7. The Goochland-Chopawamsic Terrane Boundary, Central Virginia Piedmont

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Introduction

The southern Appalachian hinterland is composed of a number of terranes with distinctly different geologic histories. Some terranes, such as the central and northern Virginia Blue Ridge, are clearly of North American or Laurentian affinity (Rankin and others, 1989; Horton and others, 1989). Others, such as the Carolina slate belt, are demonstrably exotic with respect to Laurentia (Secor and others, 1983; Hibbard and others, 2002). Still others, such as the Goochland and Chopawamsic terranes, are, because of a lack of definitive evidence, of uncertain affinity and considered to be "suspect" with respect to Laurentia. While it is generally understood that these exotic and suspect terranes were accreted to the Laurentian margin during Paleozoic orogenesis, major unresolved questions remain, including (1) the origin and affinity of such terranes, (2) the timing of their accretion, and (3) the kinematics of deformation along terrane boundaries.

In central Virginia, at the northern end of the southern Appalachians, exposed terranes include, from west to east, the Blue Ridge, the Western Piedmont, the Chopawamsic, the Goochland, and the Southeastern Piedmont (fig. 1). They are separated from each other by major fault systems along which multiple generations of motion are recognized. The present state of these boundaries holds clues to the past relations of the adjacent terranes. Understanding the affinity of these terranes and the kinematics and timing of their juxtaposition is a prerequisite for accurately describing the tectonic history of the Virginia Piedmont.

The Goochland and Chopawamsic terranes have markedly different geologic histories (fig. 2). The Goochland terrane, in the eastern Piedmont, has been described as a Middle to Late Proterozoic basement massif with relict granulite-facies mineral assemblages (Glover and others, 1982; Farrar, 1984; Farrar and Owens, 2001). The Chopawamsic terrane, in the central Piedmont, is an Ordovician volcanic-plutonic arc complex (Pavlides, 1981; Coler and others, 2000). The boundary between the Goochland and Chopawamsic terranes coincides with a pronounced northeast-trending aeromagnetic and aeroradiometric feature known as the Spotsylvania lineament. Neuschel (1970) first recognized this geophysical boundary before mapping, geochronology, and tectonic models provided an adequate framework for understanding its significance. Later workers described this discontinuity as a brittle thrust fault (Pavlides and others, 1980a), a mylonite zone (Farrar, 1984; Brown, 1986), and a "major suture" (Marr, 1991). Recent workers have named this zone the Spotsylvania high-strain zone (Spears and Bailey, 2002; Bailey and others, in press).

The purpose of this field trip is to focus on new research within and along the boundary between the Goochland and Chopawamsic terranes in central Virginia. We present new evidence describing the kinematics of deformation in the Spotsylvania high-strain zone with indications of large-scale relative displacement between the terranes. Surprising new geochronology in the Goochland terrane challenges long-standing assumptions about its history. We also examine two enigmatic fault slices and a suite of unusual mafic to ultramafic igneous rocks and speculate as to their origin. This work provides new insights into the spatial and temporal relation of the terranes, with implications for the tectonic assembly of the Piedmont.

Geology

Goochland Terrane

The Goochland terrane is composed of multiply deformed and metamorphosed gneiss, amphibolite, granite, and anorthosite (fig. 2). The oldest and structurally lowest unit in the Goochland terrane is the State Farm Gneiss (Brown, 1937), a coarse-grained granitic gneiss that crops out in a series of domes (fig. 3) that are overlain by the Sabot Amphibolite and the heterogeneous Maidens Gneiss (Poland, 1976). Both the Sabot and the Maidens are intruded by the Montpelier Anorthosite (Aleinikoff and others, 1996). U-Pb zircon analyses of the State Farm Gneiss and Montpelier

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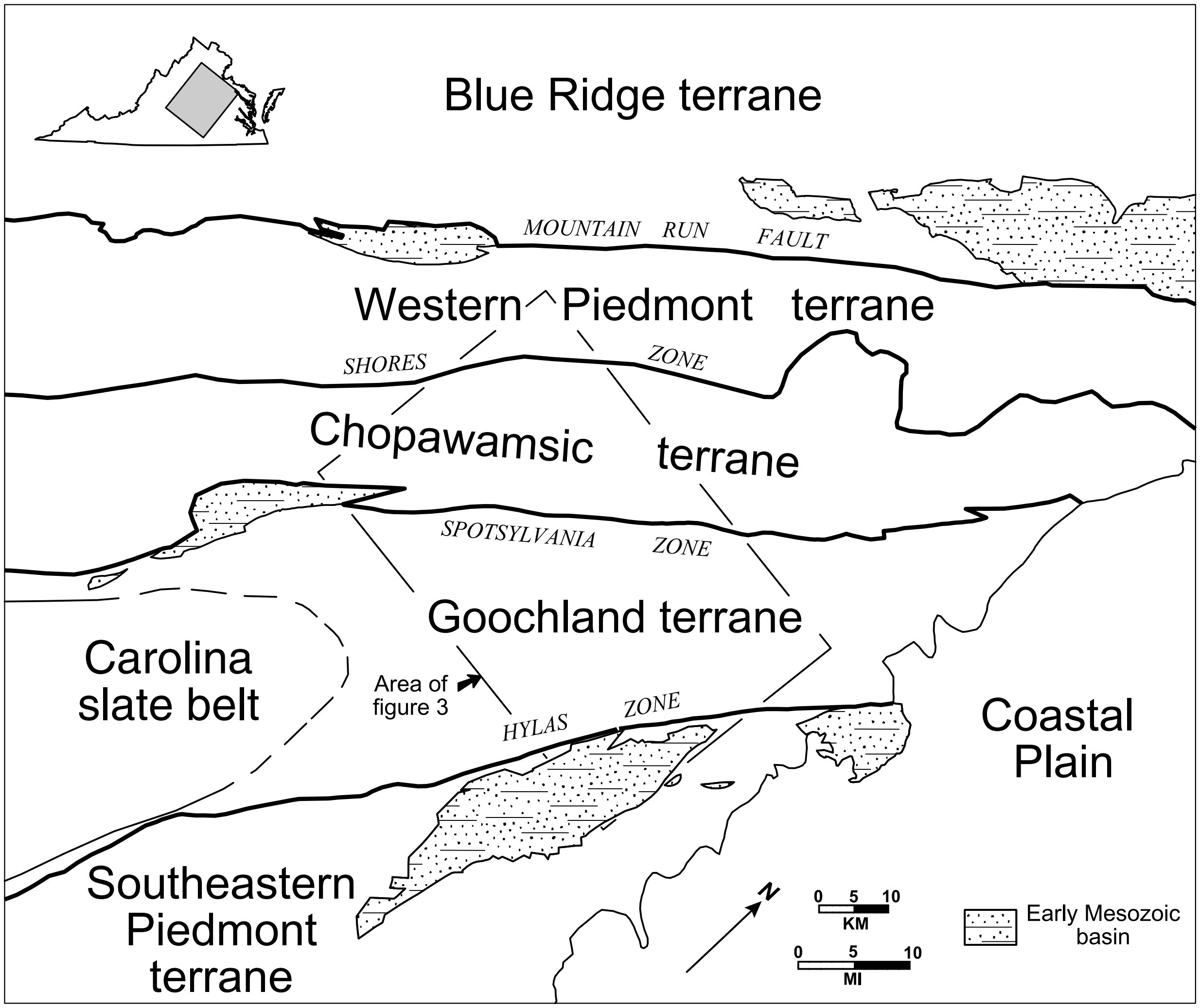

Figure 1. Map showing geologic terranes and their boundaries in central Virginia.

Anorthosite yield Mesoproterozoic ages of 1,050 to 1,020 Ma (Aleinikoff and others, 1996; Owens and Tucker, 1999). A suite of small A-type granitoid plutons with U-Pb zircon ages of ~630 Ma intrudes the State Farm Gneiss (Owens and Tucker, 2000). The Maidens, the most extensive map unit in the Goochland terrane, is dominantly pelitic (biotite-garnet and muscovite-sillimanite gneiss) with some granitic gneiss.

Rocks of the Goochland terrane experienced an early granulite-facies metamorphic event that was overprinted by a later amphibolite-facies event (Farrar, 1984; Farrar and Owens, 2001). Farrar (1984) interprets the early granulite-facies metamorphism as Mesoproterozoic and the amphibolite-facies event as Alleghanian (~300–250 Ma). The origin of the Goochland terrane is unclear; the Mesoproterozoic rocks and A-type Neoproterozoic granitoids are similar to Laurentian basement in the Blue Ridge (Glover and others, 1978; Farrar, 1984; Glover and others, 1989; Aleinikoff and others, 1996). New Nd-isotopic results reported by Owens and Samson (2001, in press) for the State Farm Gneiss and Montpelier Anorthosite show that these units are isotopically similar to other blocks of Mesoproterozoic crust along the eastern and southern margins of Laurentia (for example, Adirondacks, Blue Ridge, Llano uplift); however, other workers have suggested that the Goochland terrane may be of peri-Gondwanan affinity (Rankin and others, 1989; Hibbard and Samson, 1995).

Previously, the entire Goochland terrane was considered to be a coherent block of Mesoproterozoic crust. Mesoproterozoic crystallization ages based on modern U-Pb zircon methods have been confirmed for both the Montpelier Anorthosite (1,045±10 Ma; Aleinikoff and others, 1996) and the State Farm Gneiss (~1,046–1,023 Ma; Owens and Tucker, 2003). In addition, Horton and others (1995) reported a U-Pb zircon age of 1,035±5 Ma for a granitic gneiss within the Maidens Gneiss near Amelia Courthouse, possibly indicating that the Maidens is also Mesoproterozoic. However, new results based on electron microprobe dating of monazite in more typical Maidens lithologies (metapelites, and so forth) have thus far revealed no ages older than about 420 Ma (R.J. Tracy, B.E. Owens, and C.R. Shirvell, unpub. data). If these monazite ages reflect the timing of granulite-facies metamorphism (a plausible interpretation), the long-held assumption that the high-grade event was Grenvillian is clearly incorrect (see Burton and Armstrong, 1997). Furthermore, new U-Pb zircon results for a probable metaigneous variety of Maidens Gneiss (Stop 3) indicate a Paleozoic age, suggesting that at least some portions of the Maidens Gneiss are younger than Mesoproterozoic. An interesting additional point in this regard is that Neoproterozoic granitoids have thus far not been recognized within the Maidens Gneiss; in other words, they appear to be restricted to the State Farm Gneiss (Owens and Tucker, 2003). These points suggest the possibility of a previously unrecognized unconformity or structural discontinuity between at least the western part of the Maidens Gneiss and the more easterly (State Farm, Sabot, and Montpelier) portion of the Goochland terrane.

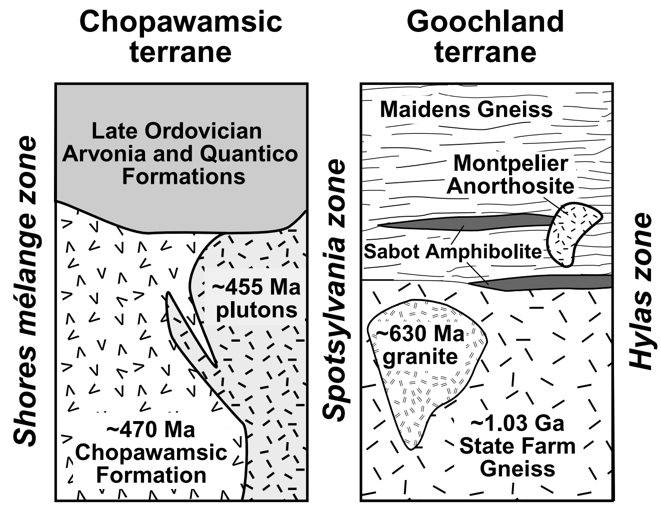

Figure 2. Generalized stratigraphy of the Chopawamsic and Goochland terranes.

Chopawamsic Terrane

The Chopawamsic terrane is composed of metamorphosed volcanic and sedimentary rocks with a suite of associated granitoid plutons, all of Middle to Late Ordovician age (fig. 2). The most widespread unit is the Chopawamsic Formation, a suite of mafic and felsic metavolcanic rocks dated at ~470 Ma (Horton and others, 1998; Coler and others, 2000). In central Virginia, the Chopawamsic is intruded by the Columbia pluton (fig. 3), a granite to granodiorite body that yielded a U-Pb SIMS (secondary ion mass spectrometry) zircon age of 457±7 Ma (Wilson, 2001). In the western part of the Chopawamsic terrane, both the Chopawamsic Formation and the Columbia pluton are unconformably overlain by the Arvonia Formation (figs. 2, 3), a metasedimentary package that contains Late Ordovician fossils (Darton, 1892; Watson and Powell, 1911; Tillman, 1970). The northeastern part of the terrane contains a similar metasedimentary unit, the Quantico Formation, which may be partly interlayered with the Chopawamsic Formation. Late Ordovician fossils also are present in the Quantico Formation (Pavlides and others, 1980b).

Rocks of the Chopawamsic terrane preserve evidence of one regional metamorphic event. Metamorphic mineral assemblages indicate that greenschist-facies conditions were reached along the northwest side of the terrane; these grade into amphibolite-facies assemblages in the southeast part of the terrane. Metamorphic hornblende from the Chopawamsic Formation dated by $^{40}Ar/^{39}Ar$ methods yielded ages of 318 to ~284 Ma (Burton and others, 2000). The Chopawamsic terrane is interpreted to be an Ordovician volcanic arc complex developed on continental crust outboard of Laurentia (Coler and others, 2000) and later accreted during the Late Ordovician Taconic orogeny (Glover and others, 1989).

Spotsylvania High-Strain Zone

The Spotsylvania high-strain zone (SHSZ) forms the boundary between the early Paleozoic Chopawamsic terrane and the Mesoproterozoic-Paleozoic(?) Goochland terrane in the central Virginia Piedmont (fig. 3). This boundary was originally recognized as a sharp geophysical (aeromagnetic and aeroradiometric) lineament (Neuschel, 1970) and interpreted as a brittle fault. In the Piedmont of southern Virginia, the SHSZ appears to connect with the Hyco shear zone, a component of the Alleghanian-age central Piedmont shear zone, a major boundary traceable for over 500 km (kilometers; 300 mi (miles)) in the southern Appalachians (Hibbard and others, 1998; Wortman and others, 1998). Hibbard and others (1998) interpreted the Hyco zone in southern Virginia to be a ductile thrust that emplaced the Carolina terrane over the Chopawamsic terrane. Farrar (1984), Pratt and others (1988), and Glover and others (1989) interpreted the Spotsylvania zone as a significant thrust fault (not a suture) along which granulite/amphibolite-facies rocks of the Goochland belt were emplaced to the northwest in the late Paleozoic. In north-central Virginia, Pavlides and others (1980a) interpreted the Spotsylvania zone to be a 2- to 3-km (1–2 mi)-wide zone of predominantly brittle en-echelon faults. In central Virginia, Marr (1991) reported the presence of a tectonic mélange zone within the SHSZ and suggested it may represent a suture. Bourland (1976) and Spears and Bailey (2002) recognized brittle fault rocks in the SHSZ and interpreted these to have formed during Mesozoic reactivation of the Paleozoic high-strain zone. The Spotsylvania zone is located within the central Virginia seismic zone (Bollinger and others, 1986; Çoruh and others, 1988) and as recently as 2003, small earthquakes have occurred at depth along this structure.

We define the SHSZ as a ~15-km (~9-mi)-wide belt of heterogeneously deformed mylonitic rocks that typically lacks

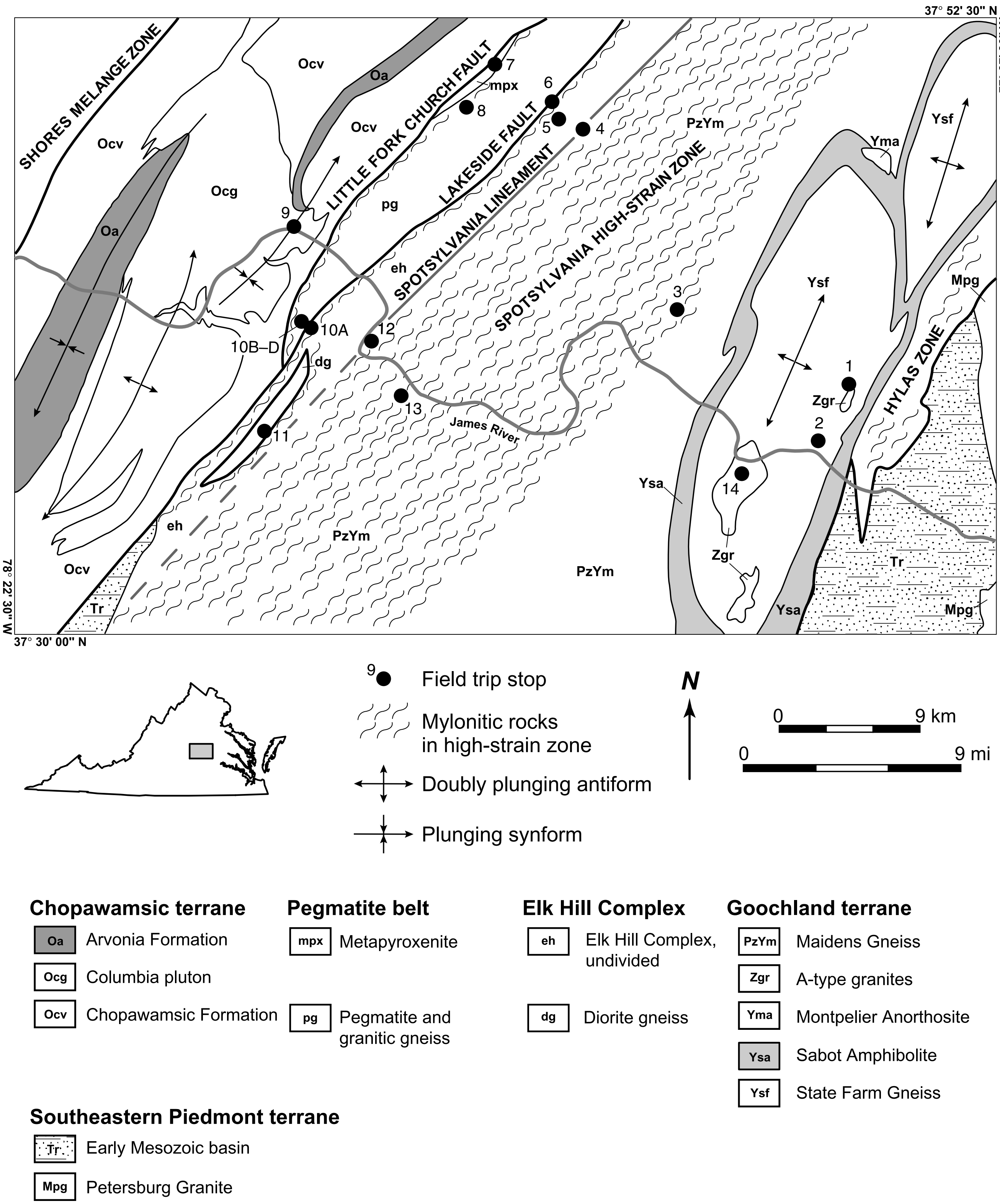

Figure 3. Generalized geologic map of the central Virginia Piedmont showing locations of field trip stops.

distinct boundaries (fig. 3). Its northwestern boundary is defined by the geophysical lineament at the contact between amphibole-rich gneisses of the Elk Hill Complex to the northwest and mylonitic rocks derived from more granitic to pelitic protoliths to the southeast. Gneissic rocks to the southeast of the Spotsylvania lineament are strongly deformed well into the Goochland terrane. Mylonitic biotite schist, granitic mylonite, biotite-rich ultramylonite, amphibolite, and protomylonitic pegmatite are the most common rock types in the SHSZ. Foliation in the SHSZ strikes to the northeast and generally dips moderately to gently to the southeast. At some locations, where SHSZ is located in the hanging wall of listric Mesozoic normal faults, dips of mylonitic foliations flattened out due to horizontal axis rotations associated with normal faulting. Lineations (both elongation and mineral) plunge shallowly to the northeast and southwest in the plane of the foliation. Asymmetric porphyroclast tails and boudins from surfaces normal to foliation and parallel to lineation consistently exhibit a strike-parallel dextral asymmetry across the SHSZ. Pegmatite dikes are commonly folded and boudinaged in a geometry consistent with bulk constrictional strain (K>1) (Bailey and others, in press). Folded dikes are asymmetric; the folds generally verge to the northwest. The geometry of asymmetric structures, both parallel and normal to the elongation lineation, is consistent with a modest triclinic deformation symmetry (Bailey and others, in press).

Minimum sectional strains, estimated from boudinaged and folded dikes on lineation-parallel surfaces, range from 8:1 to >20:1. Feldspar porphyroclasts, pegmatitic boudins, and amphibolite boudins are superficially similar to clasts or blocks in a mélange, but exhibit consistent dextral asymmetries and at many locations occur as tabular bodies with a pinch-and-swell character (Stops 3, 4, 8). Backward-rotated porphyroclasts are common in SHSZ ultramylonites and vorticity analysis yields W_n-values between 0.8 and 0.4, indicating general shear deformation that significantly deviated from simple shear (Bailey and others, in press).

Quartz grains in mylonitic rocks from the SHSZ are completely recrystallized, straight extinction is common, and strong crystallographic preferred orientations are well developed. Feldspar porphyroclasts display core and mantle structures and strong undulose extinction. In mylonites and ultramylonites, myrmekite and flame perthite are localized along high-strain grain boundaries. Synkinematic metamorphic minerals include biotite, garnet, epidote, and staurolite. Microstructures preserved in mylonitic rocks from the SHSZ are consistent with deformation conditions in the upper greenschist to lower amphibolite facies (450–500°C).

In order to better constrain the kinematics and tectonic significance of the SHSZ, Bailey and others (in press) used estimated values for vorticity and three-dimensional strain to restore the Goochland terrane to its paleogeographic position prior to dextral transpression. Deformation in the SHSZ produced significant thinning (~40–70 percent) normal to the zone and up to 500 percent stretching parallel to the zone boundaries. With the Chopawamsic terrane fixed in position, the Goochland terrane is retrodeformed to a predeformation position 80 to 300 km (50–186 mi) northeast of its present location. These displacement estimates are minimum values because strains were calculated from boudinaged and folded dikes that are, in themselves, minimum strain indicators. Furthermore, the Brookneal/Shores high-strain zone and the Mountain Run fault zone, more westerly structural discontinuities in the Virginia Piedmont (fig. 1), also exhibit dextral motion (Gates and others, 1986; Bobyarchick, 1999). Thus, the Goochland terrane, relative to the more western elements in the Virginia Piedmont, experienced significant southwestern translation during the Alleghanian orogeny.

Fault Slices of Uncertain Affinity Associated with the Terrane Boundary

Two narrow belts of rocks originally described by Taber (1913) are now recognized to be fault-bounded blocks of unknown affinity (Spears and Bailey, 2002). Although well documented by Taber (1913) and Brown (1937), the pegmatite belt and Elk Hill Complex were excluded from map compilations in the second half of the twentieth century (for example, Virginia Division of Mineral Resources, 1993). We find that both blocks exist as mappable fault-bounded units spatially associated with the terrane boundary. No published geochronology exists for any of the rocks in these two fault blocks. Comparison of these rocks to the Goochland and Chopawamsic terranes does not yield obvious correlations to units in either of the adjacent terranes.

Pegmatite Belt

Taber (1913) used the term “pegmatite belt” to describe an area underlain by pegmatite and granite in western Goochland and northern Cumberland Counties. Some later workers (Jonas, 1932; Brown, 1937) honored Taber’s nomenclature and included a similar area of pegmatite on their geologic maps. However, the 1963 geologic map of Virginia (Virginia Division of Mineral Resources, 1963) depicts this area as an extension of the Columbia granite. Farrar (1984) recognized pegmatite in this area and interpreted it to be associated with the intrusion of the Columbia pluton. However, on the 1993 geologic map of Virginia (Virginia Division of Mineral Resources, 1993), this area was mapped as biotite gneiss with small intrusions of biotite granite, all within the Chopawamsic terrane.

We find that these rocks are lithologically distinct and separated by faults from the Chopawamsic Formation and the Elk Hill Complex (fig. 3). The recently described Little Fork Church fault, mappable by a lithologic discontinuity coincident with both ductile and brittle fault rocks (Spears and Bailey, 2002) forms the western boundary of the pegmatite belt (fig. 3). The eastern boundary is defined by the Lakeside

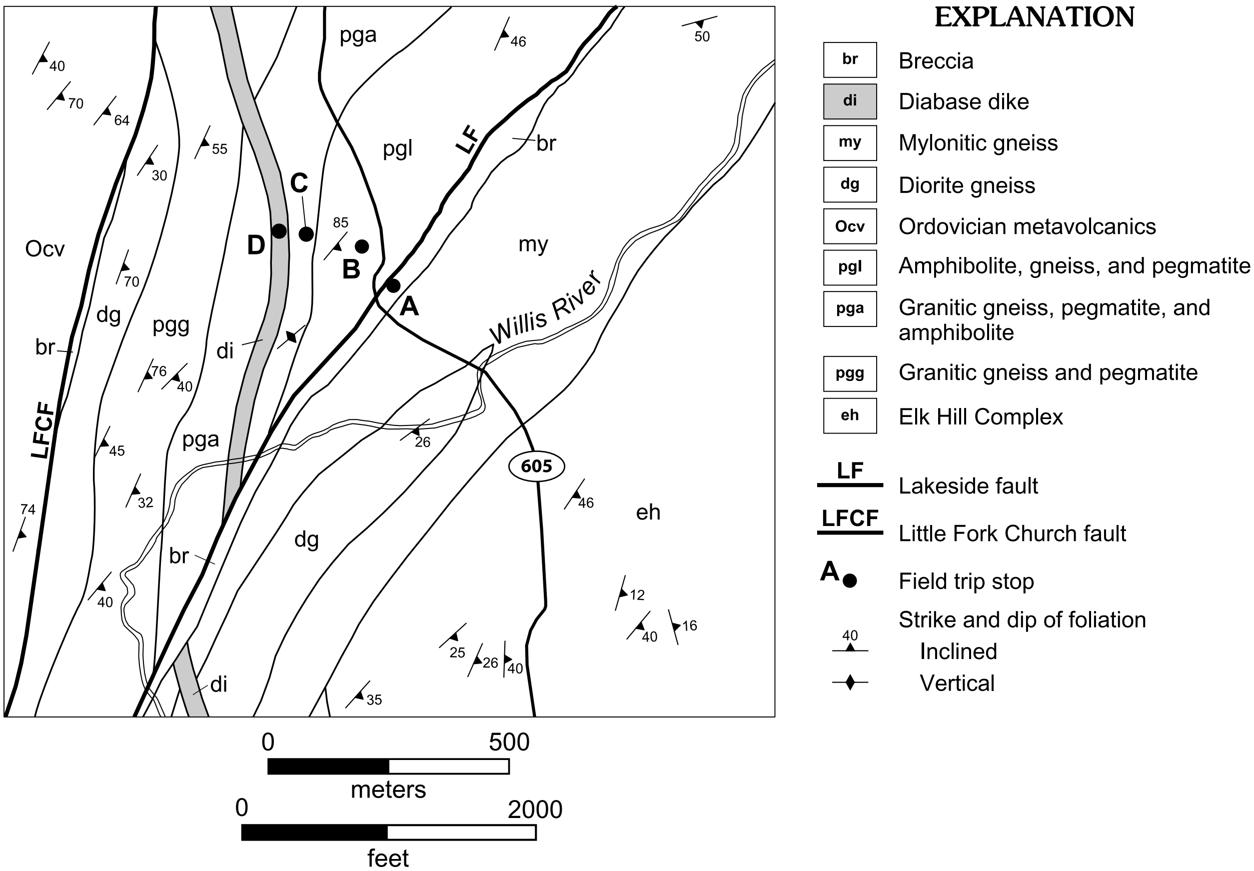

Figure 4. Bedrock geologic map of the area around Stops 10A–D, Cumberland County, Va.

fault, which separates the pegmatite belt from the Elk Hill Complex (Stops 6, 10) (fig. 3). The belt can be separated into three distinct lithologic packages from west (structurally lowest) to east (structurally highest). The structurally lowest unit (pgg) is composed of light-gray, fine-grained, weakly layered micaceous granitic gneiss with abundant white to pink potassium feldspar-quartz-muscovite pegmatite (Stop 8; fig. 4). The pegmatite is concordant with the foliation in the surrounding gneiss and is commonly deformed into lens-shaped domains containing potassium feldspar porphyroclasts in a fine-grained matrix of muscovite, quartz, and microcline. Large feldspars are commonly kaolinized and display throughgoing brittle fractures. The middle unit (pga, fig. 4) is composed of weakly layered granitic gneiss similar to the lower unit, with less pegmatite, and generally concordant bodies of fine-grained amphibolite that are commonly deformed into boudins (Stop 10C). The upper unit (pgl) is strongly compositionally layered amphibolite, biotite gneiss, and minor pegmatite (Stop 10B, fig. 4).

Elk Hill Complex

The Elk Hill Complex was named by Taber (1913) for exposures in cuts along the railroad southeast of Elk Hill plantation in western Goochland County. At its type locality, the Elk Hill is dominated by strongly compositionally layered hornblende gneiss with lesser amounts of biotite gneiss and pegmatite. We find that, in addition to these lithologies, the Elk Hill contains gneissic diorite, talc-chlorite soapstone, and, especially south of the James River, distinctive phenocrystic felsic rocks resembling pinkish, fine-grained granite in outcrop.

Brown (1937) recognized the Elk Hill Complex on his geologic map of Goochland County, but the name was excluded from the literature for the rest of the 20th century. A hornblende gneiss unit was indicated in this area on the 1963 geologic map of Virginia (Virginia Division of Mineral Resources, 1963); however, on the 1993 geologic map of Virginia (Virginia Division of Mineral Resources, 1993), rocks in this area were mapped as "biotite gneiss" contiguous with the Central Virginia volcanic-plutonic belt, which at that time was a synonym for the Chopawamsic terrane.

Our work demonstrates that the Elk Hill Complex is distinct and separated by faults from both the Chopawamsic and the Goochland terranes. The Lakeside fault, previously mapped from the early Mesozoic Farmville basin northeastward to a point just south of the James River (Virginia Division of Mineral Resources, 1993), in fact extends farther northeastward across the James River and across western Goochland County at least as far north as I-64. This fault separates the Elk Hill Complex from the pegmatite belt and the Chopawamsic Formation throughout the area mapped. The eastern boundary of the Elk Hill is marked by the strongly mylonitic rocks of the Spotsylvania high-strain zone.

Although the Elk Hill Complex and the Chopawamsic Formation are superficially similar in that they are both dominated by mafic metavolcanic rocks, we note certain dissimilarities. The Elk Hill includes, particularly south of the James River, distinctive fine-grained felsic metavolcanic rocks interlayered with amphibolite. The felsic rocks contain concentrically zoned plagioclase phenocrysts, presumably of primary volcanic origin; such phenocrysts are not observed in the Chopawamsic Formation at this latitude. Geophysically, the Chopawamsic Formation is characterized by a high-amplitude, short-wavelength pattern on total intensity aeromagnetic maps; the pattern over the Elk Hill Complex is lower amplitude and longer wavelength. Furthermore, the Chopawamsic Formation contains substantial deposits of precious metals and massive sulfides. These well-known deposits were heavily exploited beginning in the early 19th century, to the point that a well-defined band of rocks now recognized as the Chopawamsic terrane was known as the “gold-pyrite belt” (Lonsdale, 1927; Spears and Upchurch, 1997). Despite intense prospecting by gold seekers, adjacent parts of the Piedmont remained largely unproductive. The Elk Hill (as well as the pegmatite belt and the Goochland terrane) is apparently barren of metallic mineralization, as demonstrated by the total absence of known mines.

These dissimilarities raise suspicions that the Elk Hill Complex and the Chopawamsic Formation, while both ostensibly of volcanic origin, may be of different ages and affinities. Additional work is needed to fully characterize the differences between these two blocks, and to establish the possible relation of the Elk Hill to other metavolcanic units in the Piedmont.

Conclusions

The Goochland and Chopawamsic terranes have markedly different histories that indicate that they developed independently and were not juxtaposed until post-Late Ordovician. Unpublished monazite ages in the Goochland terrane, referred to above, raise the intriguing possibility that they were separate until even later, post ~420 Ma (Silurian), and that the granulite-facies metamorphic event may be middle Paleozoic. While the basement rocks of the Goochland terrane, including the State Farm Gneiss, superficially resemble Laurentian rocks of the Virginia Blue Ridge, our work on the kinematics of its western boundary indicates that it originated far to the north. Quantitative understanding of the kinematics does not resolve whether the Goochland is a native Laurentian or an exotic terrane; however it does place meaningful limits on its pre-Alleghanian position in the Appalachian orogen. If the Goochland terrane is Laurentian, it originated somewhere between the Pennsylvania reentrant and the New York promontory, not outboard of the Virginia Blue Ridge.

The Elk Hill Complex and the pegmatite belt form two fault slices of uncertain affinity between the Goochland terrane and the Chopawamsic terrane proper. In addition, we recognize an unusual suite of mafic to ultramafic rocks associated with faults along the terrane boundary. Further work is needed to establish the significance of these units and their relation to adjacent terranes. These previously unrecognized crustal elements must be considered in future models for the tectonic assembly of the southern Appalachian Piedmont.

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References Cited

Aleinikoff, J.N., Horton, J.W., Jr., and Walter, M., 1996, Middle Proterozoic age for the Montpelier Anorthosite, Goochland terrane, eastern Piedmont, Virginia: Geological Society of America Bulletin, v. 108, p. 1481–1491.

Bailey, C.M., Francis, B.E., and Fahrney, E.E., in press, Strain and vorticity analysis of transpressional high-strain zones from the Virginia Piedmont, USA: Geological Society of London Special Paper.

Bobyarchick, A.R., 1999, Kinematics of the Mountain Run fault zone, Virginia [abs.]: Geological Society of America Abstracts with Programs, v. 31, no. 3, p. 6.

Bollinger, G.A., Snoke, J.A., Sibol, M.S., and Chapman, M.C., 1986, Virginia regional seismic network; Final Report (1977–1985): Washington, D.C., U.S. Nuclear Regulatory Commission, NUREG/CR–4502, 57 p.

Bourland, W.C., 1976, Tectonogenesis and metamorphism of the Piedmont from Columbia to Westview, Virginia, along the James River: Blacksburg, Virginia Polytechnic Institute and State University, M.S. thesis, 105 p.

Brown, C.B., 1937, Outline of the geology and mineral resources of Goochland County, Virginia: Virginia Geological Survey Bulletin, v. 48, 68 p.

Brown, W.R., 1986, Shores complex and mélange in the central Virginia Piedmont, *in* Neathery, T.L., ed., Southeastern Section of the Geological Society of America: Geological Society of America Centennial Field Guide, v. 6, p. 209–214.

Burton, W.C., and Armstrong, T.R., 1997, Structural and thermobaric history of the western margin of the Goochland terrane, Virginia [abs.]: Geological Society of America Abstracts with Programs, v. 29, no. 3, p. 7–8.

Burton, W.C., Kunk, M.J., and Marr, J.D., Jr., 2000, $^{40}Ar/^{39}Ar$ age constraints on the timing of Alleghanian metamorphism in the central and southern Virginia Piedmont [abs.]: Geological Society of America Abstracts with Programs, v. 32, no. 2, p. A–8.

Coler, D.G., Wortman, G.L., Samson, S.D., Hibbard, J.P., and Stern, R., 2000, U-Pb geochronology, Nd isotopic, and geochemical evidence for the correlation of the Chopawamsic and Milton terranes, Piedmont zone, southern Appalachian orogen: Journal of Geology, v. 108, p. 363–380.

Çoruh, C., Bollinger, G.A., and Costain, J.K., 1988, Seismogenic structures in the central Virginia seismic zone: Geology, v. 16, p. 748-751.

Darton, N.H., 1892, Fossils in “Archean” rocks of the central Piedmont, Virginia: American Journal of Science, Series 3, v. 44, p. 50–52.

Farrar, S.S., 1984, The Goochland granulite terrane; Remobilized Grenville basement in the eastern Virginia Piedmont: Geological Society of America Special Paper 194, p. 215–227.

Farrar, S.S., and Owens, B.E., 2001, A north-south transect of the Goochland terrane and associated A-type granites—Virginia and North Carolina (field trip guide), *in* Field Trip Guidebook, Southeastern Section 50th Annual Meeting: Geological Society of America, p. 75–92.

Gates, A.E., Simpson, C., and Glover, L., III, 1986, Appalachian Carboniferous dextral strike slip faults; An example from Brookneal, Virginia: Tectonics, v. 5, p. 119–133.

Glover, Lynn, III, Mose, D.G., Poland, F.B., Bobyarchick, A.R., and Bourland, W.C., 1978, Grenville basement in the eastern Piedmont of Virginia; Implications for orogenic models [abs.]: Geological Society of America Abstracts with Programs, v. 10, no. 4, p. 169.

Glover, Lynn, III, Mose, D.G., Costain, J.K., Poland, F.B., and Reilly, J.M., 1982, Grenville basement in the eastern Piedmont of Virginia; A progress report [abs.]: Geological Society of America Abstracts with Programs, v. 14, no. 1 and 2, p. 20.

Glover, Lynn, III, Evans, N.H., Patterson, J.G., and Brown, W.R., 1989, Tectonics of the Virginia Blue Ridge and Piedmont: Field Trip Guidebook T363 for the 28th International Geological Congress: Washington, D.C., American Geophysical Union, 59 p.

Goodman, M.C., Dubose, J., Bailey, C.M., and Spears, D.B., 2001, Petrologic and structural analysis of the Columbia pluton, central Virginia Piedmont [abs.]: Geological Society of America Abstracts with Programs, v. 33, no. 2, p. 4.

Hibbard, J.P., 2000, Docking Carolina; Mid-Paleozoic accretion in the southern Appalachians: Geology, v. 28, no. 2, p. 127–130.

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 Cadwood, P.A., eds., Current perspectives in the Appalachian-Caledonian orogen: Geological Society of America Special Paper 241, p. 191–205.

Hibbard, J.P., Shell, G., Bradley, P., Samson, S.D., 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.

Hibbard, J.P., Stoddard, E.F., Secor, D.T., and Dennis, A.J., 2002, The Carolina zone; Overview of Neoproterozoic to early Paleozoic peri-Gondwanan terranes along the eastern flank of the southern Appalachians: Earth Science Reviews, v. 57, p. 299–339.

Horton, J.W., Jr., Aleinikoff, J.N., and Burton, W.C., 1995, Mesoproterozoic and Neoproterozoic terranes in the eastern Piedmont of Virginia, implications of coordinated field studies and U-Pb geochronology [abs.]: Geological Society of America Abstracts with Programs, v. 27, no. 6, p. A–397.

Horton, J.W., Jr., Aleinikoff, J.N., Drake, A.A., Jr., and Fanning, M.C., 1998, Significance of Middle to Late Ordovician volcanic-arc rocks in the central Appalachian Piedmont, Maryland and Virginia [abs.]: Geological Society of America Abstracts with Programs, v. 30, no. 7, p. 125.

Horton, J.W., Jr., Drake, A.A., Jr., and Rankin, D.W., 1989, Tectonostratigraphic terrranes and their Paleozoic boundaries in the central and southern Appalachians, *in* Dallmeyer, R.D., ed., Terranes in the Circum-Atlantic Paleozoic orogens: Geological Society of America Special Paper 230, p. 213–245.

Jonas, A.I., 1932, Structure of the metamorphic belt of the southern Appalachians: American Journal of Science, v. 24, p. 228–243.

Lonsdale, J.T., 1927, Geology of the gold-pyrite belt of the northeastern Piedmont, Virginia: Virginia Geological Survey Bulletin 30, 110 p.

Marr, J.D., Jr., 1991, The Ca Ira mélange—Indicator of a major suture in the Piedmont of Virginia [abs.]: Geological Society of America Abstracts with Programs, v. 23, no. 1, p. 62.

Murray, J.D., and Owens, B.E., 2002, Field, mineralogical, and geochemical constraints on the origin of a metapyroxenite dike(?), central Piedmont province, Virginia [abs.]: Geological Society of America Abstracts with Programs, v. 34, p. 23.

Neuschel, S.K., 1970, Correlation of aeromagnetics and aeroradioactivity with lithology in the Spotsylvania area, Virginia: Geological Society of America Bulletin, v. 81, p. 3575–3589.

Owens, B.E., and Samson, S.D., 2001, Nd-isotopic constraints on the magmatic history of the Goochland terrane, easternmost Grenville crust in the southern Appalachians [abs.]: Geological Society of America Abstracts with Programs, v. 33, no. 6, p. 28.

Owens, B.E., and Samson, S.D., in press, Nd-isotopic constraints on the magmatic history of the Goochland terrane, easternmost Grenvillian crust in the southern Appalachians, *in* Tollo, R.P., Corriveau, L., McLelland, J.B., and Bartholomew, M.J., eds., Proterozoic tectonic evolution of the Grenville orogen in North America: Geological Society of America Memoir 197.

Owens, B.E., and Tucker, R.D., 1999, New U-Pb zircon age constraints on the age of the State Farm Gneiss, Goochland terrane, Virginia [abs.]: Geological Society of America Abstracts with Programs, v. 31, no. 3, p. 58.

Owens, B.E., and Tucker, R.D., 2000, Late Proterozoic plutonism in the Goochland terrane, Virginia; Laurentian or Avalonian connection? [abs.]: Geological Society of America Abstracts with Programs, v. 32, no. 2, p. 65.

Owens, B.E., and Tucker, R.D., 2003, Geochronology of the Mesoproterozoic State Farm Gneiss and associated Neoproterozoic granitoids, Goochland terrane, Virginia: Geological Society of America Bulletin, v. 115, p. 972–982.

Pavlides, Louis, 1981, The central Virginia volcanic-plutonic belt; An island arc of Cambrian(?) age: U.S. Geological Survey Professional Paper 1231–A, 34 p.

Pavlides, Louis, Bobyarchick, A.R., and Wier, K.E., 1980a, Spotsylvania lineament of Virginia: U.S. Geological Survey Professional Paper 1175, p. 73.

Pavlides, Louis, Pojeta, John, Jr., Gordon, Mackenzie, Jr., Parsley, R.L., and Bobyarchick, A.R., 1980b, New evidence for the age of the Quantico Formation of Virginia: Geology, v. 8, p. 286–290.

Poland, F.B., 1976, Geology of the rocks along the James River between Sabot and Cedar Point, Virginia: Blacksburg, Virginia Polytechnic Institute and State University, M.S. thesis, 98 p.

Pratt, T., Çoruh, C., Costain, J.K., and Glover, L., III, 1988, A geophysical study of the earth's crust in central Virginia; Implications for Appalachian crustal structure: Journal of Geophysical Research, v. 93, p. 6649–6667.

Rankin, D.W., Drake, A.A., Jr., Glover, L., III, Goldsmith, R., Hall, L.M., Murray, D.P., Ratcliffe, N.M., Read, J.F., Secor, D.T., Jr., and Stanley, R.S., 1989, Pre-orogenic terranes, *in* Hatcher, R.D., Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita orogen in the United States, v. F–2 *of* The geology of North America: Boulder, Colo., Geological Society of America, p. 7–100.

Secor, D.T., Jr., Samson, S.D., Snoke, A., and Palmer, A., 1983, Confirmation of the Carolina slate belt as an exotic terrane: Science, v. 221, p. 649–651.

Smith, J.W., Milici, R.C., and Greenberg, S.S., 1964, Geology and mineral resources of Fluvanna County: Virginia Division of Mineral Resources Bulletin 79, 62 p.

Spears, D.B., and Bailey, C.M., 2002, Geology of the central Virginia Piedmont between the Arvonia syncline and the Spotsylvania high-strain zone: Guidebook, 33rd Annual Virginia Geological Field Conference, 36 p.

Spears, D.B, and Upchurch, M.L., 1997, Metallic mines, prospects and occurrences in the gold-pyrite belt of Virginia: Virginia Division of Mineral Resources Publication 147, 73 p.

Taber, S., 1913, Geology of the gold belt in the James River basin: Virginia Geological Survey Bulletin 7, 271 p.

Tillman, C.G., 1970, Metamorphosed trilobites from Arvonia, Virginia: Geological Society of America Bulletin, v. 81, no. 4, p. 1189–1200.

Virginia Division of Mineral Resources, 1963, Geologic map of Virginia: Charlottesville, Virginia Division of Mineral Resources, scale 1:500,000.

Virginia Division of Mineral Resources, 1993, Geologic map of Virginia: [Richmond], Virginia Division of Mineral Resources, scale 1:500,000.

Watson, T.L., and Powell, S.L., 1911, Fossil evidence of the age of the Virginia Piedmont slates: American Journal of Science, Series 4, v. 31, p. 33–44.

Wilson, J., 2001, U/Pb zircon ages of plutons from the central Appalachians and GIS-based assessment of plutons with comments on their regional tectonic significance: Blacksburg, Virginia Polytechnic Institute and State University, M.S. thesis 121 p.

Wortman, G.L., Samson, S.D., and Hibbard, J.P., 1998, Precise U-Pb timing constraints on the kinematic development of the Hyco shear zone, southern Appalachians: American Journal of Science, v. 298, p. 108–130.

ROAD LOG AND STOP DESCRIPTIONS FOLLOW

Road Log and Stop Descriptions

Day 1 (Sunday, March 28, 2004)

The field trip begins at the I-64/I-295 interchange west of Richmond.

Mileage

Incremental	Cumulative	
4.5	4.5	Proceed west on I-64 for 4.5 miles (mi) to Exit 173.
1.2	5.7	Turn left and go south on Va. 623 for 1.2 mi to stop sign.
0.7	6.4	Turn right (west) on U.S. 250 for 0.7 mi to Va. 621.
2.3	8.7	Turn left (south) on Va. 621 for 2.3 mi to Va. 644.
0.75	9.45	Turn right (west) and follow Va. 644 for 0.75 mi to third driveway on left after crossing Dover Creek.
0.15	9.6	Follow driveway 0.15 mi to creek crossing. Park along driveway.

Stop 1. Neoproterozoic granitoid along unnamed, east-flowing tributary of Dover Creek.

Outcrop in creek upstream (west) of driveway.

The slopes and creek bed here contain excellent exposures of a distinctive type of Neoproterozoic granitoid (Zgr) within the State Farm Gneiss (fig. 3). The rock here is characterized by a somewhat spotted appearance, reflecting oriented clusters of biotite+amphibole. This same rock type also occurs as a small body some 10 km (6 mi) to the north (not shown on figure 3 because of scale). Although the full dimensions of this pluton have not been completely mapped out, it is exposed in several drainages to the west of Dover Creek covering an area of at least 2 × 0.5 km (1–0.3 mi) (A.K. Teepe, 2001, undergraduate geology thesis, College of William and Mary). Thin sections show that the rock is dominated by microcline, plagioclase, and quartz; dark-green amphibole, yellow-brown biotite, allanite, and sparse garnet are accessory minerals. Samples from this pluton are typically quartz syenite, with SiO_2 ranging from 60 to 69 weight percent in four samples (Owens and Tucker, 2003). One sample (south of this stop) yielded a U-Pb zircon age of 588+9/-12 Ma (Owens and Tucker, 2003).

Mileage

Incremental	Cumulative	
0.15	9.75	Retrace route back to Va. 644. Turn left (west).
3.7	13.45	Follow Va. 644 for 3.7 mi to stop sign. Turn right (west) on Va. 6.
0.1	13.55	Proceed west on Va. 6 for 0.1 mi. Park on shoulder of road.

Stop 2. State Farm Gneiss and Neoproterozoic granitoid in roadcut on north side of Va. 6.

Outcrop is in roadcut on north side of road.

This location represents one of the few actual roadcuts in this part of the Goochland terrane. Although highly iron-stained, this exposure shows a key intrusive relation between a mafic variety of the State Farm Gneiss (~57 weight percent SiO_2) and a leucocratic variety of Neoproterozoic granite (~70 weight percent SiO_2). Both rock types are exposed at various places in the roadcut, but the west end shows that a number of small (centimeterscale) dikes of granite have intruded the gneiss. These dikes also are folded, indicating deformation following emplacement. A larger mass of the granite is exposed near the east end of the main roadcut, and here shows only a faint foliation. The granite here is more leucocratic than it is at Stop 1, but is mineralogically similar. Some differences include more abundant garnet, local occurrences of distinctive euhedral magnetite, and the presence of sphene. Samples from this roadcut give U-Pb zircon ages of 1039+18/-11 Ma for the State Farm Gneiss and ~654 Ma for the Neoproterozoic granite. The poorly constrained age for the granite is based on a single concordant zircon analysis, with five additional analyses showing considerable scatter (see Owens and Tucker, 2003, for additional discussion). Pegmatites of Paleozoic age, common throughout the Goochland terrane, also are present in this roadcut.

Mileage

Incremental	Cumulative	
10	23.55	Continue west on Va. 6 for 10 mi, through village of Goochland Courthouse to traffic light.
0.35	23.9	Turn right (north) on U.S. 522. Go 0.35 mi and turn right (east) on Va. 632.
0.9	24.8	Follow Va. 632 for 0.9 mi to entrance of Hidden Rock Park on left.
0.3	25.1	Turn into park, drive 0.3 mi to end of driveway and park in parking lot.

Stop 3. Maidens Gneiss at Hidden Rock Park.

Outcrops in whaleback exposures near bathrooms.

This locality contains some of the best exposures (outcrops and large blocks) of the Maidens Gneiss in this area. The gneiss here is a medium-grained, biotite plagioclase+quartz gneiss, with additional amphibole and (or) clinopyroxene present in some samples. All samples also contain sphene. The gneiss has obviously been highly injected by pegmatites for pegmatite is present in most exposures of the Maidens in this area. The protolith of the Maidens Gneiss is uncertain, but work is in progress to help answer this question on the basis of chemical compositions. Analyses of rocks from this park and several other locations (six samples, including the type locality at Maidens Cave, 4 km (2 mi) to the south) show a narrow range of bulk compositions: SiO_2=~55–62 weight percent; CaO=~4.2–6.8 weight percent; and K_2O=~2.7–4.0 weight percent (B.E. Owens, unpub. data). In addition, one sample from this locality has yielded a well-constrained U-Pb zircon age of 407±2 Ma (B.E. Owens and R.D. Tucker, unpub. data). The nearly concordant nature of the zircon analyses, in conjunction with the chemical compositions, suggests that this variety of Maidens Gneiss may have originated from an igneous protolith of intermediate composition (quartz monzodiorite to quartz monzonite or volcanic equivalents). The significance of the Paleozoic age is unclear at the present time, but work is in progress on additional samples to evaluate this surprising result.

The penetrative foliation in the gneiss, defined by amphibolite-facies minerals and microstructures, is folded into a series of northwest-verging, gently plunging, overturned antiforms and synforms (fig. 5). Burton and Armstrong (1997), in a study approximately on strike about 50 km (30 mi) southwest of this locality, interpret this fabric to be of Alleghanian age. Some pegmatitic dikes are discordant to the foliation whereas other pegmatitic dikes are folded and boudinaged in dramatic fashion. We interpret these dikes to have intruded throughout the deformation. These dikes serve as minimum strain markers and record sectional strains of ~15:1 to 20:1. Elongation lineations, where discernible, plunge gently to both the northeast and southwest parallel to fold axes. Kinematic indicators are compatible with dextral transpressive shear. These exposures are ~10 km (~6 mi) southeast of the Spotsylvania geophysical lineament at the western edge of the Goochland

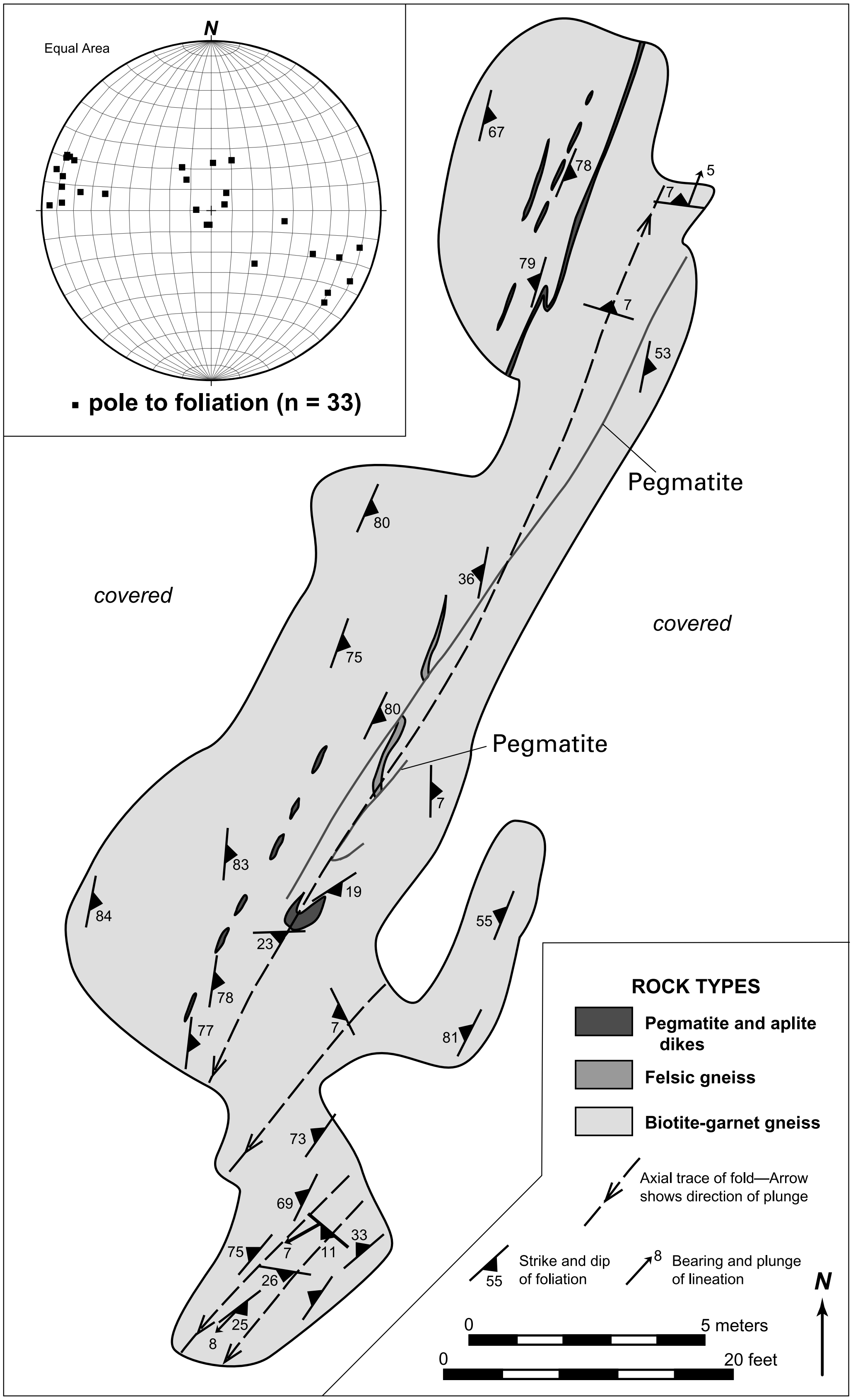

Figure 5. Outcrop map with stereogram (inset) of large whaleback exposure of mylonitic Maidens Gneiss at Hidden Rock Park, Goochland County, Va. (Stop 3). n, number of measurements.

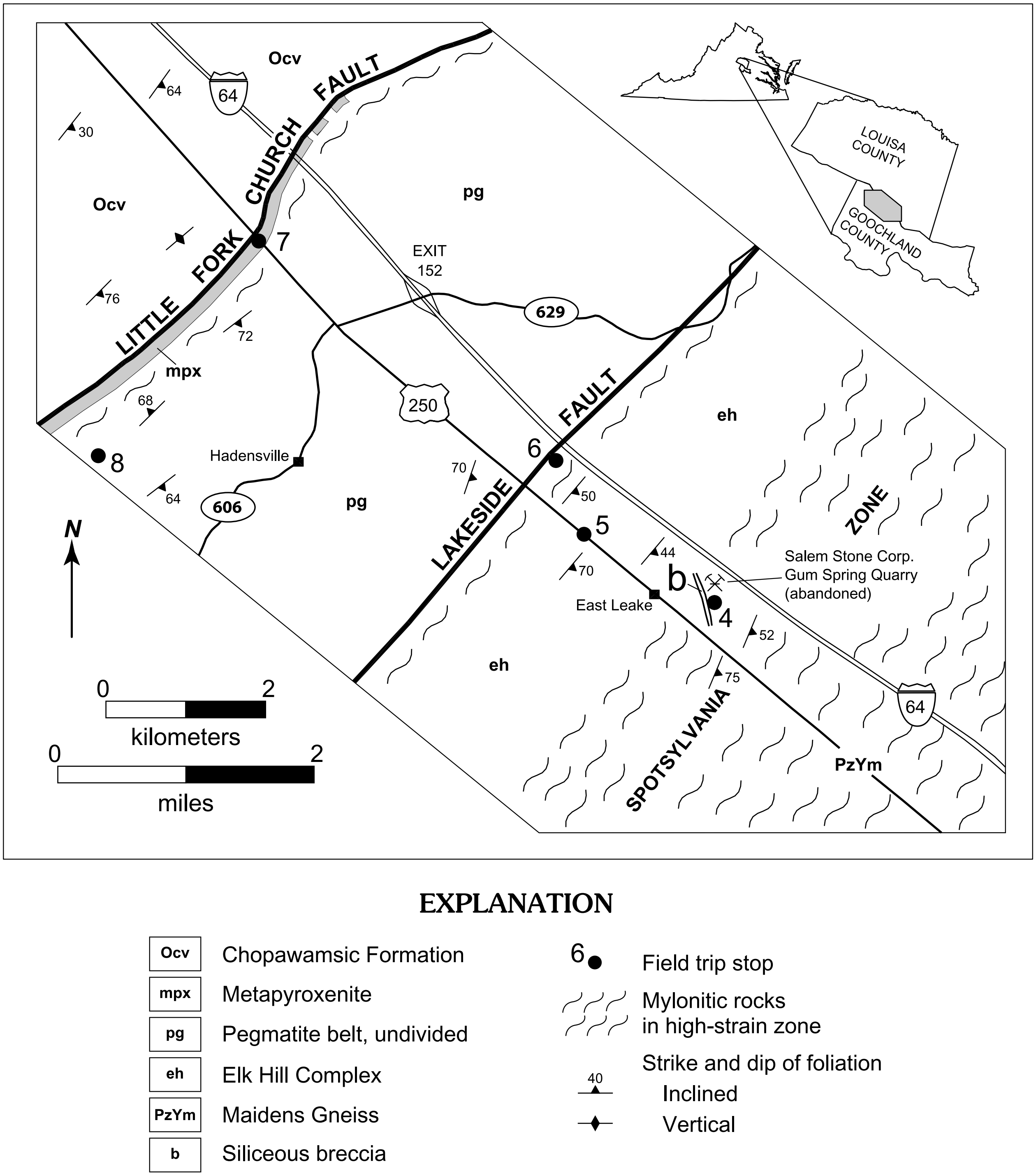

Figure 6. Generalized geologic map along I-64 and U.S. 250 in Goochland and Louisa Counties, Va., showing the locations of Stops 4 through 8.

terrane, but as evidenced by the pegmatite markers, the rocks are very strongly deformed. It is difficult to place a southeastern boundary on the Spotsylvania zone, as rocks throughout the Goochland terrane are deformed in this fashion.

Mileage

Incremental	Cumulative	
1.2	26.3	Retrace route back to Va. 632 and turn right (west), returning to U.S. 522. Turn right (north).
6.5	32.8	Follow U.S. 522 north for 6.5 mi to U.S. 250. Turn left (west).
3.3	36.1	Follow U.S. 250 west for 3.3 mi to Va. 700. Turn right (east).
0.1	36.2	Follow Va. 700 for 0.1 mi to first driveway on left. Turn around in driveway and park along north side of Va. 700. Walk north along driveway for 0.25 mi.

Stop 4. Tectonically disrupted Elk Hill Complex along western margin of Spotsylvania high-strain zone, Gum Spring Quarry.

Blocks and small outcrops in creek.

This abandoned quarry was operated by the Salem Stone Corporation during the construction of I-64 in the 1960s. We cannot safely visit the pit itself, which is filled with water and surrounded by steep highwalls, but the large quarried blocks dumped here provide an excellent view of the material blasted out of the pit. The blocks are predominantly composed of protomylonitic amphibolite and porphyroclastic mylonite. Plagioclase porphyroclasts range up to 5 cm (centimeters) (2 in (inches)) in diameter, apparently remnants of tectonized pegmatite. Blocks of dark-green to black amphibolite form tectonic inclusions in the mylonite. These range in shape from blocky to lens-shaped to extremely flattened, suggesting a wide range of competency contrasts in relation to the enclosing mylonitic gneiss. In the quarry walls, average orientation of the mylonitic foliation is 035° 42° SE.

This locality is on strike with and lithologically similar to the Ca Ira mélange of Marr (1991). While these rocks are certainly highly deformed, we note the lack of truly exotic blocks; virtually all observable tectonic inclusions are varieties of amphibolite, the dominant rock type in the nearby Elk Hill Complex. Therefore, we interpret this locality not as true mélange, but as highly deformed Elk Hill lithologies in the footwall of the Spotsylvania high-strain zone (fig. 6). Just east of here, the presence of strongly pelitic rocks (muscovite-sillimanite-garnet schist) marks the transition into the Maidens Gneiss protolith of the Goochland terrane.

A narrow zone of poorly exposed siliceous breccia trends north-northwest across the south slope of this small valley. Lithologically, the rock is similar to the breccia along the Lakeside fault: nearly white, massive cryptocrystalline silica with both quartz-filled and open fractures enclosing angular clasts of the same lithology. The siliceous breccia can be traced from the crest of a low hill on the quarry entrance road in a north-northwesterly direction for at least 500 meters (m) (1,600 feet (ft)) (fig. 6). The re-brecciated breccia indicates multiple episodes of Mesozoic brittle reactivation along the western margin of the Spotsylvania high-strain zone, although at an angle oblique to the original mylonitic foliation.

Mileage

Incremental	Cumulative	
0.1	36.3	Return to vehicles and return on Va. 700 west to U.S. 250. Turn right (west).
1.2	37.5	Follow U.S. 250 west for 1.2 mi. Park on grassy shoulder at crest of hill.

Stop 5. Elk Hill Complex on U.S. 250 near East Leake.

Small outcrops in roadcut on north side of U.S. 250.

Small outcrops of the Elk Hill Complex here were fresh and more extensive when photographed by C.B. Brown in 1937 (his pl. 7). We can still observe the general nature of the complex, compositionally layered amphibolite interlayered with biotite gneiss, as it is expressed north of the James River. The compositional layering here is parallel to a moderately developed foliation that strikes 040° and dips 70° SE. A weak mineral lineation (mostly hornblende) plunges gently northeast (20°–48°). On the north side of the road, outcrops display northeast-plunging Z-shaped refolded folds.

The main purpose of this stop is to demonstrate that the Elk Hill Complex is a coherent body of relatively undeformed amphibolitic rocks between two parallel high-strain zones (fig. 6). It is bounded on the east by the Spotsylvania high-strain zone (Stop 4) and on the west by mylonitic rocks in the hanging wall of the Lakeside fault (Stop 6). Our mapping indicates that the Elk Hill extends from here at least as far as the Farmville basin, 40 km (25 mi) to the southwest. Its northeastward extent has not been determined. While these rocks superficially resemble amphibolites in the Chopawamsic Formation, they are structurally separated from the main body of the Chopawamsic Formation to the west.

Mileage

Incremental	Cumulative	
0.4	37.9	Continue west on U.S. 250 for 0.4 mi. At bottom of hill, park on grassy shoulder. Walk through woods following creek north-northeast, about 0.3 mi.

Stop 6. Mylonitic rocks in the hanging wall of the Lakeside fault in unnamed creek north of U.S. 250.

Creek pavement outcrops near I-64 culvert.

Exposures in this streambed give us a view of mylonitic rocks in the hanging wall of the Lakeside fault (fig. 6). A fine-grained matrix of biotite, muscovite, and quartz encloses abundant porphyroclasts of plagioclase feldspar. Plagioclase-quartz pegmatite layers have been deformed into lens-shaped, generally foliation-parallel domains of various sizes. Foliation trends 042° with an average dip of 50° SE. Preliminary analysis of porphyroclast asymmetry indicates dextral oblique motion on this mylonitic zone, similar to that in the Spotsylvania high-strain zone. Creeks crossing this zone at a high angle yield outcrops that indicate a width of nearly 900 m (3,000 ft). Elsewhere, the trace of the Lakeside fault is marked by extensive development of siliceous breccia (for example, Stop 10A), an indication of Mesozoic brittle reactivation of this Paleozoic ductile fault zone. The outcrops here represent part of the case for extending the Lakeside fault northeast of the terminus shown in northern Cumberland County on the geologic map of Virginia (Virginia Division of Mineral Resources, 1993). Its northeastern termination has not yet been determined.

Mileage

Incremental	Cumulative	
2.9	40.8	Return to vehicles and continue west on U.S. 250 for 2.9 mi. Turn vehicles around in driveway near top of hill and park on south shoulder of road.

Stop 7. Amphibole-rich metapyroxenite at Hadensville, U.S. 250.

Roadcut at crest of hill on south side of U.S. 250.

This roadcut exposes one of the most prominent mafic to ultramafic dike-like bodies in the Piedmont province of Virginia. It was originally mapped as pyroxenite by Brown (1937), but labeled as hornblende gabbro on the 1963 geologic map of Virginia. Curiously, the body was omitted from the 1993 geologic map of Virginia (Virginia Division of Mineral Resources, 1993). The body is well exposed in outcrop or float for about 5.5 km (3 mi), ranges up to ~200 m (~660 ft) wide, and is oriented ~040° (Murray and Owens, 2002). Most exposures are dominated by green, medium- to coarse-grained ($\leq$1 cm), blocky calcic amphibole, and textures range from massive to slightly foliated. The blocky shapes may reflect pseudomorphic replacement of pyroxene by amphibole. In thin section, the rocks typically consist of ~85 to 90 percent calcic amphibole (actinolite to actinolitic hornblende to magnesio-hornblende), minor epidote and quartz, and rare talc (and even rarer cummingtonite). Clinopyroxene (relict igneous?) occurs in small amounts in a few samples as ragged grains within amphibole. Eight samples from along the length of the body show similar whole-rock SiO_2 (50–55 weight percent), Al_2O_3 (3–7 weight percent), and Mg# (73–82), but a range in MgO (14–23 weight percent) and CaO (5–14 weight percent). Normative mineralogy of typical samples is dominated by clinopyroxene and orthopyroxene; all are quartz normative. These observations and data suggest that the body represents a pyroxenite metamorphosed at middle- to upper-amphibolite-facies conditions, and that the protolith was a cumulate consisting largely of two pyroxenes and minor plagioclase. The mode of emplacement is an unresolved issue. The body clearly has a dike-like form, but its original cumulate character suggests that it could not have been emplaced as a liquid. In addition, no other indicators of intrusive emplacement (chilled margins, contact metamorphism, xenoliths) have been observed. Alternatively, the body was emplaced tectonically. Its proximity to the Little Fork Church fault (fig. 6) may be significant in this regard, but no clear field evidence linking these features has thus far been observed. [Much of this information is from the 2002 undergraduate geology thesis by J.D. Murray, College of William and Mary; see also Murray and Owens (2002)].

Mileage

Incremental	Cumulative	
0.9	41.7	Return east on U.S. 250 for 0.9 mi to Va. 606. Turn right (south).
1.8	43.5	Follow Va. 606 for 1.8 mi to Va. 609. Turn right (west).
1.0	44.5	Follow Va. 609 for 1.0 mi to Mill Creek. Park in driveway on left.

Stop 8. Granitic gneiss, mylonitized pegmatite, and breccia in the pegmatite belt near Mill Creek.

Outcrops on hillside north of road.

This leucocratic, fine-grained, weakly layered granitic gneiss with thin pegmatites is typical of the structurally lowest unit of the pegmatite belt (fig. 3). The pegmatites are composed mostly of pinkish-white microcline with lesser quartz and muscovite, and are typically deformed into lens-shaped bodies. Pegmatite bodies are parallel to the foliation, which strikes 052° and dips 68° NW. “Floating” porphyroclasts surrounded by fine-grained gneiss suggest that some of the granitic gneiss may be derived from extreme deformation of pegmatite. Pegmatites in this unit are the coarsest grained rocks seen in this part of the Piedmont, with individual microcline crystals up to 15 cm (6 in) long. Feldspars in the pegmatite are strongly fractured, with development of subgrains having nearly parallel crystallographic axes. Float blocks on the slope to the northeast include re-brecciated breccia similar to that found along the Lakeside fault and the western margin of the Spotsylvania high-strain zone. These blocks suggest the presence of an unmapped breccia zone, perhaps related to the Little Fork Church fault.

This locality is about 700 m (2,300 ft) southeast of the mapped trace of the Little Fork Church fault (fig. 6). Considering the high degree of deformation apparent in these rocks, and the presence of possibly tectonically separated, enigmatic, mafic to ultramafic rocks nearby (Stop 7), we must consider the possibility that the Little Fork Church fault is a major structural discontinuity.

Mileage

Incremental	Cumulative	
0.2	44.7	Continue west on Va. 609 for 0.2 mi. At stop sign, turn left (still Va. 609).
1.1	45.8	Continue on Va. 609 for 1.1 mi to stop sign. Turn left (south) on Va. 603.
3.6	49.4	Follow Va. 603 for 3.6 mi to stop sign at Va. 610. Turn left (east) for 60 yards (yd) then right (south) on Va. 603.
2.3	51.7	Follow Va. 603 for 2.3 mi to stop sign at Va. 667. Turn right (west).
4.6	56.3	Follow Va. 667 for 4.6 mi to village of Columbia.
8.0	64.3	At blinking light, turn right (west) on Va. 6 and proceed 8 mi to village of Fork Union for overnight stay.

End of Day 1.

Day 2 (Monday, March 29, 2004)

Mileage

Incremental	Cumulative	
8.0	72.3	Return east on Va. 6 for 8 mi to village of Columbia. Park in lot on right side of road 50 yd past blinking light.

Stop 9. L-tectonites in Columbia pluton at Cowherd quarry, Va. 6, Columbia.

Old dimension stone quarry on north side of Va. 6.

Granodioritic gneiss of the Columbia pluton is exposed in this old roadside quarry (fig. 3). Wilson (2001) obtained a U-Pb zircon SIMS age of 457±7 Ma on rock from this locality. The Columbia pluton ranges from granite to quartz diorite in composition and intrudes metavolcanic rocks of the Chopawamsic Formation (Smith and others, 1964; Goodman and others, 2001) (fig. 3). The Columbia pluton is part of a suite of Ordovician plutons that record magmatic activity associated with the Taconic orogeny. These plutons may have originated above a subduction zone associated with the accretion of the Carolina zone to Laurentia (Hibbard, 2000).

At the Cowherd quarry the granodioritic gneiss contains plagioclase, quartz, biotite, potassium feldspar, and epidote with minor amounts of garnet, muscovite, and opaque minerals. Feldspar and quartz microstructures are consistent with recrystallization under amphibolite-facies conditions. This rock forms a distinctive L-tectonite (fig. 7). The penetrative fabric is defined by aligned biotite and quartz aggregates. The lineation plunges ~25° towards ~050° and a very weak foliation strikes ~055° and dips ~80° NW (fig. 8*A*–*C*). Poles to biotite cleavage form a strong great circle girdle normal to the lineation (fig. 8*B*, *C*). Three-dimensional quartz fabrics in the XZ section range from 2.7 to 3.4 with K-values of 4 to 12 (strongly constrictional) (fig. 8*D*). Locally, L-tectonites are restricted to the nose of a map-scale northeast-plunging synform (fig. 3). Three-dimensional quartz fabrics in the Columbia pluton exhibit a complete range from L- to L/S- to S-tectonites.

Figure 7. Photograph of polished block of L-tectonite from the Columbia pluton, Cowherd quarry, Fluvanna County, Va. (Stop 9).

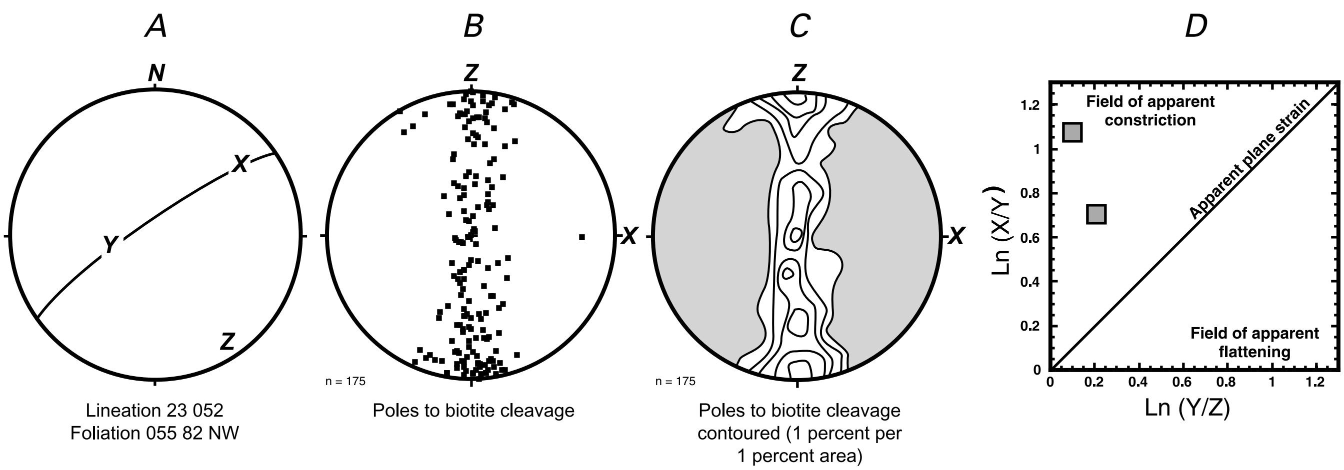

Figure 8. Synoptic diagram for fabric elements in the Columbia granodiorite gneiss at Cowherd quarry; poles and contoured poles to biotite cleavage; and logarithmic Flinn diagram for quartz grain shapes (n = 40 to 64 measurements per sample).

We view the L-tectonite as the product of cumulative deformation. At the map scale, the foliation is folded into a series of asymmetric northeast-plunging folds with axes that parallel the elongation lineation, suggesting a post-foliation deformation event. However, there is no microstructural evidence for two deformational events in these rocks. Although the quartz fabrics do not, in a strict sense, record the finite strain, they are a measure of the approximate overall strain. Here at the Cowherd quarry and at many locations in the central Piedmont, crustal rocks were apparently elongated in an orogen-parallel direction late in the Paleozoic.

Mileage

Incremental	Cumulative	
		Retrace route 50 yd back to blinking light. Turn left (south) on Va. 690.
3.1	75.4	Follow Va. 690 for 3.1 mi to Va. 602. Turn left (east).
1.0	76.4	Follow Va. 602 for 1.0 mi to Va. 605. Turn right (south).
2.1	78.5	Follow Va. 605 for 2.1 mi to edge of flood plain at bottom of hill. Park on side of road.

Stop 10. Fault breccia, pegmatite belt, and diabase at "Bodatious" race track.

A. Breccia associated with the Lakeside fault.

Outcrops on hillside northeast of road.

This prominent northeast-trending ridge is underlain by erosionally resistant siliceous fault breccia, which marks the trace of the Lakeside fault (fig. 4). This fault forms the western bounding normal fault of the Farmville basin, 20 km (12 mi) to the southwest. From here, the fault continues northeastward, crossing the James River between Columbia and Cartersville. Our mapping extends the fault at least as far north as I-64 in Goochland County (fig. 6, Stop 6).

Breccia occurs discontinuously along the fault trace. This, the largest mapped breccia body, is about 8 km (5 mi) long. The breccia is composed of cherty, cryptocrystalline silica with multiple generations of partly to fully filled fractures. Some fractures are filled with microbreccia, but more commonly they are fully or partly healed with crystalline quartz; partly open fractures display terminated quartz crystals. Angular clasts displaying truncated internal fractures are common; they are either supported by microbreccia, by other clasts, or completely surrounded by cherty silica. Bourland (1976) reports zeolite minerals and prehnite from fractures associated with this fault. The breccia apparently formed from silica-rich hydrothermal fluids migrating along the fault in the early Mesozoic; the still-active fault fractured the hydrothermal deposits repeatedly during their formation.

Cross road and enter "Bodatious" race track complex. Walk 250 yd to the northwest to dirt drag strip.

B. Structural complex in upper unit of pegmatite belt.

Large saprolite cut along north side of drag strip.

This large saprolite cut provides a rare view of the structure of the eastern part of the pegmatite belt in the footwall of the Lakeside fault (fig. 4). The strongly compositionally layered gneiss consists of amphibolite, quartzofeldspathic biotite gneiss, and thin concordant pegmatites. These lithologies are typical of the structurally highest lithologic unit in the pegmatite belt (pgl, fig. 4). Layers have been deformed into a series of upright outcrop-scale folds that plunge steeply to the northeast. The folds are cut by two families of younger normal faults, one dipping steeply to the southeast and one dipping gently to the northwest. The faults commonly contain thin discontinuous fills of vein quartz. Crosscutting relations at most fault intersections indicate that the northwest-dipping set is younger, but a few examples can be found in which the southeast-dipping set displays more recent movement.

Follow creek upstream (west) for 100 yd.

C. Granitoid gneiss and amphibolite in middle unit of pegmatite belt.

Creek pavement outcrops west of race track.

In this outcrop, light-gray, fine-grained granitoid gneiss is intruded by a 1.5-m (5-ft)-thick amphibolite dike. The irregular boundaries of the dike cut and trend more easterly than weak compositional layering in the granitoid gneiss. Foliation dips steeply to the southeast (038° 80° SE) and cuts both the dike and the country rock. The amphibolite has been deformed into Z-shaped folds and is locally stretched into boudins of various size. The presence of amphibolite boudins within granitoid gneiss is a characteristic feature of the middle unit of the pegmatite belt (pga, fig. 4). Fine brittle fractures in both lithologies, apparently related to Mesozoic deformation, are filled with epidote and zeolite minerals.

Continue upstream (west) on path along north bank for 50 yd.

D. Large diabase dike.

Stream pavement, boulders, and blocks in ruins of mill dam.

This old mill dam, now in ruins, was built of local boulders placed on top of stream pavement composed of diabase. The boulders themselves are primarily diabase, but light-gray granitic gneiss and white siliceous breccia also are evident. This diabase, one of several large, north-trending Jurassic dikes in the Virginia Piedmont, can be traced on aeromagnetic maps for at least 80 km (50 mi) to the south. To the north, this dike crosses the James River 2 km (1 mi) east of Columbia, where Brown (1937) measured its width at 75 m (250 ft).

South of this outcrop (1.2 km; 0.75 mi), the dike intersects the trace of the Lakeside fault near the Willis River (fig. 4). Although the intersection of the dike with the fault is beneath the flood plain of the river, mapping indicates that where the dike emerges from the flood plain in the hanging wall of the fault, it displays an apparent right-lateral offset of 600 m (2,000 ft) (fig. 4). This evidence suggests a degree of dextral offset on the Lakeside fault after intrusion of the diabase in Early Jurassic time.

Mileage

Incremental	Cumulative	
2.1	80.6	Return to vehicles and go south on Va. 605 for 2.1 mi to stop sign at Va. 690.
0.7	81.3	Turn left (southeast) and follow Va. 690 for 0.7 mi to stop sign at Va. 45.
4.7	86.0	Turn right (south) on Va. 45 and travel for 4.7 mi to Va. 615. Turn right (west).
1.7	87.7	Follow Va. 615 for 1.7 mi to Va. 663. Turn right (north).
1.2	88.9	Follow Va. 663 for 1.2 mi to end of gravel. Park vehicles and walk down old road to creek.

Stop 11. Gneissic diorite near Whiteville.

Outcrops and blocks in creek.

This coarse-grained melanocratic gneiss (dg), described here for the first time, occupies an area of 6 km^2 (2 mi^2) in northern Cumberland County (fig. 3). It forms an elongate fault block bounded on the west by mylonitic rocks in the hanging wall of the Lakeside fault, and on the east by a narrow band of mylonitic biotite schist that separates it from metavolcanic rocks in the Elk Hill Complex (fig. 3). Composition is dominantly hornblende+plagioclase with minor clinopyroxene, quartz, titanite, and epidote. Foliation strikes 042° and is nearly vertical; hornblende defines a mineral lineation plunging 12° and bearing 042°. The weak to moderate gneissic layering seen here (fig. 9) is quite variable, with some outcrops showing no layering or foliation. Superficially, this unit resembles dioritic rocks identified as high-grade equivalents of the Carolina slate belt generally on strike to the south (W.C. Burton, written commun., 2003). When considered with the metapyroxenite in western Goochland County (Stop 7) and poorly exposed talc-chlorite soapstone about 3 km (2 mi) to the north-east (D.B. Spears, unpub. field data), all spatially associated with mapped faults, we can

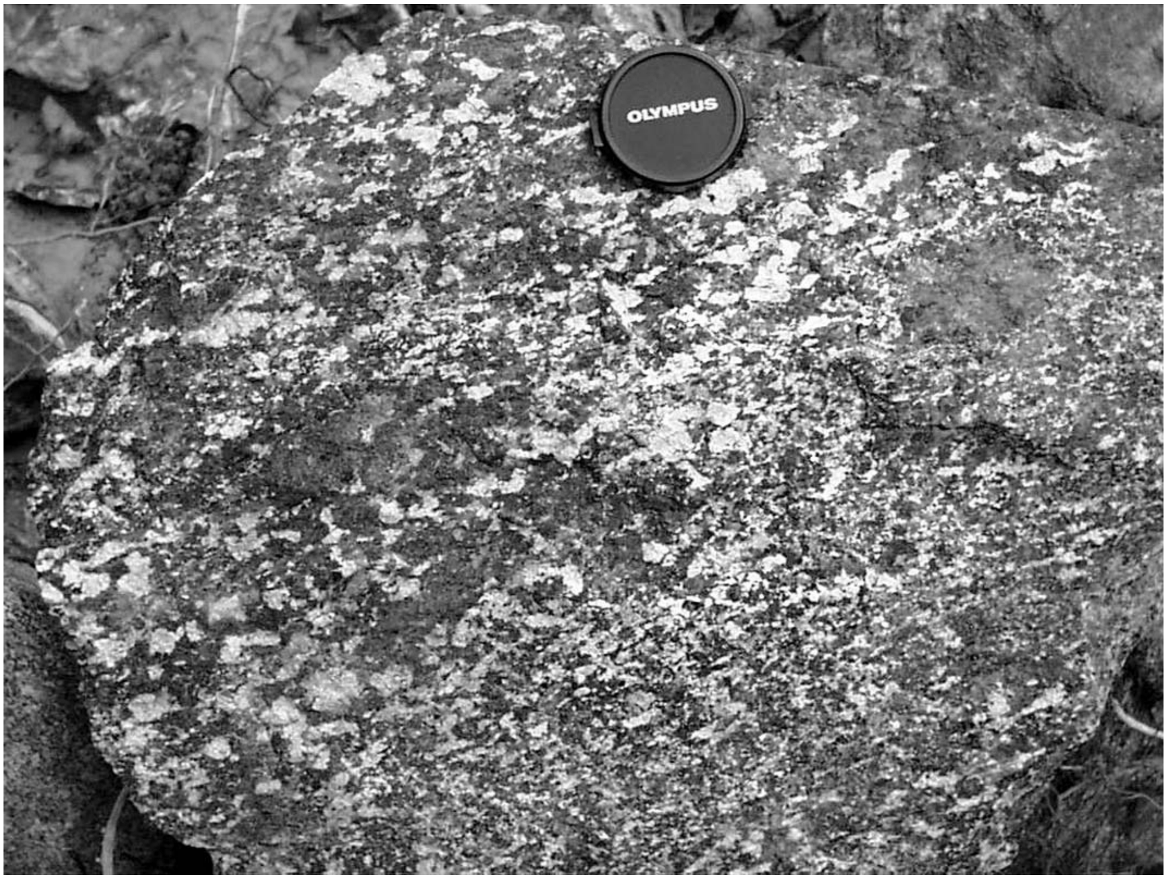

Figure 9. Photograph of block of weakly gneissic coarse-grained diorite from an outcrop near Whiteville, Cumberland County, Va. Lens cap is 4.5 cm (1.75 in) in diameter.

speculate that we are seeing the remains of a tectonically dismembered mafic-ultramafic complex. More work is needed to establish the affinity of these units and their significance with respect to the terrane boundary.

Mileage

Incremental	Cumulative	
9.9	98.8	Retrace route back to Va. 45. Turn left (north) and follow Va. 45 for 7 mi to village of Cartersville, Va.
1.25	100.05	Continue north on Va. 45, crossing James River (0.5 mi), then 0.75 mi farther to driveway of Howard's Neck Plantation on left.
1	101.05	Turn left (west) into driveway. Drive ~1 mi west on driveway and park near house. Walk westward across pasture toward James River, approximately 800 yd.

Stop 12. Mylonitic rocks along west edge of Spotsylvania high-strain zone at Howard's Neck Plantation.

Large natural pavement exposure on south side of small valley east of railroad.

This large natural outcrop exposes rocks and structures typical of the Spotsylvania high-strain zone. The country rock is a mica-rich mylonitic gneiss that has been intruded by dikes of medium-grained granitic gneiss and pegmatite. These dikes are variably dismembered; some retain a tabular shape and others form lozenge-shaped asymmetric boudins. It is possible that the granitic intrusions occurred prior to and during ductile deformation. Foliation strikes to the northeast and dips moderately to gently southeast; elongation lineations plunge subhorizontally in the plane of foliation. Asymmetric structures consistently display a dextral sense of shear. Minimum strain estimates based on boudinaged and folded pegmatites are in excess of 10:1 on lineation parallel faces. The Spotsylvania lineament is located within a few hundred meters to the west and is defined on the ground by a transition to amphibole-rich gneisses of the Elk Hill Complex that do not display a mylonitic texture.

Mileage

Incremental	Cumulative	
1	102.05	Retrace route back to Va. 45. Turn right (south).
2.25	104.3	Follow Va. 45 south for 1.25 mi, back through Cartersville, then continue south 1.0 mi to Va. 684. Turn left (east).
1.1	105.4	Follow Va. 684, 1.1 mi to road sign saying "Tam Worth."
0.25	105.65	Turn left onto gravel road, follow 0.25 mi to end. Turn vehicles around and park.

Stop 13. Maidens Gneiss at Tamworth.

Roadcuts along west side of gravel road and outcrop on east bank of Muddy Creek at mill dam.

This small roadcut contains fine-grained, weakly layered, moderately foliated quartzofeldspathic gneiss with finely disseminated biotite. A few thin, coarse-grained quartz-feldspar-muscovite-garnet pegmatites are present, concordant with the compositional layering. This locality falls into an area defined as the "Central Piedmont" terrane on the most recent geologic map of Virginia (Virginia Division of Mineral Resources, 1993), but no other reference to this terrane appears in the literature. Farrar (1984) included this area in his mapping of the Maidens Gneiss and reported high-grade pelitic assemblages (sillimanite+potassium feldspar±muscovite; sillimanite+staurolite+muscovite) from outcrops nearby. Outcrops adjacent to the mill dam are more typical Maidens biotite-hornblende gneiss with feldspar porphyroclasts showing strong dextral asymmetry.

Mileage

Incremental	Cumulative	
7.55	113.2	Retrace route back to Va. 684. Turn left (east) and travel 7.3 mi to crossroads at Provost. Continue straight (east). Road becomes Va. 621.
4	117.2	Follow Va. 621 for 4 mi to stop sign at Va. 711. Turn left (east).
5.7	122.9	Follow Va. 711 for 5.7 mi to Fine Creek Mills. Turn left (north) on Va. 628.
0.1	123.0	Follow Va. 628 for 0.1 mi and park at sharp bend. After gaining permission from landowner, walk west to Fine Creek.

Stop 14. Fine Creek Mills Granite.

Stream pavement exposures along Fine Creek.

Although this stop has been included on at least one other field trip (Farrar and Owens, 2001), it is one of the more spectacular outcrops in this part of the Piedmont province (and therefore worth re-visiting!). The Neoproterozoic Fine Creek Mills Granite (629+4/-5 Ma; Owens and Tucker, 2003) intrudes the Middle Proterozoic State Farm Gneiss. It is well exposed here along both sides of Fine Creek. This medium- to coarse-grained granite is mineralogically similar to the other Neoproterozoic granitoids previously visited. The dark minerals include both biotite and amphibole. Discrete, narrow shear zones cut a moderately developed foliation in the granite, but these have not been systematically examined.

Mileage

Incremental	Cumulative	
29.1	152.1	Retrace route back to Va. 711 and turn left (east). Follow Va. 711 approximately 15 mi back to suburban Richmond. Turn left (north) on Va. 147. Follow signs to I-64/I-295 interchange.

End of field trip.

End of Day 2.