5. Multiple Paleozoic Metamorphic Histories, Fabrics, and Faulting in the Westminster and Potomac Terranes, Central Appalachian Piedmont, Northern Virginia and Southern Maryland

By Michael J. Kunk,[1] Robert P. Wintsch,[2] C. Scott Southworth,[3] Bridget K. Mulvey,[2] Charles W. Naeser,[3] and Nancy D. Naeser[3]

Introduction

This field trip is a progress report of research on the complex rocks of the Westminster and Potomac terranes (Horton and others, 1991) of Maryland, Virginia, and Washington, D.C. (fig. 1). The study of these rocks was begun more than 60 years ago with work by Jonas and Stose (1938), Cloos and Broedel (1940), Stose and Stose (1946), and Cloos and Cooke (1953). Research continued with Fisher (1963, 1970, 1971), Hopson (1964), and Drake (1986, 1989, 1994, 1998), and continues today. Geologic mapping at a scale of 1:24,000 by the U.S. Geological Survey (USGS) in this region was begun by Avery Drake in the 1970s and resulted in a number of novel concepts and interpretations, and the publication of a large number of geologic quadrangle maps (Drake, 1986, 1994, 1998; Drake and Froelich, 1986, 1997; Drake and Lee, 1989; Fleming and others, 1994; Drake and others, 1999; Southworth, 1999). Compilations of these data at a scale of 1:100,000 were recently published (Southworth and others, 2002; Davis and others, 2002) and constitute a summary of the latest understanding of the distribution of the rocks.

During the map compilation phase of the study, rocks were sampled for $^{40}Ar/^{39}Ar$ and fission-track dating to better understand the chronology of the tectonic assemblage in the region. Specifically, rocks were sampled across the major faults along an east to west transect along the Potomac River and its tributaries. Results of the recent argon and fission-track dating compel us to reconsider many earlier interpretations and are the motivation for this field trip. In particular, $^{40}Ar/^{39}Ar$ and fission-track data identify age and thermal discontinuities that give added significance to mapped faults and identify unmapped faults and shear zone boundaries.

[1]U.S. Geological Survey, Denver, CO 80225.

[2]Department of Geological Sciences, Indiana University, Bloomington, IN 47405.

[3]U.S. Geological Survey, Reston, VA 20192.

Geologic Setting

The Westminster and Potomac terranes are exposed in southern Maryland, northern Virginia, and Washington, D.C. (fig. 1). Drake and others (1989) and Horton and others (1989) proposed that the Potomac terrane was thrust onto the Westminster terrane along the Pleasant Grove fault, and that the Westminster terrane was thrust westward along the Martic fault onto Cambrian and Ordovician continental margin strata, during the Ordovician Taconian orogeny. Horton and others (1989) also speculated that both thrust faults were reactivated with dextral strike-slip motion during the late Paleozoic Alleghanian orogeny.

Westminster terrane

The rocks of the Westminster terrane are dominated by phyllites and have been correlated with the Hamburg klippe in Pennsylvania and higher slices of the Taconic allochthon in New England and New York (Knopf, 1935; Lyttle, 1982; Drake, 1986; Drake and others, 1989; Horton and others, 1989). Both the Westminster and Hamburg terranes are considered to represent offshore, deepwater, post-rift deposits with no direct stratigraphic ties to Laurentia (Horton and others, 1989). The low-grade, polymetamorphic, and polydeformed rocks previously mapped by Jonas and Stose (1938), Cloos and Broedel (1940), Cloos and Cooke (1953), Hopson (1964), Froelich (1975), Fisher (1978), and Edwards (1986, 1988, 1994), have been mapped, compiled, and summarized by Southworth and others (2002). We will examine part of the terrane that is dominated by rocks assigned to the Marburg Formation.

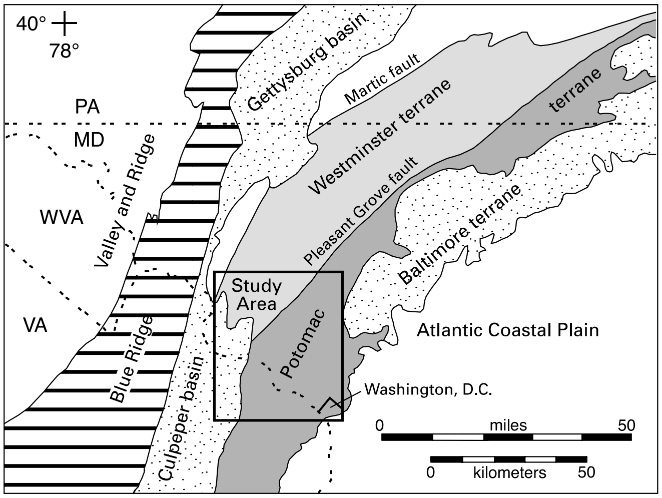

Figure 1. Terrane map of the south-central Appalachians. Box indicates the area of figures 2 and 6. Modified from Horton and others (1991).

Marburg Formation

The Marburg Formation contains primarily phyllite, metasiltstone, and quartzite. The protolith of the metasiltstone with quartz ribbons within the Marburg Formation has been interpreted to be turbidites by Southworth (1999). A few lenses of quartzite and rare greenstone have been interpreted to reflect an influx of channel deposits and volcanic sediments. Because the Marburg Formation contains some rocks that are similar to those in the Ijamsville Phyllite to the west, Marburg Formation rocks are interpreted to be composed of deepwater-rise deposits beneath and eastward of the Ijamsville Phyllite. Rocks of the Marburg Formation have been thrust onto the rocks of the Sams Creek Formation to the west along the Hyattstown fault (fig. 2). Rocks of the Marburg Formation collectively constitute a wide fault zone with multiple foliations, retrogressive phyllonites, and polydeformed vein quartz between the Hyattstown fault and the Pleasant Grove fault.

Potomac terrane

The Potomac terrane is bounded on the west by the Pleasant Grove fault and covered by Cretaceous and Tertiary Coastal Plain deposits to the east (fig. 1). The mapped units of the Potomac terrane, from west to east, are the Mather Gorge, Sykesville, and Laurel Formations (Drake and Froelich, 1997; Drake, 1998) (fig. 2). The protoliths of these rocks are interpreted to be Neoproterozoic to Early Cambrian distal slope deposits and olistostromes (Drake, 1989). These formations include mélanges that contain ultramafic rocks, and they are intruded by Early to Middle Ordovician tonalitic to granodioritic rocks (Aleinikoff and others, 2002). The three formations are separated by major faults that trend northward. The Plummers Island fault separates rocks of the Mather Gorge Formation on the west from rocks of the Sykesville Formation on the east (Drake, 1989). The Rock Creek shear zone separates rocks of the Sykesville Formation intruded by Ordovician plutons on the west from diamictite of the Laurel Formation on the east (Fleming and others, 1994; Drake and Froelich, 1997; Fleming and Drake, 1998) (fig. 2). Multiple foliations in the rocks are common, and composite foliations are strongest in phyllonitic rocks in fault zones.

Regional aeromagnetic data reflect this complex geology (Southworth and others, 2002). Pronounced patterns of magnetic highs and lows define the Mather Gorge Formation (ЄZmg, fig. 2) and the presence of ultramafic and mafic rocks. A broad low magnetic anomaly defines the rocks of the Sykesville Formation, and magnetic lineaments mark the Rock Creek shear zone.

Mather Gorge Formation

Rocks defined as the Mather Gorge Formation by Drake and Froelich (1997) consist of the metamorphosed equivalents of well-bedded graywacke and mudstone, which are now granofelsic metagraywackes and quartz-mica schists and higher grade equivalents (ЄZmg, fig. 2). This north-northeast-striking belt of rock includes poorly exposed map-scale bodies of amphibolite, serpentinite, and talc schist that have been collectively mapped as ultramafic rocks (um, fig. 2). Both the metasedimentary rocks and amphibolite are intruded by the Ordovician Bear Island Granodiorite and associated pegmatites, and Devonian lamprophyre dikes intrude the schist. An apparent Barrovian metamorphic sequence of chlorite to sillimanite grade has been described that extends from the phyllitic rocks near the margin of the Culpeper basin eastward to the migmatites on Bear Island near Great Falls (Fisher, 1970; Drake, 1989). East of Great Falls (fig. 2, Stop 4), migmatitic rocks occur in a belt and grade eastward into a zone of retrograded chlorite-sericite phyllonites (Fisher, 1970) that are truncated on the east by the Plummers Island fault (Drake and Froelich, 1997) (fig. 2). The metagraywacke near Great Falls preserves bedding and soft-sedimentary slump features (Hopson, 1964; Fisher, 1970), and the package of rocks is interpreted to have been deposited as a sequence of turbidites (Drake and Froelich, 1997).

In this study, the rocks included in the Mather Gorge Formation are subdivided into three domains that are defined on the basis of lithology, metamorphic history, structure, and geochronology. From west to east, these are the Blockhouse Point, Bear Island, and Stubblefield Falls domains (fig. 2). The Blockhouse Point domain is characterized by chlorite-sericite phyllonites and some ultramafic rock bodies. The Bear Island domain is characterized by garnet-sillimanite-grade metagraywacke and schist that is migmatitic near the eastern boundary. Well-bedded metagraywacke (type locality of the Mather Gorge Formation), large ultramafic rock bodies, migmatite, granodiorite and pegmatite closely associated with amphibolite, and lamprophyre dikes characterize this domain.

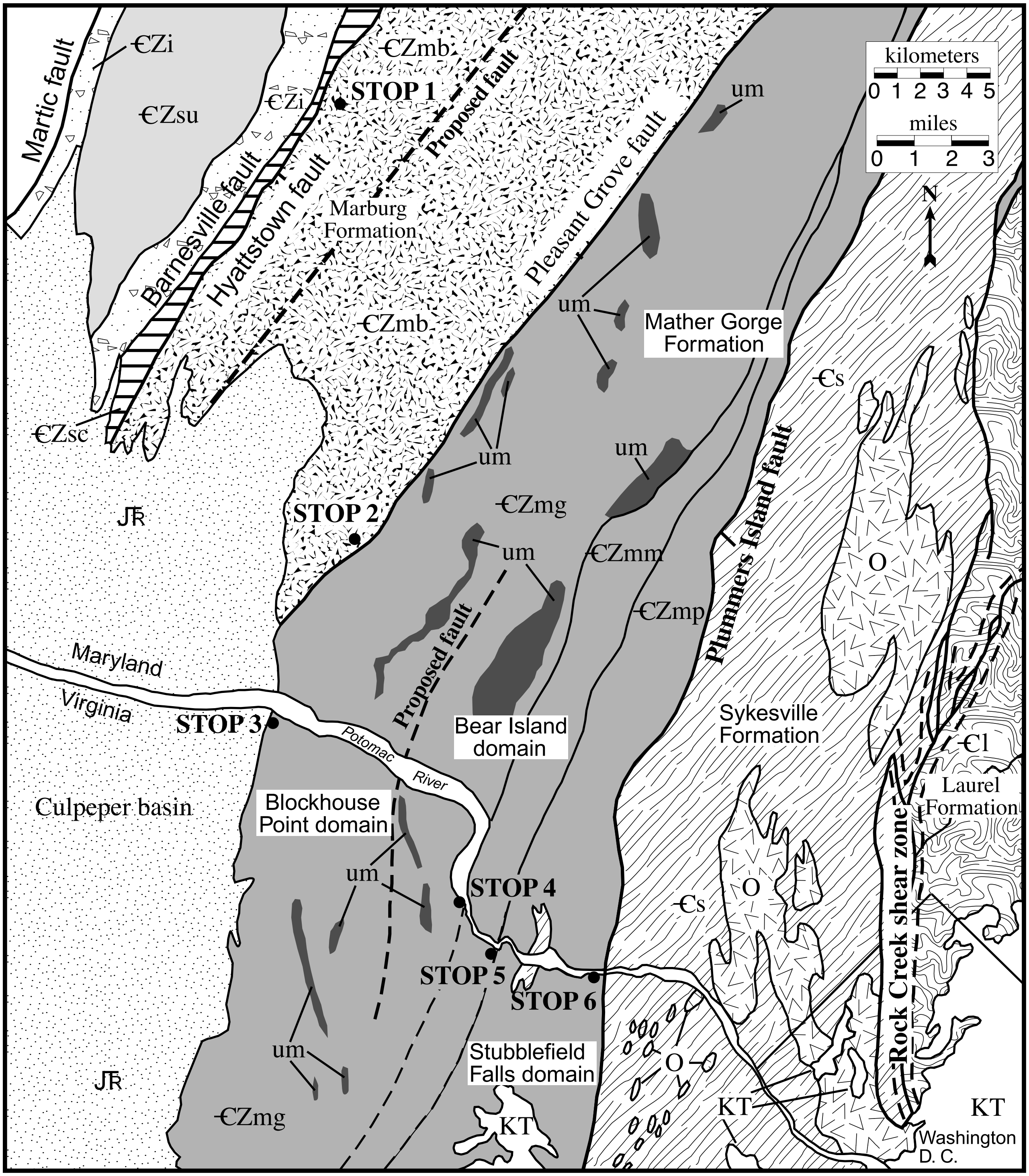

Figure 2. Geologic map of parts of the Westminster and Potomac terranes, Maryland, Virginia, and Washington, D.C. The Pleasant Grove fault separates the Westminster terrane on the west from the Potomac terrane on the east. Geologic map-unit symbols are as follows: €Zmg, Mather Gorge Formation; €Zmp, chlorite-sericite phyllonite of the Mather Gorge Formation; €Zmm, migmatitic Mather Gorge Formation; €Zi, Ijamsville Phyllite; €Zmb, Marburg Formation; €Zsc, Sams Creek Formation; €Zsu, undifferentiated metasiltstone, phyllite, quartzite, and metagraywacke; €s, Sykesville Formation; €l, Laurel Formation; O, Ordovician plutons; um, ultramafics; JR, Late Triassic and Early Jurassic rocks; KT, Cretaceous and Tertiary Coastal Plain deposits. Faults are as indicated and are dashed where inferred. Modified from Davis and others (2002).

The Stubblefield Falls domain to the east is characterized by migmatitic schist that has been retrograded to chlorite-sericite phyllonitic schist, small bodies of amphibolite, very minor granodiorite, and a few areas mapped as diamictite.

Sykesville Formation and Ordovician Plutonic Rocks

The Sykesville Formation of Hopson (1964) is a belt of metasedimentary rocks east of the Plummers Island fault and west of the Rock Creek shear zone (Ꞓs, fig. 2). These rocks have been metamorphosed to upper amphibolite facies, and intruded by a suite of Ordovician tonalitic to granodioritic rocks (O, fig. 2). Aleinikoff and others (2002) used U-Pb zircon techniques to date intrusive rocks including the Norbeck, Falls Church, Dalecarlia, and Georgetown Intrusive Suites and the Kensington Tonalite. Rocks of the Sykesville Formation have been interpreted to structurally underlie rocks of the Mather Gorge Formation under the Plummers Island fault along the Potomac River (Drake, 1989) (fig. 2), but to overlie them southwest of Baltimore to the north (Muller and others, 1989).

The sedimentary protoliths of the Sykesville Formation were diamictites and sedimentary mélanges containing clasts of amphibolite, migmatite, schist, metagraywacke, gabbroic granofels, phyllonite, greenstone, and vein quartz supported in a matrix of quartz-feldspar-muscovite granofels and schist (Drake and Froelich, 1997). Clasts within the diamictite have been interpreted to be derived from already deformed and metamorphosed rocks of the Mather Gorge Formation (Drake, 1989; Muller and others, 1989), and map-scale bodies of migmatite, phyllonite, and ultramafic schists that appear to be surrounded by diamictite have been interpreted by Drake (1989) and Fleming and others (1994) to be large olistoliths.

Laurel Formation

Rocks of the Laurel Formation are considered by Drake (1989) to be part of a separate motif (Laurel-Loch Raven), east of the Mather Gorge-Sykesville motif. The Laurel Formation (Ꞓl, fig. 2) (Hopson, 1964) forms a north-northeast-striking belt of diamictite that superficially resembles that of the Sykesville Formation. To the east it is covered by Cretaceous and younger Coastal Plain sediments, and to the west it is separated from the Sykesville Formation and Ordovician plutons by the Rock Creek shear zone (Fleming and others, 1994). These rocks were metamorphosed to upper amphibolite facies, then retrograded to phyllitic and mylonitic schists in the Rock Creek shear zone (Fleming and Drake, 1998).

In spite of the metamorphism, the protolith of the Laurel Formation is recognizably a diamictite, a sedimentary mélange with clasts of vein quartz, meta-arenite, biotite schist, actinolite schist, and local amphibolite supported by a quartzofeldspathic matrix (Fleming and others, 1994). The unit is similar to the Sykesville Formation but contains a greater number and variety of olistoliths (Drake, 1998).

Geochronology

Previous geochronology

U-Pb zircon ages reflect the time of igneous crystallization and later metamorphic overgrowths, and K-Ar, $^{40}Ar/^{39}Ar$, and Rb-Sr mica ages have been interpreted to reflect the time of cooling and, in some cases, muscovite growth. Published data are not complete enough to constrain metamorphic histories in our field area, but they provide important additional ages in our study area.

Earlier attempts at U-Pb dating of zircons in this complex setting (Davis and others, 1958, 1960; Wetherill and others, 1966; Fisher, 1970; Sinha and others, 1989) are difficult to interpret in light of recent advances in our understanding of U-Pb systems, and they will not be discussed here. U-Pb SHRIMP and TIMS analyses of zircons from plutonic rocks that intruded the Sykesville Formation in our field area (Aleinikoff and others, 2002) reveal Early to Late Ordovician ages of emplacement.

Reed and others (1970) dated two biotite separates from a lamprophyre dike at Great Falls (Stop 4) at 360±13 Ma and 363±13 Ma (2σ) using conventional K-Ar techniques. Muth and others (1979) dated muscovite cooling from the Bear Island Granodiorite within the Mather Gorge Formation, at 469±20 Ma and 469±12 Ma (2σ) using Rb-Sr techniques. Becker and others (1993) report $^{40}Ar/^{39}Ar$ ages of amphibole and muscovite from migmatitic rocks along Difficult Run (Stop 5, fig. 2) of 490 Ma and 422 Ma, respectively. They interpreted the amphibole age to represent cooling from the Cambrian-Ordovician, Penobscottian orogeny. We reinterpret the spectrum age as being the result of extraneous argon. Their muscovite age spectrum is sigmoidal because of the presence of more than one generation of muscovite, so the minimum apparent cooling age probably reflects a mixture of muscovite populations. Krol and others (1999) used $^{40}Ar/^{39}Ar$ dating of muscovite and biotite from rocks within the Pleasant Grove fault "zone." Their study did not provide any ages from the Mather Gorge, Sykesville, or Laurel Formations. They interpreted their $^{40}Ar/^{39}Ar$ data from muscovite to indicate a possible thermotectonic event between 368 and 348 Ma (Acadian), and dextral shearing of the central and northern parts of the Pleasant Grove fault "zone" at 311 Ma (Alleghanian).

New geochronology

New argon and fission-track data from the Westminster and Potomac terranes (Mulvey, 2003; Kunk and others, in press; and M.J. Kunk, unpub. data) together with published data require modifications of the previously interpreted regional framework. A summary of these data is presented in figure 3. Our sampling strategy was designed to take advantage of detailed geologic mapping summarized by Southworth and others (2002), along a traverse that extends (west to east) from near the Hyattstown fault in Maryland (Stop 1) across the Rock Creek shear zone in the District of Columbia.

Amphibole $^{40}Ar/^{39}Ar$ ages

All amphibole samples were collected from rocks that experienced upper amphibolite facies metamorphism (Drake, 1989). They contain more than 50 percent coarse-grained amphibole coexisting with, and locally including, plagioclase, magnetite, biotite, and epidote. Many samples also contain retrograde epidote and chlorite that may or may not define a late fabric. In most rocks the amphiboles define at least one foliation. In some samples, a coarser grained gneissosity is overprinted by a more pervasive schistosity, and one sample appears to retain an igneous texture. Amphibole in metagabbro intrusive to the Laurel Formation is typical, containing equant grains of amphibole up to 0.5 mm in diameter that are overgrown by acicular needles that define a second foliation (S_2, fig. 4A). The high metamorphic grade of the samples is supported by the amphibole textures which indicates temperatures >600ºC (Poirier, 1985).

The time of cooling of each of the three high-grade domains of figure 2 is estimated by at least two amphibole analyses. Three samples from the Bear Island domain contain excess argon, with two samples yielding minimum and isochron ages of 475 Ma (Stops 4 and 5). The third sample produces an overlapping isochron age of 455±23 Ma. These ages are consistent with the Rb-Sr ages of muscovite of 469±12 Ma and 469±20 Ma (Muth and others, 1979), which are also considered to have a closure temperature of ~500ºC (Jäeger, 1979). The ~455- to 475-Ma age range of these samples is accepted as the best estimate for the time of cooling of the Bear Island domain through ~500ºC.

Two samples of amphibole from rocks that intrude the Sykesville Formation also agree with each other within analytical uncertainty. A sample from the Falls Church pluton produced a near-plateau age spectrum with a minimum age of 401 Ma. This amphibole probably had a relatively simple igneous crystallization history, followed by slow cooling with relatively little deformation. The 405-Ma isochron age of a sample from the Georgetown Intrusive Suite confirms the time of cooling. Hence the Early Devonian age of ~401 Ma is a reasonable estimate of the time of regional cooling of the intrusive rocks and the country rocks of the Sykesville Formation through 500°C.

Two amphibole samples from rocks that intrude the Laurel Formation have minimum ages of 404 Ma and 398 Ma. This indicates Early Devonian cooling through 500°C for the intrusive rocks and rocks of the Laurel Formation. These ages are indistinguishable from the amphibole cooling ages of the Sykesville Formation.

Muscovite $^{40}Ar/^{39}Ar$ ages

The rocks of the Westminster terrane (Stops 1 and 2) never exceeded lower greenschist facies conditions, and thus were always below the closure temperature for diffusion of argon in muscovite (~350°C). Many of the muscovite separates (and one whole-rock sample) produced either sigmoidal or climbing age spectra (Mulvey, 2003). The shapes of these age spectra can be caused by (1) the presence of a (usually) very small population of much older detrital muscovite in the sample, (2) the presence of multiple generations of metamorphic muscovite in the sample, and (3) the presence of inseparable, intimately intergrown chlorite. Because of these complications, the muscovite age spectra provide only approximations of the maximum ages of the most recent muscovite growth and minimum ages of earlier muscovite foliations or detrital components in the Westminster terrane (Mulvey, 2003). These results are nonetheless useful at the orogenic level.

Three samples collected from the western part of the Marburg Formation in the Westminster terrane gave ages of ~435 to 430 Ma, whereas two samples from the eastern part of the Marburg Formation gave ages of ~382 to 375 Ma (Stops 1 and 2) (fig. 2) (Mulvey, 2003; M.J. Kunk, unpub. data). All of these ages are interpreted to approximate the time of growth of cleavage-forming muscovite in these samples.

All of the rocks in the Potomac terrane have been metamorphosed to at least biotite grade (Kunk and others, in press), thus any detrital muscovite in sedimentary protoliths has been either recrystallized or thermally reset. In addition, we were able to separate muscovite that was free of chlorite intergrowths in all but one of the samples from the Potomac terrane (Kunk and others, in press. Nonetheless, most of the muscovite samples from the Potomac terrane also have sigmoidal or climbing age spectra. In these rocks, older (S_1) high-grade mineral assemblages have been partly overprinted by younger (S_2), lower grade foliation(s) (crystallized below the muscovite closure temperature for argon diffusion). For these samples we have interpreted the minimum age in the spectrum as the maximum age of muscovite growth below closure, and the maximum age in the spectrum as a minimum age for cooling of the higher grade muscovite through 350°C. These age pairs for each sample are plotted in figure 3, and rocks of the Mather Gorge Formation are summarized as follows:

(1) The westernmost muscovite sample from the Blockhouse Point domain (figs. 2 and 3) produced a plateau age of 362±2 Ma (1σ) that we interpret as the time of white mica growth (S_2) in the sample. Two samples farther to the east gave ~371 Ma cooling ages (S_1) and ~362 Ma growth ages (S_2).

(2) In the Bear Island domain, cooling-age estimates from the muscovite age spectra range from 422 to 411 Ma (S_1), and below-closure growth-age estimates range from 385 to 373 Ma (S_2).

(3) In the Stubblefield Falls domain, cooling-age estimates

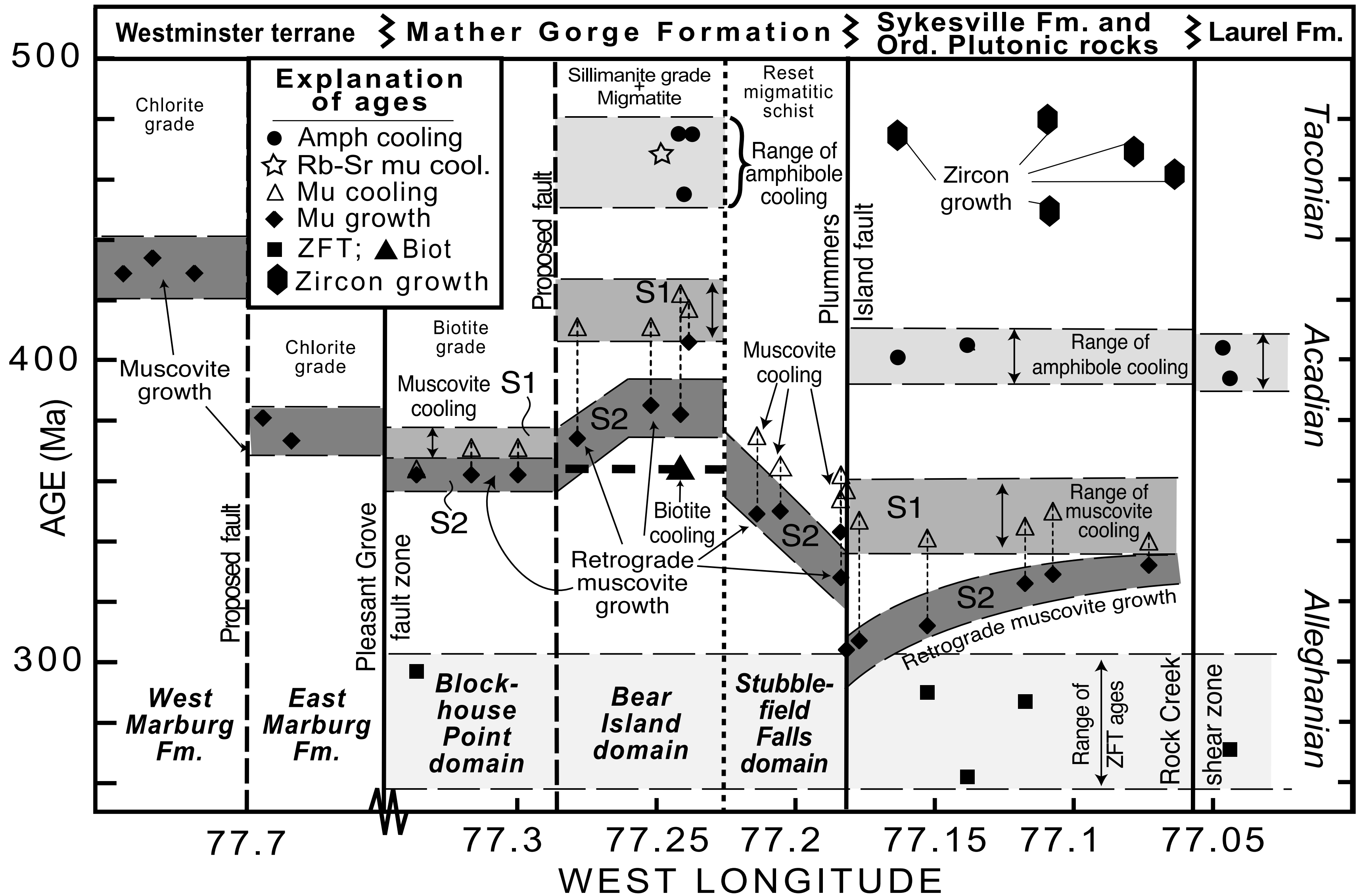

Figure 3. Diagram plotting age against sample location along west-to-east transect for parts of the Westminster and Potomac terranes. Ages are based on $^{40}Ar/^{39}Ar$ data (Kunk and others, in press; Mulvey, 2003; and M.J. Kunk, unpub. data), U-Pb data (Aleinikoff and others, 2002), Rb-Sr data (Muth and others, 1979), K-Ar data (Reed and others, 1970), and zircon fission-track data (Kunk and others, in press). The five zircon fission-track ages from the Potomac terrane are statistically indistinguishable, with a mean of 282±13 Ma, suggesting that these rocks all cooled through the ~235°C zircon closure temperature (Brandon and others, 1998) in earliest Permian time. See text for additional discussion. Modified from Kunk and others (in press). ZFT, zircon fission track; Amph, amphibole; mu, muscovite; biot, biotite; Ord., Ordovician; Fm, Formation.

from the muscovite age spectra range from 375 to 354 Ma (S_1), and growth-age estimates range from 350 to 328 Ma (S_2).

East of the Mather Gorge Formation and Plummers Island fault, cooling-age estimates from the muscovite age spectra from the Sykesville Formation range from 354 to 340 Ma (S_1), and growth-age estimates range from 332 to 304 Ma (S_2).

Biotite $^{40}Ar/^{39}Ar$ ages

Only one biotite sample was dated because of the dearth of unaltered biotites in the field area. The biotite (Stop 5, fig. 2) is from the Bear Island Granodiorite in the Bear Island domain and produced a $^{40}Ar/^{39}Ar$ total fusion age of 364±2 Ma. This age is the same, within the limits of analytical precision, as K-Ar ages reported by Reed and others (1970) for two biotite samples (360±13 Ma and 363±13 Ma) collected nearby from a lamprophyre dike (Stop 4, fig. 2). Because the biotite from our sample grew in a metamorphic environment well above its argon closure temperature, we interpret both this age and the ages from the dike to represent the timing of cooling of the biotite through ~300°C in a regional thermal gradient.

Zircon fission-track ages

Zircon fission-track ages determined for five samples from the Potomac terrane (one sample from the Blockhouse Point domain of the Mather Gorge Formation, three samples from the Sykesville Formation, and one sample from the Laurel Formation), are statistically indistinguishable, suggesting that the rocks cooled through the zircon fission-track closure temperature (~235°C; Brandon and others, 1998) from 298±46 Ma to 262±20 Ma (±2 standard errors of the mean; fig. 3). The mean zircon age calculated for the five samples is 282±13 Ma, suggesting that the rocks cooled through ~235°C in earliest Permian time.

Apatite fission-track ages

Seven samples yielded sufficient apatite for fission-track analysis. The samples span most of the Potomac composite terrane, from the shear zone separating the Blockhouse Point and Bear Island domains in the Mather Gorge complex in the west to Rock Creek Park (Laurel Formation) in the east. Apatite fission-track ages range from 198±21 Ma to 131±16 Ma (±2σ), with ages generally becoming younger to the west. The apatite fission-track age and track-length data indicate that rocks presently exposed at the surface cooled through the

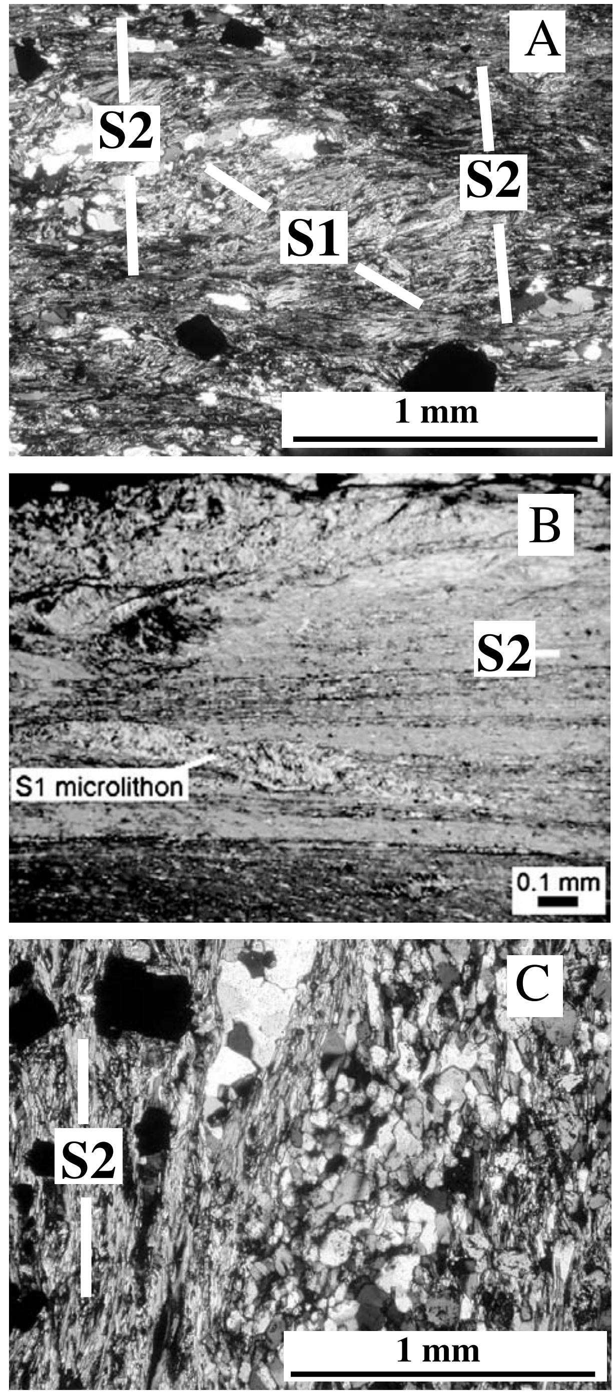

Figure 4. Photomicrographs in cross polarized light from (A) a metagabbro in the Laurel Formation, (B) the eastern Marburg Formation, and (C) the Blockhouse Point domain of the Mather Gorge Formation. See text for discussion.

apatite fission-track closure temperature (~90°C–100°C in these rocks) from the Early Jurassic to the Early Cretaceous, with the time of cooling becoming younger to the west.

Summary of recent studies

The rocks of the Potomac terrane have been metamorphosed to at least biotite grade, and contain one or more higher grade schistosities (collectively called "S_1"), which formed above the ~350°C closure temperature of muscovite. The $^{40}Ar/^{39}Ar$ ages recorded by S_1 muscovites should represent the time of their passage through ~350°C. In addition, most of these rocks and the rocks of the Marburg Formation in the Westminster terrane also contain one or more younger schistosities (collectively called "S_2"), that grew below ~350°C in the greenschist facies; their $^{40}Ar/^{39}Ar$ muscovite ages should record the time of these muscovites' crystallization. S_1 and S_2 as referred to here are clearly not the same in the various tectonic blocks that are discussed. While S_1 ages represent only the last passage of the rocks through the ~350°C isotherm, S_2 ages can represent composite schistosities and multiple episodes of mineral growth.

Westminster terrane

The muscovite growth-age estimates in the western part of the Marburg Formation (Stop 1) are ~435 to 430 Ma, in contrast to those in the eastern part of the Marburg Formation (Stop 2) where they range from 382 to 375 Ma (fig. 3). The ~50 m.y. discontinuity in age between these two groups of samples is most easily explained by a fault within the Marburg Formation between Stops 1 and 2.

Potomac terrane

Mather Gorge Formation

Blockhouse Point domain

Maximum estimates of muscovite growth ages of two samples are 362 Ma, and a third sample in the westernmost part of the Blockhouse Point domain has a plateau age of 362±2 Ma. We interpret 362 Ma as the age of the lower greenschist facies muscovite growth (Stop 3). Because the metamorphic grade of these rocks reached biotite-grade conditions in the Middle Devonian, any argon isotopic evidence of an earlier metamorphic event in these muscovites has been reset.

Bear Island domain

Higher metamorphic temperatures here resulted in formation of migmatite (Stops 5 and 6). Our amphibole data indicate that cooling through 500°C occurred between 475 and 455 Ma (fig. 3). The estimate from muscovite data for the timing of cooling through 350°C (S_1) is >422 Ma. Maximum age estimates for below-closure-temperature growth of muscovite (S_2) range from 385 to 373 Ma. A comparison with the muscovite samples of the Blockhouse Point domain shows a striking difference in the estimated time of cooling through 350°C (371 Ma versus 422 Ma), suggesting the presence of a fault zone between the two domains.

Stubblefield Falls domain

The rocks west of the Plummers Island fault were migmatitic (Stop 6), but they were later retrograded to a chlorite-sericite phyllonite (Fisher, 1970). We extend the Ordovician cooling history of the Bear Island domain here based on that earlier high-temperature history. Muscovite age spectra indicate minimum estimates for cooling through 350°C that range from 375 Ma to 354 Ma, younging to the east, suggesting reheating in the Devonian to reset the muscovite ages. Maximum estimates for the time of subsequent growth below closure of S_2 muscovite also show a general pattern of younging to the east, and range from 350 Ma in the western part of the domain to 328 Ma near the Plummers Island fault.

Sykesville Formation and Ordovician intrusive rocks

The rocks of the Sykesville Formation were intruded by Middle to Late Ordovician plutonic rock (Aleinikoff and others, 2002) prior to or during peak amphibolite facies metamorphic conditions. Amphibole samples from the Falls Church pluton and the Dalecarlia Intrusive Suite have disturbed $^{40}Ar/^{39}Ar$ ages of 401 Ma and 405 Ma, respectively, indicating cooling through 500°C in the Early Devonian. The muscovite age spectra from the Sykesville Formation give minimum estimates for cooling through 350°C that range from 357 to 340 Ma (S_1). Maximum age estimates for subsequent muscovite below-closure growth (S_2) range from 304 Ma in the Plummers Island fault to 332 Ma near the Rock Creek shear zone, and show a dramatic decrease in age to the west (fig. 3). We interpret the 304-Ma age to represent a maximum age for the time of final Alleghanian movement on the Plummers Island fault.

Laurel Formation and intrusive rocks

Two amphiboles were dated from rocks that intrude the Laurel Formation. Both had relatively flat age spectra and suggest an age of ~400 Ma for their time of cooling through 500°C.

Thermal Histories Across the Plummers Island Fault

Cooling curves provide comparison of the thermal history across the Plummers Island fault (fig. 5). The best estimate for

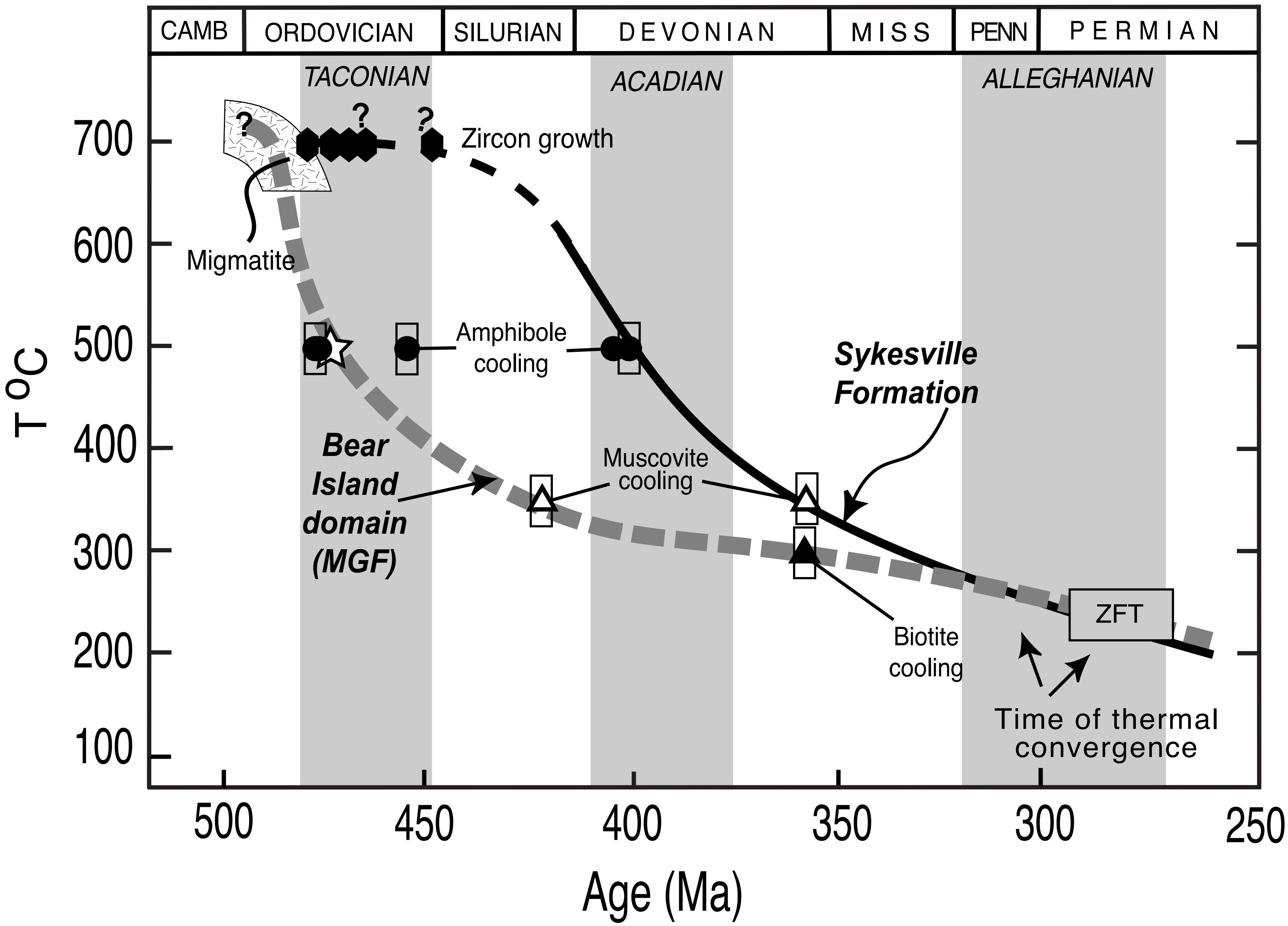

Figure 5. Cooling curves for the Bear Island domain of the Mather Gorge Formation and for the Sykesville Formation. Filled circle represents $^{40}Ar/^{39}Ar$ amphibole cooling age; open star, Rb-Sr muscovite cooling ages; open triangle, $^{40}Ar/^{39}Ar$ muscovite cooling age; filled triangle, $^{40}Ar/^{39}Ar$ biotite cooling age; filled hexagon, U-Pb zircon growth age; ZFT, zircon fission-track cooling ages; MGF, Mather Gorge Formation. Open rectangles denote error bars. All U-Pb zircon age data are on the Sykesville Formation cooling curve. Modified from Kunk and others (in press).

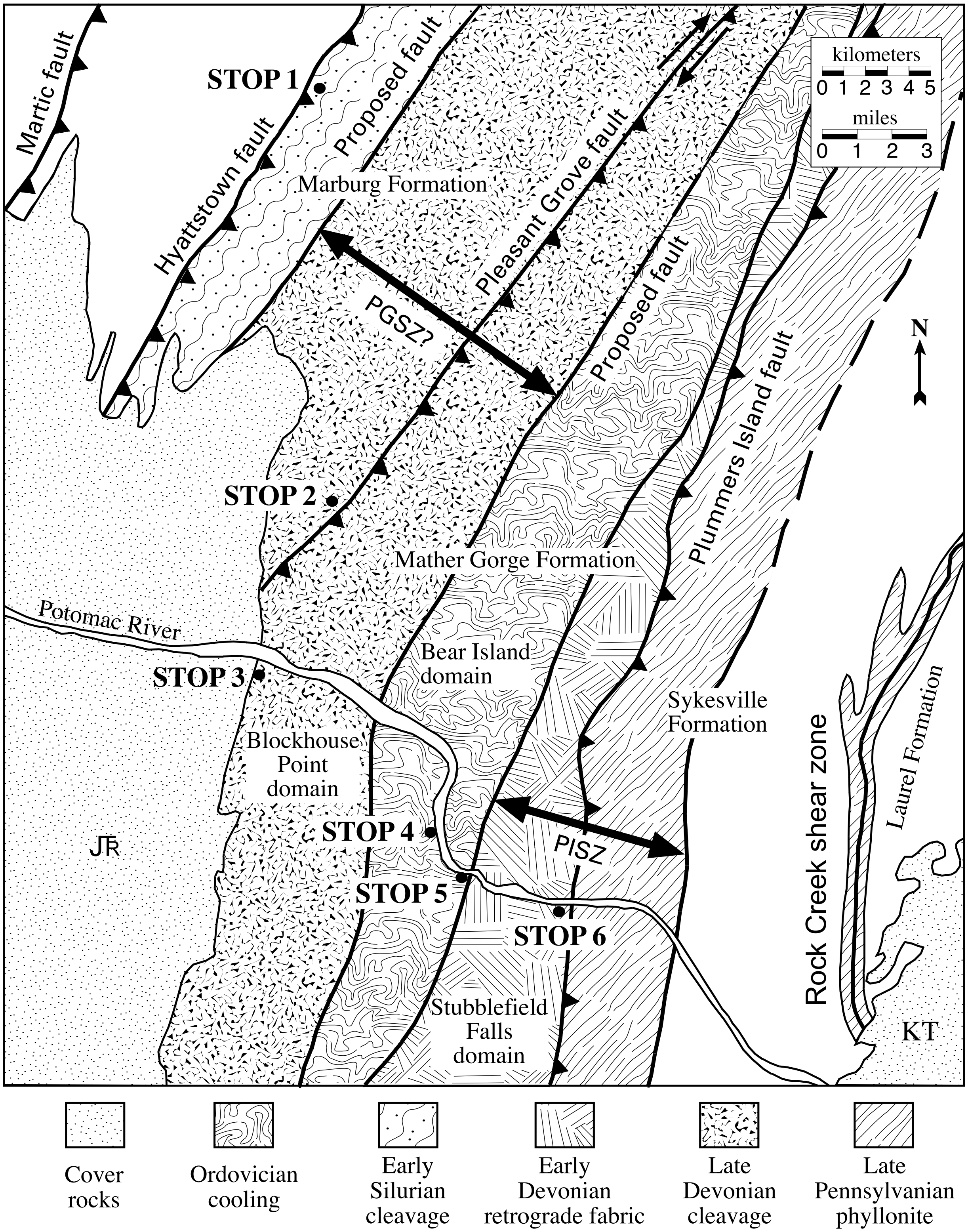

Figure 6. Tectonic domain map modified from figure 2 in response to existing lithologic and geochronologic data. The tectonic boundaries do not appear to be coincident with the formation boundaries. PISZ, Plummers Island shear zone; PGSZ, Pleasant Grove shear zone. For definitions of other symbols see figure 2.

the time of cooling of the Bear Island domain through ~500ºC is 475 to 455 Ma, obtained from the three amphibole $^{40}Ar/^{39}Ar$ ages and two Rb-Sr muscovite ages. The minimum age estimate for cooling of muscovite through its closure temperature, 422 Ma, provides a data point at ~350°C. Our biotite $^{40}Ar/^{39}Ar$ age of 364±2 Ma adds a point on the curve at ~300ºC. Regional zircon fission-track ages of ~280 Ma add a point at ~235°C. Together these points generate the concave-up cooling trend (fig. 5) typical of many metamorphic terranes. Extrapolating back from this curve, migmatitic conditions of 650 to 700ºC appear to have occurred in these rocks in the Early Ordovician (migmatite patterned polygon, fig. 5). This cooling curve also shows that metamorphic conditions did not exceed greenschist facies after mid-Paleozoic times. The planar lamprophyre dikes in fractures suggests no significant contractional deformation occurred after about 365 Ma.

Migmatitic textures in the diamictite of the Sykesville Formation indicate upper amphibolite facies metamorphism. The Ordovician ages of the five dated plutonic rocks (Aleinikoff and others, 2002) provide data points at the near-solidus temperatures of ~700°C. Our ~400-Ma cooling ages of amphiboles provide a point at ~500ºC. The minimum cooling-age estimate from the muscovite data provides a data point at 357 Ma and ~350°C, and a fourth point is established by the zircon fission-track data at 280 Ma and 235°C.

The cooling curves show independent paths throughout the Paleozoic that do not converge until ~300 to 280 Ma (fig. 5). In particular, migmatitic rocks of the Bear Island domain had cooled to greenschist-facies conditions by the time that the Sykesville Formation was still at upper amphibolite facies in the Late Silurian. These temperature contrasts reflect 3 to 6 km of net vertical displacement, depending on the geothermal gradients in the two blocks of rock. Vertical displacement may have been accompanied by an unknown, but possibly considerable, component of strike-slip movement. This difference in cooling history is not consistent with the interpretation of a Cambrian-age premetamorphic Plummers Island fault that shed clasts of metamorphosed Mather Gorge Formation into sediments that became the Sykesville Formation (Drake, 1989). Muller and others' (1989) interpretation of the Sykesville Formation being deposited in late Cambrian to Early Ordovician time from erosion of an uplifted Mather Gorge Formation (their Morgan Run Formation) is also unlikely, based on the difference in cooling histories during much of the Paleozoic.

Rocks of the Bear Island domain cooled continuously from Middle Ordovician to Late Carboniferous time, and were cooler at any given time than the rocks of the Sykesville Formation (fig. 5). Nonetheless, the cooling rate of the Sykesville Formation exceeded that of the Bear Island domain from the middle Silurian through the Pennsylvanian (fig. 5). The net crustal displacement across the fault from the Ordovician through Pennsylvanian is east side up.

Interpreted Tectonic Assemblage

By the Early to Middle Ordovician, the rocks of the Bear Island domain and, by inference, also the Stubblefield Falls domain in the Mather Gorge Formation, had been metamorphosed and were cooling through ~500°C (fig. 5), while the Sykesville Formation was still at upper amphibolite-facies prograde metamorphic conditions and was being intruded by plutons (Aleinikoff and others, 2002). The metamorphic and necessarily structural divergence precludes a geological connection between the formations in the Ordovician. Rocks of the Blockhouse Point domain had not been detectably metamorphosed, so they were also physically separated from the Bear Island domain.

By the Early Silurian the rocks of the westernmost Marburg Formation had been metamorphosed to lower greenschist facies when an S_1 cleavage was produced, while the eastern Marburg Formation apparently remained unmetamorphosed. During the Early Devonian (figs. 5, 6), hot rocks of the Sykesville Formation and associated plutons were being thrust over the Stubblefield Falls domain, heating the muscovite to temperatures well above argon closure, along an early Plummers Island shear zone (Schoenborn, 2002). At ~400 Ma, the Laurel and Sykesville Formations simultaneously cooled through 500°C, the closure temperature for argon diffusion in amphibole, suggesting that they were at the same structural level at that time.

By the Late Devonian, the Blockhouse Point domain had cooled from biotite-grade metamorphism (>400°C). A shear zone with strain distributed over a zone as much as 12 km wide, from the Blockhouse Point domain west into the Westminster terrane, produced S_2 cleavage defined by muscovite that crystallized below its closure temperature. At about the same time, rocks of the Stubblefield Falls domain, and later of the Sykesville Formation, cooled through ~350°C while the rocks of the Bear Island domain cooled through 300°C, demonstrating that these blocks were at different structural levels at the time (figs. 5, 6).

In the Late Pennsylvanian, the rocks of the Stubblefield Falls domain of the Mather Gorge Formation moved up relative to the Sykesville Formation on the steep, west-dipping Plummers Island fault and mylonite zones (Schoenborn, 2001) within an existing Plummers Island shear zone (figs. 5, 6). Shearing formed S_2 cleavage with below-closure muscovite growth and more pervasive S_2 cleavage in the Sykesville Formation. By the earliest Permian, all of the rocks in the Potomac terrane had cooled through 235°C (figs. 3, 5). Apatite fission-track data indicate cooling through ~90°C to 100°C in Early Jurassic to Early Cretaceous time, with increasing ages to the east, suggesting kilometer-scale rotation of the Potomac terrane in the Cretaceous and (or) Tertiary, with the west side up.

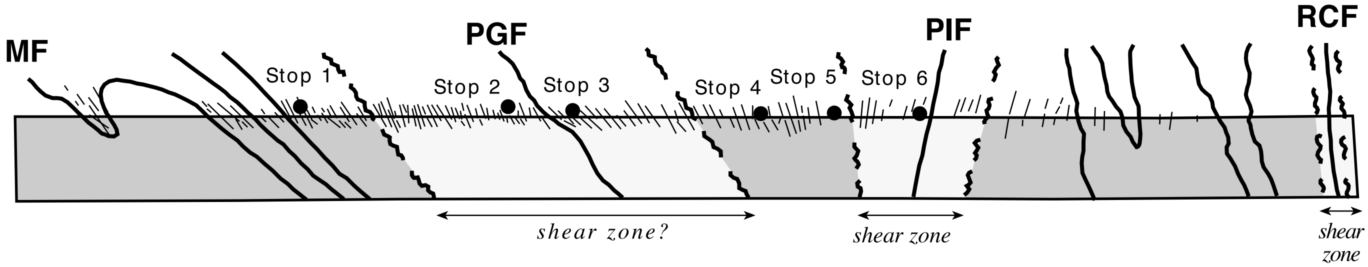

Figure 7. Tentative, conceptual cross section of study area showing the Ordovician Potomac River fan structure of Drake (1989). The data discussed in this study indicate that the Potomac River fan structure is a composite of foliations formed throughout the Paleozoic. Approximate locations of field stops are indicated. MF, Martic fault; PGF, Pleasant Grove fault; PIF, Plummers Island fault; RCF, Rock Creek fault.

Faults and Shear Zones: Plummers Island, Pleasant Grove, and Rock Creek

In summary, the assemblage of the rocks of the Potomac and Westminster terranes occurred during the Acadian orogeny in the Devonian, with fault reactivation during the Alleghanian orogeny in Pennsylvanian time. The apparent Barrovian metamorphic sequence of chlorite to sillimanite grade (west to east) (Fisher, 1970), and the Potomac River fan structure (fig. 7) (Drake, 1989), both interpreted to be of Ordovician age (Drake, 1989), are obviously a composite of different events throughout the Paleozoic.

If our analysis is correct, the 5-km-wide Early Devonian (Acadian) Plummers Island shear zone was reactivated in the Carboniferous (Alleghanian) under lower greenschist-facies conditions as the Plummers Island fault (fig. 6). The muscovite cooling (S_1) and growth ages (S_2) in the Blockhouse Point domain are similar to growth ages in the eastern part of the Westminster terrane. Therefore, Late Devonian (Acadian) deformation in a 12-km-wide Pleasant Grove shear zone may have extended from the Blockhouse Point domain west *across* the Pleasant Grove fault into the Marburg Formation of the Westminster Terrane. There is no isotopic evidence of pre-Devonian or significant post-Devonian movement on this part of the Pleasant Grove fault. However, shear-band cleavage with dextral strike-slip kinematics supports Alleghanian movement of unknown significance within the Pleasant Grove shear zone.

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ROAD LOG AND STOP DESCRIPTIONS FOLLOW

Road Log and Stop Descriptions

This trip transects the Piedmont beginning with Stops 1 and 2 in the chlorite-grade rocks of the Westminster terrane west of the Pleasant Grove fault. The remainder of the trip will be in several different tectonothermal domains of the Potomac composite terrane east of the Pleasant Grove fault. Stop 3 is in biotite-grade rocks of the Blockhouse Point domain, the westernmost part of the Potomac terrane. Stop 4 and lunch is in kyanite-grade rocks of the western Bear Island domain. Stop 5 is in staurolite-sillimanite-grade rocks of the eastern Bear Island domain. Stop 6 is in sillimanite-grade rocks retrograded to chlorite grade in the Stubblefield Falls domain in the Plummers Island fault zone.

Mileage

Incremental	Cumulative	
0.0	0.0	Depart from back door, Tysons Corner Hilton. Drive around front, and turn right on Jones Branch Road.
1.2	1.2	Turn right on Spring Hill Road.
0.1	1.3	Turn right on Va. 267 east, Dulles Toll Road.
1.1	2.4	Exit to I-495 north.
7.2	9.6	Exit to I-270 north.
21.4	31.0	Exit to Md. 109 (Exit 22, Hyattstown, Barnesville).
0.2	31.2	Turn left on Md. 109 north.
0.5	31.7	Turn right on Md. 355.
0.1	31.8	Turn left on Frederick Road–Hyattstown Mill Road.
0.7	32.5	Use parking area by rusty footbridge at junction of Hyattstown Mill Road and Prescott Road to turn around and head back westbound on Hyattstown Mill Road.
0.3	32.8	Pull off to the right at trailhead to Dark Branch Trail. Outcrop is on north side of road, on small hill on the right side (east) of small valley of Dark Branch.

Stop 1. Hyattstown.

Western Westminster terrane above Hyattstown thrust fault, in metasiltstone and phyllite of the Marburg Formation, Urbana, Md., 7.5-minute quadrangle (Southworth, 1999).

The rocks at this stop are chlorite-grade metasiltstone, phyllite, and thin quartzite assigned to the Neoproterozoic and Early Cambrian Marburg Formation (Southworth, 1999). The foliation regionally and in the rocks here strikes northeast and dips steeply to the southeast. This foliation is a composite of nearly coplanar cleavages, bedding, and transposed vein quartz. Where bedding is at a high angle to cleavage it can be conspicuous, as it is on the left side of the knoll here as we climb up from the parking area. Here, graded beds of metasiltstone strike northwest and dip moderately to the southwest. Bedding is made conspicuous by beds that are relatively rich and poor in hematite, giving the rock a strikingly banded appearance (fig. 8A). Also visible here are isoclinally folded quartz veins (fig. 8B). These are significant in that they cut older foliation, but have limbs transposed into the schistosity, and axial planes parallel to the later composite foliation. They thus demonstrate the composite nature of the foliation here. Late quartz veins do exist, however, that are relatively undeformed and cut this cleavage at moderately high angles.

Regionally, similar Marburg Formation rocks comprise a ~12-km-wide lithotectonic belt in the eastern part of the Westminster terrane. The belt is separated from the Potomac composite terrane to the east by the Pleasant Grove fault zone. To the west 4.7 km, the 50-km-long Hyattstown thrust fault places rocks of the Marburg Formation above greenstone and phyllite of the Sams Creek Formation. Rocks of the Marburg Formation are distinctively different from the rocks to the west of the Hyattstown thrust fault, which are a diverse assem-

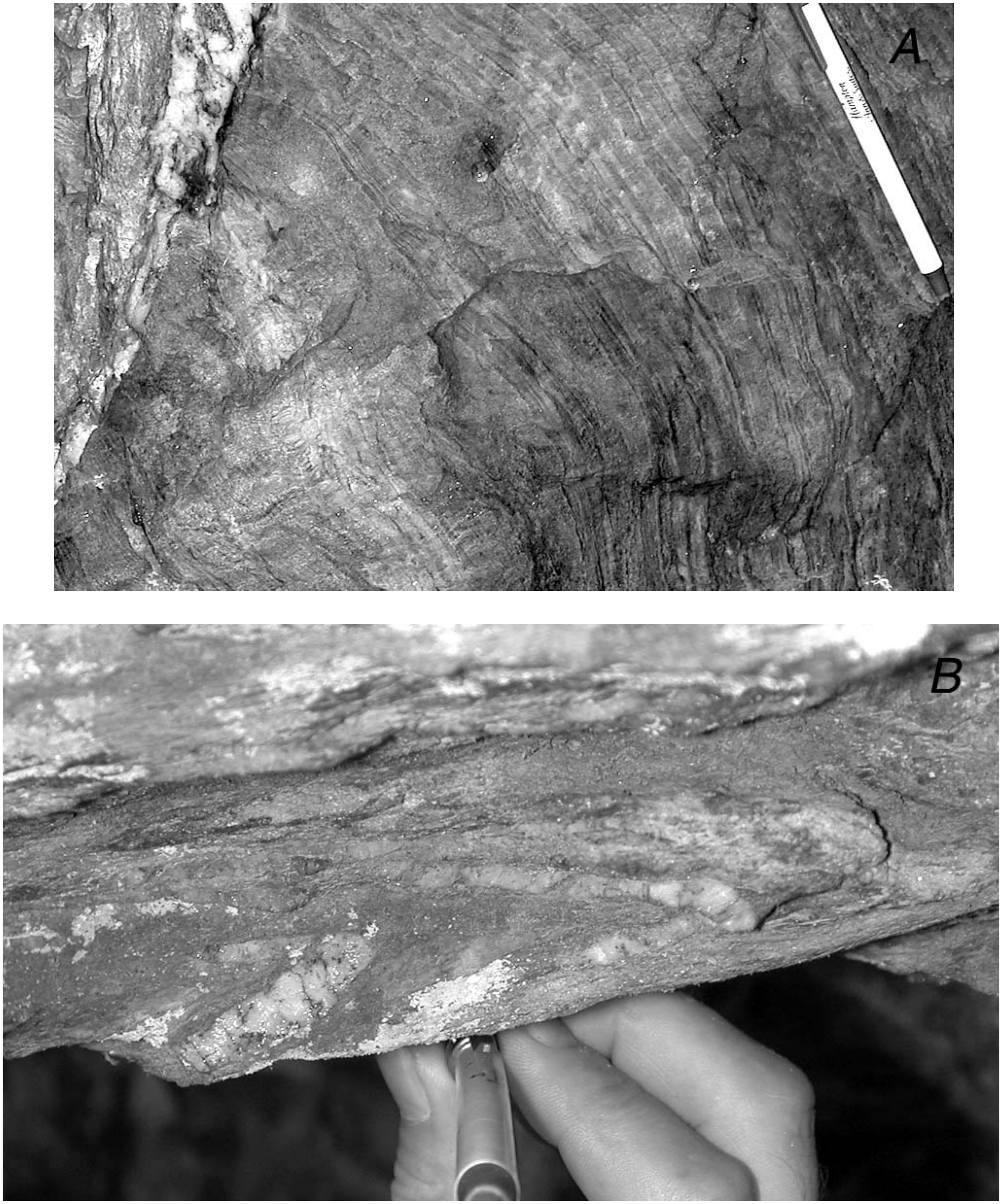

Figure 8. Photographs of rocks of the Marburg Formation at Stop 1. *A*, Intersection of laminated bedding (trending upper left to lower right) with cleavage that is parallel to the outcrop face and page; both are cut by vein quartz that is transposed (upper left). View is to the east on the face of an outcrop. Pen segment shown is 10 cm long. *B*, Steep downdip view (to the southeast) of northeast-striking cleavage and transposed vein quartz with dextral kinematic motion. Pen is 1 cm in diameter.

blage of phyllite, phyllonite, metasiltstone, quartzite, metagraywacke, greenstone, marble, and metalimestone (Southworth and others, 2002). In contrast to the fine-grained rocks of the Sams Creek Formation and Ijamsville Phyllite immediately west of the fault, the phyllite and metasiltstone of the Marburg Formation locally contain paragonite as well as porphyroblasts of albite and chloritoid. The metasiltstone commonly has a distinctive pinstriped appearance of quartz laminae and ribbons interlayered with chlorite phyllite; a later crenulation cleavage crinkles these ribbons, in many places to produce a characteristic texture. The quartz laminae may represent thin turbidites or metamorphic segregations. Within the 12-km-wide belt of the Marburg Formation there are a few meter-thick beds of metagraywacke and pebbly quartzite, and rare bodies of greenstone. To the northeast about 25 km, rocks of the Prettyboy Schist are in gradational contact with rocks of the Marburg Formation.

Age spectra from three samples from this part of the Westminster terrane (Kunk, unpub. data; Mulvey, 2003) give ages of ~435 to 430 Ma. These samples all contain muscovite preserved in multiple generations of spaced cleavage. Typically, older generations contain muscovite intergrown with chlorite, whereas later generations contain primarily chlorite. We interpret the reproducible early Silurian ages of muscovites from several samples, including a marble, to be a close approximation to the time of S_2 muscovite growth, thus indicating a Silurian cleavage-forming event.

Mileage

Incremental	Cumulative	
0.5	33.3	Return to vehicles and head west on Frederick Road. Turn right at stop sign onto Md. 355.
0.1	33.4	Turn left on Md. 109 south.
0.6	34.0	Turn left on I-270 south.
7.3	41.3	Exit to Md. 118 south (Exit 15A).
6.2	47.5	Turn right on Md. 28 west.
1.0	48.5	Turn right on Black Rock Road.
0.6	49.1	Park in lot on left at Black Rock Mill.
		Walk across bridge of Great Seneca Creek and walk left (west) about 15 m to large bluff.

Stop 2. Black Rock Mill.

Metagraywacke and phyllite of the Marburg Formation, eastern part of Westminster terrane, Damascus, Md., 7.5-minute quadrangle (A.A. Drake, Jr., unpub. data; Southworth and others, 2002).

The rocks exposed on the north bank of Great Seneca Creek are metagraywacke interbedded with phyllite and metasiltstone assigned to the Marburg Formation by A.A. Drake, Jr. (unpub. data) and Southworth and others (2002). At this location we are about 1.75 km west of the Pleasant Grove fault zone. Like the rocks at Stop 1, the regional foliation here strikes northeast, dips steeply to the southeast and locally is vertical. Well-cemented metagraywacke beds are relatively resistant, and probably are responsible for the exposure here. They form rapids in the streambed, and are well exposed in a bluff across and downstream from the mill. There the nearly vertical schistosity of the rocks is axial planar to vertical isoclinal folds (fig. 9A). Note also that the phyllitic limbs of these folds contain lozenges or boudins of quartz, undoubtedly representing dismembered lenses of once-continuous quartz veins (fig. 9B)

In thin section (fig. 4B) the phyllites are composed of phyllosilicate-rich layers (~60 percent) separated by quartz microlithons and veins (~40 percent). The phyllosilicate-rich layers contain ~90 percent muscovite flakes up to 80 µm long. Accessory minerals include 10- to 100-µm grains of chlorite (5 percent), rutile (5 percent), and quartz (<1 percent). The quartz microlithons and veins are elongate parallel to compositional layering and range in thickness from 1 to 9 mm. Although several generations of white mica can be identified, by far the dominant and coarsest mica is S_2. Because of its coarse grain size, it is also the mica that is concentrated in the sample analyzed isotopically. Replicate analyses of two different

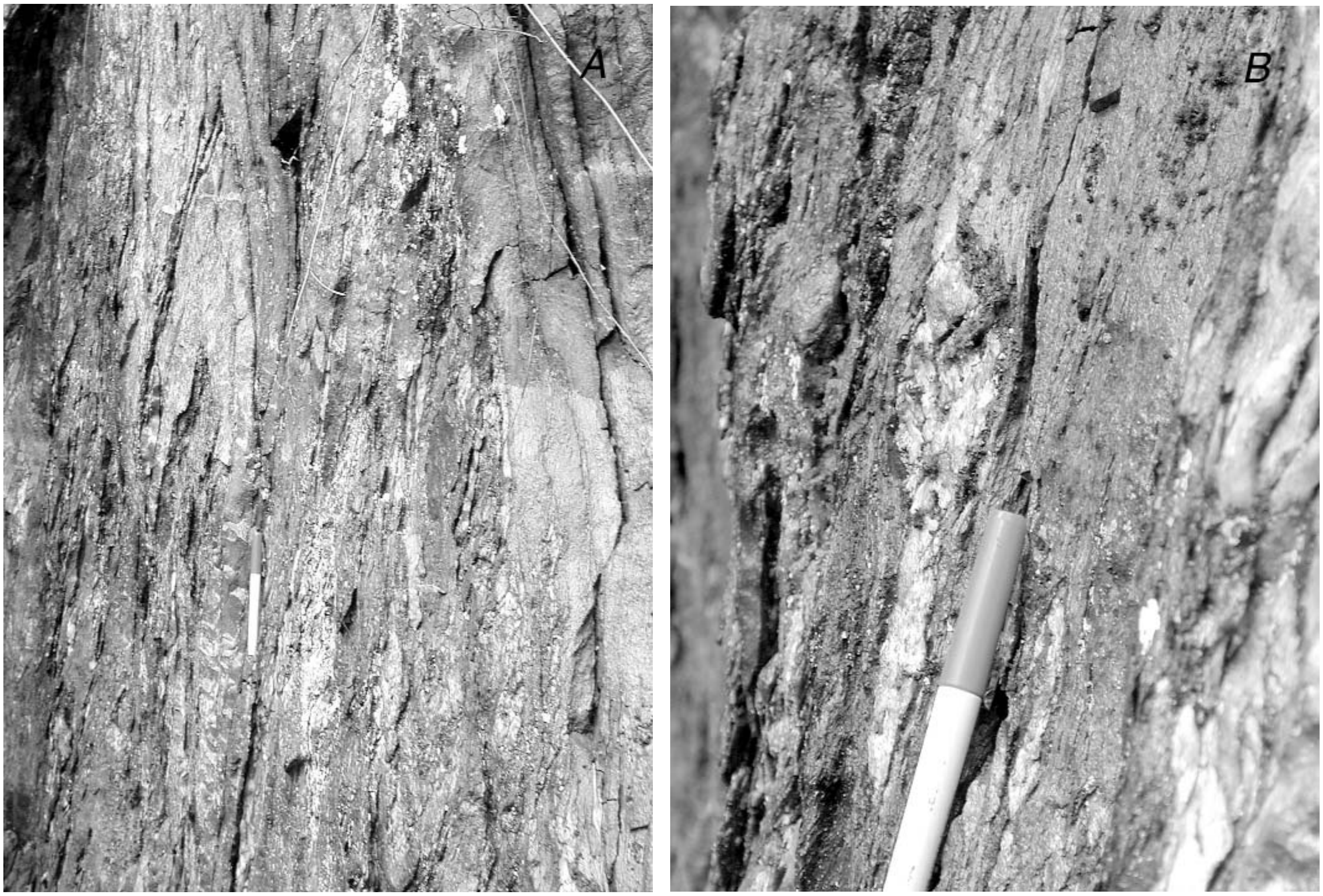

Figure 9. Photographs of rocks of the Marburg Formation at Stop 2, looking north. *A*, Isoclinal folds of thin metagraywacke and phyllite (with axial plane cleavage?) are transected by cleavage that dips steeply to the northwest (left). Pen is 14 cm long. *B*, Closeup view of vein quartz transposed in the early folds and foliation. Pen segment shown is 10 cm long.

samples both record an age of ~375 Ma, approximately the age of S_2 mica. This age is distinct from the age determined for the samples at Stop 1, and clearly reflects a Middle Devonian cleavage-forming event that was not recorded in the phyllites of Stop 1. This is the basis for interpreting a fault or boundary of a shear zone between Stops 1 and 2.

Mileage

Incremental	Cumulative	
0.0	49.1	Return to vehicles and go north on Black Rock Road.
1.9	51.0	Turn left on Md. 118 north.
3.6	54.6	Bear right onto entrance ramp to I-270 south.
11.7	66.3	Bear right onto I-495 south.
6.4	72.7	Exit to Va. 193; bear left to avoid Exit 43.
0.7	73.4	Bear right and take Exit 44.
0.1	73.5	Turn right at traffic light onto Georgetown Pike, Va. 193 west.
9.3	82.8	Turn right onto Seneca Road, Va. 602.
2.3	85.1	Continue straight at No Outlet sign.
1.4	86.5	At end of road, park on right of roadside. Walk north along paved road (gated) to the bottom of the hill and follow the gravel road to the right (east) for about 10 m. Outcrops are on forested bluff on the right.

Stop 3. Seneca Road/Northern Virginia Regional Park.

Chlorite phyllonite of Mather Gorge Formation, western Blockhouse Point domain, Potomac terrane, Seneca, Va.-Md., 7.5-minute quadrangle (Drake and others, 1999).

The rocks exposed here are chlorite phyllite and phyllonite with transposed and folded vein quartz speckled with magnetite. These chlorite-grade rocks were called the Upper Pelitic Schist of the Wissahickon Formation by Fisher (1970), chlorite schist and lesser metasiltstone of the Peters Creek Schist (Drake, 1989), and later were assigned to the metagraywacke and lesser semi-pelitic schist unit of the Mather Gorge Formation by Drake and others (1999). This is the westernmost part of the Blockhouse Point domain in the western part of the Potomac terrane of Kunk and others (in press) and is Stop 1 of Drake (1989).

The regional composite foliation strikes northeast and dips gently to moderately to the southeast. The eastern margin of the Mesozoic Culpeper basin unconformably overlies these rocks about 0.5 km to the west beneath Quaternary alluvium. The southwestward projection of the Pleasant Grove fault is about 1.5 km to the west but is also unconformably overlain by Late Triassic rocks of the Culpeper basin and by alluvium.

At this stop, we can recognize both muddy and gritty protoliths, now phyllites and thin lenses of lithic and arkosic quartzites. These are intruded by several generations of quartz veins, and deformed and folded by several cleavage-forming events. A composite cleavage composed of S_1 and S_2 (at least) gives the overall steep cleavage of the outcrop (fig. 10). This composite cleavage contains transposed bedding, intrafolial folds, and dismembered quartz veins, and shear-band cleavage records a dextral, transpressive fabric. An S_3 cleavage anastomoses across this structure, giving the composite cleavage a wavy fabric. Finally, there is a late, gently dipping discontinuous cleavage, S_4, that locally cuts all previous structures.

In thin section our nearby analyzed sample (Kunk and others, in press) (fig. 4C) is a differentiated quartz-muscovite phyllonite. Most phyllosilicate layers are dominated by muscovite (>90 percent), but contain ~10 percent chlorite, with accessory sphene, magnetite, and albite, and trace amounts of epidote. Most of the muscovite grains that define the foliation in these layers are 200 to 400 μm long and 50 μm thick, but some are over 500 μm long and 100 μm thick.

The age spectrum of this sample is very slightly sigmoidal, but forms an age plateau (Fleck and others, 1977; Haugerud and Kunk, 1988) at 362±2 Ma that contains 70 percent of the ^{39}Ar released from the sample. The vast majority of the gas released from the sample is from muscovite flakes that together with chlorite define S_2. The muscovite-chlorite association is interpreted to reflect below-closure growth, and the plateau age is interpreted to represent the age of this cleavage-forming event. By this analysis, the younger cleavages, S_3 and S_4, must be Carboniferous or younger. This interpretation is completely consistent with our results from the Plummers Island fault (Stop 6).

Return to vehicles, retrace route south on Seneca Road, and turn left (east) on Georgetown Pike, Va. 193.

Mileage

Incremental	Cumulative	
8.7	95.2	Turn left into Great Falls Park.
1.0	96.2	Park entrance. Park in parking lot.

Lunch Stop. Restrooms are available at the Visitor Center en route to Overlook 2, which affords a view of the Great Falls of the Potomac River. Bag lunches can be eaten at the overlook or at the picnic tables to the south.

Figure 10. Photograph of chlorite metasiltstone and phyllonite of the Blockhouse Point domain of the Mather Gorge Formation, Stop 3, looking east into the foliation. Thin layers of metagraywacke, metasiltstone, and vein quartz dipping to the northeast (left) are domains cut by anastomosing shear-band cleavage with dextral kinematic indicators (lower center). Pen is 14 cm long.

Stop 4. Great Falls Park.

Metagraywacke and staurolite schist of the Mather Gorge Formation, Bear Island domain, Vienna and Falls Church, Va.-Md., 7.5-minute quadrangles (Drake and Lee, 1989; Drake and Froelich, 1997).

The level ground of the parking area and Visitor Center is a bedrock strath terrace of the Potomac River that may be as young as 30 ka (Bierman and others, this volume). The current position of the Great Falls of the Potomac River is situated at perhaps the thickest section of metagraywacke exposed in the Potomac River valley (fig. 11A). Formerly called the Wissahickon Formation and Peters Creek Schist, these rocks were renamed the Mather Gorge Formation by Drake and Froelich (1997), based on this type locality, and are in the

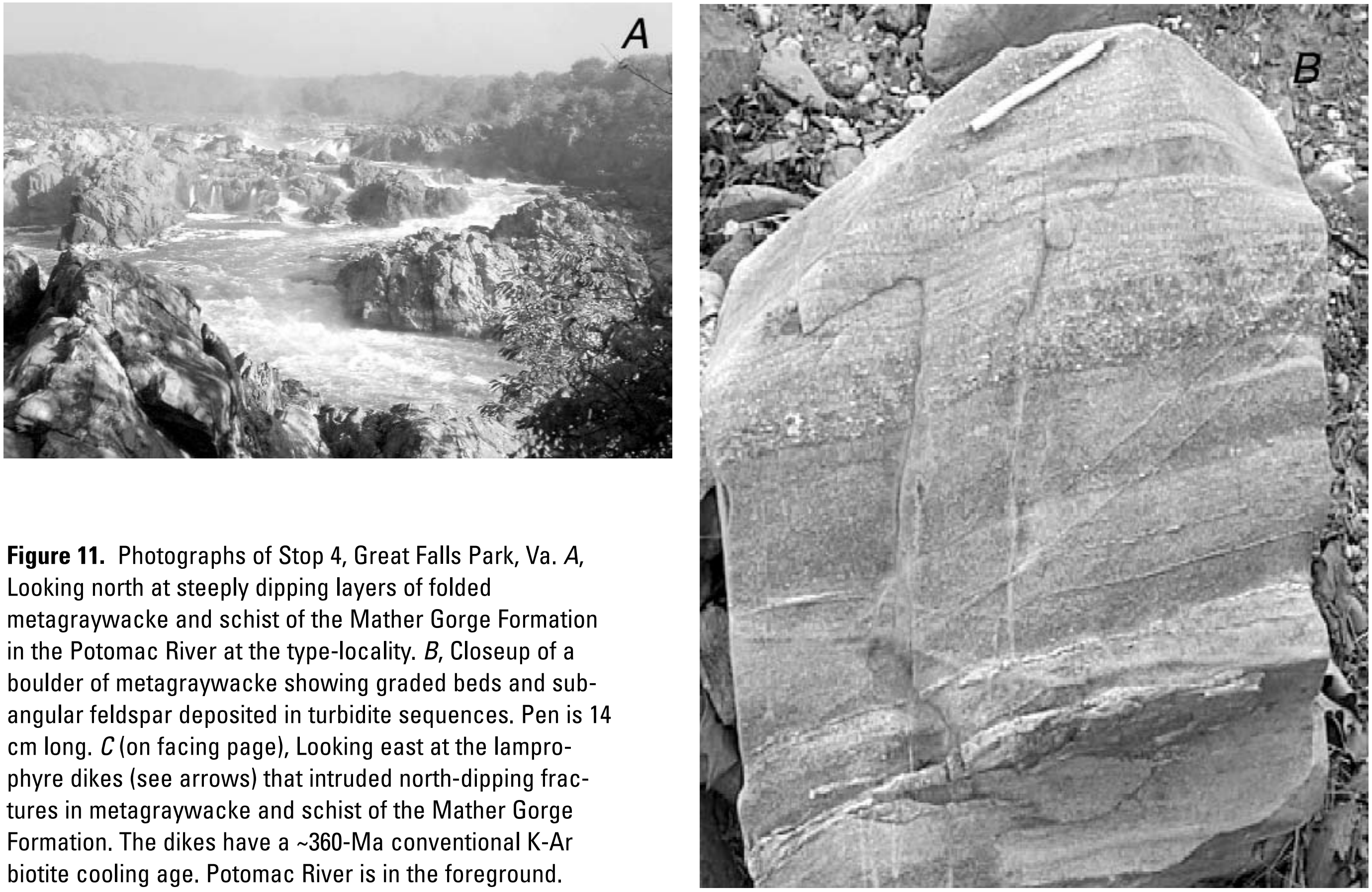

Figure 11. Photographs of Stop 4, Great Falls Park, Va. *A*, Looking north at steeply dipping layers of folded metagraywacke and schist of the Mather Gorge Formation in the Potomac River at the type-locality. *B*, Closeup of a boulder of metagraywacke showing graded beds and subangular feldspar deposited in turbidite sequences. Pen is 14 cm long. *C* (on facing page), Looking east at the lamprophyre dikes (see arrows) that intruded north-dipping fractures in metagraywacke and schist of the Mather Gorge Formation. The dikes have a ~360-Ma conventional K-Ar biotite cooling age. Potomac River is in the foreground.

Bear Island domain of Kunk and others (in press). In general, rocks mapped as Mather Gorge Formation are dominantly schist interbedded with metagraywacke; metagraywacke interbedded with schist is subordinate but best exposed here. The metagraywacke consists of well-graded beds of quartz and detrital feldspar (fig 11B). Soft-sedimentary features exposed along Bear Island to the east support the interpretation that these are turbidite deposits (Hopson, 1964; Drake and Morgan, 1981). Isoclinal recumbent folds of metagraywacke and schist are locally refolded upright. About 1 km to the west are bodies of ultramafic rocks, and about 1.5 km to the east are bodies of amphibolite and granodiorite/pegmatite. Immediately east of the overlook along the bluffs is one of the northwest-dipping, undeformed lamprophyre dikes that has conventional K-Ar biotite cooling ages of ~360 Ma (Reed and others, 1970), similar to the dikes shown in figure 11C.

Mileage

Incremental	Cumulative	
1.4	97.6	Return to vehicles, leave park, and turn left (east) on Georgetown Pike, Va. 193.
0.6	98.2	Turn right into parking lot of Difficult Run.
		Follow the trail at the south end of the parking area around the meander.
		Go under the bridge carrying Va. 193.
		Continue along trail on the north side of the creek for about 500 m
		to a broad outcrop on the bank near a sharp north bend in Difficult Run.

Figure 11. Continued

Stop 5. Difficult Run.

Migmatitic schist of the Mather Gorge Formation, amphibolite, and Bear Island Granodiorite, eastern boundary of Bear Island domain, Potomac terrane, Falls Church, Va.-Md., 7.5-minute quadrangle (Drake and Froelich, 1997)

This outcrop of a variety of rocks was scoured clean by the floods of Hurricane Agnes in 1972, and was Virginia stop 8 of Reed and others (1980) and stop 5 of Drake (1989). These sillimanite-grade rocks were called the Upper Pelitic Schist of the Wissahickon Formation (Fisher, 1970) and the metagraywacke and semipelitic schist of the Mather Gorge Formation (Drake and Froelich (1997); they are the Bear Island domain of the Mather Gorge Formation of Kunk and others (in press). The dominant rock is gray coarsely mottled mica schist that contains conspicuous dark-green 1- to 2-cm-diameter crystals of garnet, staurolite, cordierite(?), and shimmer aggregates. The schist also contains segregated leucosomes of quartz and albite or sodic oligoclase, forming a wavy migmatite. Several 2-m-thick layers of dark-green, fine-grained epidote-plagioclase-hornblende amphibolite are found within the schist, and are probably gabbro sills or basalts whose origin may have been either intrusive, extrusive, or as olistoliths. Drake (1989) suggests that the amphibolite intruded the schist prior to deformation. The known distribution of amphibolite is restricted to the sillimanite-grade migmatites of the eastern part of the Bear Island domain.

Both the amphibolite and schist are cut by tabular dikes of light-gray granite and granodiorite called the Bear Island Granodiorite (fig. 12). Streaks of biotite define flow foliation in these dikes. The largest dike here is cut by a pegmatite 5 to 15 cm thick. Small bod-

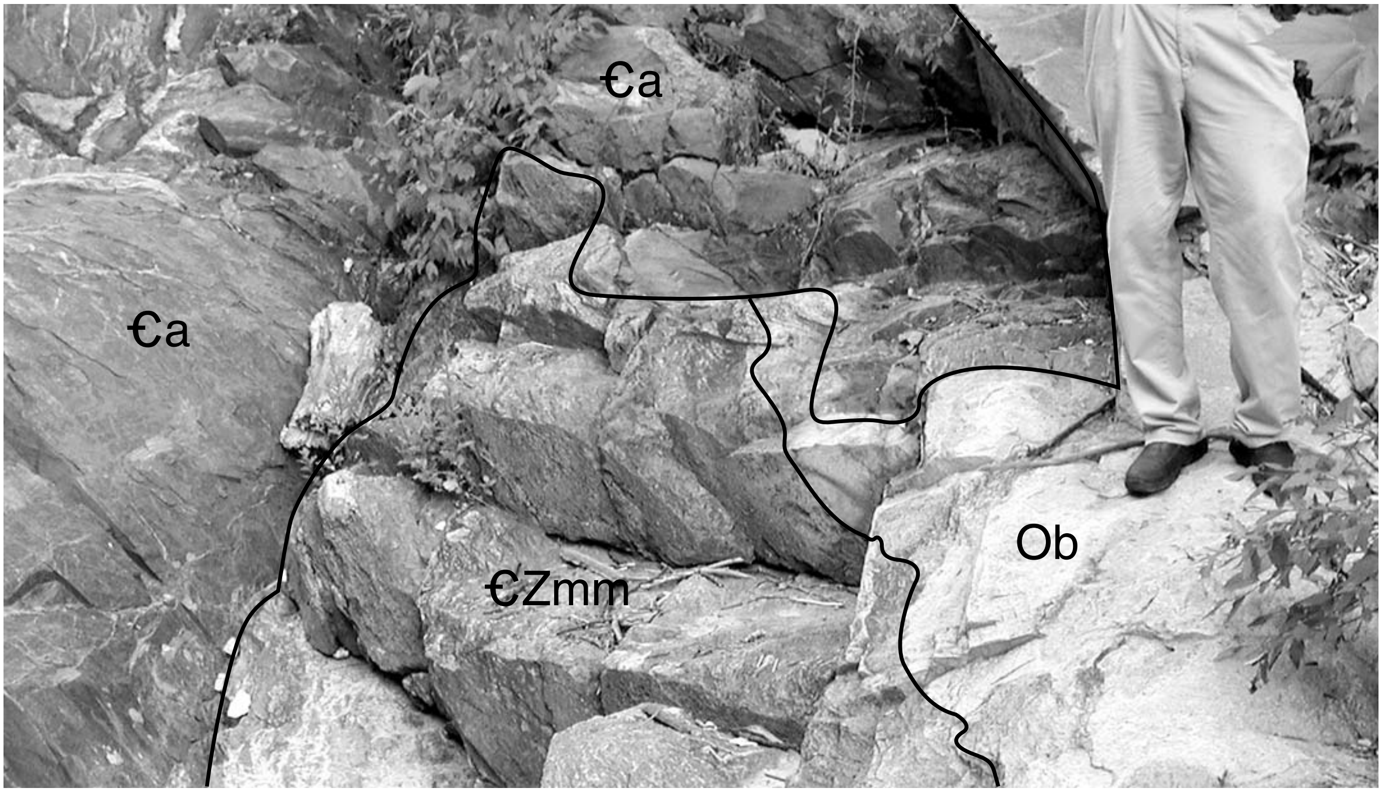

Figure. 12. Photograph of rocks along Difficult Run, Stop 5, looking north at east-dipping foliated rocks. The person is standing on Ordovician Bear Island Granodiorite (Ob) (east dipping) which intrudes both amphibolite (€a) and migmatitic schist of the Mather Gorge Formation (€Zmm). Man's foot is 28 cm long.

ies of Bear Island Granodiorite are abundant in the migmatites of the Bear Island domain and in the deformed schists of the Stubblefield Falls domain. The distribution of these dikes seems to be structurally controlled, in that dikes are most common cutting fractures and boudin necks in the amphibolite. It is possible that these dikes were passively injected into dilational sites caused by breakup of the competent amphibolite layer within ductile schist under anatectic conditions. The Bear Island Granodiorite is commonly seen associated with amphibolite, but it is recognized only where metamorphic grade reached at least sillimanite zone, an area that spans both east and west of the known distribution of amphibolite. Most of the dikes are undeformed as they are here, but similar dikes are locally folded. Muscovite from this pegmatite yielded the 469-Ma Rb-Sr cooling ages (Muth and others, 1979). Fisher (1963, 1970), Hopson (1964), and Drake (1989) suggest that the granodiorite had a source at depth, and was emplaced well after the climax of regional metamorphism and deformation.

Amphibole from an outcrop near here yielded a disturbed $^{40}Ar/^{39}Ar$ age spectrum with an isochron age of 475 Ma, which is interpreted as the time of cooling through 500°C. Further cooling below 500°C (staurolite to biotite grade) was complete by the end of the Devonian. With this Early Ordovician amphibole cooling age, the highest metamorphic grade and melting of these rocks (T>650°C) could very possibly be older than Ordovician and thus predate the classic Taconian orogeny.

Mileage

Incremental	Cumulative	
0.0	98.2	Return to vehicles, turn right (east) on Georgetown Pike, Va. 193.
3.7	101.9	Drive past I-495 overpass and turn left at traffic light onto Balls Hill Road.
0.4	102.3	Turn left on Live Oak Drive, cross over I-495, and continue north.

0.9 103.2 Park on right at neck of cul-de-sac next to the trailhead of the National Park Service Potomac Heritage Trail. Follow the trail down to within sight of the Potomac River (do not take the footbridge right across the culvert and go under I-495). Take the foot trail into the woods and walk west along the river to the large outcrops beneath the cliffs.

Stop 6. Plummers Island Shear Zone.

Phyllonitic schist and migmatite, and migmatitic phyllonitic schist, Mather Gorge Formation, eastern boundary of Stubblefield Falls domain of the Mather Gorge Formation, Potomac terrane, Falls Church, Va.-Md., 7.5-minute quadrangle (Drake and Froelich, 1997).

The rocks seen at this stop are very difficult to interpret (Drake, 1989, Stop 6). Fisher (1970) mapped these sillimanite- to staurolite-grade rocks as the Upper Pelitic Schist of the Wissahickon Formation. Beneath the American Legion (I-495) Bridge, he mapped a transitional contact with the diamictite of the Sykesville Formation. Fisher (1963, 1970) and Hopson (1964) describe the transition between Peters Creek Schist and Sykesville diamictite as containing a decreasing amount of olistoliths in the Sykesville Formation. Drake (1989) described these rocks as retrograded chlorite-sericite phyllonite of the quartzose schist of the Peters Creek Schist, and called Fisher's (1963, 1970) contact with the rocks of the Sykesville Formation the Plummers Island fault. He suggested that the Sykesville is choked with olistoliths of Peters Creek Schist near its contact with that unit. Drake and Froelich (1997) later classified rocks at this stop as the upper part of the Sykesville Formation, with the upper part containing 50 percent or more phyllonite olistoliths, interpreted as having been derived from rocks of the Mather Gorge Formation. Drake and Froelich (1997) placed the Plummers Island fault, the contact between phyllonite of the Mather Gorge Formation and the rocks of the upper part of the Sykesville Formation, about 0.5 km to the west of this stop.

We retain the original contact of Fisher (1963, 1970) as the Plummers Island fault of Drake (1989), but suggest that this linear fault was reactivated as a wide Alleghanian shear zone. The major (Alleghanian) foliation in rocks across the fault strikes northeast and dips steeply to the northwest. This steep northwest-dipping to near-vertical foliation begins in the Stubblefield Falls domain and continues with a decreasing amount of muscovite recrystallization for 11 km east, to the Rock Creek shear zone. To the west of the Plummers Island fault of Fisher (1963, 1970), the rocks exposed on scoured outcrops on the south side of the Potomac River appear to be a phyllonitized migmatite that has been later remigmatized and sheared and retrograded. Blocks and rafts of the disrupted phyllonitic migmatite appear as "olistoliths," along with subrounded quartz "cobbles" and rootless quartz veins that are transposed (fig. 13). The blocks and rafts of first-generation phyllonitic migmatite contain foliations that strike in many different directions, and are supported by a matrix of feldspathic second-generation migmatite (fig. 12). The matrix is migmatitic, not granular quartzofeldspathic like the Sykesville. Overprinted on this is a strong north-south foliation that is subparallel to the late (Alleghanian) movement on the Plummers Island fault.

$^{40}Ar/^{39}Ar$ age spectra of muscovites from the Stubblefield Falls domain provide estimates of the minimum time of cooling (S_1) through 350°C, decreasing from 375 Ma to the west to 354 Ma here at the Plummers Island fault. $^{40}Ar/^{39}Ar$ age spectra of muscovites from the rocks of the Sykesville Formation to the east give an estimate of the minimum time of cooling through 350°C at 357 Ma. This age is virtually identical to the time of cooling on the eastern side of the Stubblefield Falls domain, and is interpreted as a minimum age for thrusting of the Sykesville Formation over the Mather Gorge Formation in the Devonian (Acadian).

Estimates of the time of below-closure growth of muscovite (S_2) also decrease from west to east in the Stubblefield Falls domain, to a minimum of 328 Ma at the Plummers Island fault. In Sykesville Formation rocks to the east, on the other side of the fault, the below-closure ages increase dramatically from 304 Ma at the fault to 332 Ma near the Rock Creek shear zone. The ~304-Ma age within the fault is a maximum estimate of the time of the last Alleghanian movement on the fault.

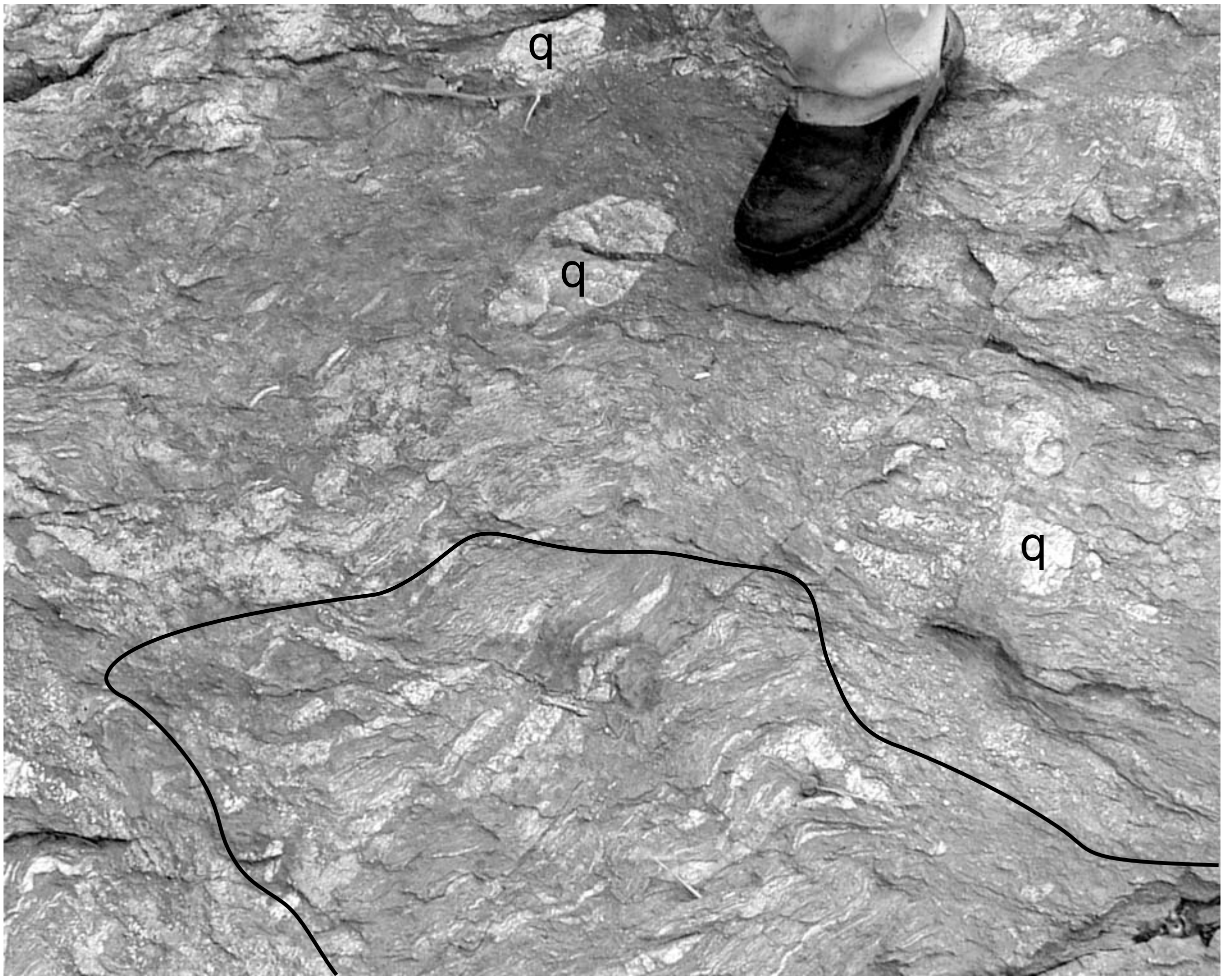

Figure 13. Photograph of complex rocks exposed at Stop 6 immediately west of the American Legion (I-495) Bridge on a scoured section along the Potomac River, in the Stubblefield Falls domain. These rocks were interpreted by Drake and Froelich (1997) to be olistoliths of Mather Gorge Formation and quartz cobbles in a Sykesville Formation matrix. The outcrop consists of disrupted, foliated blocks of Mather Gorge Formation (outlined in lower part of photograph) and dismembered quartz veins (q) associated with a small amount of migmatite. Man's foot is 10 cm wide. Potomac River is to the right of the photographed area.

Return to vehicles and retrace route back to Georgetown Pike, Va. 193.

Mileage

Incremental	Cumulative	
1.3	104.5	Turn right on Georgetown Pike, Va. 193.
0.7	105.2	Turn left on Swinks Mill Road, Va. 685.
1.6	106.8	Turn right on Lewinsville Road.
0.9	107.7	Turn left at traffic light on Spring Hill Road, Va. 694.
0.4	108.1	Turn left at traffic light on Jones Branch Drive.
1.2	109.3	Turn left into Tysons Corner Hilton.
0.1	109.4	End of Field Trip.