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NORTHWARD EXTENSION OF CAROLINA SLATE BELT STRATIGRAPHY AND STRUCTURE, SOUTH-CENTRAL VIRGINIA: RESULTS FROM GEOLOGIC MAPPING

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ABSTRACT. Geologic mapping in south-central Virginia demonstrates that the stratigraphy and structure of the Carolina slate belt extend northward across a steep thermal gradient into upper amphibolite-facies correlative gneiss and schist. The Neoproterozoic greenschist-facies Hyco, Aaron, and Virgilina Formations were traced northward from their type localities near Virgilina, Virginia, along a simple, upright, northeast-trending isoclinal syncline. This syncline is called the Dryburg syncline and is a northern extension of the more complex Virgilina synclinorium. Progressively higher-grade equivalents of the Hyco and Aaron Formations were mapped northward along the axial trace of the refolded and westwardly-overturned Dryburg syncline through the Keysville and Green Bay 7.5-minute quadrangles, and across the northern end of the Carolina slate belt as interpreted on previous geologic maps. Hyco rocks, including felsic metatuff, metawacke, and amphibolite, become gneisses upgrade with areas of local anatexis and the segregation of granitic melt into leucosomes with biotite selvages. Phyllite of the Aaron Formation becomes garnet-bearing mica schist. Aaron Formation rocks disconformably overlie the primarily felsic volcanic and volcaniclastic rocks of the Hyco Formation as evidenced by repeated truncation of internal contacts within the Hyco on both limbs of the Dryburg syncline at the Aaron-Hyco contact. East-northeast-trending isograds, defined successively by the first appearance of garnet, then kyanite ± staurolite in sufficiently aluminous rocks, are superposed on the stratigraphic units and synclinal structure at moderate to high angles to strike. The textural distinction between gneisses and identifiable sedimentary structures occurs near the kyanite ± staurolite-in isograd. Development of the steep thermal gradient and regional penetrative fabric is interpreted to result from emplacement of the Goochland terrane adjacent to the northern end of the slate belt during Alleghanian orogenesis. This mapping study indicates that the Carolina slate belt does not terminate on the north against through-going faults or rest on higher-grade basement as previously suggested.

INTRODUCTION

The Carolina slate belt and higher-grade rocks of the adjacent Charlotte terrane are considered to represent major crustal components of the exotic Carolina Zone sutured into the Appalachians during Paleozoic construction of the orogen (fig. 1) (Hibbard and others, 2002). In this paper, we focus on the northernmost termination of greenschist-facies rocks of the Carolina slate belt in an area which lies across what has been interpreted as a terrane boundary or fault on regional geologic maps (Horton and others, 1991; Virginia Division of Mineral Resources, 1993). Stratigraphic and structural relationships observed in our mapping study indicate that the classic greenschist-facies metasedimentary and metavolcanic stratigraphic sequence of the northern Carolina slate belt, the Neoproterozoic Virgilina sequence (Laney, 1917), continues northward unbroken into an area of lithologically-correlative medium- to high-grade gneisses. This is an important result because previous workers had concluded that the gneisses at the northern boundary represented either an older basement upon which the Carolina slate belt succession rested in unconformable or

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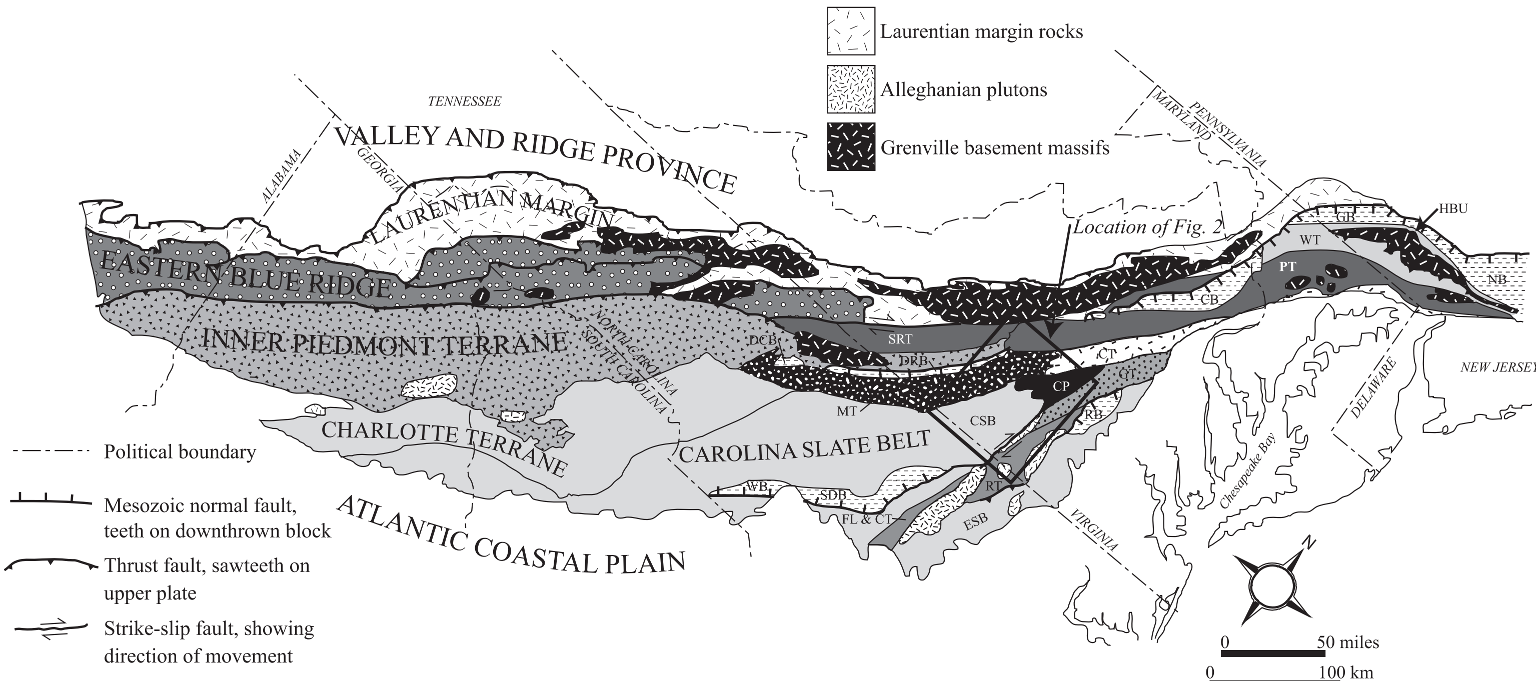

Fig. 1. Index map showing tectonic elements of the central and southern Appalachians and the previously interpreted northern termination of the Carolina slate belt (CSB) of Virginia. CP = Central Piedmont (as designated by the Virginia Division of Mineral Resources, 1993), GT = Goochland terrane, RT = Raleigh terrane, FLT = Falls Lake terrane, CT = Crabtree terrane, ESB = eastern slate belt, WT = Westminster terrane, HBU = Honeybrook Upland, MT = Milton terrane, PT = Potomac terrane, SRT = Smith River terrane, CT = Chopawamsic terrane, NB = Newark basin, GB = Gettysburg basin, CB = Culpeper basin, RB = Richmond basin, SDB = Sanford-Durham basin, WB = Wadesboro basin, DCB = Davies County basin, DRB = Dan River basin. From Glover and others (1983), Horton and others (1989), Virginia Division of Mineral Resources (1993), and Hibbard and others (2006). The Charlotte terrane and Carolina slate belt together are considered to represent major components of the exotic Carolina Zone of Hibbard and others (2002).

fault contact (Laney, 1917), or that an unspecified fault or terrane boundary defined the northern extent of the slate belt (Horton and others, 1991; Virginia Division of Mineral Resources, 1993).

The relatively low grade of metamorphism and deformation in Carolina slate belt rocks as compared to adjacent areas of the Appalachian Piedmont historically have prompted intensive study through a combination of stratigraphic, petrologic, geochemical, paleontological, and geochronological investigations (summarized by papers in Bearce and others, 1982; Nance and Thompson, 1996; Glover and Gates, 1997). Most workers agree that the Carolina slate belt belongs to a peri-Gondwanan terrane exotic with respect to Laurentia, primarily based on an assemblage of Middle Cambrian Atlantic province trilobites identified in slate belt metasedimentary rocks (Secor and others, 1983; Samson and others, 1990). However, there has been less agreement on the nature of the relationships of the Carolina slate belt to surrounding areas of higher grade rocks. In particular, many workers examining the western boundary of the Carolina slate belt, where it is adjacent to medium- to high-grade gneisses in the Charlotte or Milton terrane (fig. 1), have presented conflicting interpretations of the nature of the boundary. The varied historical interpretations of this important orogen-scale feature were summarized by Wortman and others (1996), and Coler and others (2000), and include two primary hypotheses: 1) the Carolina slate belt is in a suprastructural position to the related infrastructural Charlotte terrane, and is separated from it by a steep metamorphic gradient or intraterrane shear zone, and 2) the boundary is a regional shear zone or suture separating two distinctly different and unrelated crustal blocks. In North and South Carolina, some workers have considered that the greenschist-facies rocks of the Carolina slate belt are the suprastructural part of an island arc system, while the westwardly-adjacent, amphibolite-facies rocks of the Charlotte terrane are the deeper-level, infrastructural part of the arc, separated from each other by a steep metamorphic gradient or intraterrane shear zone (Tobisch and Glover, 1969, 1971; Secor and others, 1983, 1986; Baird, 1991; Baird and Glover, 1997; Boland, 1998). Other workers have questioned the suprastructure-infrastructure relationship on the basis of systematic isotopic and geochronologic differences (Wortman and others, 1996; Coler and others, 2000), or structural style (Hibbard and others, 1998). This leads to the alternative interpretation that the boundary between the Charlotte terrane and the Carolina slate belt is a crustal shear zone or decapitated suture, juxtaposing terranes of separate affinity (Horton and others, 1989; Wortman and others, 1996; Hibbard and others, 1998; Coler and others, 2000; Hibbard and others, 2002).

The nature of the northernmost termination of the Carolina slate belt is similarly controversial, but has received much less attention than the western border. Speculations regarding the northern limit have been hindered by a lack of detailed geologic mapping in the area, and previously have been rendered only as an unspecified fault or terrane boundary on regional geologic maps (Horton and others, 1991; Virginia Division of Mineral Resources, 1993). Herein, we examine the nature of the northern Carolina slate belt boundary, building upon geologic mapping and geochronologic work that was completed by USGS geologists working in southern Virginia during 1992–1998 in support of the geologic mapping of the South Boston 30 x 60 quadrangle (for example, Horton and others, 1993; Nelson, 1993; Burton, 1995; Kunk and others, 1995; Peper and others, 1996; Burton and Armstrong, 1997; Nelson and Nelson, 1997; Peper and Wygant, 1997; Peper and Olinger, 1998; Hackley and Peper, 1998; Peper and Hackley, 1999; Horton and others, 1999; Hackley and others, 2000; Burton and others, 2000). Collectively, these workers traced the Virgilina stratigraphy and structure northward from near the Virginia-North Carolina border into the area of the current study.

The purpose of this contribution is to describe the further northward continuation of the stratigraphy and structure of the classic Virgilina sequence, focusing on the results of geologic mapping of the Keysville (Hackley and Peper, 1998), and Green Bay (Peper and Hackley, 1999) 7.5-minute quadrangles, which contain the northern limit of the Carolina slate belt as interpreted on previous regional geologic maps (Horton and others, 1991; Virginia Division of Mineral Resources, 1993). This work expands upon earlier mapping studies in the area (Achtermann, ms, 1985), and confirms that the Carolina slate belt continues northward across a steep Barrovian metamorphic gradient into correlative upper amphibolite-facies gneiss and schist.

REGIONAL GEOLOGIC SETTING

Geological study of the northern Carolina slate belt of south-central Virginia dates to the pioneering work of Laney (1917), who mapped the geology of the Virgilina copper district from Virgilina, Virginia, to near Keysville, Virginia (fig. 2). Laney identified the upright, north-northeast-trending Virgilina synclinorium, which folds greenschist-facies metamorphosed volcanic, volcaniclastic, and sedimentary rocks that he named, from oldest to youngest, the Hyco quartz porphyry and Goshen schist, the Aaron slate, and the Virgilina greenstone. Laney interpreted these rocks as a cover sequence unconformably overlying or in fault contact with the older, higher-grade basement rocks to the west. Jonas (1932) used the northern termination of Laney's mapping as the northern boundary for the slate belt stratigraphic succession in a regional study of kyanite deposits in Virginia. Geologic mapping by Kreisa (1980) at the Virginia-North Carolina border revealed several structural complexities superposed on the simple Virgilina synclinorium of Laney (1917), including local synclinal and anticlinal folding of the stratigraphic sequence (fig. 2). Kreisa (1980) modified the stratigraphic nomenclature of Laney (1917) by renaming the Hyco quartz porphyry/ Goshen schist the Hyco Formation, and the Aaron slate the Aaron Formation (table 1). Furthermore, Kreisa (1980) included Laney's Virgilina greenstone as a middle member of the Aaron Formation. Harris and Glover (1988) proposed that the deformational event which created the Virgilina synclinorium was regional in nature and offered a revised stratigraphic nomenclature for the slate belt of North Carolina and Virginia, adopted in this paper (table 1). Achtermann (ms, 1985) mapped part of the area covered in this paper and suggested that a band of schist that he correlated with the Aaron Formation, flanked by units of felsic gneiss that he correlated with Hyco Formation rocks, could represent a northern extension of the Virgilina synclinorium, a hypothesis supported and developed in the current work.

Peper and Olinger (1998) demonstrated that the Virgilina synclinorium north of the Dan River is a simple syncline, slightly overturned to the northwest, which they named the Dryburg syncline. Their evidence for the syncline consists of the symmetry of stratigraphic units on opposite limbs and sedimentary facing criteria. Geologic mapping in the South Boston 30 x 60 minute quadrangle as part of the National Cooperative Geologic Mapping Program of the U.S. Geological Survey has traced the Hyco, Aaron and Virgilina Formations and the Dryburg syncline from the Virginia-North Carolina border to the southern margin of the area of this report (fig. 3) (Horton and others, 1993; Burton, 1995).

Glover and Sinha (1973) identified the upper part of the Hyco Formation as Neoproterozoic (620 ± 20 Ma) in northern North Carolina by U-Pb analysis of zircon, and they postulated a $\sim$620 to 575 Ma contractional event called the Virgilina deformation. A detailed field study by Harris and Glover (1988) delineated an angular unconformity between the Virgilina sequence and younger slate belt strata, including the Uwharrie Formation and Albemarle Group. The unconformity and evidence for the Virgilina deformation was identified on the basis of the discordance of fold geometries and lineations between the older and younger strata. The Virgilina

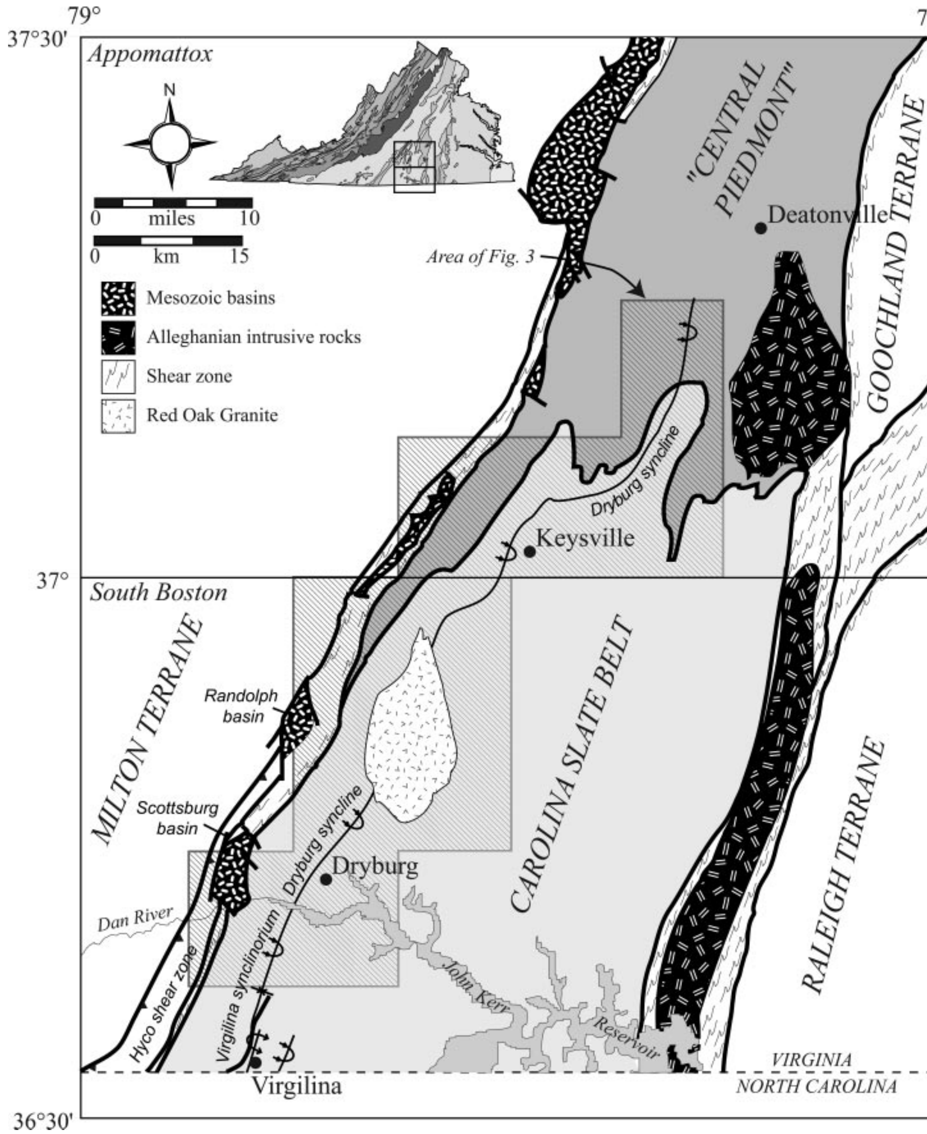

Fig. 2. Generalized geologic map of Appomattox and South Boston 30 x 60 minute quadrangles showing boundaries of major tectonic elements. Inset shows location of Appomattox and South Boston quadrangles in Virginia. From Virginia Division of Mineral Resources (1993), Horton and others (1993), and Peper and others (1996). The Dryburg syncline is a northern extension of the more complex Virgilina synclinorium of Laney (1917), as modified by Kreisa (1980). The Hyco shear zone thrust fault shown west of the Scottsburg basin (Hibbard and others, 1998; Bradley and others, 2006) terminates to the north at Mesozoic faults associated with the Randolph basin (J. W. Horton, Jr. and A. E. Nelson, unpublished geologic mapping). The "Central Piedmont" of the Virginia Division of Mineral Resources (1993) as shown in figure 2 was not defined as a tectonic element or terrane. Furthermore, the type and kinematics of the inferred fault separating the Carolina slate belt from the northward Central Piedmont was not specified by the Virginia Division of Mineral Resources (1993). More recently, rocks of the Central Piedmont were tentatively considered to be part of the Charlotte terrane as defined by Hibbard and others (2002). However, we herein assert that the Central Piedmont is a northern high-grade continuation of the Carolina slate belt.

Table 1

Stratigraphic nomenclature of the Virgilina sequence used in the south-central Virginia and North Carolina slate belt

	Laney (1917), Virgilina district, VA-NC	Kriesa (1980), Omega area, VA	Harris and Glover (1988), central NC slate belt	This report
	Aaron Slate	Aaron Fm., upper Member	Virgilina Fm., sedimentary unit	not present
Neoproterozoic	Virgilina Greenstone	Aaron Fm., Middle member	Virgilina Fm., greenstone unit	Virgilina Fm.
	Aaron Slate	Aaron Fm., Lower member	Aaron Fm.	Aaron Fm.
	Hyco Quartz Porphyry and Goshen Schist	Hyco Fm.*	Hyco Fm.*	Hyco Fm.*

FM. = Formation. *Dated at ~621–614 Ma by U-Pb of zircon at various locations throughout the slate belt of Virginia and North Carolina (Glover and Sinha, 1973; Wortman and others, 1998; Horton and others, 1999).

deformation caused isoclinal folding of the older stratigraphy; however, the lack of evidence for associated regional Neoproterozoic metamorphism and for development of a pervasive regional schistosity has been puzzling. However, penetrative rock fabrics that may be associated with the Virgilina deformation have been identified (Hibbard and Samson, 1995; Hibbard and others, 1995; Dennis, 1995). More recent conventional U-Pb dating of zircons from stratified felsic volcanic rocks of the Hyco Formation in southern Virginia give ages of 621 to 616 Ma, similar to the age data published by Glover and Sinha (1973), and zircons from plutons that locally crosscut the pre-foliation folds give ages of 583 to 568 Ma, providing a minimum age for the Virgilina deformation (Horton and others, 1999).

Studies to the south in the North Carolina portion of the slate belt have documented primarily Ordovician ages for growth of cleavage/foliation-defining minerals (Noel and others, 1988; Offield and others, 1995). However, work in the northern Carolina slate belt in Virginia closer to our field area has identified a younger age of deformation. Burton and Armstrong (1997) described amphibolite, felsite, and staurolite-bearing schist approximately 30 to 40 km northeast of our study area that they suggested may be northern high-grade equivalents of the Carolina slate belt rocks. Burton and Armstrong (1997) noted that the development of the dominant north-south-trending regional fabric was synchronous with intrusion of the 312 Ma Burkeville pluton (Horton and others, 1995), and thus Alleghanian. Horton and others (1995) suggested that Alleghanian metamorphism in this area reached amphibolite-facies, based on resetting of titanite and monazite ages to ~297 to 321 Ma. Mineral ages (284 – 318 Ma) from locations in the Virginia Carolina slate belt about 40 km

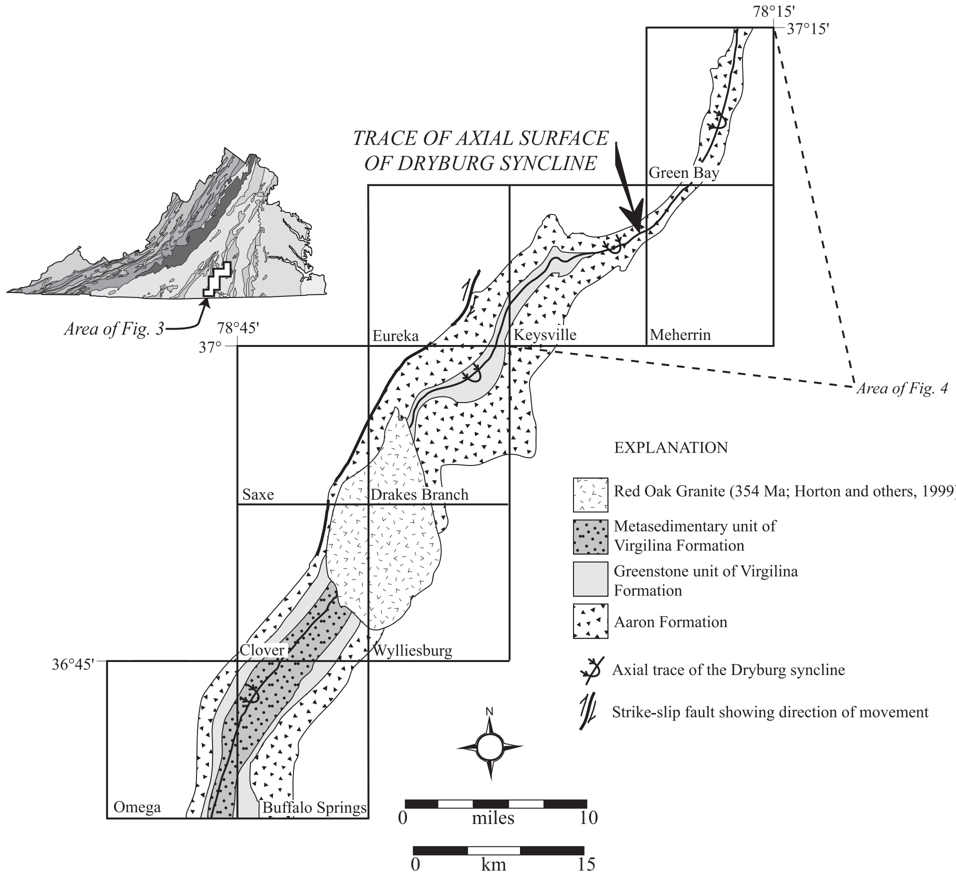

Fig. 3. Trace of the axial surface of the Dryburg syncline and flanking Aaron and Virgilina Formation strata north of the Dan River to the latitude of the study area. Hyco Formation lithologies immediately flank the Aaron on both limbs of the structure; however, the total extent of the Hyco Formation in all of the quadrangles shown is not completely known, and the westward Hyco contact with Milton terrane lithologies is unconstrained. Geologic mapping of Omega 7.5-minute quadrangle by Kreisa (1980), Buffalo Springs by Peper and Olinger (1998), Clover and Wylliesburg by J. D. Peper (unpublished geologic mapping), Saxe by J. W. Horton Jr. (unpublished geologic mapping), Drakes Branch by W. C. Burton and J. W. Horton, Jr. (unpublished geologic mapping), Eureka and Meherrin by J. D. Peper and P. C. Hackley (unpublished geologic mapping), Keysville by Hackley and Peper (1998), and Green Bay by Peper and Hackley (1999).

south-southwest of our mapping also provide evidence of Alleghanian metamorphism (Burton and others, 2000), although with a significant older growth component present (Kunk and others, 1995).

STRATIGRAPHY

The following sections provide brief descriptions of the Hyco and Aaron Formations, with attention drawn to details that illustrate the northward increase in metamorphic grade across the study area shown in figure 4. More specific information and lithologic descriptions of individual map units are provided in Hackley and Peper (1998), and Peper and Hackley (1999).

Hyco Formation

Rocks of the Hyco Formation underlie the greatest total area in our study (approximately 55 percent of the Keysville and Green Bay quadrangles, fig. 4);

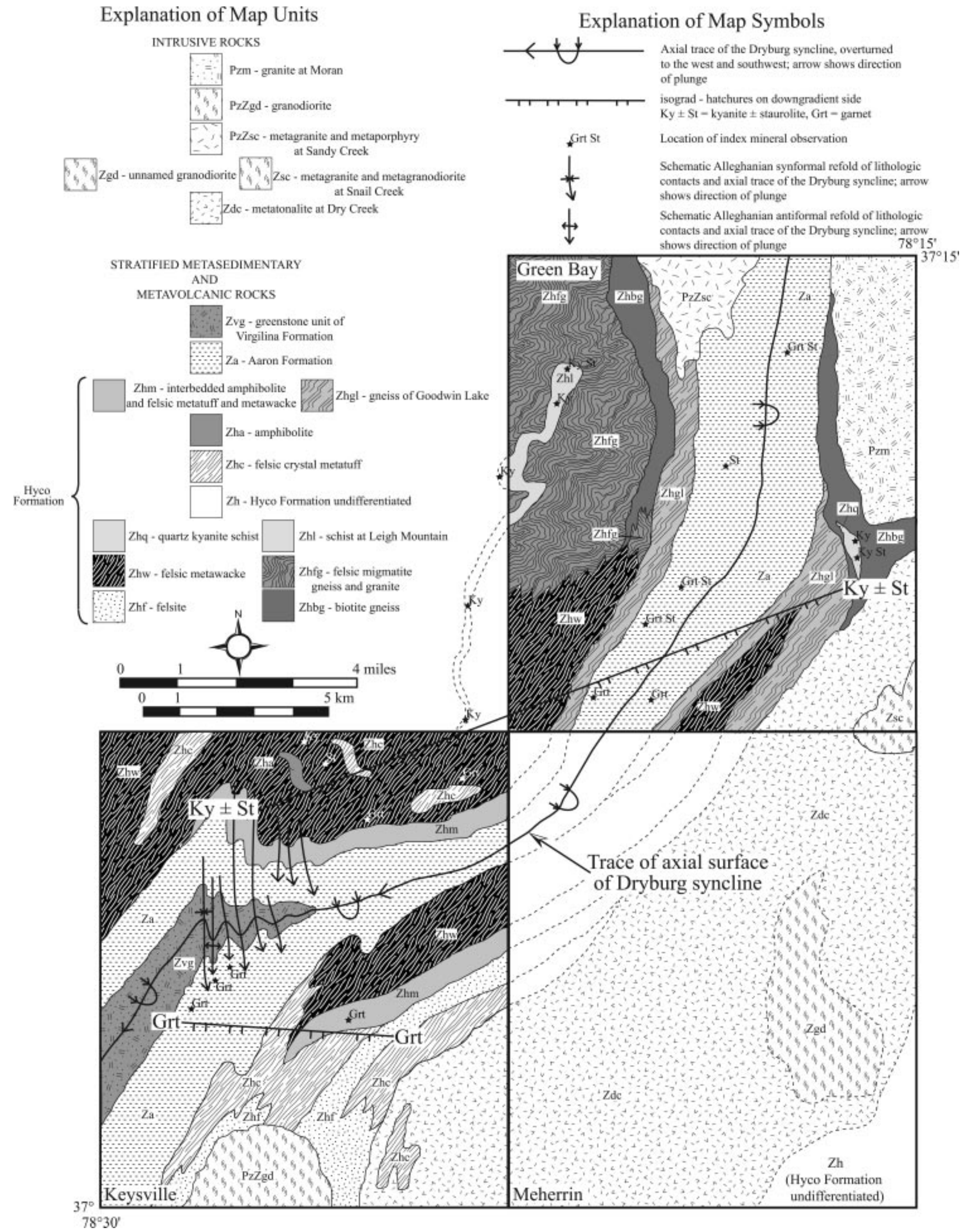

Fig. 4. Generalized geologic map of the Keysville (Hackley and Peper, 1998), Meherrin (unpublished mapping, J. D. Peper and P. C. Hackley, 1997), and Green Bay (Peper and Hackley, 1999) 7.5-minute quadrangles showing locations of metamorphic isograds, the axial trace of the refolded Dryburg syncline, and the distribution of lithologic units. Sillimanite occurs northeast of the map area, but the location and trend of the sillimanite-in isograd are unknown. Contacts are dashed in the Meherrin quadrangle to indicate unpublished reconnaissance mapping. The illustrated refolding of the Dryburg syncline and lithologic contacts in the Keysville quadrangle is schematic and interpretive; see Hackley and Peper (1998) for original data.

therefore, most attention was devoted to identifying and delineating the internal stratigraphy of this formation during our mapping campaign. The Hyco Formation primarily comprises felsic volcanic and volcaniclastic rocks whose diverse lithofacies allowed for delineation of ten informal units including; (1) Zhw – felsic metawacke, and its higher-grade equivalents, (2) Zhfg – felsic migmatite gneiss and granite, and (3) Zhbg – biotite gneiss, (4) Zhm – interbedded felsic metatuff, metawacke, and amphibolite, and its higher-grade equivalent, (5) Zhgl – gneiss of Goodwin Lake, (6) Zhc – felsic metatuff, (7) Zha – amphibolite, (8) Zhf – felsite, (9) Zhq – quartz + kyanite ± garnet schist, and (10) Zhl - schist of Leigh Mountain.

Felsic metawacke (Zhw), comprised of fine- to medium-grained, dark reddish brown to moderate brown-weathering metawacke and metasandstone, underlies the majority of the northern part of the Keysville quadrangle on the western limb of the Dryburg syncline, and was traced directly upgrade into felsic migmatite gneiss and granite (Zhfg). Felsic migmatite gneiss and granite (Zhfg) primarily consists of fine-grained, tan- to brown-weathering plagioclase + quartz + K-feldspar(?) ± biotite ± muscovite gneiss. Gneissosity is evident in layers of biotite-rich rock alternating with layers of primarily quartz + feldspar composition on a scale of mm to cm. *In situ* concordant layers of segregated leucocratic granite to trondjhemite with biotite selvages indicate local anatexis. Biotite gneiss (Zhbg) also represents a higher-grade equivalent of felsic metawacke on both limbs of the syncline and is composed of tan to dark-tan-weathering, medium-grained, leucocratic granodioritic to trondjhemitic layers with variable biotite content. Interbedded amphibolite and felsic metatuff and metawacke (Zhm) was traced upgrade into the gneiss of Goodwin Lake (Zhgl) in the Green Bay quadrangle. Gneiss of Goodwin Lake (Zhgl) consists of amphibolite, interpreted to be metamorphosed mafic volcaniclastic and volcanic rock, interlayered in about equal proportions with felsic gneiss layers of metamorphosed volcaniclastic rock. Higher-grade gneissic Hyco units were traced northward to the Green Bay quadrangle boundary and into a cross-cutting pluton (fig. 4).

North of the kyanite ± staurolite-in isograd, several aluminous lenses of the Hyco Formation were mapped as separate units due to the abundance of kyanite. These rocks were first noted by Espenshade and Potter (1960) who described quartz kyanite schist and kyanite quartzite of Leigh Mountain (Zhl) in a regional study of aluminosilicate mineral occurrences. A similar kyanite ± porphyroblastic garnet schist unit (Zhq) occurs as a lens within biotite gneiss (Zhbg) on the eastern limb of the syncline. The presence of kyanite-bearing aluminous units within the Hyco on both limbs of the Dryburg syncline (fig. 4) is herein interpreted to indicate that there are no major structural boundaries separating the lithologies on opposite sides of the fold axial trace.

Aaron Formation

The Aaron Formation (Za) consists of a linear, northeast- and north-trending belt of relatively homogeneous fine-grained phyllite and mica schist, flanked by Hyco Formation lithologies on both limbs of the Dryburg syncline. Sparse, thin ($\leq$0.6 m) mafic interbeds include greenstone, epidote amphibolite, amphibolite, and chlorite schist. Schist and phyllite of the Aaron Formation in the southern part of the study area are characterized by the even distribution of a fine-grained opaque oxide, whereas north of the garnet-in isograd and particularly in the central and northern parts of the Green Bay quadrangle, the Aaron is characterized by the appearance of post-kinematic, fine-grained, euhedral garnets. Mapping of the Aaron Formation into the study area has been completed northward continuously from the type locality on Aarons Creek in the Buffalo Springs quadrangle (fig. 3) (Peper and Olinger, 1998); garnet is not present in the Aaron south of the Keysville quadrangle.

Similar to the Hyco, the Aaron schist also was traced northward to the quadrangle boundary and into a cross-cutting pluton (fig. 4). Northward continuation of the Hyco and Aaron lithologies into high-grade correlative gneisses and schist as mapped herein conflicts with the previous interpretation by the Virginia Division of Mineral Resources (1993), which showed the northern end of the slate belt as an unspecified arcuate fault boundary lying athwart the field area (fig. 2). In contrast, our study did not identify any evidence for a fault or major structural boundary at the northern end of the slate belt.

Disconformity at the Hyco-Aaron Contact

The Aaron-Hyco contact represents a disconformity and is evident from repeated truncation of internal contacts within the Hyco Formation at the contact. Evidence for this disconformable relationship has been mapped northward from the North Carolina border to the southern boundary of our study area (Horton and others, 1993; Peper and others, 1996; Peper and Wygant, 1997; Peper and Olinger, 1998; see fig. 3 for additional unpublished mapping credits). Northward through the Keysville and Green Bay quadrangles, the Hyco-Aaron contact truncates numerous internal contacts within the Hyco on both limbs of the Dryburg syncline (fig. 4). The Hyco-Aaron contact also was interpreted as a disconformity by Harris and Glover (1988) in a detailed field study of slate belt lithologies to the south in North Carolina. Harris and Glover (1988) noted that sediments incorporated into the Aaron Formation originated in part from Hyco volcaniclastic rocks, and postulated that differential uplift and subsidence was the agent responsible for erosion, consistent with the relationships observed in our study. There is no evidence for a major hiatus of sediment deposition or for a deformational event at the disconformity.

The Hyco-Aaron contact locally has been sheared on steep, southeast-dipping dextral mylonite zones located southwest of the current study area along the western limb of the Dryburg syncline (fig. 3). Mylonites splay off northward from the contact into the Hyco Formation in the Eureka quadrangle. These steeply-dipping features are interpreted to result from late Alleghanian dextral shear (Peper and Hackley, 1999), and are not thought to be Alleghanian thrusts, which are described as occurring on a shallow to moderately-dipping detachment surface in the Hyco shear zone to the southwest (Hibbard and others, 1998).

INTRUSIVE ROCKS

The stratified Virgilina sequence in the study area is intruded by a number of plutonic bodies of interpreted Neoproterozoic to Paleozoic age (fig. 4). Plutonic rocks in the study area have not been dated by radiogenic techniques, but were assigned ages (Hackley and Peper, 1998; Peper and Hackley, 1999) consistent with their similarity to nearby plutonic bodies that have been isotopically dated. Future research should include radiometric dating of these units, particularly the metatonalite of Dry Creek (Zdc), which underlies the southeastern part of the study area (fig. 4). The pluton and its map-scale enclaves (Zgd, Zsc; fig. 4) may represent a composite pluton with several distinct intrusive phases, possibly consanguineous with the overlying Hyco Formation volcanic strata (Achtermann, ms, 1985). The metatonalite complex is considered to be Neoproterozoic in age as suggested by similarity to other slate belt felsic intrusive bodies of Neoproterozoic age including the 546 ± 3 Ma Roxboro Granite (Glover and Sinha, 1973; Wortman and others, 1995), the 566 ± 46 Ma Parks Crossroads granodiorite (Tingle, 1982), and similar diorites and granodiorites south of the study area (Horton and others, 1999).

Strongly foliated, metamorphosed metagranite and metaporphyry at Sandy Creek (PzZsc) intrudes the Virgilina sequence and the axial trace of the Dryburg syncline. This unit is well exposed along the eastern banks of the Sandy Creek reservoir in the northern Green Bay quadrangle where it resembles rock of the Neoproterozoic Vance pluton of the North Carolina slate belt (Hadley, 1974; Butler, 1990). A radiometric date of the metagranite at Sandy Creek would further constrain the minimum age of the Virgilina deformation.

STRUCTURE AND METAMORPHISM

Dryburg Syncline

The most prominent map-scale structure in the study area is the refolded Dryburg syncline, which is a northern extension of the more complex Virgilina synclinorium (Peper and Olinger, 1998). Across the study area, the Dryburg syncline is overturned slightly to the west and is refolded in places by map-scale, south-southeast plunging folds (described below). The existence of the Dryburg syncline in the Keysville and Green Bay area cannot be directly proved due to obliteration of sedimentary facing criteria by the development of the regional penetrative structural fabric and also due to the asymmetry, in places, of Hyco stratigraphic units on opposite limbs of the fold (fig. 4). However, multiple lines of indirect evidence suggest that the Dryburg syncline extends northward across the study area. (1) The structure has been traced to the southern margin of our study area, as demonstrated by sedimentary facing criteria and stratigraphic symmetry (Peper and Olinger, 1998; unpublished geologic mapping by J. D. Peper, J. W. Horton, Jr., and W. C. Burton). (2) The central belt of Virgilina greenstone in the core of the Dryburg syncline is symmetrically flanked by Aaron metasedimentary rocks in the Keysville quadrangle (fig. 4). (3) Metasedimentary rocks of the Aaron Formation are flanked by felsic volcanic and volcaniclastic rocks of the Hyco Formation, locally having symmetry of lithofacies on either side of the fold axial trace [note symmetry of gneiss of Goodwin Lake (Zhgl) in the southern part of the Green Bay quadrangle; fig. 4]. (4) The Hyco-Aaron contact is symmetrically disconformable on both limbs of the syncline as demonstrated by truncation of lithofacies within the Hyco at this boundary. (5) Mapping to the northeast of the current study area by W. C. Burton has delineated a central belt of garnet + sillimanite schist flanked by felsic gneisses, interpreted to be correlative with the Aaron and Hyco Formations, respectively, southeast of a mapped thrust fault.

Petrofabrics

The main regional fabric is a penetrative foliation defined mostly by the alignment of micas and chlorite that strikes generally north-northeast and dips moderately to steeply southeast in the Keysville quadrangle (fig. 5A). Northeastward into the Green Bay quadrangle, regional dip is more variable (fig. 5B). Poles to foliation illustrated in figure 5B appear to define a great circle girdle, indicating a late broad fold of the penetrative fabric which plunges gently to the northeast. Measured structural fabrics generally are parallel to compositional layering (where present) and parallel to subparallel to mapped lithologic contacts. However, foliation locally is observed at moderate to high angles to mapped contacts and to the axial trace of the refolded Dryburg syncline. This observation is consistent with development of the penetrative fabric after the regional synclinal folding of the stratigraphy during the ~620 to 575 Ma Virgilina deformation of Glover and Sinha (1973).

During our mapping campaign, there were no unambiguous identifications of an older penetrative Virgilina deformation fabric. However, the regional fabric in the northern part of the slate belt may represent a cumulative expression of a transposed Virgilina foliation and foliation produced by Late Paleozoic orogenesis. Older mineral ages (if present) for cleavage-defining phases must have all been reset by late Paleozoic events; isotopic ages from greenschist- to amphibolite-facies foliation-defining minerals to the immediate south-southwest and north-northeast of the study area primarily indicate growth during the Carboniferous-Permian Alleghanian orogeny (Burton and

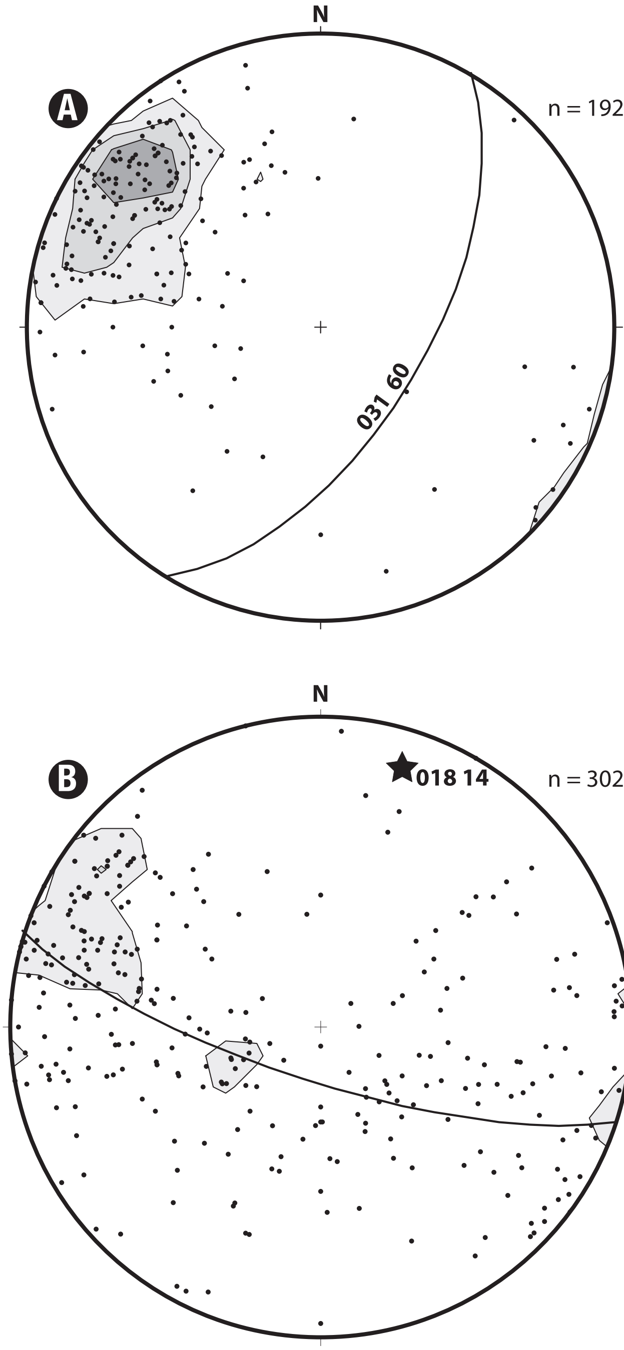

Fig. 5. (A) Lower hemisphere equal-area stereographic projection of poles to foliation in Keysville quadrangle. Mean foliation indicated by great circle girdle. (B) Lower hemisphere equal-area stereographic projection of poles to foliation in Green Bay quadrangle. Folding of the foliation indicated by great circle girdle with pole 018 14. Contour interval is 3 percent per 1 percent area in A and B.

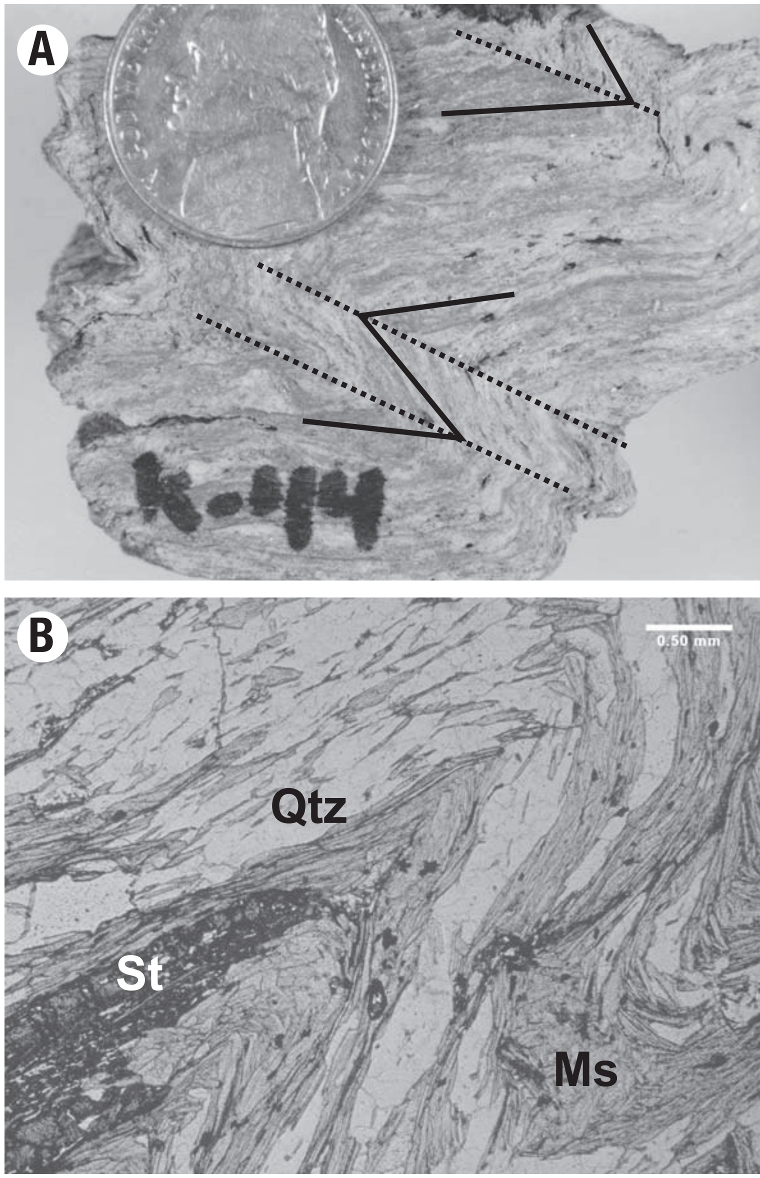

Fig. 6. (A) Tight folds of schistosity in Hyco Formation schist (schist lens in unit Zhw). From outcrops on unnumbered forest road, northwest Keysville quadrangle, at approximate latitude 37° 6′ 30″ north and longitude 78° 26′ 34″ west. Coin is 2 cm in diameter. Dashed lines indicate axial surface traces; solid lines indicate fold limbs. (B) White mica platelets wrapping around fold nose in Hyco Formation staurolite-bearing schist (schist lens in unit Zhw) indicating folding occurred subsequent to development of the regional penetrative fabric. From outcrops on State Road 634, northeast Keysville quadrangle, at approximate latitude 37° 6′ 53″ north and longitude 78° 25′ 34″ west. Abbreviations: St = staurolite, Ms = muscovite, Qtz = quartz.

others, 2000), with some limited evidence for inheritance of an older growth stage farther to the south in Virginia and into North Carolina (Offield and others, 1990, 1995; Kunk and others, 1995).

Map-scale, south-southeast-plunging, steeply-inclined, west-verging tight to isoclinal folds fold lithologic contacts, including the Hyco-Aaron disconformity. These folds also are interpreted to refold the Dryburg syncline northeast of Keysville (shown schematically in fig. 4). Outcrop-scale tight to locally isoclinal folds of foliation and compositional layering (where present) (fig. 6A) have the same general orientation, and presumably are parasitic on the larger map-scale folds. In thin section, foliation-defining white mica platelets wrap around fold noses (fig. 6B), indicating folding occurred subsequent to development of the regional penetrative fabric, consistent with structural observations from the Goochland terrane boundary to the northeast (Burton and Armstrong, 1997).

Primary sedimentary structures in the study area have been rendered unrecognizable by the formation of the dominant penetrative structural fabric, which is well-developed throughout the study area. However, relict bedding structures, including facing criteria, are well-preserved in Virgilina sequence strata to the south (Peper and Olinger, 1998), and some Hyco units in the Keysville quadrangle locally preserve rare transposed bedding laminations.

Gneissic compositional layering, expressed by alternating biotite and quartz + feldspar-rich layers on a scale of mm to cm, is common in the higher-grade felsic migmatite gneiss and granite and biotite gneiss units in the northern part of the study area. Gneissosity is parallel to the preferred alignment of metamorphic biotite.

Metamorphic Isograds

East-northeast-trending isograds, defined by the successive northward appearance of prograde garnet, then kyanite ± staurolite, in sufficiently aluminous rocks, are superposed on the stratigraphic units and on the trace of the Dryburg syncline at moderate to high angles to strike (fig. 4). Isograds were located based on the identification of garnet and kyanite ± staurolite in the field and in thin sections (Hackley and Peper, 1998; Peper and Hackley, 1999). In addition, data from the previous mapping and petrologic studies of Jonas (1932), Espenshade and Potter (1960), Bennett (ms, 1961), and Achtermann (ms, 1985) were evaluated to locate isograds. The locations of the isograds shown in figure 4 are reasonably well-constrained by the mapping and thin section observations; however, future field study could be allocated to better defining their position and trajectory. In addition, modification of the isograds by folding and faulting associated with the opening of Mesozoic basins may have altered their trajectory from the interpretive straight lines that we have shown on figure 4.

The garnet-in isograd occurs in the southern Keysville quadrangle (fig. 4), where fine-grained porphyroblastic garnet first appears in aluminous Aaron Formation schist. Garnet was not identified in correlative rocks mapped to the south (Burton, 1995). Garnet is sub- to euhedral and contains minute inclusions of matrix minerals (fig. 7A). Locally, garnet is pseudomorphed by fine-grained white mica. In the northern part of the study area, fine-grained, post-kinematic euhedral garnet is common in Aaron schist and coarse-grained post-kinematic garnet porphyroblasts occur in quartz kyanite schist.

The kyanite ± staurolite-in isograd is placed near the northern boundary of the Keysville quadrangle (fig. 4). Staurolite contains aligned inclusions of matrix phases which are, in some cases, rotated with respect to the matrix fabric indicating pre- or synkinematic growth. Staurolite also occurs aligned in the matrix fabric and typically is anhedral in habit (fig. 7B). Kyanite occurs in Hyco Formation units on both limbs of the Dryburg syncline in the northern part of the study area.

Fibrous sillimanite replacing kyanite was identified during our field mapping, and our previous reports placed a sillimanite-in isograd in the northern part of the Green

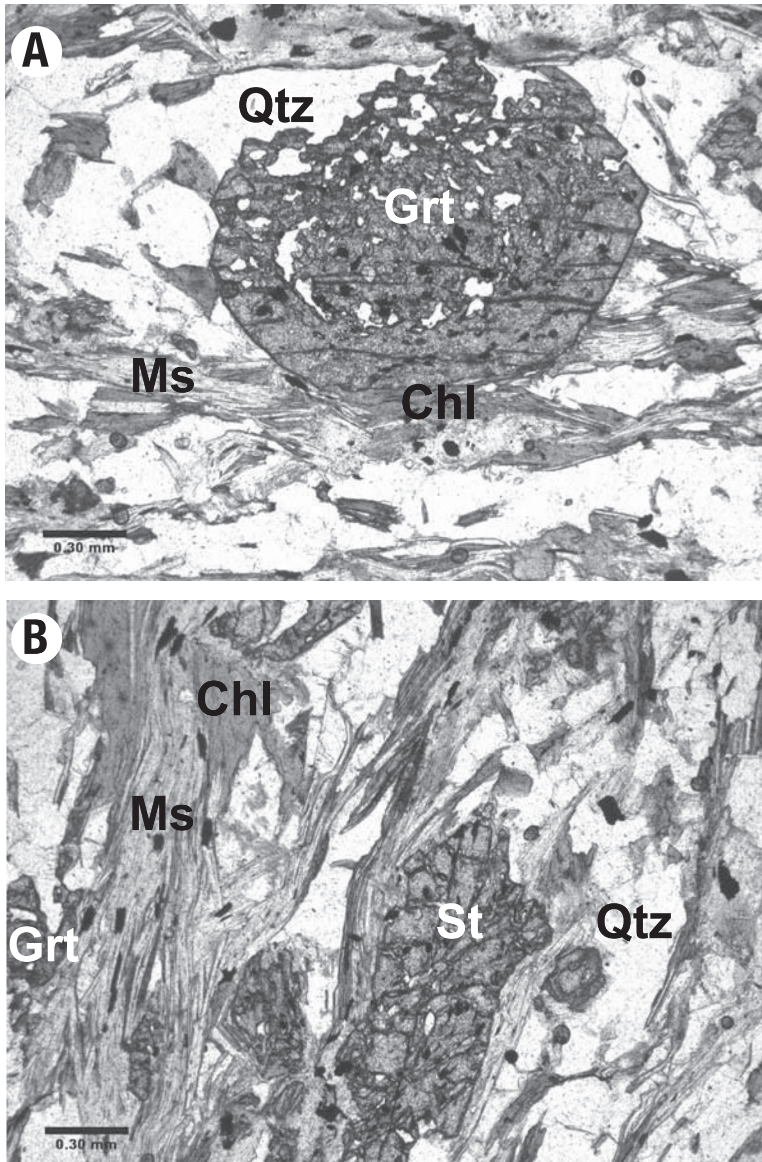

Fig. 7. (A) Garnet in thin section. Plane-polarized light; scale bar in lower left. (B) Staurolite in thin section. Plane-polarized light; scale bar in lower left. Both A and B from Aaron Formation schist (Za) in south-central Green Bay quadrangle, at approximate latitude 37° 9′ 20″ north and longitude 78° 19′ 4″ west. Abbreviations: St = staurolite, Ms = muscovite, Qtz = quartz, Grt = garnet, Chl = chlorite.

Bay quadrangle (Peper and Hackley, 1999; Hackley and others, 2000). However, subsequent thin section and X-ray diffraction studies of collected samples have failed to conclusively identify sillimanite/fibrolite in our sample suite. Sillimanite has been identified in thin sections of correlative rocks from farther northeast (Burton and Armstrong, 1997), but the location of a sillimanite-in isograd cannot be precisely located in our study area based on the currently available data.

Partial Melting

In the northwestern part of the Green Bay quadrangle, local anatexis of Hyco Formation strata is indicated by the segregation of minimum granite melt into migmatite leucosomes. Biotite selvages around leucosomes suggest that these occurrences are the products of *in situ* melting. Distinct felsic intrusives also are present as dikes and sills in outcrops of Hyco Formation strata; intrusives are in sharp discordant contact with the country rock and do not display biotite selvages. Presence of *in situ* minimum granite melt suggests crustal temperatures reached >600°C (Tuttle and Bowen, 1958) during Alleghanian orogenesis, consistent with the results of the thermobarometric study by Burton and Armstrong (1997) to the northeast. Burton and Armstrong (1997) concluded that peak T and P conditions reached 550 to 600°C and 6 kbars in rocks they considered northern high-grade equivalents of the slate belt strata.

Age of Metamorphism and Deformation

Prograde metamorphism and the development of the penetrative structural fabric in the study area are assigned to the Alleghanian, based on the ages of foliation-defining minerals from locations nearby (Kunk and others, 1995; Horton and others, 1995; Burton and Armstrong, 1997; Burton and others, 2000). Development of the steep chlorite to kyanite ± staurolite thermal gradient over the lateral distance of 5 to 10 km is consistent with the spacing of isograds mapped nearby in the North Carolina-Virginia Piedmont (Tobisch and Glover, 1969; Henika, 1977), and farther to the north in northern Virginia and into Maryland (Drake, 1989). We interpret the isograds mapped in our study area to represent a simple Barrovian metamorphic gradient resulting from Alleghanian orogenesis. However, recent work in the northern Virginia Piedmont demonstrated that thermochronologic evaluation of metamorphic minerals can recognize thermal discontinuities not revealed by geologic mapping alone (Kunk and others, 2005). Confirmation of the mapped Barrovian metamorphic gradient interpreted herein to result from a single event awaits detailed thermochronological investigation.

DISCUSSION

Northward Continuation of the Slate Belt

The most salient result of this study is recognition of the unbroken continuity of the stratigraphy and structure of the Carolina slate belt northward into higher-grade correlative gneiss and schist. The idea of a northward extension of slate belt lithologies was earlier suggested by Burton and Armstrong (1997), and Horton and others (1999), and was confirmed by our work in the current study area (Hackley and Peper, 1998; Peper and Hackley, 1999). Our mapping has demonstrated the continuation of the slate belt stratigraphy and structure northward across the study area and into a cross-cutting intrusive body (fig. 4). This result is in conflict with previous interpretations which delineated the northern end of the Carolina slate belt as an unspecified terrane boundary (Horton and others, 1991), or as a fault separating the slate belt from rocks of the undefined "Central Piedmont" to the north (Virginia Division of Mineral Resources, 1993).

The term "Central Piedmont" was used as a map division by geologists working on the compilation of the 1993 Geologic Map of Virginia to designate mostly high-grade gneiss and schist occurring northeast of the Carolina slate belt, and sandwiched between the Goochland and Chopawamsic terranes (Virginia Division of Mineral Resources, 1993). However, the Central Piedmont was not defined, nor was it placed in a regional context, thus leaving its origin and interpretation as a discrete crustal element rather cryptic. A synoptic review of exotic tectonic elements in the southern

Appalachians by Hibbard and others (2002) tentatively included the Central Piedmont rocks of the Virginia Division of Mineral Resources (1993) as part of the Charlotte terrane. However, we herein assert that the Central Piedmont of the Virginia Division of Mineral Resources (1993) is in fact a northward continuation of the Carolina slate belt, albeit at higher metamorphic grade, and that the term Central Piedmont should not be used in the context of defining a discrete crustal element or terrane.

Farther to the northeast of the current study area, in the Deatonville and Cumberland quadrangles, unpublished geologic mapping by W. C. Burton has delineated an area of garnet + sillimanite schist flanked by felsic gneisses, interpreted to be correlative with the Aaron and Hyco Formations, respectively, in a further northward continuation of the Dryburg syncline (fig. 8). These units occur southeast of an Alleghanian thrust fault that may represent a major structural discontinuity juxtaposing the slate belt with rocks of uncertain affiliation.

Felsic metavolcanic rocks in the Deatonville quadrangle southeast of the thrust yielded a 554 ± 4 Ma U-Pb zircon age (Horton and others, 1995). This age is significantly younger than the zircon dates obtained from Hyco metavolcanics farther to the south in the slate belt (~621 – 616 Ma; Horton and others, 1999), and the ~614 Ma upper intercept age obtained for gneiss in the Hyco shear zone on the western boundary of the slate belt (Wortman and others, 1998). However, the ~554 Ma age is very similar to a 551 ± 8 Ma zircon age (Ingle-Jenkins and others, 1999) obtained from felsic Uwharrie Formation volcanic rocks, which overlie the Virgilina sequence in angular unconformity in the North Carolina slate belt (Harris and Glover, 1988). Further detailed study of petrofabrics to identify this unconformity, or a thrust fault discontinuity, will be necessary in the Deatonville quadrangle in order to understand the significance of the younger age, and if the 554 Ma felsic metavolcanic rock is in fact a northern correlative of the Uwharrie Formation.

Emplacement of the Goochland Terrane

Metamorphism in the northern slate belt occurred during Alleghanian orogenesis at ~320 to 280 Ma, as determined by the cooling ages of foliation-defining metamorphic minerals (Kunk and others, 1995; Horton and others, 1995; Burton and Armstrong, 1997; Burton and others, 2000). In the northern part of the study area, metamorphic grade reached upper amphibolite-facies as demonstrated by the occurrence of prograde garnet, staurolite, and kyanite, and by the occurrence of *in situ* leucogranite melt accumulations in metasedimentary rocks. Metamorphic grade abruptly decreases southward across the study area to greenschist-facies (fig. 4; Hackley and Peper, 1998), and the slate belt is at greenschist-facies southward to the North Carolina border (Kunk and others, 1995; Horton and others, 1999).

We interpret Alleghanian tectonism and the steep thermal gradient in the northern slate belt to be caused by emplacement of the Grenville-age Goochland terrane (fig. 1) to the north-northeast during dextral transpressional accretion (Bartholomew and Tollo, 2004). Crustal loading over the northern end of the slate belt and the development of the steep thermal gradient would have occurred through the stacking of now-eroded thrust slices (Burton and Armstrong, 1997), as the Goochland crustal block was emplaced.

The Goochland terrane itself is an enigmatic crustal element of uncertain Laurentian affinity accreted (or reaccreted) into the Appalachians by southward-directed dextral translation (Bartholomew and Tollo, 2004; Bailey and others, 2005). Our study does not concern itself with the controversial ancestry of the Goochland terrane, only that emplacement of the Goochland block was accompanied by crustal shortening and the stacking of thrust slices over the northern end of the slate belt. Emplacement of elements of the Goochland terrane or thrust-faulted elements of the slate belt, over the northern end of the slate belt, would have resulted in the forcing of

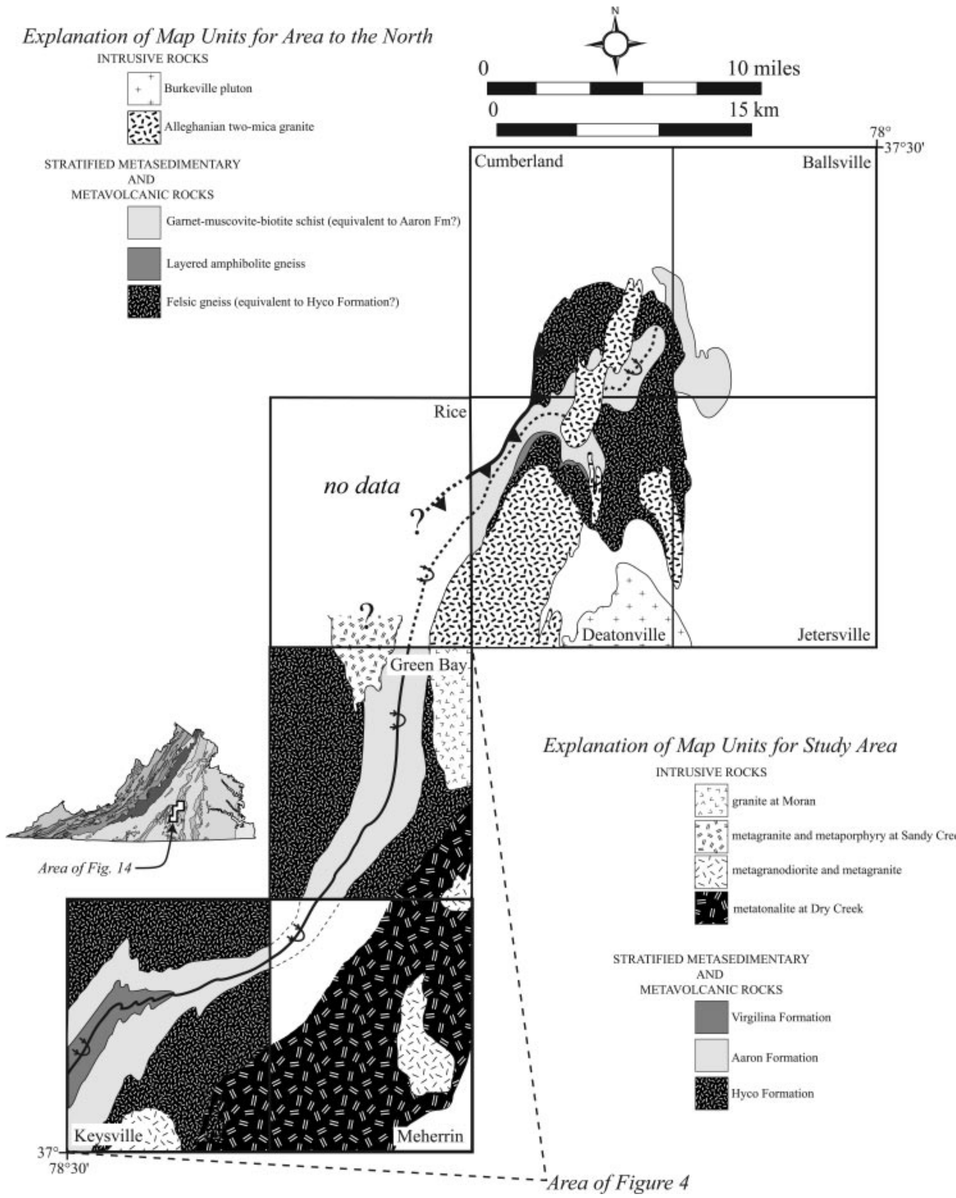

Fig. 8. Unbroken continuation of Dryburg syncline and Carolina slate belt stratigraphy northward into higher-grade correlative gneiss and schist. Unpublished mapping in Cumberland, Ballsville, Deatonville, and Jetersville quadrangles by W. C. Burton. Contacts are dashed in the Meherrin quadrangle to indicate unpublished reconnaissance mapping, and are speculatively projected in the Rice quadrangle as indicated by queries.

the Virgilina sequence to deeper crustal levels, accompanied by partial melting and the development of upper amphibolite-facies conditions.

Emplacement of the Goochland terrane at the northern end of the slate belt may have been the agent responsible for the well-characterized Alleghanian dextral slip and thrust-faulting of the Carolina terrane over the Milton terrane that is recognized farther to the southwest (Hibbard and others, 1998; Wortman and others, 1998; Bradley and others, 2006). We hypothesize that Goochland accretion adjacent to the northern slate belt may have activated movement on the western boundary of the Carolina slate belt crustal block, causing Alleghanian transpressive movement and thrusting of the slate belt over the Milton terrane on the Hyco shear zone (Hibbard and others, 1998). Emplacement of the Goochland terrane also is here inferred to have developed the northeast-striking, moderate to steeply southeast-dipping penetrative foliation that characterizes the southern part of the study area, and which appears to be broadly folded in the northern part of the area. Post-kinematic prograde garnet widely recognized at outcrop indicates prolonged deep crustal residence following final emplacement and late refolding of the penetrative fabric.

Evidence Against An Alternative Hypothesis

An alternative interpretation to northward continuity of the Carolina slate belt is that the disconformity present at the Hyco-Aaron contact on the western limb of the Dryburg syncline is instead a northwest-verging Alleghanian thrust fault, which brings the slate belt over the higher-grade rocks of the Milton terrane. In this model, rocks interpreted to be northern high-grade Hyco Formation correlative gneiss and schist on the western limb of the Dryburg syncline in the Green Bay quadrangle would be Milton terrane rocks. Evidence that could be cited in support of a permissive thrust at the Hyco-Aaron contact includes several observations. Hyco lithologies observed in the northern part of the study area, including kyanite ± staurolite schist (Zhl and Zhq), biotite gneiss (Zhbg), and felsic migmatite gneiss and granite (Zhfg) are similar to rocks described from the Milton terrane (Coler and others, 2000; Bradley and others, 2006). In addition, refolding of isoclinal folds characterizing the Dryburg syncline in the study area is a commonly-described structural element in the Milton terrane (Henika, 2002; Bradley and others, 2006). However, similarities in lithology and structure are not definitive evidence for a thrust and, more importantly, slate belt lithologies were traced directly upgrade over the location of the proposed thrust with no break in continuity.

Truncation of internal contacts within the Hyco as described in this study, and the northward loss of basal Aaron metaconglomerate above the Hyco (Virginia Division of Mineral Resources, 1993) are not inconsistent with a thrust at the contact. However, the Hyco-Aaron contact is interpreted as a disconformity, primarily based on the truncation of internal contacts within the Hyco on both limbs of the Dryburg syncline (and which may have occurred as a result of differential uplift and erosion prior to Aaron deposition, as described earlier). In addition, there is no field evidence to document fault truncation of the Aaron metaconglomerate occurring at the base of the Aaron south of the Red Oak Granite (fig. 2). Loss of the Aaron metaconglomerate could just as easily be accounted for by lateral facies changes or nondeposition.

Parts of the contact on the western limb of the Dryburg syncline were mapped as a fault by USGS researchers working northward from the North Carolina border (fig. 3). However, these faults are steeply-dipping dextral strike-slip faults associated with late Alleghanian shear, and do not contain structures which preserve kinematic evidence for west-over-east-directed thrusting.

The contact is northeastward along strike from the well-characterized Hyco shear zone which separates the Carolina slate belt from the Milton terrane (Hibbard and others, 1998; Wortman and others, 1998; Bradley and others, 2006), and could tie in with the thrust fault mapped by W. C. Burton in the Deatonville quadrangle (fig. 8). However, no evidence for a thrust fault or major structural discontinuity such as increasing frequency of mylonite zones was observed near the contact in the study area. As described by Hibbard and others (1998), the Hyco shear zone at the Carolina-Milton terrane boundary southwest of the study area is an 8 km+ wide zone of strongly sheared tectonites. Our field observations which constrain the Hyco-Aaron disconformity occur within $<$1 km on either side of the contact (and locally within $<$10 m), with no discernible evidence for a high strain zone.

In addition to these arguments, similar high-grade lithologies including kyanite ± staurolite schist and amphibolite are present on both limbs of the Dryburg syncline (fig. 4). Were a thrust fault to separate the low-grade slate belt from Milton terrane at the Hyco-Aaron contact on the west limb of the syncline, high-grade kyanite ± staurolite schist and amphibolite would not be expected on the eastern limb. Furthermore, evidence for the garnet-in isograd mapped during our study (fig. 4) is located on the east limb of the Dryburg syncline and is contained entirely within what are unambiguously slate belt rocks. Therefore, even if the Hyco-Aaron disconformity is reinterpreted as an Alleghanian thrust bringing the slate belt over the Milton terrane, evidence is present for a steep metamorphic gradient on the slate belt side of the supposed fault, consistent with continuity of slate belt stratigraphy and structure to the north. Based on the evidence outlined above, the results of this mapping study are interpreted to indicate unbroken northward continuation of the Carolina slate belt into higher-grade correlative gneiss and schist.

Directions for Future Research

Better resolution of the nature of the relationships between the northernmost Carolina slate belt and adjacent terranes will be accomplished by additional mapping, structural analysis, petrologic, and geochronologic research completed by future workers. In particular, we suggest the following areas and problems which deserve further examination: (1) Detailed petrofabric analysis at selected locations on the Hyco-Aaron contact, which could potentially resolve questions regarding a structural discontinuity versus a disconformity interpretation of the contact. (2) Mapping and petrologic studies to constrain in detail the western contact of the Hyco Formation with the Milton terrane, and to trace the northward extent of the Hyco shear zone. (3) Radiometric dating of the felsic metavolcanic and intrusive rocks mapped in this study. In particular, the metagranite and metaporphyry at Sandy Creek (PzZsc), which intrudes the Hyco-Aaron disconformity and the Dryburg syncline (fig. 4), should yield a late Alleghanian age if the Hyco-Aaron contact is a thrust. Dating of Hyco gneisses in the northwestern Green Bay quadrangle (fig. 4) would yield a Neoproterozoic age in our model; however, if the Hyco-Aaron contact is a thrust contact at the Carolina slate belt-Milton terrane boundary, the gneisses should have Ordovician ages similar to those reported by Coler and others (2000) for Milton terrane rocks. (4) A petrologic and geochronologic study of the metatonalite at Dry Creek (fig. 4) and its possible genetic lineage with Hyco Formation metavolcanic rocks. (5) Detailed geologic mapping of the Rice quadrangle immediately north of the study area to further trace the Dryburg syncline and to tie in with W. C. Burton's unpublished mapping (fig. 8). (6) A petrofabric analysis of the felsic metavolcanics in the Deatonville quadrangle to identify a potential structural discontinuity or angular unconformity that brings in rocks of Uwharrie age to the northernmost Carolina slate belt. These are among several of many directions for future workers to pursue.

CONCLUSIONS

Geologic mapping of the northernmost Carolina slate belt in south-central Virginia has extended the classic greenschist-facies Virgilina stratigraphy and structure of Laney (1917) northward through an increase in metamorphic grade into higher-grade correlative gneiss and schist. The Neoproterozoic Hyco, Aaron, and Virgilina Formations are folded into the regional, north-to northeast-trending, isoclinal Dryburg syncline, which is a northern extension of the Virgilina synclinorium. The syncline probably formed during the Neoproterozoic (prior to ~568 Ma) as suggested by the ages of crosscutting plutonic rocks farther south in Virginia (Horton and others, 1999), possibly during the Virgilina deformation of Glover and Sinha (1973). Rocks of the syncline were refolded and metamorphosed at greenschist- to amphibolite-facies during the Carboniferous-Permian Alleghanian orogeny, which produced the pervasive regional foliation and the Barrovian metamorphic gradient. Garnet, and kyanite ± staurolite isograds are at moderate to high angles to the trace of lithologic contacts, allowing the identification of progressive mineralogical and textural changes in individual lithologic units as a function of increasing metamorphic grade to the north. The emplacement of the Goochland terrane to the northeast and the stacking of intervening thrust slices over the northernmost slate belt are interpreted to be responsible for the development of the isograds, development of the penetrative structural fabric, and refolding of the Dryburg syncline. Rocks of the Carolina slate belt do not end on the north against through-going faults or rest on higher-grade basement, as previously suggested, and upper amphibolite-facies equivalents of the same rocks continue northward.

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