72 | 97.33 | 0.32 | 279.1±2.6 |
| Fusion | 19.40 | 0.00738 | 0.061 | 0.51 | 88.75 | 0.23 | 275.7±7.5 |
| Total | 18.35 | 0.0331 | 0.007 | 100.00 | 94.71 | 0.07 | 277.9±0.7 |
| Total without 550°, 925° C, and fusion | | | | 94.43 | | | 277.7±0.5 |

***Sample 6*** - Fine-grained muscovite schist from Augusta fault zone.
**Location**: Long. 82° 02' 24-26", Lat. 33° 32' 11-14". Samples are from upper southwest benches of Augusta, Georgia Martin Marietta quarry, just northwest of where I-20 crosses the Savannah River. Described as Stop 12 in Secor (1987). On U.S.G.S. 7.5' Martinez topographic quad.
**Mineralogy**: quartz, muscovite (about 30%, 1-2 mm length), plagioclase, unknown sericitized feldspar, opaques, traces of garnet, chlorite, epidote.
J=0.010033

| Release T°C | $(^{40}Ar/^{39}Ar)^*$ | $(^{36}Ar/^{39}Ar)^*$ | $(^{37}Ar/^{39}Ar)^c$ | $^{39}Ar$ % of total | $\%^{40}Ar^+$ non-atmos | $^{36}Ar/Ca\%$ | Apparent age (Ma)** |
|---|---|---|---|---|---|---|---|
| 550 | 19.01 | 0.00912 | 0.010 | 4.44 | 85.79 | 0.03 | 273.3±0.7 |
| 625 | 17.10 | 0.00197 | 0.008 | 6.04 | 86.56 | 0.12 | 276.4±0.6 |
| 660 | 16.95 | 0.00184 | 0.005 | 7.03 | 96.76 | 0.08 | 274.7±0.5 |
| 690 | 17.14 | 0.00256 | 0.004 | 9.23 | 95.55 | 0.05 | 274.4±0.5 |
| 720 | 17.20 | 0.00282 | 0.004 | 9.55 | 95.12 | 0.04 | 274.1±0.6 |
| 760 | 17.11 | 0.00240 | 0.005 | 8.21 | 95.82 | 0.06 | 274.7±0.4 |
| 800 | 17.08 | 0.00244 | 0.004 | 14.60 | 95.74 | 0.04 | 273.9±0.9 |
| 845 | 17.23 | 0.00310 | 0.005 | 13.14 | 94.66 | 0.05 | 273.4±1.1 |
| 890 | 17.29 | 0.00294 | 0.004 | 13.57 | 94.94 | 0.04 | 275.0±0.8 |
| 940 | 17.14 | 0.00234 | 0.004 | 11.37 | 95.93 | 0.04 | 275.4±0.5 |
| Fusion | 17.73 | 0.00422 | 0.009 | 2.83 | 92.94 | 0.06 | 276.0±1.2 |
| Total | 17.25 | 0.00290 | 0.005 | 100.00 | 95.04 | 0.05 | 274.5±0.7 |
| Total without 550° C | | | | 95.56 | | | 274.7±0.6 |

* measured.
$^c$ corrected for post-irradiation decay or 37Ar (35.1 day half-life).
$^+$ $[^{40}Ar_{total} - (^{36}Ar_{atmos.})(295.5)]/^{40}Ar_{tot}$.
** calculated using correction factors of Dalrymple and others (1981); two-sigma, intralaboratory errors.
This is the same for the other two tables.

during high-temperature portions of each analysis generally display systematically decreasing apparent K/Ca ratios and record slightly older apparent ages in comparison with the intermediate-temperature plateau ages. Sample 7 displays generally similar age and apparent K/Ca spectra

TABLE 3

*$^{40}Ar/^{39}Ar$ analytical data for incremental-heating experiments on whole rock phyllite from the eastern Piedmont, Georgia and South Carolina*

**Sample 2** White mica button (D4 composite surfaces) phyllite from middle position within Modoc fault zone.
**Location**: Long. 82° 10' 57", Lat. 33 42' 14". Large outcrop where power lines cross Buzzard Creek in U.S.G.S. 7.5' Clark Hill topographic quadrangle area. Logging road access.
**Mineralogy**: quartz, muscovite (about 25%, .5-2.5 mm length), plagioclase, garnet, biotite, penninite, opaques, trace of perovskite (?).
J=0.006575

| Release T°C | $(^{40}Ar/^{39}Ar)^*$ | $(^{36}Ar/^{39}Ar)^*$ | $(^{37}Ar/^{39}Ar)^c$ | $^{39}Ar$ % of total | $\%^{40}Ar$ + non-atmos | $^{36}Ar/Ca\%$ | Apparent age (Ma)** |
|---|---|---|---|---|---|---|---|
| 450 | 61.63 | 0.12151 | 0.315 | 0.73 | 41.46 | 0.07 | 279.1±21.3 |
| 500 | 24.91 | 0.01929 | 0.031 | 1.41 | 76.98 | 0.05 | 214.2±6.0 |
| 535 | 29.23 | 0.01936 | 0.090 | 1.40 | 80.32 | 0.13 | 258.9±9.2 |
| 570 | 29.10 | 0.01082 | 0.063 | 2.43 | 88.91 | 0.17 | 283.4±9.1 |
| 605 | 30.47 | 0.01204 | 0.085 | 1.55 | 88.22 | 0.20 | 293.6±3.4 |
| 640 | 31.23 | 0.01499 | 0.084 | 2.90 | 85.72 | 0.16 | 292.5±5.1 |
| 670 | 27.13 | 0.00431 | 0.115 | 3.97 | 95.20 | 0.77 | 283.0±2.8 |
| 700 | 26.48 | 0.00520 | 0.067 | 5.18 | 94.08 | 0.37 | 273.6±1.3 |
| 730 | 25.76 | 0.00244 | 0.074 | 10.16 | 97.07 | 0.86 | 274.6±0.9 |
| 760 | 25.44 | 0.00186 | 0.066 | 12.41 | 97.71 | 1.02 | 273.1±0.7 |
| 790 | 25.53 | 0.00304 | 0.100 | 9.42 | 96.37 | 0.94 | 274.5±1.4 |
| 820 | 25.44 | 0.00136 | 0.112 | 11.83 | 98.31 | 2.36 | 275.6±1.1 |
| 850 | 25.74 | 0.00211 | 0.109 | 11.30 | 97.47 | 1.48 | 275.4±1.2 |
| 890 | 26.11 | 0.00263 | 0.106 | 8.19 | 96.92 | 1.16 | 277.7±0.6 |
| 940 | 26.62 | 0.00369 | 0.144 | 7.30 | 95.79 | 0.57 | 279.7±1.6 |
| Fusion | 27.42 | 0.00276 | 0.162 | 9.82 | 96.93 | 1.67 | 290.6±1.3 |
| Total | 26.63 | 0.00468 | 0.098 | 100.00 | 95.34 | 1.11 | 276.7+1.9 |
| Total without 450° to 670°, 940°C and fusion | | | | 68.49 | | | 274.4+1.0 |

**Sample 7** White-mica phyllite in upper portion of the Augusta fault zone.
**Location**: Long. 82° 02' 24-26", Lat. 33° 32' 11-14". Samples are from top southwest bench of Augusta, Georgia Martin Marietta quarry, just northwest of where I-20 crosses the Savannah River. Described as Stop 12 in Secor, 1987.
**Mineralogy**: fine-grained white mica (about 40%, .1-.4 mm length), quartz, plagioclase, opaques, minor chlorite.
J=0.009255

| Release T°C | $(^{40}Ar/^{39}Ar)^*$ | $(^{36}Ar/^{39}Ar)^*$ | $(^{37}Ar/^{39}Ar)^c$ | $^{39}Ar$ % of total | $\%^{40}Ar$ + non-atmos | $^{36}Ar/Ca\%$ | Apparent age (Ma)** |
|---|---|---|---|---|---|---|---|
| 350 | 17.50 | 0.00494 | 0.008 | 2.48 | 91.62 | 0.04 | 249.6±5.1 |
| 390 | 19.73 | 0.00162 | 0.005 | 3.83 | 97.54 | 0.09 | 295.6±4.1 |
| 430 | 20.38 | 0.00041 | 0.004 | 6.97 | 99.38 | 0.25 | 310.0±1.1 |
| 470 | 20.75 | 0.00042 | 0.007 | 10.01 | 99.38 | 0.44 | 305.2±0.9 |
| 500 | 20.69 | 0.00031 | 0.002 | 12.02 | 99.54 | 0.18 | 315.4±1.0 |
| 530 | 20.69 | 0.00022 | 0.002 | 16.62 | 99.65 | 0.22 | 315.1±0.6 |
| 560 | 21.02 | 0.00017 | 0.006 | 15.20 | 99.74 | 1.02 | 319.9±1.4 |
| 590 | 19.95 | 0.00012 | 0.013 | 12.62 | 99.80 | 3.02 | 305.1±0.7 |
| 620 | 19.47 | 0.00033 | 0.011 | 5.71 | 99.47 | 0.93 | 297.4±0.8 |
| 650 | 18.92 | 0.00015 | 0.019 | 5.11 | 99.91 | 0.46 | 291.3±2.1 |
| 690 | 18.06 | 0.00136 | 0.041 | 2.31 | 97.76 | 0.83 | 273.0±1.6 |
| 740 | 17.36 | 0.00016 | 0.031 | 2.73 | 99.70 | 5.07 | 268.1±2.5 |
| 800 | 15.55 | 0.00105 | 0.022 | 2.31 | 97.97 | 0.58 | 238.0±1.3 |
| fusion | 10.84 | 0.00189 | 0.037 | 2.06 | 94.83 | 0.54 | 163.9±5.5 |
| Total | 19.89 | 0.00049 | 0.009 | 100.00 | 99.17 | 0.90 | 302.5±1.4 |

TABLE 3

*(continued)*

**Sample 8** White mica phyllite from basal Belair belt stratigraphic unit.
**Location:** Long. 82° 02' 35-37', Lat. 33° 31' 12-15". Samples are from a ridge outcrop just south of the south fork of Rock creek, just several 100 m east of Stevens Creek Road. on U.S.G.S. 7.5' Martinez topographic quad.
**Mineralogy:** fine-grained white mica (about 50%, .05-.2 mm length), quartz, plagioclase, opaques, minor chlorite.
J=0.006520

| Release T °C | $(^{40}Ar/^{39}Ar)^*$ | $(^{36}Ar/^{39}Ar)^*$ | $(^{37}Ar/^{39}Ar)^c$ | $^{39}Ar$ % of total | %$^{40}Ar$ + non-atmos | $^{36}Ar/Ca\%$ | Apparent age (Ma)** |
|---|---|---|---|---|---|---|---|
| 375 | 19.19 | 0.03044 | 0.051 | 0.59 | 52.97 | 0.05 | 115.8±16.4 |
| 405 | 19.60 | 0.00937 | 0.027 | 0.98 | 85.70 | 0.08 | 187.5±13.0 |
| 435 | 22.62 | 0.01317 | 0.011 | 1.89 | 82.63 | 0.02 | 207.4±6.8 |
| 475 | 27.77 | 0.00220 | 0.018 | 1.97 | 97.53 | 0.24 | 293.4±4.5 |
| 505 | 29.57 | 0.00675 | 0.014 | 2.36 | 93.13 | 0.06 | 297.9±3.0 |
| 540 | 29.35 | 0.00319 | 0.008 | 4.85 | 96.66 | 0.07 | 306.2±2.5 |
| 575 | 29.52 | 0.00081 | 0.007 | 8.13 | 99.06 | 0.26 | 314.8±1.9 |
| 605 | 29.83 | 0.00202 | 0.010 | 8.19 | 97.88 | 0.14 | 314.3±1.1 |
| 635 | 29.55 | 0.00106 | 0.002 | 12.60 | 98.81 | 0.06 | 314.4±1.4 |
| 665 | 29.36 | 0.00129 | 0.003 | 12.46 | 98.57 | 0.07 | 311.8±0.7 |
| 695 | 29.27 | 0.00058 | 0.002 | 16.11 | 99.28 | 0.07 | 313.0±0.8 |
| 730 | 30.71 | 0.00425 | 0.014 | 5.26 | 95. 79 | 0.10 | 316.6±1.8 |
| 765 | 32.50 | 0.00770 | 0.026 | 2.76 | 92.89 | 0.10 | 324.1±2.1 |
| 805 | 33.34 | 0.00517 | 0.061 | 3.02 | 95.32 | 0.34 | 339.8±4.0 |
| 895 fusion | 36.80 | 0.00625 | 0.284 | 4.18 | 95.95 | 1.30 | 370.3±3.3 |
| Total | 29.83 | 0.00247 | 0.021 | 100.00 | 97.32 | 0.17 | 312.9±1.6 |
| Total without 375° to 540°, 765-895°C & fusion | | | | 78.41 | | | 314.0±1.8 |

characteristics except that anomalously young apparent ages are systematically recorded in the higher temperature portions of the analysis (matched by systematically decreasing apparent K/Ca ratios). Intermediate-temperature increments (470°–560°C) record mutually similar apparent ages ranging between about 315 and 320 Ma.

The three whole-rock samples are composed primarily of fine-grained white mica. However, systematic intrasample variations in apparent K/Ca ratios suggest that several other phases likely contributed gas at various stages in the whole-rock analyses. These appear to have included: (1) a more non-retentive phase with a relatively low apparent K/Ca ratio and (2) a more refractory phase with a relatively low apparent K/Ca ratio. Mineralogical characteristics and observed modal variations suggest that for samples 2 and 8 these phases are chlorite and detrital plagioclase feldspar, respectively. Most of the observed spectra discordance is attributed to differences in the modal abundances of these phases relative to white mica in the three whole-rock samples analyzed. In samples 7 and 8, segments with varying K/Ca ratio exhibit similar ages, suggesting that contributions from phases other than white mica are negligible, that these phases have similar retention temperatures, or that very rapid cooling occurred. The mineralogical cause of the high-temperature spectra discordance displayed by sample 8 is uncertain. The plateau ages

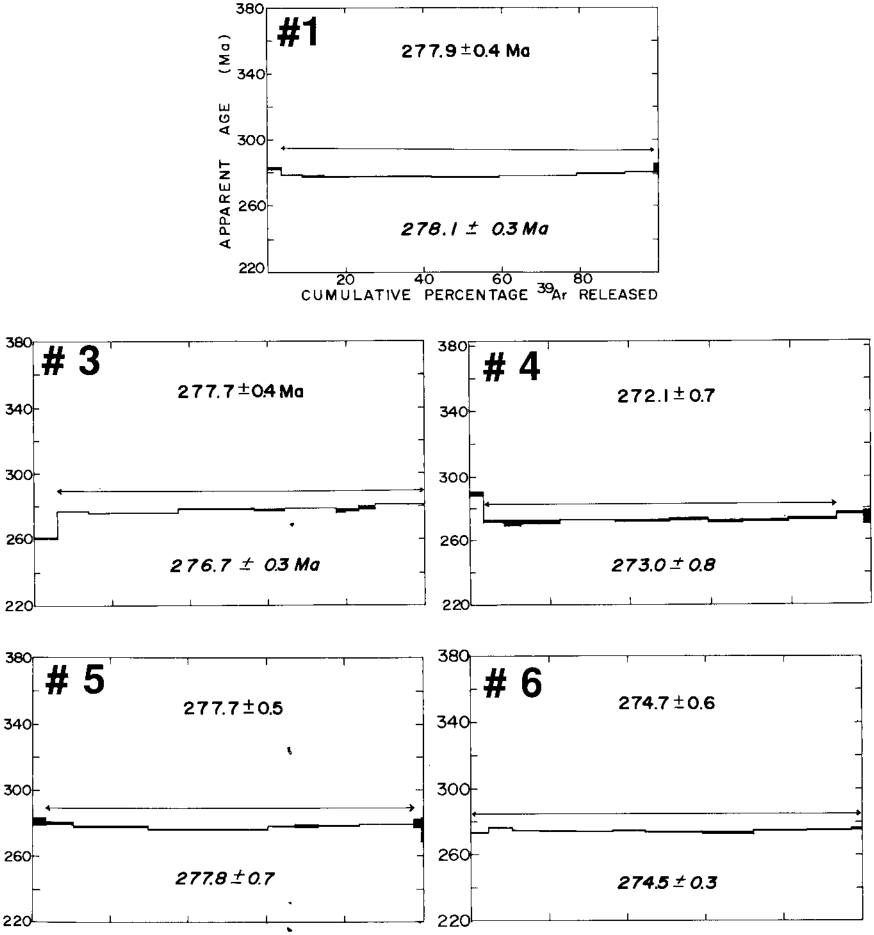


Fig. 3. $^{40}Ar/^{39}Ar$ age spectra of muscovite concentrates from rocks within the Modoc zone (nos. 1 and 2), the Savannah River terrane (nos. 4 and 5), and Augusta fault zone (no. 6). Two-sigma, intralaboratory uncertainties indicated by vertical width of bars. Experimental temperatures of argon evolution increase from left to right. Total-gas or plateau ages (upper number) listed on each spectrum with plateau segments outlined by arrows.

defined by intermediate-temperature fractions are considered to relate to gas evolved predominantly from white mica, since it is the dominant phase, and therefore are interpreted to date the last cooling through appropriate intracrystalline argon retention temperatures. This is assumed to be close to but less than the 400°C retention temperature for muscovite considering the fine grain size. Consistent with this assumption, the whole-rock phyllite sample from within the Modoc fault zone (fig. 2, sample 2) records a plateau age (274 Ma) which is within the 272 to

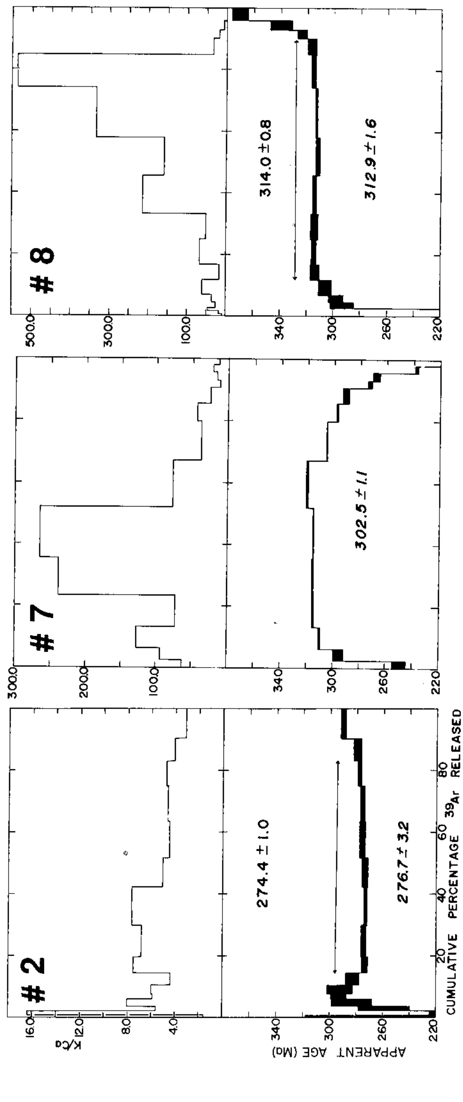


Fig. 4. $^{40}Ar/^{39}Ar$ age spectra and apparent K/Ca spectra of whole rock phyllite samples from within the Modoc zone (no. 2), Augusta fault zone (no. 7), and the Augusta terrane (no. 8). Data plotted as in figure 3.

278 Ma range defined by the 5 muscovite separates from elsewhere in the Modoc fault zone and from the Savannah River terrane.

## THERMAL HISTORY OF THE SAVANNAH RIVER AND AUGUSTA TERRANES

Muscovite concentrates from the Modoc fault zone (samples 1 and 3) and the Savannah River terrane (samples 4 and 5) record $^{40}Ar/^{39}Ar$ ages of 272 to 278 Ma. In addition, phyllonite within a late dextral shear zone (fig. 4, sample 2) records a whole-rock plateau age of about 274 Ma. Similar ages are recorded by diverse lithologies (migmatitic paragneiss, mylonitic orthogneiss, phyllonite, and a late kinematic granite) which display different fabrics. The record of mutually similar ages is interpreted to indicate that the whole presently exposed level of the Savannah River terrane and Modoc fault zone cooled as a relatively intact structural unit through muscovite and white mica argon retention temperatures during about 272 to 278 Ma.

By contrast, sample 8 from the Augusta terrane (fig. 4) displays a well defined plateau age of about 314 Ma, suggesting cooling from a pre-Alleghanian metamorphic event for these rocks. Strong similarities in protoliths, metamorphic grade, and geochemistry exist between the Carolina and Augusta terranes (Maher, 1987, 1979; Shelley ms). Sample 8 falls within the range of whole-rock $^{40}Ar/^{39}Ar$ ages recorded by phyllites within the Carolina terrane distal to the Modoc fault zone northern border in central South Carolina (Dallmeyer and others, 1986). Similarities of the two terranes, suggesting they were once united, strengthens a conclusion that the 314 Ma cooling age is representative of the Augusta terrane as a whole.

Notable concordance of fraction ages in the spectra (fig. 4) indicates sample 7 likely partially records the same cooling event as sample 8, that is, although sample 7 displays greater spectral discordance, significant increments define approx 315 Ma ages (fig. 4), which are similar to the plateau age of sample 8. Micas in both samples 6 and 7 exhibit composite planar fabrics characteristic of the Augusta fault zone (Maher, 1987) and are interpreted to indicate hanging-wall-down motion (Maher, 1987). Compositional similarity and gradational changes between the sampled upper Augusta fault zone rocks (fig. 5) and the overlying basal Augusta stratigraphic unit indicate they are part of the same unit (Maher, 1987; Prowell, 1980). Sample 8 was collected from this same unit. Thus, Augusta fault zone samples 6 and 7 are hanging wall rocks, both incorporated into the ductile shear zone but affected to different degrees by shear zone processes such as recrystallization, intrusion-related reheating, and footwall heating, and both, therefore, have different thermal histories.

Together these results suggest that Augusta belt rocks cooled through white-mica argon-retention temperatures at about 315 Ma, similar to their Carolina terrane counterparts. Therefore, the Augusta fault zone appears to separate rocks with markedly different thermal histories: Augusta terrane rocks had cooled below about 400°C (assumed argon retention temperature for the white mica in phyllites) significantly prior to those now exposed in adjacent segments of the Savannah River terrane with their 273 to 278 Ma span of muscovite cooling ages. Ostensibly they resided at higher crustal levels (given subhorizontal isotherms) at about 278 Ma.

This contrast in age is heightened by the likelihood that the older whole-rock phyllite ages reflect cooling through somewhat lower closure temperatures than the younger ages recorded by the coarser-grained muscovite separates. Relative uniformity of the muscovite ages across the Modoc fault zone and Savannah River terrane and a consistent metamorphic assemblage across the Savannah River terrane as the Augusta fault zone is approached (figs. 2, 5) argue against tilting of geotherms across the antiformal structure as an explanation for the different cooling times. Movement within the Augusta fault zone was therefore the most likely cause of the tectonic juxtaposition of these rocks.

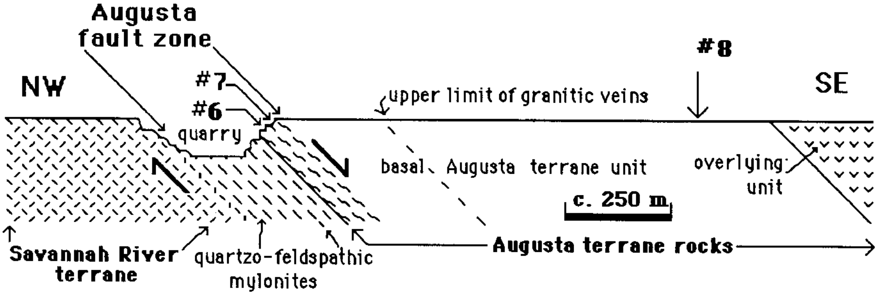


Fig. 5. Simplified cross-section diagram of relative position of samples 6 to 8. Note that nos. 6 and 7 come from the basal unit of Augusta terrane rocks within the Augusta fault zone.

## AGE OF MOVEMENT ON THE AUGUSTA FAULT ZONE

Some feldspathic mylonites in the fault zone show polygonal quartz-grain textures and extensive feldspar recrystallization (Maher, 1987), indicating temperature-sensitive recovery processes operated. Such feldspar recrystallization characteristics amphibolite-facies metamorphic conditions at temperatures in excess of 450° to 500°C when water is available (Voll, 1976; Tullis and Yund, 1980). Other mylonites within the Augusta fault zone, especially rocks within structurally higher portions, locally exhibit extensive quartz undulose extinction, feldspar cataclasis, and limited recrystallization, and are predominantly low-T retrograde mylonites. A population of striae and minor brittle faults record the same direction and sense as the ductile structures (Maher, 1987). These relationships indicate some parts of the Augusta fault zone underwent ductile shear during cooling through a range of temperatures that includes that of muscovite Ar-retention. Hence, the 274 Ma age of sample 6 is thought to date closely movement of the Augusta fault zone.

In addition, structural and textural relationships suggest that sample 6 was rejuvenated by processes related to shear within the Augusta fault zone. As previously stated, sample 6 likely consists of basal Augusta-terrane rocks incorporated into the shear zone. It, therefore, likely cooled through Ar retention temperatures for white mica at about 315 Ma, along with samples 7 and 8, but was reset by a later thermal event. This event is generally manifest as an increase in white-mica grain size and an increase in volume of granitic veins downward into the fault zone and as a growth of biotite and garnet in Augusta-terrane protoliths within the fault zone (phases absent in the hanging-wall Augusta-terrane rocks). Muscovite grain length in sample 6 is about 1 to 2 mm, while in samples typical of the basal Augusta-terrane unit white-mica grain length is an order of magnitude less, specifically suggesting muscovite recrystallization and growth occurred in sample 6. Ductile shear-zone fabric development, intrusion, and metamorphism are thought to be coeval (Maher, 1987), and the thermal evolution possible for sample 6 rejuvenation can be explained by the combined local effects of initial juxtaposition against hotter Savannah River-terrane rocks, synkinematic intrusion, fault-related shear, and subsequent cooling within an extensional setting.

Sample 7, even though proximal to sample 6 and exhibiting a similar composite shear zone fabric (fig. 5), does not show similar rejuvenation. A deeper structural position, greater shear strain and associated recrystallization, and nearby emplacement of a synkinematic orthogneiss sheet 5 to 10 m thick may have been responsible for the total rejuvenation of sample 6. Subsequent ductile excisement likely reduced the original structural distance between samples 6 and 7. Ductile strain and associated excisement during normal movement would likely concentrate in the upper portion of the Augusta fault zone, since the Augusta terrane rocks here (fig. 5) would be incompetent relative to the quartzo-feldspathic mylonites below. Evidence for significant brittle faulting was not observed in the quarry section between the two samples. Overall, the Augusta fault zone is notably heterogeneous with respect to development of shear-zone textures, to grain sizes, and to abundance of intrusions (Maher, 1987). The spectral discordance displayed by sample 7 closer to the top of the Augusta fault zone could reflect a partial, but unresolvable reset (possibly volumetrically minor phases affected by shear-zone-related processes) of the whole-rock system. While Augusta fault zone movement imparted a normal slip crenulation fabric (Dennis and Secor, 1987) to sample 7, in this part of the fault zone thermal and recrystallization processes were insufficient to rejuvenate the sample.

## ALLEGHANIAN EXTENSION IN THE SOUTHERN APPALACHIAN PIEDMONT

Extensional movements within both the Augusta fault (Maher, 1987) and the Modoc shear zones (Sacks and Secor, 1986; Snoke and Frost, 1989) together with their flanking positions along the foliation arch cored by the Savannah River terrane (fig. 1) suggested the two structures were coeval and perhaps constituted a "metamorphic core complex" with a transcurrent component (Maher, Sacks, and Secor, 1991). Secor, Snoke, and Dallmeyer (1986) bracketed activity on the Modoc fault zone between 295 and 315 Ma. The change in argon-cooling ages from within the Modoc fault zone and the central part of the Carolina terrane (low-grade portion) of central South Carolina is gradational and can be attributed to folding of Alleghananian isotherms (Secor, Snoke, and Dallmeyer, 1986) and not by necessity to extensional fault juxtaposition as is the case with the Augusta fault zone. The age of Modoc fault zone activity is significantly older than that evident for the Augusta fault zone, and hence a one-event, "core complex" model for the foliation arch is rejected. It appears that both "early" and "late" extensional components existed within the southern Appalachian Alleghanian orogeny.

Movement of the Augusta fault zone could instead correlate more closely in time to postmetamorphic dextral shear along the Irmo shear zones (localized within the Modoc fault zone in the vicinity of the Savannah River but diverging into the Carolina terrane in central South Carolina; Secor and others, 1986; Dennis, Sacks, and Maher, 1987). Concurrent extensional and dextral motions would imply kinematic decoupling late in the Alleghanian. Concurrent dextral motion along the Modoc fault zone and thin-skinned, contractional deformation in the Valley and Ridge also imply kinematic decoupling earlier in the Alleghanian (Dallmeyer and others, 1986). Decoupling late in the Alleghanian may, in part, have been controlled by the existence of the asymmetric foliation arch (fig. 2). Dextral strike-slip was partitioned into the subvertical northwest limb while extension occurred on the moderately dipping southeast limb. The mechanics of such partitioning on slip planes of different orientation and strength are discussed by Beck (1986).

Evidence for extensional faults exists within other sections of the southern Appalachian Piedmont. The Goat Rock fault zone, exposed near the Alabama-Georgia border (fig. 1), is characterized by foliations and slip surfaces that dip moderately to the southeast and display sense-of-shear structures that indicate both hanging-wall-down and dextral motion (Hanley and Redwine, 1986; Hanley and Steltenpohl, 1989; Steltenpohl, personal communication). A lack of detailed mapping and intermittent Coastal Plain cover do not permit a direct connection to be made between the Augusta and Goat Rock fault zones, but they could be members of the same population.

The Towaliga fault (fig. 1), which separates cover rocks of the Pine Mountain terrane (southeast) from Inner Piedmont rocks (northwest) in western Georgia, is thought to have both a large, but unspecified, amount of Alleghanian dextral motion (Steltenpohl, 1988; Hooper and Hatcher, 1988) and imply 9 km of extension-related offset along northwest-dipping surfaces (Nelson and others, 1987). Nelson and others (1987) suggest that the extension postdated dextral motion and thus was of either late Paleozoic or Mesozoic age. Hence, the Towaliga fault could also be the product of reactivation during orogen-perpendicular, late Alleghanian extension.

Alleghanian extension has also been suggested for both the "Kiokee belt thermal axis" (occupied by the Savannah River terrane) and its North Carolina counterpart, the Raleigh metamorphic belt, by Vynhal and McSween (1990) on the basis of granite geobarometry. They estimate about 15 km of crustal throw for the Augusta fault zone in particular and describe the Kiokee and Raleigh metamorphic belts as "ductile horsts." However, concomitant dextral motion, folding of Alleghanian fabrics, and two phases of extension appear to be involved in "ductile horst" formation (Maher, 1987). Structural evidence for components of Alleghanian extension on faults framing the Raleigh belt has not been reported.

Recently, Getty and Gromet (1992a,b) describe geochronologic and structural evidence for Alleghanian extension along a shear zone at the basement-cover contact of the Willimantic dome in the New England Appalachians at about 275 Ma, essentially coeval with that proposed here for the Augusta fault zone. Other parallels between the two shear zones include inferred northwest-southwest stretching, involvement of granitic and pegmatitic dikes, and structures that developed during a transition from ductile to brittle conditions. These similarities suggest late Alleghanian extension may have occurred along the length of most of the orogen. Getty and Gromet (1992b) propose that following crustal thickening at about 305 to 290 Ma "the thickened composite structural section underwent extensional collapse shortly afterward at about 265 to 280 Ma."

Nelson and others (1987) wonder "whether other mylonite zones in the interior of the Appalachians might also have a significant component of late normal slip. . ." (p. 834). We believe evidence continues to accumulate "that late normal faulting . . . has played a much more important role in the development of the exposed southern Appalachians than has generally been considered to date" (Nelson and others, 1987, p. 832). We further suggest that (1) the geochronology presented here indicates that Piedmont normal faulting is not solely Mesozoic (Heck, 1989) but includes late Alleghanian episodes, and (2) documenting the position, timing, and extent of these structures is an important future research objective.

## OROGEN-PERPENDICULAR EXTENSION WITHIN THE ALLEGHANIAN

The contractional character of the Alleghanian tectonism in the Valley and Ridge led to the initial perception of the Alleghanian as a climatic collisional orogeny. The work described in this paper indicates that not only must a dextral component be added to the Alleghany story (Bobyarchick, 1988) but an extensional one as well. Dewey (1988) summarized descriptions of and models for extension within contractional orogenic settings in numerous mountain belts. Burchfiel and Royden (1985), in particular, proposed a model for orogen-parallel extensional faults within the Himalayas. They used stress modeling to document that extension could be related to collapse of an orogenic topographic front. Similarities between the Himalayan extensional fault and the Augusta fault zone were pointed out by Maher (1987), and Burchfiel and Royden's model was cited as one of several possible models for the Augusta fault zone. A collapse model requires substantial crustal thickening prior to extension in order to develop the requisite orogenic topography. For the Himalayas about 10 to 25 Ma separated the onset of crustal thickening and initiation of orogen-perpendicular extension (Burchfiel and Royden, 1985).

Extensional gravitational collapse differs distinctly from the delamination model proposed by Sacks and Secor (1990) for orogen-perpendicular extension during contraction. Extension associated with delamination and separation of sub-oceanic lithosphere in the subducting slab would be expected to have occurred during initial phases of continental collision and prior to significant crustal thickening (Sacks and Secor, 1990; Charlton, 1991). In part, Sacks and Secor's model was developed as a way to explain evidence for early Alleghanian extension on the Modoc fault zone.

Constraints on movement within the Augusta fault zone provided by the $^{40}Ar/^{39}Ar$ data presented here indicate that extension there occurred late in the Alleghanian phase and well after initiation of Alleghanian crustal shortening in the Valley and Ridge and Blue Ridge (327+/−21 Ma, Secor and others, 1986) and folding in the Piedmont (Secor and others, 1986; Maher, 1987b). This is the chronology expected during extensional collapse, and hence this model is favored for the Augusta fault zone.

## CONCLUSIONS

1. The Savannah River terrane cooled through muscovite Ar-retention temperatures as a relatively intact block, significantly after the Augusta belt cooled through Ar-retention temperatures for white mica.

2. Proximity of samples with disparate cooling histories and geologic relations indicate that motion on the Augusta fault zone juxtaposed these terranes.

3. Augusta fault-zone movement spanned ductile to brittle conditions which include Ar-retention temperatures for muscovite and whole-rock phyllite. Rejuvenation of Augusta-terrane phyllites within the fault zone is associated with shear-zone structures. The 274 Ma cooling age therefore closely dates initiation of extensional movement on the Augusta fault zone.

4. Alleghanian extensional events have been proposed for the Augusta, Goat Rock, Modoc, and Towaliga fault zones and for the New England Willimantic dome. Extension may have been an important control on tectonic architecture in the southern Appalachian Piedmont, if not the entirety of the Appalachian orogen.

5. The Augusta fault zone is not a conjugate counterpart to the Modoc fault zone. Extension may have occurred more than once within the Alleghanian.

6. Extension late in the Alleghanian of the southern Appalachian is consistent with gravitational collapse of thickened crust as described by Burchfiel and Royden (1986) for the Himalaya and proposed for New England by Getty and Gromet (1992a,b).

ACKNOWLEDGMENTS

This research was supported by NSF grants EAR-8803833 and EAR-8803675. We thank Andy Bobyarchick, Allen Dennis, Peter Gromet, and Steve Schamel for reviews which led to substantial improvements to an earlier version of this manuscript.

REFERENCES

Beck, M. E., 1986, Model for late Mesozoic-early Tertiary tectonics of coastal California and western Mexico and speculations on the origin of the San Andreas Fault: Tectonics, v. 5, p. 49–64.

Bobyarchick, A. R., 1981, The Eastern Piedmont fault system and its relationship to Alleghanian tectonics in the southern Appalachians: Journal of Geology, v. 89, p. 335–347.

——— 1988, Location and geometry of Alleghanian dispersal-related strike-slip faults in the southern Appalachians: Geology, v. 16, p. 915–919.

Burchfiel, B. C., and Royden, L. H., 1985, North-south extension within the convergent Himalayan region: Geology, v. 13, p. 679-682.

Charlton, T. R., 1991, Post-collision extension in arc-continent collision zone, eastern Indonesia: Geology, v. 19, p. 28–31.

Dallmeyer, R. D. and Gil-Ibarguchi, J. I., 1990, Age of amphibolitic metamorphism in the ophiolitic unit of the Morais allocthon (Portugal): implications for early Hercynian orogenesis in the Iberian Massif: Journal of the Geological Society, v. 147, p. 873–889.

Dallmeyer, R. D., Wright, J. E., Secor, D. T., Jr., and Snoke, A. W., 1986, Character of the Alleghanian orogeny in the southern Appalachians: Part II. Geochronological constraints on tectonothermal evolution of the eastern Piedmont in South Carolina: Geological Society of America Bulletin, v. 97, p. 1329–1344.

Dalrymple, G. B., Alexander, E. C., Lanphere, M. A., and Kraker, G. P., 1981, Irradiation of samples for $^{40}Ar/^{39}Ar$ dating using the Geological Survey TRIGA reactor: U. S. Geological Survey Professional Paper 1176, 55 p.

Dennis, A., Sacks, P. E., Maher, H. D., Jr., 1987, Nature of the Late Alleghanian Strike-slip deformation in the Eastern South Carolina Piedmont: The Irmo Shear zone, *in* Secor, D. T., editor, Anatomy of the Alleghanian Orogeny as seen from the Piedmont of South Carolina and Georgia; South Carolina Geological Survey, Columbia, S. C., Carolina Geological Society Field Trip Guidebook, p. 35–48.

Dennis, A., and Secor, D. T., Jr., 1987, A model for development of crenulations in shear zones with applications from the southern Appalachian Piedmont: Journal of Structural Geology, v. 9, p. 809–817.

Dewey, J. F., 1988. Extensional collapse of orogens: Tectonics, v. 7, p. 1123–1139.

Dodson, M. H., 1973, Closure temperature in cooling geochronological and petrological systems: Contributions to Mineralogy and Petrology, v. 40, p. 259–274.

Gates, A. E., Speer, J. A., and Pratt, T. L., 1988. The Alleghanian Southern Appalachian Piedmont: A transpressional model: Tectonics, v. 7, p. 1307–1324.

Getty, S. R., and Gromet, L. P., 1992a, Geochronologic constaints on ductile deformation, crustal extension, and doming about a bsement-cover boundary, New England Appalachians: American Journal of Science, v. 292, p. 359–397.

——— 1992b, Evidence for extension at the Willimantic Dome, Connecticut; Implications for the Late Paleozoic evolution of the New England Appalachians: American Journal of Science, v. 292, p. 398–420.

Hanley, T. B., and Redwine, J. C., 1986, The Bartletts Ferry and Goat Rock fault zones north of Columbus, Georgia, *in* Neathery, T. L., ed., Southeastern Section of Geological Society of America, Colorado, Geological Society of America, Centennial Field Guide, v. 6, p. 291-296.

Hanley, T. B., and Steltenpohl, M. G., 1989, Observations on late Paleozoic southeast-directed structures associated with the Goat Rock fault zone, Alabama and Georgia: Geological Society of America Abstracts with Program, v. 21, p. 20.

Harrison, T. M., and Fitzgerald, 1981, Diffusion of 40Ar in Hornblende: Contributions to Mineralogy and Petrology, v. 78, p. 324–331.

Hatcher, R. D., Jr., Howell, D. E., and Talwani, P., 1977, Eastern Piedmont fault system: Speculation on its extent: Geology, v. 5, p. 636–640.

Heck, F. R., 1989, Mesozoic extension in the southern Appalachians: Geology, v. 17, p. 711–714.

Hooper, R. J., and Hatcher, R. D., Jr., 1988, Pine Mountain terrane, a complex window in the Georgia and Alabama Piedmont; evidence from the eastern termination: Geology, v. 16, p. 307–310.

Horton, J. W., and Zullo, V. A., 1991, An introduction to the Geology of the Carolinas, *in* Horton, J. W., and Zullo, V. A., editors, The Geology of the Carolinas: University of Tennessee Press, p. 1–10.

Jåger, E., 1979, Introduction to geochronology, *in* Jager, E., and Hunziker, J. C., editors, Lectures in Isotope Geology: Berlin, Springer Verlag, p. 1–12.

Maher, H. D., Jr., 1979, The Belair Belt of South Carolina and Georgia; Stratigraphy and Depositional Regime as Compared to the Carolina Slate Belt: Geological Society of America Abstract with Program, v. 11, no. 4, p. 187.

——— 1987a, Kinematic history of mylonitic rocks from the Augusta fault zone, South Carolina and Georgia: American Journal of Science, v. 287, p. 795–816.

——— 1987b, D3 folding in the eastern Piedmont associated with Alleghanian thrusting, *in* Secor, D. T., Jr., editor, Anatony of the Alleghanian orogeny as seen from the Piedmont of South Carolina and Georgia: Carolina Geological Society Guidebook. South Carolina Geological Survey, Columbia, S. C., p. 35–48.

Maher, H. D., Jr., Sacks, P. E., and Secor, D. T., 1991, The Eastern Piedmont of South Carolina, *in* Horton, R. W., and Zullo, V., editors, The Geology of the Carolinas, Carolina Geological Society 50th Anniversary v., University of Tennessee Press, p. 93–108.

Maher, H. D., Jr., Sacks, P., Secor, D., and Wright, J., 1992, Magmatic softening in the orogenic hinterland; southern Appalachian Piedmont, Georgia: Geological Society of America Abstracts with Program, v. 24, no. 2.

Nelson, K. D., Arnow, J. A., Giguere, M., and Schamel, S., 1987, Normal fault boundary of an Appalachian basement massif?: Results of COCORP profiling across the Pine Mountain belt in western Georgia: Geology, v. 15, p. 832–836.

Noel, J. R., Spariosu, D. J., and Dallmeyer, R. D., 1988, Paleomagnetism and 40Ar/39Ar ages from the Carolina slate belt, Albemarle, North Carolina: Implications for terrane amalgamation: Geology, v. 16, p. 64–68.

Overstreet, W. C., and Bell, H. III, 1965, The crystalline rocks of South Carolina: U. S. Geological Survey Bulletin 1183, 126 p.

Prowell, D. C., 1980, Ductile and brittle faulting in the southern Kiokee belt and Belair belt of eastern Georgia and South Carolina, *in* Frey, R. W., editor, Excursions in southeastern geology: Leesburg, Virginia, American Geological Institute, p. 80–89.

Robbins, C. S., ms, 1972, Radiogenic argon diffusion in muscovite under hydrothermal conditions: M.S. thesis, Brown University, Providence, Rhode Island, 88 p.

Roddick, J. C., 1978, The application of isochron diagrams in 40Ar/39Ar dating: Earth and Planetary Science Letters, v. 41, 233–244.

Roeder, D., and Witherspoon, W. D., 1978, Palinspastic map of east Tennessee: American Journal of Science, v. 278, p. 543–550.

Sacks, P. E., and Dennis, A. J., 1987, The Modoc zone—D2 Early Alleghanian in the eastern Appalachian Piedmont, South Carolina and Georgia, *in* Secor, D. T., Jr., editor, Anatomy of the Alleghanian orogeny as seen from the Piedmont of South Carolina and Georgia: Columbia, South Carolina, South Carolina Geological Survey, Carolina Geological Society Guidebook: 19–34.

Sacks, P. E., Maher, H. D., Jr., Secor, D. T., Jr. and Dallmeyer, R. D., 1989b, Structural transect across the Kiokee belt and adjacent Carolina and slate belts, South Carolina and Georgia: Geological Society of American Abstracts with Programs: v. 21, no. 3, p.

Sacks, P. E., Maher, H. D., Jr., Secor, D. T., Jr., and Shervais, J. W., 1989, The Burks Mountain complex, Kiobee belt southern Appalachian Piedmont of South Carolina and Georgia: Geological Society of American Special Paper 231, p. 75–86.

Sacks, P. E., and Secor, D. T., Jr., 1986, Alleghanian down-to-the-north slip along the Modoc zone in the southern Appalachian Piedmont: Geological Society of America Abstracts with Program, v. 18, no. 6, p. 737.

——— 1990, Delamination in collisional orogens: Geology, v. 18, p. 999–1003.

Samson, S. D., and Alexander, E. C., Jr., 1987, Calibration of the interlaboratory $^{40}Ar/^{39}Ar$ dating standard, Mmhb-1: Chemical Geology (Isotope Geoscience Section), v. 66, p. 27–34.
Samson, S. A., Palmer, A. R, Robison, R. A., and Secor, D. T., Jr., 1990, Biogeographical significance of Cambrian trilobites from the Carolina slate belt: Geological Society of America Bulletin, v. 102, p. 1459–1470.
Secor, D. T., editor, 1987, Anatomy of the Alleghanian Orogeny as seen from the Piedmont of South Carolina and Georgia: Carolina Geological Society Field Trip Guidebook, South Carolina Geological Survey, Columbia, S. C., 97 p.
Secor, D. T., Jr., Samson, S. L., Snoke, A. W., and Palmer, A. R., 1983, Confirmation of the Carolina slate belt as an exotic terrane: Science, v. 221, p. 649–651.
Secor, D. T., Jr., Snoke, A. W., Bramlett, K. W., Costello, O. P., and Kimball, O. P., 1986, Character of the Alleghanian orogeny in the southern Appalachians, part I: Alleghanian deformation in the eastern Piedmont of South Carolina: Geological Society of America Bulletin, v. 97, p. 1319–1328.
Secor, D. T., Jr., Snoke, A. W., and Dallmeyer, R. D., 1986, Character of the Alleghanian orogeny in the southern Appalachians: Part III Regional tectonic relations: Geological Society of America Bulletin, v. 97, p. 1345–1353.
Selverstone, J., 1988, Evidence for east-west crustal extension in the Eastern Alps: Implications for the unroofing history of the Tauern Window: Tectonics, v. 7, p. 87–105.
Shelley, S., ms. 1988, Geochemical characterization of metavolcanic rocks of the Carolina slate belt—south-central South Carolina: M.S. thesis, University of South Carolina, Columbia, 81 p.
Snoke, A. W., Secor, D. T., Jr, Bramlett, K. W., and Prowell, D. C., 1980, Deformed Hercynian granitic rocks from the Piedmont of South Carolina: American Journal of Science, v. 280, p. 1018–1034.
Snoke, A. W., and Frost, B. R., 1990, Exhumation of high pressure pelitic schist, Lake Murray Spillway, South Carolina: Evidence for crustal extension during Alleghanian strike-slip faulting: American Journal of Science, v. 290, p. 853–881.
Steiger, R. H. and Jager, E., 1977, Subcommission on geochronology convention on the use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 36, p. 359–362.
Steltenpohl, M. G., 1988, Kinematics of the Towaliga, Bartletts Ferry, and Goat Rock fault zones, Alabama: The late Paleozoic dextral shear system in the southernmost Appalachians: Geology, v. 16, p. 852–855.
Tullis, J., and Yund, R. A., 1980, Hydrolytic weakening of experimentally deformed Westerly granite and Hale albite rock: Journal of Structural Geology, v. 2, p. 439–451.
Wagner, G. A., Reimer, G. M., and Jager, E., 1977, Cooling ages derived from apatite fission, mica Rb-Sr and K-Ar dating: the uplift and cooling history of the central Alps: Padovia University Institute of Geology Mineral Memoir, v. 30, p. 1–27.
Vick, H. K., Channell, J. E. T., and Opdyke, N. D., 1987, Ordovician docking of the Carolina slate belt: Paleomagnetic data: Tectonics, v. 6, p. 573–583.
Voll, G., 1976, Recrystallization of quartz, biotite and feldspars from Ertsfield to the Leventina Nappe, Swiss Alps, and its geologic significance: Schweizer Mineralogie et petrographie Mitteilunga, v. 56, p. 641–47.
Vynhal, C. R. and McSween, H. Y., Jr., 1990, Constraints on Alleghanian vertical displacements in the southern Appalachian Piedmont, based on aluminum-in-hornblende barometry: Geology, v. 18, p. 938–941.
Williams, H., 1978, Tectonic lithofacies map of the Appalachian orogen: Memorial University Newfoundland, 1:1,000,000
York, D., 1969, Least squares fitting of a straight line with correlated errors: Earth and Planetary Science Letters, v. 5, p. 320–324.