[AMERICAN JOURNAL OF SCIENCE, VOL. 298, FEBRUARY, 1998, P. 108–130]

PRECISE TIMING CONSTRAINTS ON THE KINEMATIC DEVELOPMENT OF THE HYCO SHEAR ZONE: IMPLICATIONS FOR THE CENTRAL PIEDMONT SHEAR ZONE, SOUTHERN APPALACHIAN OROGEN

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ABSTRACT. The recently discovered Hyco shear zone is a major tectonic boundary that separates terranes (Milton and Carolina) with sharply contrasting rock types, structural and metamorphic histories, and Nd isotopic compositions. Precise U-Pb zircon dates for an orthogneiss, a granitic gneiss, and synkinematic granites within the Hyco shear zone constrain the timing of motion, deformation, and metamorphism along this fundamental southern Appalachian structure. The synkinematic Yanceyville granite gneiss yields an upper intercept date of 335.4 ± 2.2 Ma. The syn- to late-synkinematic Kilgore granite crystallized at 327 ± 1.5 Ma. A Neoproterozoic hornblende gneiss from the northern portion of the zone yields a lower intercept date of 322.5 ± 2.7 Ma, which is interpreted to reflect the timing of deformation and metamorphism. The crystallization age of the Farmers Lake granite, a late-synkinematic intrusion, is 319.6 ± 0.7 Ma. These new dates document that the Hyco shear zone was active by mid-Mississippian time and that deformation and metamorphism were in their final stages by latest Mississippian time.

The Hyco shear zone is considered the northernmost segment thus far recognized of the central Piedmont shear zone, an orogen-scale structure within the southern Appalachians that separates rocks of uncertain crustal affinity in the Piedmont zone from exotic, arc-related rocks of the Carolina zone. Comparison of the kinematic history of the Hyco shear zone with kinematic histories of more southerly segments of the central Piedmont shear zone indicates that Alleghanian deformation and metamorphism probably occurred contemporaneously along the entire shear zone. These observations are permissive of a model for the central Piedmont shear zone as an Alleghanian ductile shear zone that may extend from Georgia into the central Appalachians.

INTRODUCTION

The recently discovered Hyco shear zone (fig. 1) has been recognized as a major, regional-scale structure within the southern Appalachian orogen (Hibbard and others, this issue). The shear zone juxtaposes greenschist to amphibolite facies metavolcanic and metaplutonic rocks of the Carolina terrane (Secor and others, 1983) against amphibolite facies schists and gneisses of the Milton terrane (Butler, 1980; Horton, Drake, and Rankin, 1989). The Hyco shear zone separates rocks with contrasting compositions, ages, structural histories (Hibbard and Samson, 1995), and Nd isotopic compositions (Wortman, Samson, and Hibbard, 1996). Hibbard and others (this issue) consider the Hyco shear zone the northern-most documented segment of the central Piedmont shear zone, a fundamental tectonic structure within southern Appalachians that separates rocks of Carolina zone from those of the Piedmont zone (fig. 1; Hibbard and Samson, 1995).

Although it is a structure of fundamental importance within the orogen, surprisingly little is known about timing of displacement along the central Piedmont shear zone, because reliable geochronological timing constraints on deformation and metamorphism within the shear zone are lacking over much of its areal extent. Nowhere is this lack of geochronologic information more apparent than along the Hyco shear zone segment of the central Piedmont shear zone. While it has long been known that the majority of the rocks of the Carolina terrane, which constitute the eastern boundary of

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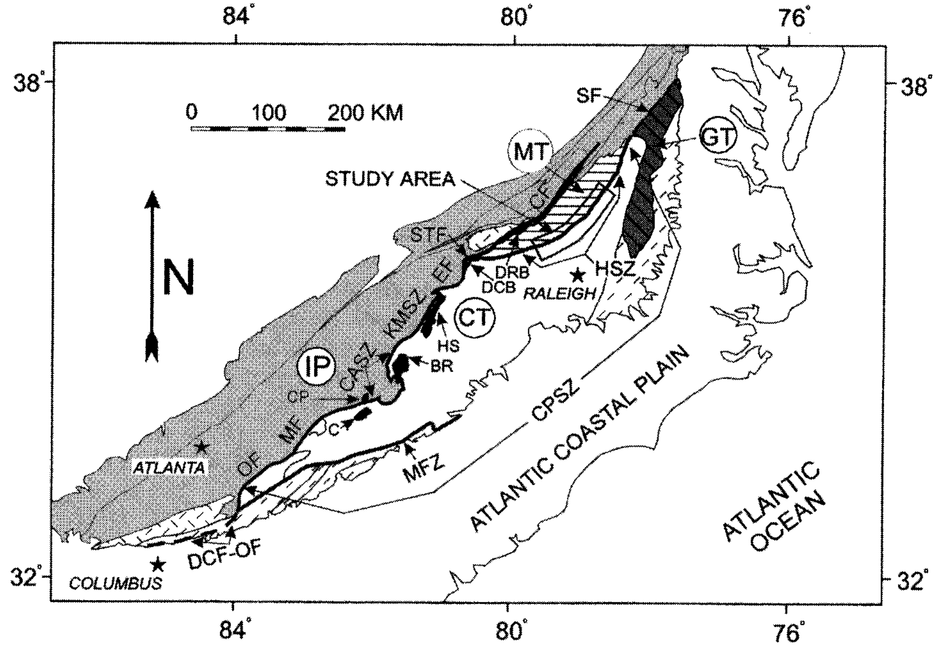

Fig. 1. Regional extent of the central Piedmont shear zone (CPSZ). Postulated correlations of the CPSZ with other faults are shown as dashed lines. Only terranes specifically related to this paper are identified. The Piedmont zone (Hibbard and Samson, 1995) includes the Milton terrane and all terranes shaded in light gray shown west and northwest of the CPSZ. The Carolina zone includes all terranes shown east and southeast of the CPSZ, except the Goochland terrane, which belongs to the Goochland zone. Modified after Horton, Drake, and Rankin (1989), West and others (1995), and West (1997). Terranes: CT = Carolina terrane GT = Goochland terrane IP = Inner Piedmont terrane MT = Milton terrane Fault zones: CASZ = Cross Anchor shear zone CF = Chatham fault DCF = Deans Creek fault EF = Eufola fault HSZ = Hyco shear zone KMSZ = Kings Mountain shear zone MF = Middleton fault MFZ = Modoc fault zone OF = Ocmulgee fault SF = Spotsylvania fault STF = Shacktown fault Mesozoic Basins: DCB = Davie County basin DRB = Dan River basin Late Paleozoic Granites: BR = Bald Rock granite C = Coronaca granite CP = Cold Point granite HS = High Shoals granite.

the shear zone, are late Neoproterozoic in age (Glover and others, 1971; Glover and Sinha, 1973; Wortman, Samson, and Hibbard, 1995), the ages of Milton-terrane rocks, which form the western boundary of the Hyco shear zone, are not well constrained. Furthermore, nothing is known about the ages of the many igneous bodies that intrude the shear zone. An understanding of the precise timing constraints on the kinematic development of the Hyco shear zone is critical to understanding the tectonic history of this part of the southern Appalachians and has important implications for the kinematic development of the central Piedmont shear zone in other parts of the orogen.

In this paper we report U-Pb dates for zircon and titanite and an $^{40}Ar/^{39}Ar$ date for hornblende from a prekinematic hornblende gneiss within the Hyco shear zone. We also report precise U-Pb zircon dates for a synkinematic granitic gneiss and two late-synkinematic granites that intrude the shear zone. These isotopic dates place new constraints on the timing of displacement, deformation, and metamorphism within this important southern Appalachian structure. Using these new timing constraints, we compare the kinematic history of the Hyco shear zone with the kinematic histories of other segments of the central Piedmont shear zone, based on available published geochronological data, and consider the implications for the kinematic development of the entire shear zone. The companion paper (Hibbard and others, this issue) describes in detail the stratigraphy and structure of lithologic units within and adjacent to the shear zone and provides interpretations of the field relations among the pre-kinematic lithologic units and the syn- and late-synkinematic granitic rocks that intrude the shear zone.

THE CENTRAL PIEDMONT SHEAR ZONE

The central Piedmont shear zone (Hibbard and others, this issue) separates the exotic, volcanic arc-related terranes of the Carolina zone (Hibbard and Samson, 1995) from terranes of uncertain crustal affinity in the Piedmont zone (fig. 1). Originally named the central Piedmont suture by Hatcher and Zietz (1980), it extends at least 800 km from central Georgia to central Virginia and juxtaposes terranes with sharply contrasting Bouguer gravity and magnetic anomaly patterns, rock types, and structural styles. The central Piedmont shear zone is considered a composite fault zone composed of a northeast-trending series of related ductile faults and shear zones (fig. 1). Faults traditionally assigned to the central Piedmont shear zone include the Ocmulgee fault (Hooper and Hatcher, 1990), the Lowndesville-Middleton fault (Griffin, 1979), the Kings Mountain shear zone (Horton, 1981), and the Eufola fault (Milton, 1981; Goldsmith, Milton, and Horton, 1988; fig. 1).

However, on the basis of detailed mapping in South Carolina, West (1997) argues that the Lowndesville fault was cross cut and transported to its present location by the Cross Anchor shear zone (fig. 1). West (1997) interprets the Cross Anchor shear zone to juxtapose Carolina terrane rocks against Inner Piedmont terrane rocks and, therefore, to constitute the surface expression of the central Piedmont shear zone between the Middleton fault segment and the Kings Mountain shear zone. The Hyco shear zone (Hibbard, 1993; Shell, ms; Bradley, ms; Hibbard and others, this issue) constitutes the northernmost recognized segment of the central Piedmont shear zone. Hibbard and others (this issue) propose that the central Piedmont shear zone may extend northeastward from the Hyco shear zone into the central Appalachians. The southernmost extent of the central Piedmont shear zone is controversial. West (1997) terminates the trace of the central Piedmont shear zone at the intersection between the Ocmulgee fault and the Modoc fault zone (fig. 1). Hooper and Hatcher (1997) consider the Uchee terrane part of the Carolina (their Avalon) zone and continue the boundary between the Carolina and Piedmont zones southwestward along the Dean's Creek fault (fig. 1). The location of the boundary between the Carolina and Piedmont zones in western Georgia and eastern Alabama is uncertain. Hooper and Hatcher (1990) suggested that the Dean's Creek fault may pass north of Columbus, Georgia. However, Hanley and others (1997) do not recognize a fault boundary north of Columbus, Georgia, with characteristics similar to faults elsewhere along the central Piedmont shear zone, and suggest that the boundary between the Carolina and Piedmont zones might be buried beneath the Atlantic coastal plain.

The central Piedmont shear zone has been regarded as a terrane boundary related to the accretion of the Carolina terrane to the Inner Piedmont terrane and Laurentia (Hatcher and Zietz, 1980; Secor and others, 1983, 1986). The timing of accretion of the Carolina terrane to Laurentia is controversial. Some workers have proposed that the Carolina terrane was accreted to Laurentia in Ordovician time during the Taconic Orogeny (Secor and others, 1983, 1986; Vick and others, 1987; Noel and others, 1988; Hatcher, 1989; Horton, Drake, and Rankin, 1989). Others have suggested that it was accreted during Siluro-Devonian time (Williams and Hatcher, 1982, 1983; Hatcher, 1987; Dennis, 1991). The central Piedmont shear zone has been considered by some a polygenetic structure that initially formed during early- or middle-Paleozoic orogenesis and was later reactivated along suitably oriented segments as dextral strike-slip faults during the Alleghanian orogen (Hatcher, 1989; Dennis, 1991, 1995). However, on the basis of deep seismic reflection data, McBride and Nelson (1991) interpret the central

Piedmont shear zone as an Alleghanian structure. Detailed mapping by Hibbard and others (this issue) and West (1997) documents that Alleghanian thrusting is the earliest motion recognized along the Hyco and Cross Anchor shear zones. These authors argue that there is no evidence that pre-Alleghanian fault rocks exist within these two shear zones and that they are probably representative of the central Piedmont shear zone as a whole. Hibbard and others (this issue) propose that the central Piedmont suture of Hatcher and Zietz (1980) is really an Alleghanian thrust that overrides the original suture between the Carolina and Piedmont zones and that the term "suture" be abandoned in favor of "shear zone." On this basis, the term central Piedmont shear zone supplants the term central Piedmont suture.

Geochronologic Constraints on the Central Piedmont Shear Zone

The degree to which the timing of deformation and metamorphism are constrained along the different fault segments comprising the central Piedmont shear zone varies. This study was designed specifically to place tight timing constraints on deformation, metamorphism, and motion in the Hyco shear zone. Timing constraints for some of the other segments of the central Piedmont shear zone are provided indirectly by published results of studies not specifically designed to constrain their motion, such as isotopic dates for late Paleozoic granites near the shear zone (Fullagar and Butler, 1979), or $^{40}Ar/^{39}Ar$ studies of metamorphism in the region (Dallmeyer and others, 1986). Because results of this study provide the most direct constraints on deformation and metamorphism within the central Piedmont shear zone, the geochronologic constraints on the Hyco shear zone are documented first. Then, timing constraints on deformation and metamorphism along other segments of the central Piedmont shear zone are discussed, using the Hyco shear zone as a reference point. Published isotopic dates cited in the text are summarized in table 1.

THE HYCO SHEAR ZONE

The general stratigraphy of the Milton and Carolina terranes within the Hyco shear zone and the synkinematic granites that constrain its history are shown in figure 2. Felsic schists and gneisses of the Milton terrane reside in the footwall of the shear zone, whereas the mafic gneisses and mafic to felsic metavolcanic and metasedimentary rocks of the Carolina terrane reside in the hangingwall.

Carolina-terrane rocks in the region are late Neoproterozoic in age (Glover and Sinha, 1973; Wortman, Samson, and Hibbard, 1995). The age of Milton-terrane rocks is uncertain. Glover and others (1971) considered the Milton terrane Neoproterozoic in age, based on a U-Pb zircon date of 740 Ma for a gneiss from the eastern part of the terrane. However, Wortman, Samson, and Hibbard (1995) have argued that this date actually represents a mixing line between older and younger zircons within the rock and is geologically meaningless. More recent dates for rocks within the Milton terrane indicate that the bulk of the terrane may be Ordovician in age (Hund, ms; Wortman, Samson, and Hibbard, 1995). Both the Carolina and Milton terranes within the shear zone are intruded by numerous granitic rocks of uncertain age.

The only published isotopic dates that provide constraints on deformation and metamorphism along the Hyco shear zone come from $^{40}Ar/^{39}Ar$ dates reported by Kunk, Horton, and Peper (1995) for Milton- and Carolina-terrane rocks near the shear zone (table 1). Kunk, Horton, and Peper (1995) reported $^{40}Ar/^{39}Ar$ hornblende dates (no errors quoted) for Milton-terrane rocks of 313 Ma for a rock from the eastern part of the terrane near the shear zone and 323 Ma for a rock in a more internal part of the terrane. Kunk, Horton, and Peper interpreted these $^{40}Ar/^{39}Ar$ hornblende dates as an indication of the time of amphibolite-facies metamorphism in the Milton terrane. Kunk, Horton, and Peper (1995) also noted that white mica from some Carolina terrane rocks in the area also showed evidence for a significant Alleghanian component.

TABLE 1

Available geochronologic constraints on deformation and metamorphism along previously recognized segments of the central Piedmont shear zone

Unit dated	Reported date (Ma)	Isotopic system	Significance to Alleghanian central Piedmont shear zone deformation and metamorphism	Reference
Ocmulgee fault segment:				
Unnamed rock	331	U-Pb zircon	metamorphism	Student and Sinha (1992), (abstract, no errors quoted)
Cross Anchor shear zone segment:				
Bald Rock granite	323 ± 3	U-Pb zircon	pre- to syn-kinematic	Dennis and Wright (1995), West (1997)
Unnamed metagranite	326 ± 3	U-Pb zircon	pre- to syn-kinematic	Dennis and Wright (1995), West (1997)
Coronaca granite	278 ± 2	Rb/Sr whole rock	post-kinematic	Fullagar and Butler (1979)
Cold Point granite	299 ± 9	Rb/Sr whole rock	post-kinematic	McSween, Speer, and Fullagar (1991)*
Cold Point granite	Ca. 312	U-Pb zircon		$^{207}Pb/^{206}Pb$ age, no error quoted, Horton and McConnell (1991)**
Inner Piedmont terrane rocks (undivided country rocks)	300 ± 6	$^{40}Ar/^{39}Ar$ hornblende	post-metamorphic cooling to 500°C	Dallmeyer and others (1986)
	296 ± 6	$^{40}Ar/^{39}Ar$ hornblende		
	282 ± 5	$^{40}Ar/^{39}Ar$ biotite	post-metamorphic cooling to 300°C	Dallmeyer and others (1986)
	271 ± 5	$^{40}Ar/^{39}Ar$ biotite		
	259 ± 5	$^{40}Ar/^{39}Ar$ biotite		
Carolina terrane rocks: (undivided country rocks)	310 ± 6	$^{40}Ar/^{39}Ar$ hornblende	post-metamorphic cooling to 500°C	Dallmeyer and others (1986)
	203 ± 6	$^{40}Ar/^{39}Ar$ hornblende		
	302 ± 6	$^{40}Ar/^{39}Ar$ hornblende		
	296 ± 6	$^{40}Ar/^{39}Ar$ hornblende		
	286 ± 6	$^{40}Ar/^{39}Ar$ hornblende		
	289 ± 5	$^{40}Ar/^{39}Ar$ hornblende		
	313 ± 6	$^{40}Ar/^{39}Ar$ biotite	post-metamorphic cooling to 300°C	Dallmeyer and others (1986)
	292 ± 5	$^{40}Ar/^{39}Ar$ biotite		
	291 ± 5	$^{40}Ar/^{39}Ar$ biotite		
	289 ± 5	$^{40}Ar/^{39}Ar$ biotite		
	289 ± 5	$^{40}Ar/^{39}Ar$ biotite		
	288 ± 5	$^{40}Ar/^{39}Ar$ biotite		
	277 ± 5	$^{40}Ar/^{39}Ar$ biotite		
	275 ± 5	$^{40}Ar/^{39}Ar$ biotite	post-metamorphic cooling to 300°C	Dallmeyer and others (1986)
	274 ± 5	$^{40}Ar/^{39}Ar$ biotite		
	267 ± 5	$^{40}Ar/^{39}Ar$ biotite		
	265 ± 4	$^{40}Ar/^{39}Ar$ biotite		

Newberry granite	271 ± 5	$^{40}Ar/^{39}Ar$ biotite		
Newberry granite	270 ± 5	$^{40}Ar/^{39}Ar$ biotite		
Winnsboro granite	268 ± 5	$^{40}Ar/^{39}Ar$ biotite		
Inner Piedmont window:	280 ± 6	$^{40}Ar/^{39}Ar$ hornblende	post-metamorphic cooling to 500°C	Dallmeyer and others (1986), West (1997)
(Undivided country rocks)	278 ± 6	$^{40}Ar/^{39}Ar$ hornblende		
	255 ± 5	$^{40}Ar/^{39}Ar$ biotite	post-metamorphic cooling to 300°C	Dallmeyer and others (1986), West (1997)
	251 ± 5	$^{40}Ar/^{39}Ar$ biotite		
	243 ± 4	$^{40}Ar/^{39}Ar$ biotite		
Kings Mountain shear zone segment:				
Spodumene pegmatite dikes	345 ± 5	Rb/Sr whole rock	syn- to late-syn-kinematic	Kish (1977 and ms); Horton (1981); Horton and others (1987)
High Shoals granite	317 (±6)	U-Pb zircon	late synkinematic	Horton and others, 1987 (1 analysis, 2 percent uncertainty reported)
High Shoals granite	320	U-Pb zircon		LeHuray (1986) (2 analyses, no errors quoted)
Foliated amphibolite xenolith in High Shoals granite	318 ± 1.8	$^{40}Ar/^{39}Ar$ hornblende	post-metamorphic cooling to 500°C	Horton and others (1987)
Hornblende bearing gneiss	321.5 ± 1.9	$^{40}Ar/^{39}Ar$ hornblende		
Hornblende bearing gneiss	323 ± 2.6	$^{40}Ar/^{39}Ar$ hornblende		
Foliated amphibolite xenolith	302 ± 6	$^{40}Ar/^{39}Ar$ hornblende	post-metamorphic cooling to 500°C	Dallmeyer and others (1986)
Eufola fault segment:				
Cross-cutting pegmatitie dikes in Chatham fault zone	321	Rb/Sr biotite	pre-Mesozoic motion	Robinson (1979, abstract)
Hyco shear zone segment:				
Milton terrane rocks:	313	$^{40}Ar/^{39}Ar$ hornblende	post-metamorphic cooling to 500°C	Kunk, Horton, and Peper (1995, abstract)
	323	$^{40}Ar/^{39}Ar$ hornblende		

Notes: *These authors cite Fullagar, unpublished data. **These authors cite Stern and Nelson, unpublished data.

Detailed descriptions of the stratigraphy and structure of the Hyco shear zone and interpretations of the field relationships of the intrusive granitic rocks discussed in this paper are given in Hibbard and others (this issue).

SAMPLES

To constrain the timing of deformation and metamorphism within the Hyco shear zone, four samples were collected for U-Pb zircon dating. The samples were chosen on the basis of field interpretations of their relative ages with respect to the early, middle, and late stages of tectonothermal activity within the shear zone. Sample locations are shown in figure 2 and described in table 2.

Yanceyville Granite Gneiss

The Yanceyville granite gneiss was sampled just east of Yanceyville, North Carolina. It is interlayered with, but locally crosscuts, mafic gneisses of the Carolina terrane in the footwall of the shear zone (Hibbard and others, this issue). The gneiss is early synkinematic with respect to the shear zone, as it is overprinted by the same polydeformational fabrics as the enclosing gneiss (Hibbard and others, this issue). Thus, deformation and metamorphism were active by the time the Yanceyville granite gneiss intruded the Hyco shear zone.

South Boston Hornblende Gneiss

The South Boston hornblende gneiss was collected from an outcrop in the Vulcan Quarry northeast of South Boston, Virginia, where Carolina-terrane rocks in the hangingwall of the shear zone are exposed. The hornblende gneiss is interpreted as an orthogneiss of intermediate composition and is part of a layered gneiss sequence exposed throughout the quarry. The layered gneiss sequence is overprinted by all deformational fabrics associated with the shear zone and is intruded by granitic dikes interpreted as synkinematic (Hibbard and others, this issue).

Kilgore Granite

The Kilgore granite was sampled approx 5 km west of Semora, North Carolina. It intrudes Milton-terrane rocks in the footwall and is interlayered with but locally cuts mafic gneisses of the Carolina terrane in the hangingwall (Hibbard and others, this issue). The Kilgore granite is less deformed than the country rock in most places and has been interpreted as a syn- to late-synkinematic intrusion (Hibbard and others, this issue).

Farmers Lake Granite

The Farmers Lake granite intrudes Milton-terrane rocks in the footwall as well as Carolina-terrane rocks in the hangingwall. It has only a weak, late-stage deformational fabric and has been interpreted as late-synkinematic (Hibbard and others, this issue). Thus, the Farmers Lake granite constrains the final stages of deformation in the shear zone. A dike associated with the Farmers Lake granite was sampled just south of Yanceyville, North Carolina.

ANALYTICAL METHODS

U-Pb Analyses

Analytical methods followed Samson (1995) with the following modifications. The Pb mass bias used in the calculations is 0.18 ± 0.07 percent amu^{-1} for single Daly collector analyses and 0.10 ± 0.05 percent amu^{-1} for static Faraday multicollector analyses. U was loaded with colloidal graphite and analyzed as metal. U fractionation was directly determined for each analysis, by using a mixed ^{233}U-^{235}U tracer solution (typical values were −0.003 percent amu^{-1}). Data reduction and regression analysis followed Ludwig (1989, 1990). For zircon analyses, the isotopic composition used in

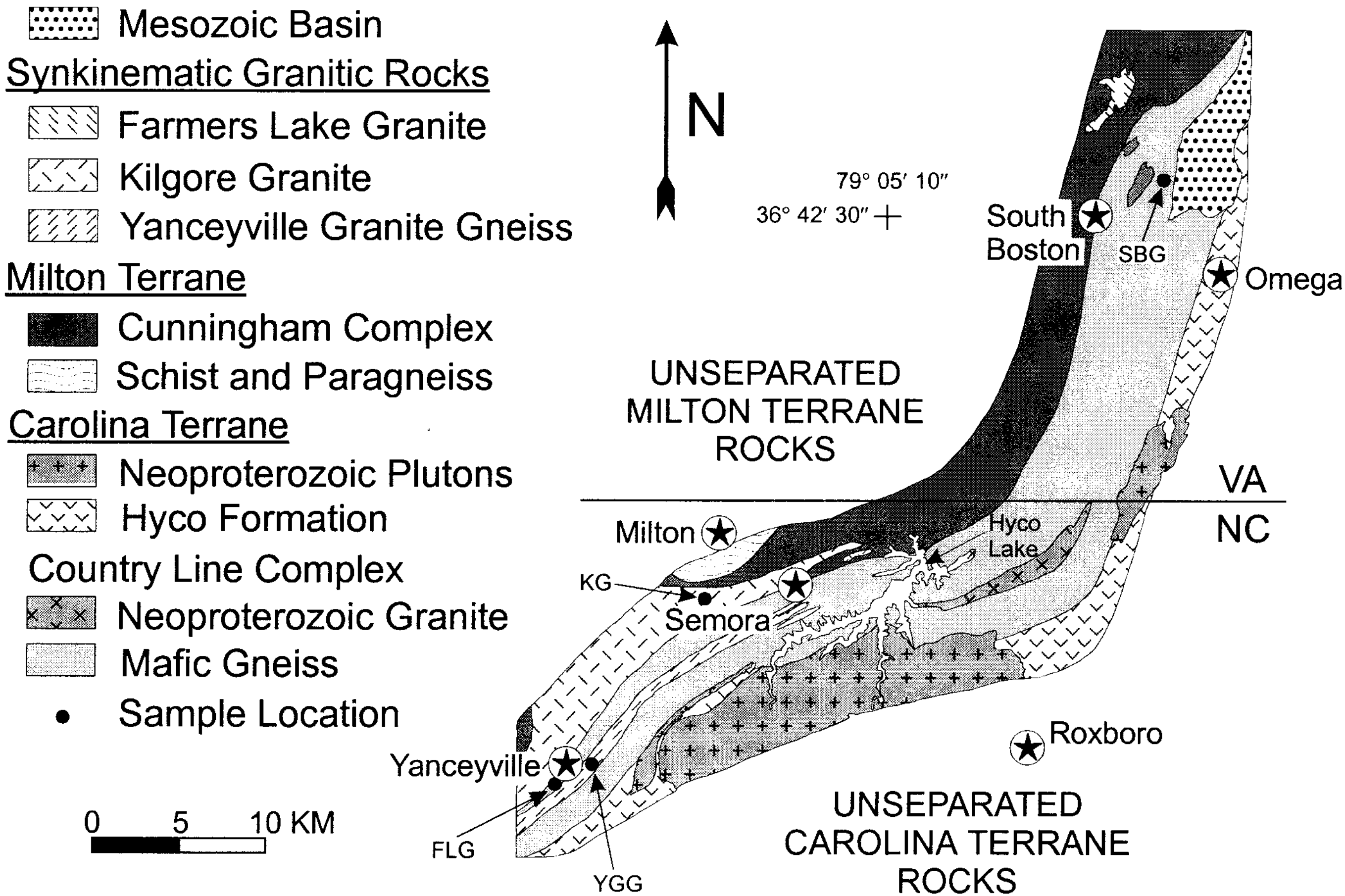

Fig. 2. General geology of the Milton and Carolina terranes within the Hyco shear zone, modified after Hibbard and others (this issue). The map approximates the boundaries of the shear zone. Portions of both terranes outside the shear zone are shown as unseparated rocks. See figure 1 for regional location. Sample locations are indicated and geographic coordinates are given in table 2. FLG = Farmers Lake granite KG = Kilgore granite SBG = South Boston gneiss YGG = Yanceyville granite gneiss.

TABLE 2
Sample locations

Sample	Latitude	Longitude	Remarks
Farmers Lake granite	36°23′43″	79°20′11″	Located along small creek 0.5 km south-southwest of Dillard Jr High School, Yanceyville, North Carolina
Yanceyville granite gneiss	36°24′25″	79°18′34″	Outcrop along state road 86, approx 1 km east of intersection with state road 62 near Yanceyville, North Carolina
Kilgore granite	36°29′15″	79°12′18″	Located approx 5 km west of Semora, North Carolina, along Kilgore Creek
South Boston gneiss	36°43′39″	78°50′44″	Outcrop in the Vulcan South Boston quarry, approx 5 km northwest of South Boston, Virginia

making the initial common Pb correction was estimated by using the Pb evolution model of Stacey and Kramers (1975). For titanite, the Pb isotopic composition of an acid-leached K-feldspar separate from the rock was used. All analytical uncertainties are reported at the 2σ level. Laboratory analytical blanks ranged from 1 to 10 picograms for Pb and from 0.5 to 1 picograms for U during the course of this study. All zircons were abraded prior to dissolution (Krogh, 1982).

$^{40}Ar/^{39}Ar$ Analysis

$^{40}Ar/^{39}Ar$ analysis of hornblende was performed, using the resistance furnace technique, at the CLAIR facility at the Massachusetts Institute of Technology (M.I.T.). Details of the analytical procedures and typical Ar blanks at M.I.T. are given in Hodges and others (1994). Hornblende grains were hand picked using a binocular microscope to assure that no grains contained adhering material. Following irradiation, the hornblende separate was heated under vacuum in a resistance furnace over fifteen temperature increments. Analytical errors for all Ar isotopic ratios for each temperature increment and for the irradiation parameter J are reported at the 2σ uncertainty level. We consider a plateau to be defined by three or more consecutive increments in the release spectra that constitute at least 50 percent of the total ^{39}Ar in the sample and have apparent ages that overlap within their 2σ uncertainties (not including uncertainties in the J value).

GEOCHRONOLOGIC RESULTS AND INTERPRETATION

Yanceyville Granite Gneiss

Results.–Four multigrain zircon fractions were analyzed from the Yanceyville granite gneiss (fig. 3 and table 3), all of which were of clear, pale yellow, euhedral crystals. Two different morphologies were observed in the zircons from this sample: fractions A and B contained acicular needles having aspect ratios of 8:1 or greater, whereas fractions C and D contained tetragonal prisms with aspect ratios of 2:1 to 4:1. The analyses define a linear array, anchored by a concordant data point (fig. 3). A regression line through all four analyses yields an upper intercept date of 335.4 ± 2.2 Ma and a lower intercept date of 41 ± 78 Ma (MSWD = 0.043).

Interpretation.–Although the Yanceyville metagranite intrudes the Neoproterozoic rocks of the Carolina terrane, the U-Pb systematics of the rock appear to be simple, with no evidence of older, inherited xenocrystic zircons. The upper intercept date, 335.4 ± 2.2 Ma, is interpreted as the crystallization age of this rock.

Hornblende Gneiss from the South Boston Layered Gneiss Sequence

Results.–Four multigrain zircon fractions consisting of clear, pale yellow, euhedral crystals were analyzed from the South Boston gneiss (fig. 4 and table 3). The zircons in three of the multigrain fractions consisted of stubby tetragonal prisms having aspect

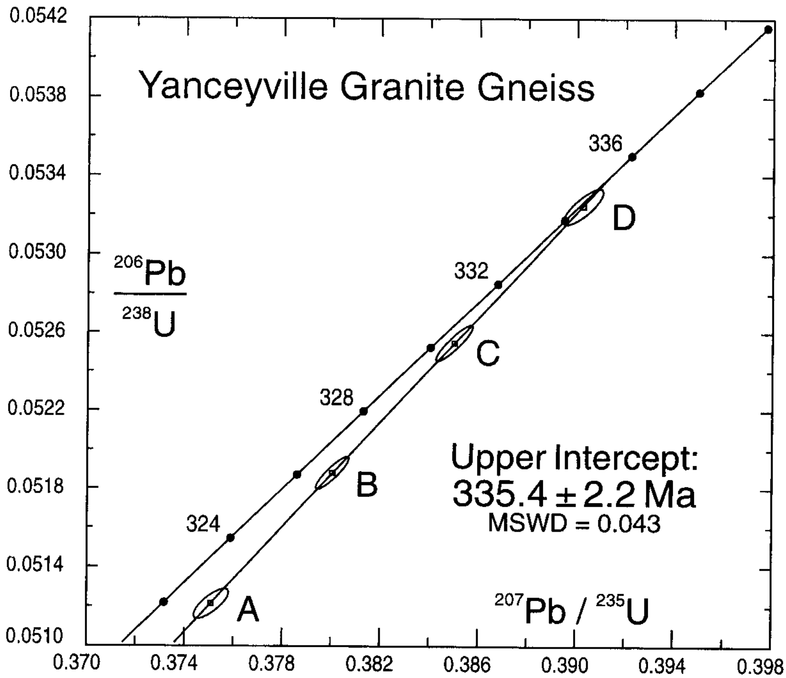

Fig. 3. U-Pb concordia diagram for zircon analyses of the Yanceyville granite gneiss. Labeled ellipses correspond to letters in table 1.

ratios between 2:1 and 4:1. A fourth multigrain fraction consisted of acicular needles having aspect ratios between 6:1 and 10:1. The multigrain zircon analyses (C-E) are discordant, have $^{207}Pb/^{206}Pb$ ages ranging from 332 to 452 Ma, but define a linear array. A regression line through these four analyses yields an upper intercept age of 615 ± 11 Ma and a lower intercept age of 322.8 ± 3.3 Ma (MSWD = 1.7).

Two pale pink, slightly cloudy single zircons also were analyzed. One of the zircons was a doubly terminated tetragonal prism about 0.5 mm long, with an aspect ratio of 5:1. It contained small, white to light gray, blade-like inclusions aligned parallel to the c-axis of the crystal. The other zircon crystal was about 0.4 mm long, with an aspect ratio of 2:1. The grain lacked well-defined crystal terminations, had a rounded morphology, but contained no visible inclusions. The presence of a fabric defined by inclusions in the first zircon crystal and the morphology of the second one suggests the possibility that they might be metamorphic zircons. Both the single zircon analyses (A and B) are concordant and have $^{207}Pb/^{206}Pb$ ages of 322.3 and 323.4 Ma, (fig. 4, inset, and table 3). A regression line (fig. 4) through the combined single and multigrain zircon analyses has an upper intercept with concordia of 613.9 ± 9.3 Ma and a lower intercept of 322.5 ± 2.7 Ma (MSWD = 0.87). These upper and lower intercepts are the same, within error, as those produced by regressing only the multigrain analyses.

Analysis of a titanite fraction from the rock yielded a slightly discordant $^{207}Pb/^{206}Pb$ date of 323 ± 6 Ma (fig. 4, inset, and table 3), an age identical to those of the single zircon analyses.

Hornblende separated from the rock yielded an internally discordant $^{40}Ar/^{39}Ar$ incremental-release age spectra (fig. 5 and table 4). The lower-temperature heating steps (1-9) yielded apparent ages ranging from 1608 to 333 Ma, probably related to excess argon, and released 6.8 cumulative percent of the gas. Heating steps 10 to 14 released

TABLE 3

U-Pb zircon and titanite data

Analysis	Total U (ng)	Total Pb (pg)	Total[a] Common Pb (pg)	Atomic Ratios $^{206}Pb^{b}/^{204}Pb$	$^{206}Pb^{c}/^{208}Pb$	$^{206}Pb^{d}/^{238}U$	% error	$^{207}Pb^{d}/^{235}U$	% error	$^{207}Pb^{d}/^{206}Pb$	% error	Ages (Ma) $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	Rho[e]
Yanceyville granite gneiss															
A (104)	35.00	1729	12.0	8930 (.55)	9.38	.0512125	.120	.375102	.157	.0531217	.100	322.0	323.4	334.0	.771
B (65)	27.80	1423	17.2	5230 (.20)	10.72	.0518813	.132	.380039	.147	.0531272	.065	326.1	327.1	334.2	.898
C (111)	24.70	1318	14.9	5450 (.19)	8.07	.0525475	.144	.384998	.160	.0531379	.067	330.1	330.7	334.7	.908
D (83)	27.40	1452	28.0	3250 (.62)	10.32	.0523450	.140	.390244	.174	.0531564	.100	334.4	334.6	335.5	.818
South Boston hornblende gneiss															
A (1)	3.44	176	6.5	1730 (.84)	9.98	.0513087	.464	.373866	.635	.0528475	.428	322.6	322.5	322.3	.738
B (1)	5.65	318	14.4	1290 (.47)	4.93	.0512881	.310	.373901	.415	.0528736	.271	322.4	322.5	323.4	.756
C (15)	12.30	660	13.8	2920 (.61)	7.10	.0520917	.234	.381185	.276	.0530721	.144	327.4	327.9	331.9	.853
D (11)	20.90	1228	7.3	10800 (.62)	16.55	.0611329	.084	.466207	.107	.0553099	.066	382.5	388.6	424.8	.785
E (90)	17.00	1047	10.7	6200 (1.70)	12.70	.0629426	.131	.483941	.221	.0557631	.176	393.5	400.8	443.0	.6071
F (103)	20.80	1322	4.9	16600 (1.90)	11.70	.0646419	.078	.499056	.108	.0559931	.074	403.8	411.1	452.1	.727
Titanite	464.94	26630	4100	384.8 (.10)	6.61	.0509182	.078	.371246	.294	.0528794	.262	320.3	320.6	323.6	.525
Kilgore granite															
A (1)	2.83	139	1.7	4700 (.75)	16.58	.0512414	.232	.374148	.246	.0529567	.079	322.1	322.7	327.0	.946
B (1)	4.24	207	3.8	3380 (.70)	19.45	.0513406	.301	.374881	.337	.0529580	.148	322.8	323.3	327.0	.899
C (1)	1.40	71	1.7	2200 (1.08)	11.56	.0515670	.310	.376551	.359	.0529604	.177	324.1	324.5	327.1	.871
D (1)	6.58	311	7.3	2720 (1.16)	27.59	.0501050	.251	.366821	.297	.0530972	.152	315.2	317.3	333.0	.858
E (1)	1.71	97	3.9	1550 (1.52)	11.64	.0578718	.495	.430540	.593	.0539566	.310	362.7	363.6	369.2	.853
F (1)	2.04	129	1.8	4070 (.92)	10.20	.0636603	.237	.481722	.254	.0548873	.088	397.9	399.3	407.6	.938
G (1)	1.35	72	6.6	703 (.49)	14.55	.0651914	.693	.411226	.747	.0550362	.265	340.2	349.8	413.7	.935
H (1)	1.01	59	1.8	1930 (1.54)	20.65	.0608178	.328	.476576	.415	.0568329	.244	380.6	395.7	485.1	.809
I (6)	2.55	129	5.2	1620 (.60)	13.60	.0518863	.457	.379960	.489	.0531109	.165	326.1	327.0	333.6	.942
J (15)	12.86	631	8.9	4650 (.90)	20.54	.0516743	.124	.378530	.154	.0531281	.090	324.8	326.0	334.3	.813
K (13)	10.45	508	8.9	3850 (.43)	34.33	.0521369	.147	.381940	.168	.0531312	.080	327.6	328.5	334.4	.880
L (23)	9.50	489	18.0	1728 (.33)	15.32	.0528172	.165	.390446	.193	.0536147	.098	331.8	334.7	354.9	.863
M (10)	3.00	157	4.2	2430 (.78)	17.22	.0543238	.292	.402266	.327	.0537059	.142	341.0	343.3	358.7	.901
N (8)	7.49	374	3.3	7530 (.67)	19.96	.0525882	.135	.390629	.154	.0538735	.074	330.4	334.8	365.8	.882
O (8)	6.78	378	7.0	3450 (1.01)	10.56	.0561975	.213	.418508	.254	.0540115	.134	352.5	355.0	371.5	.851
P (10)	14.86	747	9.9	4950 (.95)	17.54	.0524536	.121	.394265	.154	.0545145	.093	329.6	337.5	392.4	.798
Farmers Lake granite															
A (1)	13.70	678	2.0	16700 (.81)	11.32	.0503004	.466	.365986	.470	.0527706	.057	316.4	316.7	319.0	.993
B (1)	7.61	376	3.1	7500 (.54)	11.93	.0503914	.215	.366747	.224	.0527847	.065	316.9	317.2	319.6	.957
C (1)	4.63	227	1.9	6900 (.82)	13.66	.0505862	.219	.368198	.232	.0527896	.076	318.1	318.3	319.8	.945
D (1)	10.04	501	1.4	19100 (.80)	10.13	.0503797	.210	.366781	.217	.0528020	.057	316.9	317.3	320.3	.965
E (1)	3.80	188	2.5	4070 (.58)	11.24	.0500978	.221	.365246	.234	.0528769	.075	315.1	316.1	323.5	.947
F (1)	5.52	279	1.5	8500 (.78)	11.25	.0515012	.214	.376429	.224	.0530108	.068	323.7	324.4	329.3	.953
G (1)	1.53	101	2.6	1990 (.60)	10.48	.0661603	.257	.511391	.283	.0560601	.116	413.0	419.4	454.8	.912

Notes: Zircon analyses are indicated by letters. The number of grains for each zircon analysis is shown in parentheses. Data reduction follows Ludwig (1989, 1990).

[a] Includes common Pb in zircon (or titanite) and laboratory blank Pb.

[b] Measured ratio corrected for fractionation only. The fractionation correction used is 0.10% (±0.05%) amu^{-1} for static Faraday multicollector analyses and 0.18% (±0.07%) amu^{-1} for single Daly collector analyses. 2σ errors are indicated in parentheses after each ratio.

[c] Corrected for fractionation, spike, and blank.

[d] Corrected for fractionation, spike, blank, and initial common Pb. Quoted errors are at the 2σ confidence level (% for atomic ratios, absolute for ages). Pb blank ranged from 1–10 pg (±50%) during the course of the study; U blank is 0.5 pg (±50%). Composition of initial common Pb in zircon analyses was calculated using the two-stage Pb evolution model of Stacey and Kramers (1975). For the analysis of titanite from the South Boston quarry gneiss, initial common Pb was determined by analyzing a HF acid-leached K-feldspar separate from the rock: $^{206}Pb/^{204}Pb = 18.521$ $^{207}Pb/^{204}Pb = 15.625$ $^{208}Pb/^{204}Pb = 38.185$.

[e] $^{207}Pb/^{235}U - ^{206}Pb/^{238}U$ error correlation coefficient calculated following Ludwig (1989).

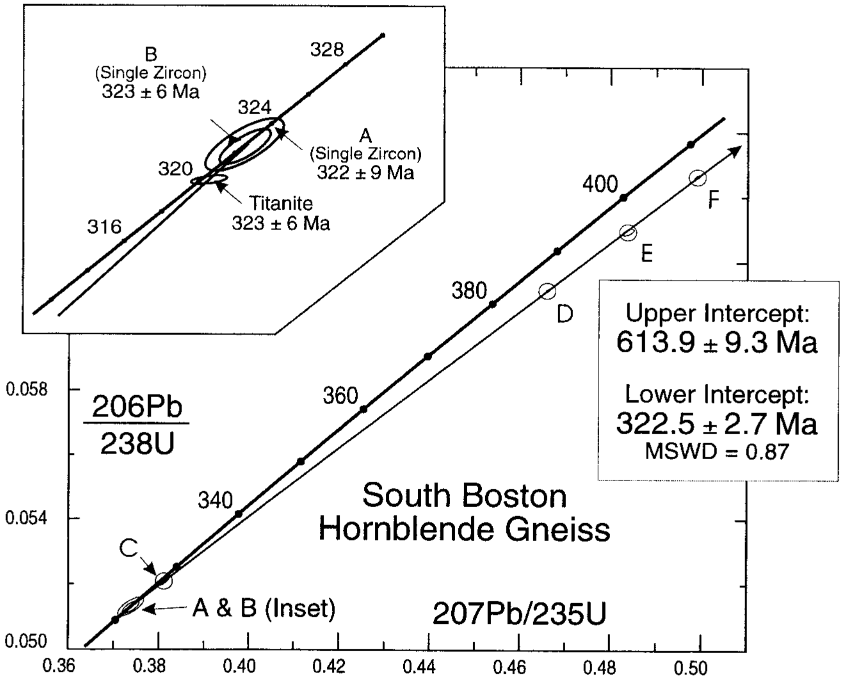

Fig. 4. U-Pb concordia diagram for zircon and titanite analyses of the South Boston hornblende gneiss. Labeled ellipses correspond to letters in table 1. Error ellipses for multigrain zircon analyses are circled for clarity. Inset diagram shows analyses of two single zircons and one titanite fraction from the gneiss.

93.2 cumulative percent of the gas and yielded concordant apparent ages, at the 2-sigma uncertainty level, that define a plateau age of 322.9 ± 2.8 Ma (error does not incorporate uncertainty in J-value) or 322.9 ± 7.8 Ma (error includes uncertainty in J-value). The 322.9 Ma plateau age agrees, within error, with the total gas age of 325.7 ± 6 Ma.

Interpretation (zircon U-Pb data).–One possible interpretation of the regression line (fig. 4) is that the two single zircons are magmatic, and thus their age of 323 Ma defines the crystallization age of the rock. In this interpretation, the upper intercept age of 614 Ma defines the age of a single inherited xenocrystic component. The upper intercept age is identical, within error, to reported ages for Carolina-terrane rocks near the shear zone (Glover and Sinha, 1973; Wortman, Samson, and Hibbard, 1995), and rocks such as these might have been a source of xenocrystic zircons. However, if xenocrysts of different ages had been analyzed in the multigrain fractions or if Pb loss had occurred in the xenocrysts prior to magmatic zircon growth, it is likely that the analyses would have defined a scattered, wedge-like pattern rather than a single line.

An alternative interpretation is that the regression line defines Pb loss: in this case, the upper intercept defines the crystallization or protolith age of the gneiss (614 Ma), and the lower intercept defines the timing of severe Pb loss during amphibolite-grade metamorphism, deformation, and magmatism within the shear zone. Episodic Pb loss during a discrete event would produce a linear array like the one observed for this rock. However, if the two concordant single zircons (A and B) originally crystallized at 614 Ma, then this second interpretation requires that the Pb isotope systematics of the two zircons were completely reset during metamorphism.

A third possibility is that the two concordant single zircons are metamorphic and that the regression line defines two-component mixing between older and younger

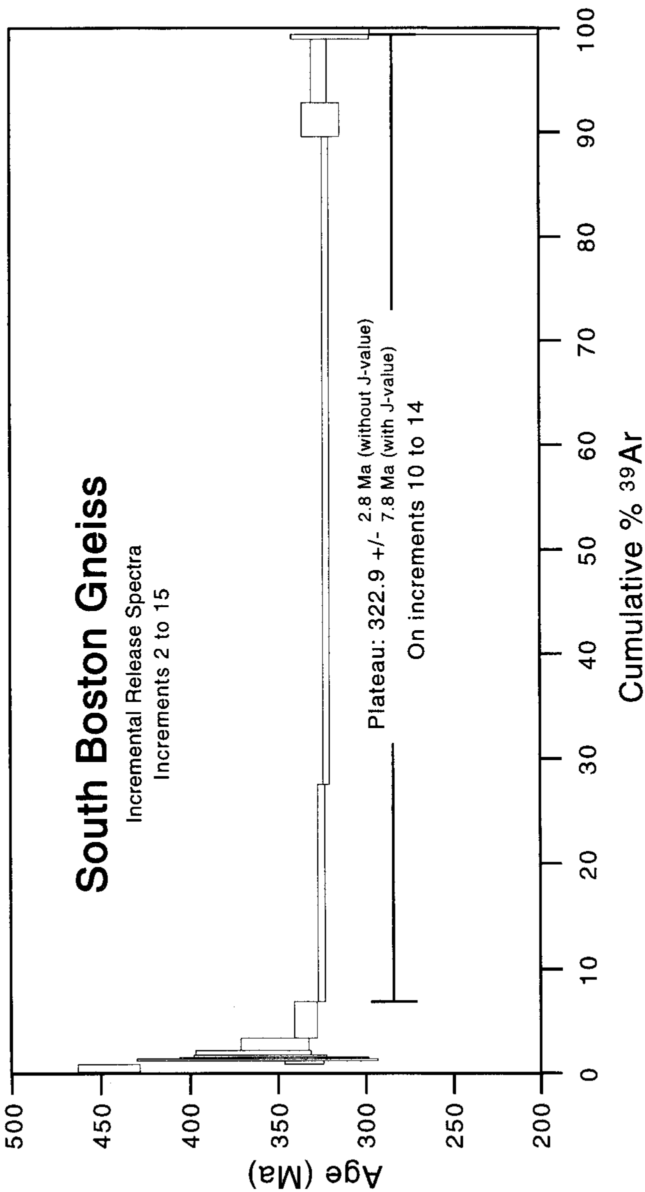

Fig. 5. $^{40}Ar/^{39}Ar$ incremental release spectra for a hornblende separate from the South Boston gneiss. The plateau is defined by increments 10 to 14.

TABLE 4

$^{40}Ar/^{39}Ar_k$ data for hornblende from the South Boston gneiss

Heating Increment	Temperature °K	$^{36}Ar/^{40}Ar$ ($\times 10^{-4}$)	$^{39}Ar/^{40}Ar$ ($\times 10^{-2}$)	$^{39}Ar_k$ ($\times 10^{-13}$ moles)	Cumulative Percent ^{39}Ar	$^{40}Ar^*$ (percent)	Apparent Age (Ma)
1	975	22.0 (0.299)	0.260 (0.035)	0.020	0.10	35.1	1608.8 ± 145.9 (144.7)
2	1100	19.4 (0.452)	1.619 (0.050)	0.146	0.84	42.6	445.3 ± 18.8 (17.4)
3	1150	3.7 (0.995)	4.659 (0.070)	0.065	1.17	89.1	334.3 ± 12.4 (11.1)
4	1175	0.0 (6.888)	4.807 (0.240)	0.034	1.35	100.0	361.1 ± 68.8 (68.6)
5	1200	0.0 (4.592)	4.954 (0.497)	0.031	1.50	100.0	351.4 ± 54.2 (53.9)
6	1225	1.8 (2.391)	4.568 (0.395)	0.043	1.72	94.5	359.3 ± 38.3 (37.9)
7	1250	0.4 (1.202)	4.714 (0.436)	0.086	2.16	98.7	363.4 ± 33.4 (32.9)
8	1275	0.0 (0.527)	4.959 (0.291)	0.228	3.32	100.0	351.1 ± 20.2 (19.4)
9	1300	0.1 (0.231)	5.233 (0.105)	0.693	6.84	99.7	333.4 ± 8.4 (6.5)
10	1350	0.4 (0.216)	5.347 (0.011)	4.079	27.59	98.8	324.2 ± 5.6 (2.0)
11	1400	0.0 (0.203)	5.465 (0.009)	12.190	89.60	100.0	321.3 ± 5.5 (1.8)
12	1450	0.0 (0.684)	5.418 (0.162)	0.639	92.85	100.0	323.9 ± 11.9 (10.7)
13	1500	0.0 (0.342)	5.401 (0.061)	1.186	98.88	100.0	324.7 ± 6.9 (4.5)
14	1550	0.0 (1.158)	5.522 (0.376)	0.083	99.31	100.0	318.2 ± 22.8 (22.2)
15	1950	10.5 (5.733)	5.181 (0.287)	0.136	100.00	68.9	238.9 ± 57.1 (57.0)

Plateau age: 322.9 ± 2.8 Ma (error does not incorporate uncertainty in J-value)
322.9 ± 7.8 Ma (error incorporated uncertainty in J-value)

Total gas age: 325.7 ± 6.0 Ma

Note: Values in parentheses after isotopic ratios indicate the 2σ uncertainties. Uncertainties in apparent ages obtained for each healing increment are ±2σ. The first value shown after each apparent age includes the uncertainty in the irradiation parameter J. The second value, given in parentheses, does not include the uncertainty in the J value (J = 0.01065 ± 0.00019).

zircon components. In this case, multigrain analyses C-F consist of composite zircons that contain 323 Ma metamorphic zircon overgrowths on ~614 Ma igneous zircons of the protolith.

Interpretation (titanite U-Pb data).–A multigrain titanite fraction was analyzed further to constrain interpretations of the zircon data. The 323 ± 6 Ma date for the titanite analysis, identical to those of the single zircon analyses, suggests that 323 Ma dates either the time of titanite formation (that is, metamorphic titanite) or complete isotopic resetting of 614 Ma igneous titanite. In either scenario, coincidence of the U-Pb titanite date with the zircon lower-intercept date of 323 Ma is considered strong evidence that significant deformation and metamorphism occurred at that time.

Interpretation (hornblende $^{40}Ar/^{39}Ar$ data).–The $^{40}Ar/^{39}Ar$ data for hornblende from this rock further suggests that significant deformation and metamorphism occurred at 323 Ma. $^{40}Ar/^{39}Ar$ dates constrain the time that a mineral last cooled through its closure temperature and began to retain significant quantities of radiogenic argon in its crystal structure. The closure temperature of hornblende has been shown to be dependent upon grain-size, cooling rate and, perhaps, composition (Harrison, 1981). An estimate of the average closure temperature for Ar in hornblende, such as that found in this rock, is 500° ± 25°C (Harrison, 1981). Thus, the 322.9 ± 7.8 Ma $^{40}Ar/^{39}Ar$ date for hornblende from this amphibolite facies hornblende gneiss is interpreted to reflect the time the rock cooled through ~500°C following peak metamorphism. These results are consistent with $^{40}Ar/^{39}Ar$ dates of 323 and 313 Ma for hornblende from strongly deformed and metamorphosed Milton-terrane rocks nearby (Kunk, Horton, and Peper, 1995).

Summary.–The protolith age of the South Boston gneiss cannot be definitively determined because there is not a unique interpretation of the significance of the U-Pb upper and lower intercept dates. However, on the basis of the U-Pb date for titanite in the gneiss and the $^{40}Ar/^{39}Ar$ date for hornblende in this rock and those in nearby Milton-terrane rocks, the simplest interpretation of the zircon data is that the upper intercept

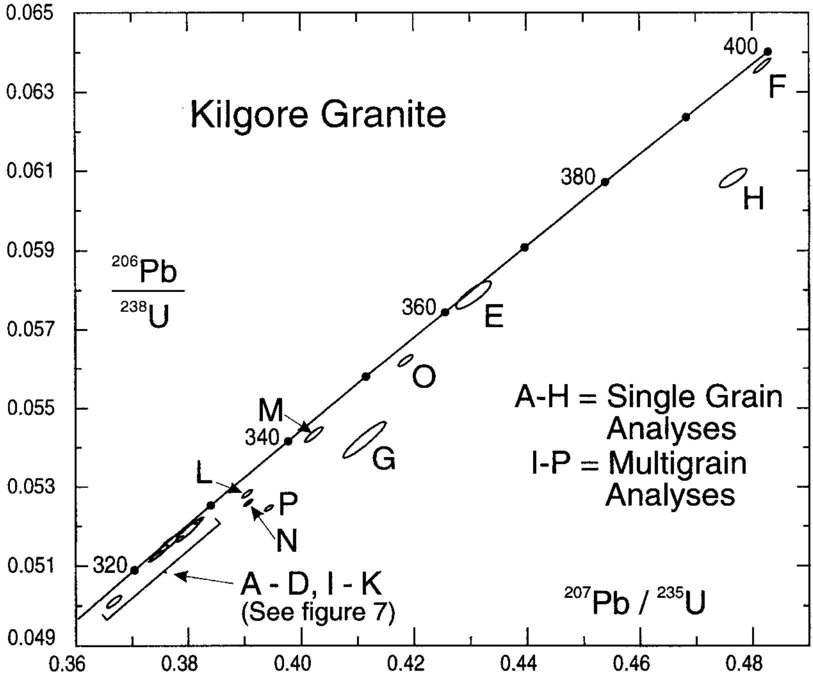

Fig. 6. U-Pb concordia diagram for all single- and multigrain-zircon analyses of the Kilgore granite. Labeled ellipses correspond to letters in table 1.

defines the age of the protolith of the gneiss (613.9 ± 9.3 Ma), whereas the lower intercept (322.5 ± 2.7 Ma) defines the timing of significant deformation and metamorphism of the gneiss.

Kilgore Granite

Results.–Eight multigrain zircon fractions were analyzed from the Kilgore granite (fig. 6 and table 1). Six of the fractions consisted of stubby tetragonal prisms with aspect ratios of 2:1 to 4:1, whereas two of them consisted of acicular needles. The zircons were euhedral, pale yellow, and free of opaque inclusions. The multigrain analyses (I-P) show a great deal of scatter with $^{207}Pb/^{206}Pb$ ages ranging from 334 to 392 Ma. The range in $^{207}Pb/^{206}Pb$ ages for the multigrain analyses indicates the presence of a complex, xenocrystic component in the zircons from this rock. It is extremely unlikely that a crystallization age for the rock could be obtained by multigrain zircon analyses alone. Therefore, eight single zircons (A-H) were analyzed to try to minimize the likelihood of analyzing xenocrystic components. However, the $^{207}Pb/^{206}Pb$ ages of the single zircon analyses range from 327 to 485 Ma (fig 6 and table 3).

Interpretation.–The complex, wedge-shaped pattern defined by the single- and multigrain zircon analyses indicates that this rock contains xenocrystic zircons with a variety of ages and Pb-loss histories. Figure 7 shows the younger single and multigrain zircon analyses from this rock (A-D and I-K) that define two distinct age populations. Four of the analyses (D, I, J, and K) have $^{207}Pb/^{206}Pb$ ages ranging from 333 to 334 Ma. A regression line through these four analyses yields an upper intercept with concordia of 335.2 ± 4 Ma and a lower intercept of 37 ± 101 Ma (MSWD = 0.085). Three single zircons (analyses A-C) are resolvably younger than this age. They have $^{207}Pb/^{206}Pb$ ages of 327 Ma, with one analysis less than 1 percent discordant (fig. 7) and are interpreted as

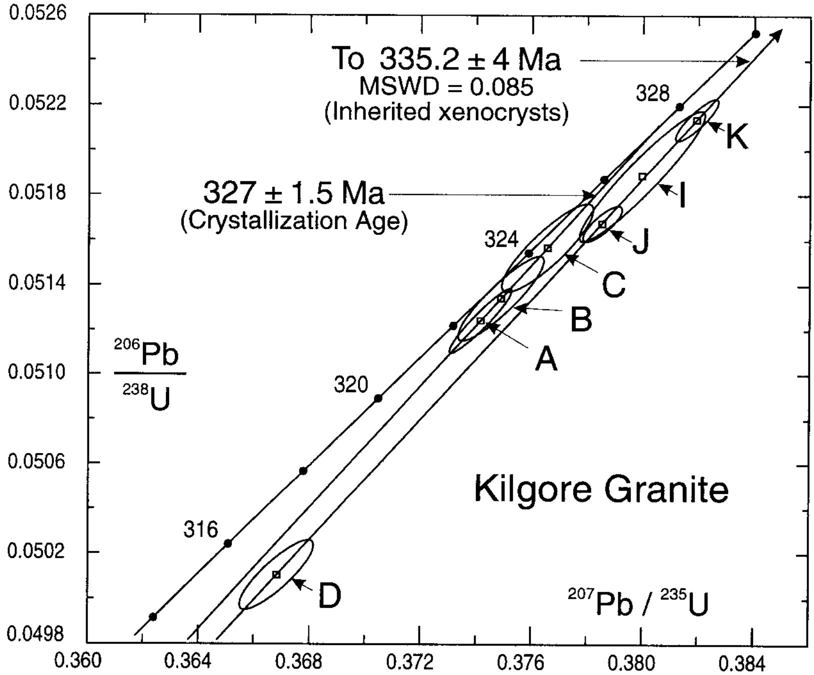

Fig. 7. U-Pb concordia diagram for youngest subset of zircon analyses of the Kilgore granite. Labeled ellipses correspond to letters in table 1. A to D = single zircon analyses I to K = multigrain zircon analyses.

free of inheritance. These analyses lie too close together to yield a meaningful regression age, thus a weighted mean of the $^{207}Pb/^{206}Pb$ dates was calculated, which is 327 ± 1.5 Ma. This date is interpreted to be the crystallization age of the Kilgore granite. The 335.2 Ma date, defined by analyses D, I, J, and K, is interpreted as the age of one population of xenocrystic zircons. A likely source of the 335 Ma xenocrystic zircons in the Kilgore granite is the nearby 335.4 ± 2.2 Ma Yanceyville granite gneiss.

Farmers Lake Granite

Results.–Five single zircons were analyzed from the Farmers Lake granite (fig. 8 and table 3). The crystals were clear, pale yellow, and free of opaque inclusions. The single zircon analyses are all discordant. Two zircons (analyses B and D) have $^{207}Pb/^{206}Pb$ ages of 319.6 and 320.3 Ma, whereas the other three zircons (analyses E-G) have older $^{207}Pb/^{206}Pb$ ages of 324, 329, and 455 Ma and are considered xenocrysts or containing xenocrystic cores. In an attempt to eliminate the possibility of analyzing zircon grains containing any core material, two zircon crystals were intentionally broken, and the tips from each crystal were heavily abraded and analyzed. The zircon tip analyses (A and C) have $^{207}Pb/^{206}Pb$ ages of 319 and 319.8 Ma, with one of them only 0.5 percent discordant.

Interpretation.–The analyses of the two youngest single zircons (B and D) and those of the zircon tips (A and C) are interpreted to be free of inheritance and thus reflect the time of crystallization of the Farmers Lake granite. The analyses are too close together to yield a meaningful regression age for the rock. The best estimate of the emplacement age of the granite is thus the weighted mean of the four $^{207}Pb/^{206}Pb$ ages, which is 319.6 ± 0.7 Ma.

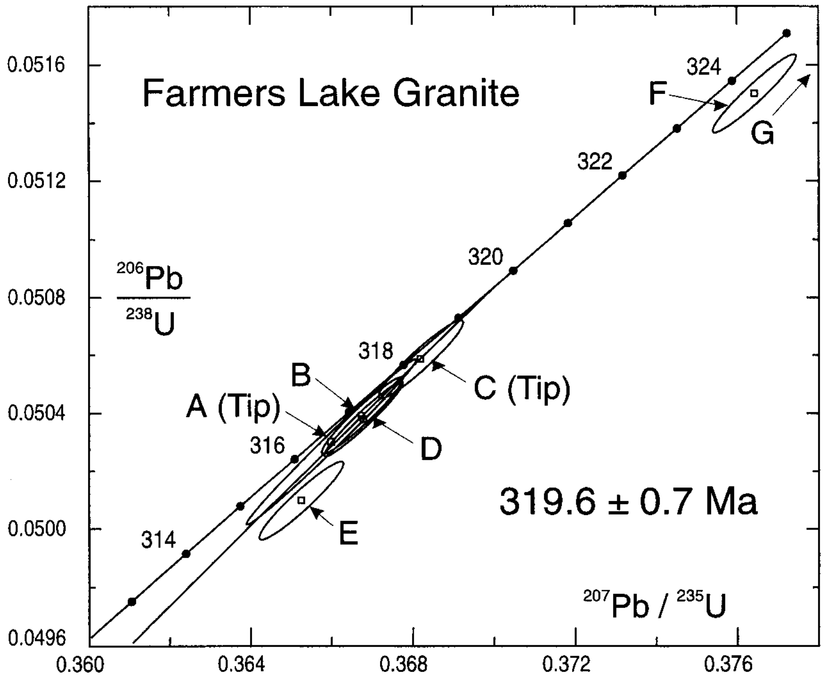

Fig. 8. U-Pb concordia diagram for zircon analyses of the Farmers Lake granite. Labeled ellipses correspond to letters in table 1. Analysis G lies off the diagram (indicated by arrow).

DISCUSSION

Timing Constraints on the Hyco Shear Zone

The onset of deformation in the Hyco shear zone is not constrained. However, field relationships document that deformation and metamorphism had begun by the 335.4 ± 2.2 Ma emplacement of the early-synkinematic Yanceyville granite gneiss. Continued deformation and metamorphism within the shear zone is indicated by the 327 ± 1.5 Ma crystallization age of the syn- to late-synkinematic Kilgore granite. The waning stages of deformation and metamorphism are constrained by the Farmers Lake granite and the South Boston hornblende gneiss. In the South Boston region, the 322.5 ± 2.7 Ma U-Pb zircon lower-intercept date, the 323 ± 6 Ma U-Pb titanite date, and the 322.9 ± 7.8 Ma $^{40}Ar/^{39}Ar$ hornblende date for the South Boston gneiss document that deformation and metamorphism had occurred, albeit in their waning stages, by 323 ± 3 Ma. Similar $^{40}Ar/^{39}Ar$ hornblende dates for a rock near the shear zone and in the central part of the Milton terrane (Kunk, Horton, and Peper, 1995) suggest the possibility that the entire terrane was affected by metamorphism related to tectonothermal activity associated with the Hyco shear zone. In the Hyco Lake region, the late-synkinematic Farmers Lake granite crosscuts main-phase deformational fabrics within the shear zone and post-dates most of the deformation. These field relations document that by 319.6 ± 0.7 Ma, the crystallization age of the Farmers Lake granite, deformation and metamorphism within the Hyco shear zone were in their final stages.

We emphasize that the ages of the granitic intrusive rocks are resolvable from one another within the quoted precision of the dates. Equally important is the fact that the chronology of emplacement of these granitic bodies, as documented by the U-Pb zircon dates, is consistent with, and indeed predicted by, field-based interpretations of the relative timing of their emplacement (Hibbard and others, this issue). These new U-Pb zircon dates provide the most stringent timing constraints on deformation and metamorphism reported for any part of the central Piedmont shear zone.

It must be emphasized that the Kilgore and Farmers Lake granites could not have been dated successfully by traditional approaches of analyzing multigrain fractions of zircon. The multigrain-analysis approach would have yielded geologically meaningless dates for these rocks because their zircon systematics are too complex. Only by analyzing single zircons or parts of zircons could precise ages of these rocks be established.

Comparison with Other Segments of the Central Piedmont Shear Zone

Having established robust timing constraints on the kinematic history of the Hyco shear zone, it can be compared, where adequate constraints exist, to the kinematic histories of more southerly segments of the central Piedmont shear zone. Here, published timing constraints on deformation and metamorphism along each fault segment of the central Piedmont shear zone are described and compared with those established for the Hyco shear zone (table 1).

Eufola fault.–The Eufola fault truncates the Kings Mountain shear zone (Milton, 1981; Goldsmith, Milton, and Horton, 1988) and, presumably, the Hyco shear zone (Hibbard and others, this issue). It is the southern extension of a group of southeast-dipping normal faults that also includes the Shacktown and Chatham faults (fig. 1). The last movement on this group of faults occurred during Mesozoic time. However, Robinson (1979) reported a Rb/Sr mica date of 321 Ma (no error quoted) for pegmatite interpreted as crosscutting pre-Mesozoic mylonites within the Chatham fault. On this basis, the Chatham fault and, by inference, the Shacktown and Eufola faults are suspected to be late Paleozoic structures that were reactivated during the Mesozoic. Although the history of late-Paleozoic motion along the Eufola fault is poorly constrained and is inferred indirectly, based on correlation with the Shacktown and Chatham faults, the Rb/Sr mica date reported by Robinson (1979) is in agreement with both the 319.6 $\pm$ 0.7 Ma U-Pb zircon date for the late-synkinematic Farmers Lake granite and the 322.5 $\pm$ 2.7 Ma U-Pb zircon lower intercept date for the South Boston gneiss. Thus, indirect evidence suggests that late Paleozoic tectonothermal activity in the Eufola fault zone occurred contemporaneously with that in the Hyco shear zone.

Kings Mountain shear zone.–Although deformation along the Kings Mountain shear zone is not constrained by dates on plutonic rocks that actually crosscut the zone, the available timing constraints are in agreement, for the most part, with those for the Hyco shear zone. The High Shoals granite pluton is a strongly deformed body that intrudes rocks of the Carolina terrane east of the shear zone. On the basis of structural relationships, Horton and others (1987) interpreted deformation of the High Shoals granite to have been synchronous with its crystallization. Horton and others (1987) reported a U-Pb date of 317 Ma for the High Shoals granite, based on analysis of one zircon fraction (slightly reversely discordant, two percent uncertainty quoted). LeHuray (1986) reported a U-Pb zircon date of ~320 Ma for the High Shoals granite, based on the analyses of two zircon fractions (also slightly reversely discordant, no errors quoted). An amphibolite-facies xenolith within the High Shoals pluton yielded a $^{40}Ar/^{39}Ar$ hornblende date of 318 $\pm$ 1.8 Ma, and country rocks southwest of the pluton, unaffected by contact metamorphism, yielded $^{40}Ar/^{39}Ar$ hornblende dates of 323 $\pm$ 2.6 and 321.5 $\pm$ 1.9 Ma (table 1; Horton and others, 1987). On the basis of these indistinguishable (within error) U-Pb zircon and $^{40}Ar/^{39}Ar$ hornblende dates, Horton and others (1987) interpreted intrusion of the High Shoals granite as being synchronous with deformation and regional metamorphism in Carolina-terrane rocks near the shear zone. Thus, along the eastern margin of the Kings Mountain shear zone, U-Pb zircon and $^{40}Ar/^{39}Ar$ hornblende dates constraining the final stages of deformation and metamorphism are identical, within error, to those in the Hyco shear zone.

Horton (1981) considered a suite of heterogeneously deformed spodumene-pegmatite dikes intruding rocks of the Inner Piedmont terrane, on the periphery of the shear zone, syn- to late-synkinematic. Kish (1977 and ms) reported a Rb/Sr whole-rock date of 345 ± 5 Ma for one of these dikes (table 1). Their peripheral location and the heterogeneity of the deformation make the true relationship between these dikes and the timing of motion in the shear zone uncertain. However, interpretation of these dikes as synkinematic intrusions (Horton, 1981) is in reasonable agreement with the 335.4 ± 2.2 Ma age of the synkinematic Yanceyville granite gneiss. The timing of metamorphism in Inner Piedmont terrane rocks adjacent to the Kings Mountain shear zone is not well constrained. Horton and others (1987) reported a $^{40}Ar/^{39}Ar$ total gas date of 355.9 Ma for hornblende from an amphibolite within the Inner Piedmont terrane, adjacent to the shear zone. However, the analysis yielded an $^{40}Ar/^{39}Ar$ release spectra with a complex, stair-step pattern rather than a well defined plateau, and the significance of the reported date is thus questionable. Horton and others (1987) regard the Kings Mountain shear zone, at least in part, as a metamorphic boundary because they consider the age of amphibolite-facies metamorphism in Inner-Piedmont-terrane rocks adjacent to the shear zone older than that in the opposing Carolina-terrane rocks. However, $^{40}Ar/^{39}Ar$ hornblende dates of 300 ± 6 and 296 ± 6 Ma were reported by Dallmeyer and others (1986) for Inner Piedmont rocks adjacent to the Cross Anchor shear zone, approx 30 km southward. Therefore, while the age of metamorphism in much of the Inner Piedmont terrane may be early to middle Paleozoic (Horton and others, 1987 and references therein), Alleghanian metamorphism has been documented in Inner-Piedmont-terrane rocks immediately adjacent to the central Piedmont shear zone, not far from the Kings Mountain shear zone. On this basis, the available geochronologic data are permissive of the interpretation that deformation and metamorphism within the Kings Mountain shear zone was synchronous with that of the Hyco shear zone.

Cross Anchor shear zone.–The Bald Rock granite and an unnamed metagranite constrain the early stages of deformation and metamorphism in the Cross Anchor shear zone. West (1997) interprets the Bald Rock granite as a rootless pluton that was cut by the Cross Anchor shear zone and is pre- or synkinematic with respect to motion along the shear zone. West (1997) also considers the unnamed metagranite, which lies within the zone, pre- or synkinematic with respect to the Cross Anchor shear zone. Dennis and Wright (1995) reported U-Pb zircon dates of 323 ± 3 Ma for the Bald Rock granite and 326 ± 3 Ma for the unnamed metagranite, documenting that the shear zone was active contemporaneously with the Hyco shear zone. Rb/Sr whole-rock dates on postkinematic plutons proximal to the Cross Anchor shear zone include a date of 278 ± 2 Ma for the Coronaca granite (Fullagar and Butler, 1979) and a date of 299 ± 9 Ma for the Cold Point granite (Fullagar, unpublished, reported in McSween, Speer, and Fullagar, 1991). A U-Pb zircon date of ~312 Ma ($^{207}Pb/^{206}Pb$ age, no errors quoted) also was reported for the Cold Point granite (Stern and Nelson, unpublished, reported in Horton and McConnell, 1991). The isotopic dates for the Cold Point granite, particularly the U-Pb zircon date, are very similar to the date for the late-synkinematic Farmers Lake granite in the Hyco shear zone. This indicates that deformation in the Cross Anchor shear zone ended at a time similar to, or closely following, the end of deformation in the Hyco shear zone.

Timing constraints on cooling of Inner Piedmont and Carolina-terrane rocks in the vicinity of the Cross Anchor shear zone following peak-metamorphism come from $^{40}Ar/^{39}Ar$ dates for hornblende and biotite reported by Dallmeyer and others (1986; table 1). They report $^{40}Ar/^{39}Ar$ plateau dates of 300 ± 6 and 296 ± 6 Ma for hornblende from two Inner-Piedmont-terrane rocks along the shear zone. $^{40}Ar/^{39}Ar$ plateau dates for hornblende from seven Carolina-terrane rocks in the vicinity of the shear zone range from 310 ± 6 to 289 ± 5 Ma, similar to those of the Inner-Piedmont-terrane rocks. Two rocks yielded younger $^{40}Ar/^{39}Ar$ hornblende dates of 280 ± 6 and 278 ± 6 Ma. Dallmeyer and others (1986) reported $^{40}Ar/^{39}Ar$ dates of 272 ± 5, 271 ± 5, and 259 ± 5 Ma for biotite from Inner-Piedmont-terrane rocks near the shear zone. $^{40}Ar/^{39}Ar$ dates for biotite from most Carolina-terrane rocks near the shear zone range from 291 ± 5 to 265 ± 4 Ma. Three rocks yielded younger $^{40}Ar/^{39}Ar$ dates of 255 ± 5, 251 ± 5, and 243 ± 4 Ma. One rock yielded an anomalously high $^{40}Ar/^{39}Ar$ biotite date of 313 ± 6 Ma, older than the 302 ± 6 Ma date for hornblende in the same rock, which was attributed to extraneous argon contamination. Dallmeyer and others (1986) interpreted these ranges of hornblende and biotite dates as approximating the time at which the minerals had cooled through their respective closure temperatures following Alleghanian metamorphism (~500°C for hornblende, 310-278 Ma, and ~300°C for biotite, 292-243 Ma). However, the rocks with the young $^{40}Ar/^{39}Ar$ hornblende and biotite dates occur in what has recently been recognized as an Inner-Piedmont-terrane window within the Carolina terrane (West, 1997). Excluding the anomalously young dates for rocks within the Inner-Piedmont-terrane window, the range in $^{40}Ar/^{39}Ar$ dates of Inner Piedmont and Carolina-terrane rocks near the shear zone is significantly narrower. $^{40}Ar/^{39}Ar$ dates range from 310 ± 6 to 289 ± 6 Ma for hornblende and from 292 ± 5 to 259 ± 5 Ma for biotite (table 1). The $^{40}Ar/^{39}Ar$ hornblende dates are somewhat younger than those for the South Boston hornblende gneiss and adjacent Milton terrane rocks (323-313 Ma). These younger dates indicate that metamorphism in the region of the Cross Anchor shear zone might have ended later than in the region of the Hyco shear zone. Alternatively, rocks in the Cross Anchor shear zone region might have been subject to a slower cooling rate than those proximal to the Hyco shear zone.

Ocmulgee fault.–The timing of deformation in the Ocmulgee fault is unconstrained. The timing of metamorphism within the Ocmulgee fault is loosely constrained by a single date for zircons from an unspecified location within the fault zone. Student and Sinha (1992) reported a U-Pb lower-intercept date of 330 Ma and an upper-intercept date of 1364 Ma. These authors interpret the lower-intercept date as the time of Pb loss (or U gain) induced by metamorphism. No errors are reported for this date, which is based on a regression through three zircon analyses. However, Student and Sinha (1992) reported that the least discordant of the analyses had U-Pb ages that differed by 5 Ma. This date, within its probable uncertainties, overlaps the dates constraining the final stages of deformation documented along the Hyco, Kings Mountain, and Cross Anchor shear zones, and the $^{40}Ar/^{39}Ar$ hornblende dates constraining metamorphism on the Hyco and Kings Mountain shear zones.

Implications for the Central Piedmont Shear Zone

Comparison of the kinematic history of the Hyco shear zone, documented in this paper, with what is known of the kinematic histories of other fault and shear zone segments considered part of the central Piedmont shear zone indicates that, within the errors of the timing constraints, there is significant overlap with one another. This observation is permissive of the interpretation that all the fault segments of the central Piedmont shear zone underwent deformation and metamorphism contemporaneously. Such an interpretation suggests the possibility that the central Piedmont shear zone constitutes all, or part of, a single Alleghanian shear zone of such proportions as the great Appomattox overthrust proposed by Jonas (1932). Obviously, this proposition requires further testing. The timing of deformation and metamorphism in some of the fault segments of the shear zone is poorly constrained or not constrained at all. Furthermore, the regional extent of the central Piedmont shear zone northeast of the Hyco shear zone and southwest of the Ocmulgee fault still is uncertain.

CONCLUSIONS

The Hyco shear zone is a fundamental tectonic boundary that separates strongly contrasting rocks of the Milton and Carolina terranes. Thus far, it is the northernmost recognized segment of the central Piedmont shear zone, an orogen-scale system of ductile fault zones that separates rocks of the Piedmont zone from rocks of the Carolina zone. New, precise U-Pb zircon dates for prekinematic, synkinematic, and late-synkinematic gneisses and granites within the Hyco shear zone demonstrate that this portion of the central Piedmont shear zone was active by 335 ± 2 Ma (mid-Mississippian time) and that by 320 ± 1 Ma (latest Mississippian time) deformation and metamorphism were in their final stages.

Available constraints on the kinematic history of some more southerly segments of the central Piedmont shear zone indicate that deformation and metamorphism were occurring along the entire shear zone at roughly the same time as along the Hyco shear zone. This observation is permissive of a model for the central Piedmont shear zone as a single, orogen-scale Alleghanian structure that may extend, based on proposed correlation with more northerly fault zones, from Georgia into the central Appalachians.

Results of this study also document the futility of analyzing large, multigrain zircon fractions when applying conventional U-Pb zircon techniques to dating rocks that contain complex, multi-age zircon populations. Ion microprobe techniques, although ideally suited to dating parts of zircons, could not produce adequately precise U-Pb dates because of the very young ages of these rocks. Thus, although difficult and time consuming, analysis of single zircons and parts of zircons by low Pb-blank thermal-ionization techniques is the only reliable method to determine precisely the ages of these complex late Paleozoic granites.

ACKNOWLEDGMENTS

This work has been supported by grants from the National Science Foundation to SDS (EAR-9219583) and JPH (EAR-9219979). We thank K. V. Hodges and B. Olszewski at M.I.T. for $^{40}Ar/^{39}Ar$ analysis of hornblende from the South Boston gneiss. A. J. Dennis, D. T. Secor, R. Tucker, and an anonymous reviewer are thanked for insightful comments that improved the manuscript. Thanks to D. G. Coler, G. S. Shell, and J. K. Wilkins for discussions in the field and assistance in sample collection.

REFERENCES

Bradley, P. J., ms, 1996, The structural relationship between the Hyco shear zone and the Milton terrane in the South Boston, Virginia area: M.S. thesis, North Carolina State University, Raleigh, North Carolina, 86 p.

Butler, J. R., 1980, Review of potential host rocks for radioactive waste disposal in the piedmont province of North Carolina: report to E. I. du Pont de Nemours and Company, Report DP-1562, 47 p.

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 the tectonothermal evolution of the eastern Piedmont in South Carolina: Geological Society of America Bulletin, v. 97, p. 1329–1344.

Dennis, A. J., 1991, Is the central Piedmont suture a low-angle normal fault?: Geology, v. 19, p. 1081–1084.

——— 1995, The Carolina terrane in northwestern South Carolina: Relative timing of events and recent tectonic models, *in* Hibbard, J. P., van Staal, C. R., and Cawood, P. A., editors, Current Perspectives in the Appalachian-Caledonian Orogen: Geological Association of Canada Special Paper 41, p. 173–189.

Dennis, A. J., and Wright, J. E., 1995, Mississippian (ca. 326-323 Ma) U-Pb crystallization ages for two granitoids in Spartanburg and Union counties, South Carolina: South Carolina Geology, v. 38, p. 23–28.

Glover, L., III, and Sinha, A. K., 1973, The Virgilina deformation, a late Precambrian to early Cambrian(?) orogenic event in the central Piedmont of Virginia and North Carolina: American Journal of Science, v. 273-A, p. 234–251.

Glover, L., III, Sinha, A. K., Higgins, M. W., and Kirk, W. S., 1971, U-Pb dating of Carolina slate belt and Charlotte belt rocks, Virgilina district, Virginia and North Carolina: Geological Society of America Abstracts with Programs, v. 3, no. 5, p. 313.

Goldsmith, R., Milton, D. J., and Horton, J. W., Jr., 1988, Geologic map of the Charlotte 1° × 2° quadrangle, North Carolina and South Carolina: United States Geological Survey Miscellaneous Investigations Series Map I-1251-E, scale 1:250,000.

Griffin, V. S., Jr., 1979, Geology of the Abbeville East, Abbeville West, Latimer, and Lowndesville quadrangles, South Carolina: South Carolina Geological Survey, MS-24, 58 p.

Fullagar, P. D., and Butler, J. R., 1979, 325 265 m.y.-old granitic plutons in the Piedmont of the southeastern Appalachians: American Journal of Science, v. 279, 161–185.

Hanley, T. B., Chalokwu, C. I., and Steltenpohl, M. G., 1997, Constraints on the location of the Carolina/Avalon terrane boundary in the southernmost exposed Appalachians, western Georgia and eastern Alabama, *in* Glover, L., III, and Gates, A. E., editors, Central and Southern Appalachian Sutures: Results of the EDGE Project and Related Studies: Boulder Colorado, Geological Society of America Special Paper 314, p. 15–24.
Harrison, T. M., 1981, Diffusion of ^{40}Ar in hornblende: Contributions to Mineralogy and Petrology, v. 78, p. 324–331.
Hatcher, R. D., 1987, Tectonics of the southern and central Appalachian internides: Annual Review of Earth and Planetary Sciences, v. 15, p. 337–362.
——— 1989, Tectonic synthesis of the U.S. Appalachians, *in* Hatcher, R. D., Jr., Thomas, W. A., and Viele, G. W., editors, The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, The Geology of North America, v. F-2, p. 233–318.
Hatcher, R. D., and Zietz, I., 1980, Tectonic implications of regional aeromagnetic and gravity data from the southern Appalachians, *in* Wones, D. editor, Proceedings, the Caledonides in the U.S.A., Virginia Polytechnical Institute and State University, Blacksburg, Virginia, Memoir 2, p. 83–90.
Hibbard, J. P., 1993, The Milton belt-Carolina slate belt boundary: The northern extension of the central Piedmont suture?, *in* Hatcher, R. D. and Davis, T., editors, Studies of Inner Piedmont Geology: 1993 Carolina Geological Society Guidebook, p. 85–89.
Hibbard, J. P., and Samson, S. D., 1995, Orogenesis exotic to the Iapetan cycle in the southern Appalachians, *in* Hibbard, J. P., van Staal, C. R., and Cawood, P. A., editor, Current Perspectives in the Appalachian-Caledonian Orogen: Geological Association of Canada Special Paper 41, p. 191–205.
Hibbard, J., Shell, G., Bradley, P., Samson, S., and Wortman, G., 1998, The Hyco shear zone in North Carolina and Southern Virginia: implications for the Piedmont zone-Carolina zone boundary in the southern Appalachians: American Journal of Science, v. 298, p. 85–107.
Hodges, K. V., Hames, W. E., Olszewski, W., Burchfiel, B. C., Royden, L. H., and Chen, Z., 1994, Thermobarometric and ^{40}Ar/^{39}Ar geochronologic constraints on Eohimalayan metamorphism in the Dinggyê area, southern Tibet: Contributions to Mineralogy and Petrology, v. 117, p. 151–163.
Hooper, R. J., and Hatcher, R. D., 1990, The Ocmulgee fault: The Piedmont-Avalon terrane boundary in central Georgia: Geology, v. 18, p. 708–711.
——— 1997, The character of the Avalon terrane and its boundary with the Piedmont terrane in central Georgia, *in* Glover, L., III, and Gates, A. E., editors, Central and Southern Appalachian Sutures: Results of the EDGE Project and Related Studies: Boulder Colorado, Geological Society of America Special Paper 314, p. 1–14.
Horton, J. W., Jr., 1981, Shear zone between the Inner Piedmont and Kings Mountain belts in the Carolinas: Geology, v. 9, p. 28–33.
Horton, J. W., Jr., Drake, A. A., Jr., and Rankin, D. W., 1989, Tectonostratigraphic terranes and their Paleozoic boundaries in the central and southern Appalachians, *in* Dallmeyer, R. D., editor, Terranes in the circum-Atlantic Paleozoic orogens: Boulder, Colorado, Geological Society of America Special Paper 230, p. 213–245.
Horton, J. W., Jr., and McConnell, K. I., 1991, The western Piedmont, in Horton, J. W., Jr., and Zullo, V. A., editors, The Geology of the Carolinas: Knoxville, Tennessee, University of Tennessee Press, p. 36–58.
Horton, J. W., Jr., Sutter, J. F., Stern, T. W., and Milton, D. J., 1987, Alleghanian deformation, metamorphism, and granite emplacement in the central Piedmont of the southern Appalachians: American Journal of Science, v. 287, p. 635–660.
Hund, E., ms, 1987, U-Pb dating of granites from the Charlotte belt of the southern Appalachians: M.S. thesis, Virginia Polytechnical Institute and State University, Blacksburg, Virginia, 73 p.
Jonas, A. I., 1932, Structure of the metamorphic belt of the southern Appalachians: American Journal of Science, v. 224, p. 228–243.
Kish, S. A., ms, 1983, A geochronological study of deformation and metamorphism in the Blue Ridge and Piedmont of the Carolinas: Ph.D. Thesis, University of North Carolina, Chapel Hill, North Carolina, 220 p.
Kish, S. A., 1977, Geochronology of plutonic activity in the Inner Piedmont and Kings Mountain belt of North Carolina, *in* Burt, E. R., editor, Field guides for Geological Society of America: Winston-Salem, North Carolina, Southeastern Section Meeting, p. 144–149.
Krogh, T. E., 1982, Improved accuracy of U-Pb zircon ages by the creation of more concordant systems using an air abrasion technique: Geochimica et Cosmochimica Acta, v. 46, p. 637–649.
Kunk, M., Horton, W., and Peper, J., 1995, Preliminary ^{40}Ar/^{39}Ar mineral ages from the Raleigh metamorphic belt, Carolina slate belt, and Milton belt in the South Boston, Virginia, North Carolina 30 × 60 quadrangle: Geological Society of America Abstracts with Programs, v. 27, no. 2, p. 67.
LeHuray, A. P., 1986, Isotopic evidence for a tectonic boundary between the Kings Mountain and Inner Piedmont belts, southern Appalachians: Geology, v. 14, p. 784–787.
Ludwig, K. R., 1989, PBDAT: a computer program for processing raw Pb-U-Th isotope data: United States Geological Survey Open File Report 88-557, 39 p.
——— 1990, ISOPLOT: a plotting and regression program for radiogenic-isotope data: United States. Geological Survey Open-File Report 90-445, 39 p.
McBride, J. H., and Nelson, K. D., 1991, Deep seismic reflection constraints on Paleozoic crustal structure and definition of the Moho in the buried southern Appalachian orogen, *in* Meissner, R., Brown, L., Dürbaum, H. J., Franke, W., Fuchs, K., and Seifert, F., editors, Continental Lithosphere: Deep Seismic Reflections: American Geophysical Union, Geodynamics Series, v. 22, p. 9–20.
McSween, H. Y., Jr., Speer, J. A., and Fullagar, P. D., 1991, Plutonic rocks, *in* Horton, J. W., Jr., and Zullo, V. A., editors, The Geology of the Carolinas: Knoxville, Tennessee, University of Tennessee Press, p. 109–126.

Milton, D. J., 1981, The northern termination of the Kings Mountain belt, *in* Horton, J. W., Jr., Butler, J. R., and Milton, D. J., editors, Geological investigations of the Kings Mountain belt and adjacent areas in the Carolinas, Carolina Geological Society, Field Trip Guidebook 1981: Columbia, South Carolina Geological Survey, p. 1–5.

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

Robinson, G. R., 1979, Pegmatite cutting mylonite-evidence supporting pre-Triassic faulting along the western border of the Danville Triassic basin, southern Virginia: Geological Society of America Abstracts with Programs, v. 11, p. 210.

Samson, S. D., 1995, Is the Carolina terrane part of Avalon?, *in* Hibbard, J. P., van Staal, C. R., and Cawood, P. A., editors, Current Perspectives in the Appalachian-Caledonian Orogen: Geological Association of Canada Special Paper 41, p. 207–223.

Secor, D., 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., Snoke, A. W., Bramlett, K. W., Costello, O. P., and Kimbrell, 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.

Shell, G. S., ms, 1996, Nature of the Carolina slate belt–Milton belt boundary near Yanceyville, North Carolina: M.S. thesis, North Carolina State University, Raleigh, North Carolina, 96 p.

Stacey, J. S., and Kramers, J. D., 1975, Approximation of terrestrial lead isotope evolution by a two-stage model: Earth and Planetary Science Letters, v. 26, p. 207–221.

Student, J. J., and Sinha, A. K., 1992, Carboniferous U-Pb ages of zircons from the Box Ankle and Ocmulgee faults, central Georgia: Implications for accretionary models: Geological Society of America Abstracts with Programs, v. 24, no. 2, p. 69.

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.

West, T., 1997, Structural studies along the Carolina-Inner Piedmont terrane boundary in South Carolina and Georgia: Implications for the tectonics of the Southern Appalachians: Columbia, South Carolina, University of South Carolina, 97 p..

West, T., Secor, D. T., Jr., Pray, J., Boland, I., and Mahar, H., 1995, New field evidence for an exposure of the Appalachian decollement at the east end of the Pine Mountain terrane, Georgia: Geology, v. 23, p. 621–624.

Williams, H., and Hatcher, R. D., 1982, Suspect terranes and accretionary history of the Appalachian orogen: Geology, v. 10, 530–536.

——— 1983, Appalachian suspect terranes, *in* Hatcher, R. D., Williams, H., and Zietz, I., editors, Contributions to the tectonics and geophysics of mountains: Boulder, Colorado, Geological Society of America Memoir 158, p. 33–53.

Wortman, G. L., Samson, S. D., and Hibbard, J. P., 1995, U-Pb Zircon geochronology of the Milton and Carolina slate belts, southern Appalachians: Geological Society of America Abstracts with programs, v. 27, no. 2, p. 98.

——— 1996, Discrimination of the Milton belt and Carolina terrane in the southern Appalachians: a Nd isotopic approach: Journal of Geology, v. 104, p. 239–247.