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Defining the West Grove Metamorphic Suite: Implications for tectonic interpretations of the central Appalachian piedmont

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INTRODUCTION

This trip focuses on metasedimentary rocks in the core of the central Appalachian orogen historically known as Wissahickon Formation (Bascom, 1902, 1905; Bascom et al., 1909; Bascom and Stose, 1932, 1938). Named for exposures along Wissahickon Creek in Philadelphia, Pennsylvania, the Wissahickon Formation once extended throughout the mid-Atlantic piedmont, from New Jersey into Virginia. Presently, the name is used in Pennsylvania, Delaware and New Jersey. Differences between the Wissahickon Formation east of the Rosemont shear zone, including the type locality in Philadelphia, and the Wissahickon west of the Rosemont (Fig. 1) have been recognized at least for 25 years, since Faill and MacLachlan (1989) defined the Philadelphia terrane (east) and Brandywine terrane (west). Since that time, the informal nomenclature associated with lithologic units within the terranes has evolved, but the name "Wissahickon" has been retained for rocks in both terranes. Herein, we outline differences in the detrital zircon populations, geochemistry of interlayered amphibolite, and metamorphic history between the western and eastern rocks. We propose that these differences are sufficient to adopt a new lithodeme, the West Grove Metamorphic Suite (WGMS), for the segment of the Wissahickon west of the Rosemont shear zone. The name Wissahickon Formation is applied only to metasedimentary rock east of the Rosemont shear zone.

A relatively complete picture of the Paleozoic evolution is emerging. The data demonstrate that the WGMS is an early Cambrian, Laurentian rift-related sequence and that the Wissahickon Formation was deposited in an arc-related basin during the Ordovician. Monazite ages suggest that the WGMS experienced middle to late Ordovician metamorphism, but that maximum temperatures were attained in the late Silurian to early Devonian. Deformation associated with emplacement of basement gneiss-cored nappes is broadly synchronous with this metamorphism. East of the Rosemont shear zone, Silurian-aged metamorphism in the Wissahickon Formation is associated with pluton emplacement (Bosbyshell, 2001; Bosbyshell et al., 2007) while regional Barrovian-style metamorphism is middle Devonian in age. ^{40}Ar-^{39}Ar white mica cooling ages are latest Devonian in both the WGMS and Wissahickon Formation (Blackmer et al., 2007), confirming that the units were assembled in the Devonian at relatively high-temperature and cooled together.

GEOLOGIC SETTING

The central Appalachian piedmont in Pennsylvania and Delaware can be divided into external and internal zones, both of which contain Mesoproterozoic gneiss-cored thrust sheets and Neoproterozoic to lower Paleozoic metasedimentary cover rocks. The external zone – north of the Martic Line and including Mine Ridge and the Honey Brook Upland (Fig. 1) – experienced metamorphism no higher than greenschist facies during Paleozoic orogenesis (Sutter et al., 1980; Crawford and Hoersch, 1984; Pyle, 2006). The rocks in the southeastern internal zone, the focus of this trip, comprise the high-grade, metamorphic core of the orogen and contain evidence for multiple episodes of amphibolite to granulite facies metamorphism (Crawford and Mark, 1982; Wagner and Srogi, 1987; Bosbyshell et al., 1999).

The structural geology in the Pennsylvania and Delaware piedmont has been debated for nearly one hundred years and remains controversial (Bliss and Jonas, 1916; Knopf and Jonas, 1923; McKinstry, 1961, Mackin, 1962; Wise, 1970; Wiswall, 1990; Alcock, 1994; Valentino et al., 1994; Alcock and Wagner, 1995). The framework presented on this trip is based on relatively recent mapping by the Pennsylvania and Delaware geological surveys (Plank et al., 2000; Blackmer, 2004a, 2004b, 2005; Bosbyshell, 2005a, 2005b, 2006, 2008; Wiswall, 2005; Blackmer et al., 2010). The Embreeville Thrust (Stop 2) is the lowest structure in a series of gneiss-cored nappes or thrust sheets that include, from lowest to highest, the West Chester massif, Woodville nappe, Avondale massif, and Mill Creek (Hockessin-Yorklyn) anticline (Plank et al., 2000). The gneiss in the cores of these structures is thought to be similar to Mesoproterozoic basement gneiss in Maryland and is called Baltimore Gneiss (Bascom et al., 1909; Bascom and Stose, 1932), although available sparse geochronological data indicate that gneiss within the Avondale massif may not be Mesoproterozoic-aged (Grauert et al., 1973, 1974; Bosbyshell et al., 2006). The WGMS is part of the latest Neoproterozoic to Cambrian cover sequence in the nappes. The thrust sheets are truncated to the east by the steeply-dipping Rosemont shear zone (Valentino et al., 1995; Bosbyshell 2005a, 2005b), which is the western boundary of Ordovician-aged (475 to 485 Ma; Aleinikoff et al., 2006) granulite facies metaigneous rock of the Wilmington Complex magmatic arc (Wagner and Srogi, 1987), and other magmatic arc-related metaigneous rock and metasedimentary rock of the Wissahickon Formation.

WEST GROVE METAMORPHIC SUITE

The metasedimentary units that make up the West Grove Metamorphic Suite were most recently part of the "Glenarm Wissahickon," a name introduced by Faill and Wiswall (1994) and adopted by the Pennsylvania Geological Survey on an informal basis. The name has been used for schist and gneiss that form the cover sequence of the gneiss-cored massifs described above, to distinguish these rocks from the type locality of the Wissahickon Formation and to emphasize their association with the Glenarm Group – the Cockeysville Marble and Setters Formation – which is absent east of the Rosemont shear zone (Fig. 1). Recent 1:24000 scale maps subdivide the "Glenarm Wissahickon" into informal units: the Doe Run schist, Mt. Cuba gneiss and Laurels schist (Blackmer, 2004a, 2004b; Wiswall, 2005). Given the data described below, we abandon "Glenarm Wissahickon" and adopt the name West Grove Metamorphic Suite to emphasize that these rocks are not related to the Wissahickon Formation. The WGMS comprises the Doe Run Schist, Laurels Schist, Mt. Cuba Gneiss, White Clay Creek Amphibolite, and Kennett Square Amphibolite. The name "West Grove" is chosen because the Borough of West Grove straddles the mapped trace of the Street Road Fault, the contact between the Doe Run Schist and Mt. Cuba Gneiss (Fig. 1), and because all units in the WGMS, except the Laurels Schist, underlie the West Grove 7.5-minute quadrangle.

Doe Run Schist is silvery to dark gray schist dominated by medium-grained muscovite giving the rock a spangled appearance. The unit is largely pelitic containing quartz, plagioclase, muscovite, biotite, garnet, staurolite and kyanite. Sillimanite is present in some locations. Staurolite, garnet and kyanite are commonly quite coarse, up to centimeter-scale dimensions. Locally, quartz and feldspar content is sufficient to make the rock psammitic. Tourmaline and epidote are common accessory minerals. Near the Embreeville thrust the rock has experienced retrogression; staurolite and kyanite are replaced by mats of sericite and sufficient chlorite is present to impart a greenish cast to weathered surfaces (Wiswall, 2005). The Doe Run Schist is in the hanging wall of the Embreeville Thrust, in contact with Baltimore Gneiss of the West Chester massif and with the Glenarm Group and Baltimore Gneiss in the Woodville nappe (Blackmer, 2004a).

The Laurels Schist (Blackmer, 2004a; Wiswall, 2005) is fine-grained, silvery to grayish-green, muscovite-chlorite phyllitic schist occurring in a narrow band adjacent to the trace of the Embreeville Thrust. Small, millimeter-scale garnets are common; tourmaline and magnetite are common accessory minerals.

Mt. Cuba Gneiss consists of interlayered pelitic gneiss and pelitic schist. Pelitic gneiss is fine to medium grained quartz-plagioclase-biotite-muscovite gneiss, with varying amounts of sillimanite and garnet. Gneissic layering is the result of metamorphic differentiation and partial melting. Small bodies of granitic pegmatite appear to be locally-derived products of partial melting. Pelitic schist has abundant biotite, prismatic sillimanite and fibrolite, and large garnets. Mt. Cuba Gneiss is the metasedimentary cover rock above the Street Road Fault in the Avondale nappe (Blackmer, 2004b). Mt. Cuba Gneiss also overlies Baltimore Gneiss in the Mill Creek anticline, although the bedrock

Geologic Map of Southeastern Pennsylvania and Northern Delaware

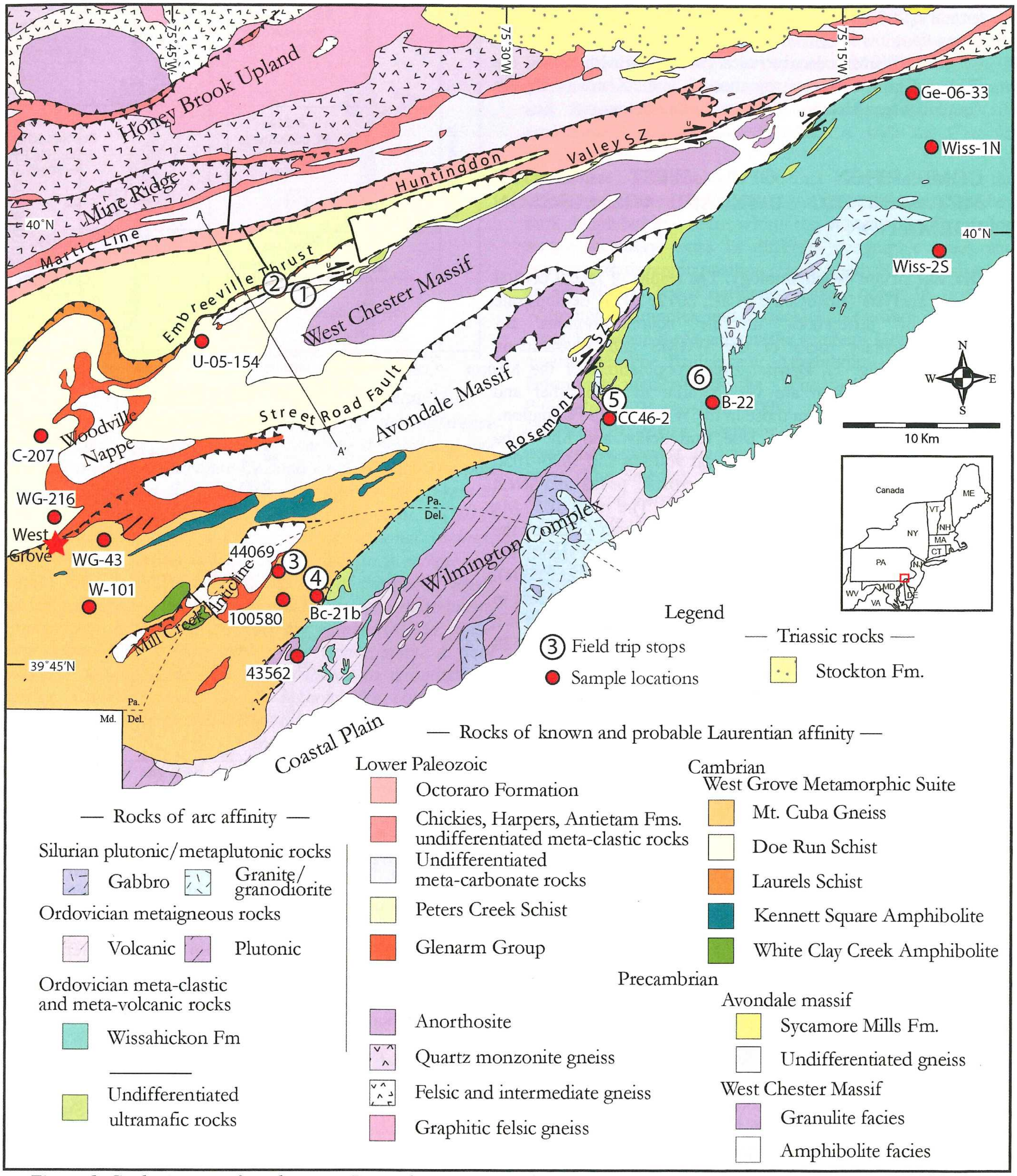

Figure 1. Geologic map of southeastern Pennsylvania and northern Delaware, with field trip stops and sample locations mentioned in text.

geologic map of Delaware (Plank et al., 2000) uses the older formal nomenclature and the unit is shown as Wissahickon Formation.

The WGMS also includes two amphibolite units, the White Clay Creek Amphibolite and Kennett Square Amphibolite, which are described further below.

COMPARISON OF WEST GROVE METAMORPHIC SUITE AND WISSAHICKON FORMATION

Detrital zircon geochronology. The results of recent detrital zircon analysis (Bosbyshell et al., 2012, 2013) demonstrate significant differences in the source regions for metasedimentary rocks of the WGMS and Wissahickon Formation (Fig. 2). Detrital zircon populations of the Mt. Cuba and Doe Run are very similar to each other and markedly different from those in the Wissahickon Formation.

Most samples in the Doe Run Schist and Mt. Cuba Gneiss exhibit well-defined peaks at 960 Ma and 1020–1050 Ma, an array of smaller Mesoproterozoic peaks and latest Neoproterozoic peaks at 550 Ma (Fig. 2). The 1020–1050 Ma zircons correspond to the well-known Ottawan phase of the Grenville orogeny, while 960 Ma is younger than significant magmatism in the Laurentian Grenville (Tollo et al., 2004). Doe Run samples contain Archean zircon, which is absent in the Mt. Cuba. The youngest zircon in the Doe Run Schist is a grain in sample C-207 which yielded a concordant age of 528 Ma. The youngest zircon in the Mt. Cuba gneiss is 544 Ma. Thus, the WGMS can be no older than Cambrian, and the depositional age of the Doe Run Schist may be younger than that of the Mt. Cuba Gneiss.

Detrital zircon populations in three samples from the Wissahickon Formation east of the Wilmington Complex (Fig. 1) contain Mesoproterozoic zircon, but the distribution of peaks is considerably different from those in the WGMS (Fig. 2). At the same time, the three samples are somewhat different from each other. Two samples, CC46-2, which is intruded by arc-related magmatic rock near the contact with the Wilmington Complex, and WISS-1N, from the type locality in Philadelphia, contain zircon as young as 480 Ma, constraining the maximum depositional age to the early Ordovician. These samples exhibit peaks at 630 Ma and 880 Ma that do not correspond to known Laurentian sources (e.g. Condie et al., 2009). The Windy Hills Gneiss, a meta-volcaniclastic unit within the Wilmington Complex, also contains small populations of zircon that do not have a known Laurentian source (Aleinikoff et al., 2006). These results suggest that the Wilmington Complex and the Wissahickon Formation may not have a peri-Laurentian origin, or that a peri-Gondwanan source was proximal to Laurentia in the early Ordovician when the Wilmington Complex arc was active.

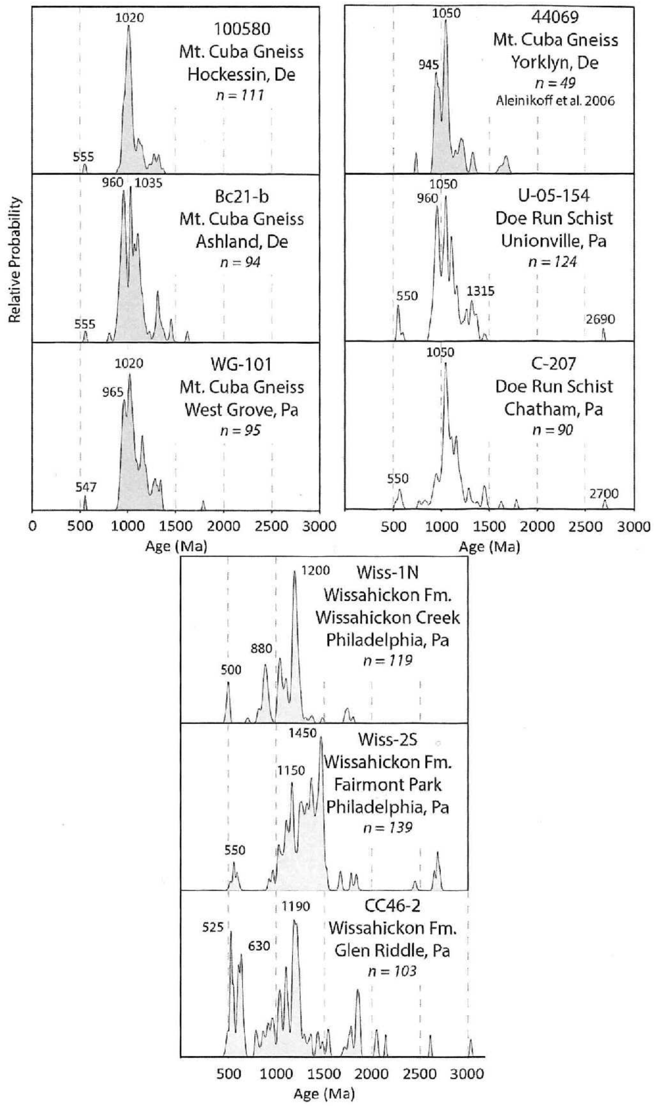

Figure 2. A comparison of the ages of detrital zircon from the West Grove Metamorphic Suite and Wissahickon Formation.

Cawood et al. (2012) found a consistent relationship in detrital zircon populations with tectonic setting based on the cumulative probability distribution of the difference between zircon crystallization age and depositional age. Following Cawood et al.'s (2012) analysis, an extensional depositional environment is inferred for the Doe Run Schist and Mt. Cuba Gneiss. Wissahickon Formation samples plot in or near arc, collisional, and extensional fields (Fig. 3).

Amphibolites. The West Grove Metamorphic Suite includes the Kennett Square Amphibolite and White Clay Creek Amphibolite. For detailed description and analysis of these units, the reader is referred to Smith and Barnes (1994, 2004) and Plank et al. (2001). The Kennett Square Amphibolite occurs within the Mt. Cuba Gneiss in a belt along the southern margin of the Avondale massif (Fig. 1). The White

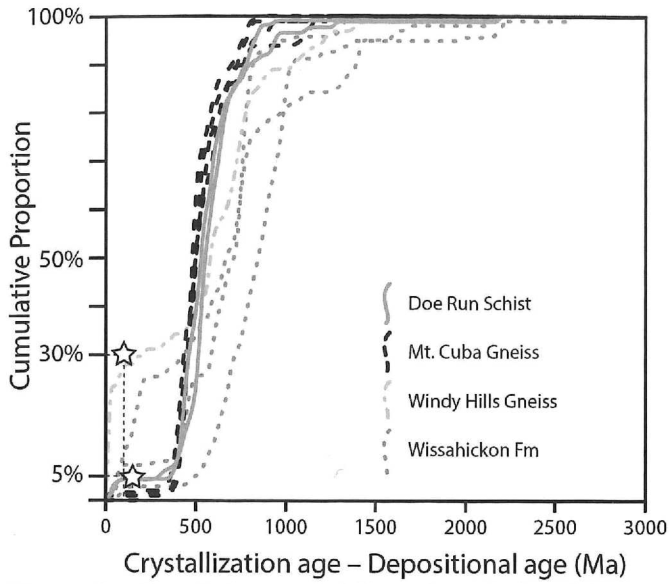

Figure 3. Cumulative probability plot of the difference between zircon crystallization ages and the depositional age of study area samples, after Cawood et al. (2012). The plot was prepared using the age of the youngest zircon present in each unit as the depositional age. Cawood et al.'s (2012) analysis suggests that in extensional depositional settings, fewer than 5% of the detrital zircon ages in a sample are within 150 Ma of the depositional age of the rock (curves which pass below the lower star). In an arc environment, greater than 30% of zircon ages are within 100 Ma of the depositional age (to the left of the upper star). A field between these end members is attributed to a collisional setting. Cawood et al., (2012) acknowledge considerable overlap in their fields and we note that both the Windy Hills Gneiss (loc. 43562, Fig. 1) and one Wissahickon sample (CC46-2) were almost certainly deposited in an arc environment, but plot outside the arc field.

Clay Creek Amphibolite occurs as 10 cm to 10 m thick layers within the Mt. Cuba Gneiss and as two amphibolites interlayered with Doe Run Schist (Blackmer, 2004b).

The Kennett Square Amphibolite (KSA) occurs as map-scale bodies up to 10 km long, with outcrop width as great as 0.6 km. On chondrite normalized multi-element diagrams, the KSA is characterized by flat REE patterns with slight LREE depletion or enrichment that is characteristic of mid-ocean ridge basalt (MORB) (Smith and Barnes, 1994; Plank et al., 2001). Smaller amphibolite bodies with similar geochemical characteristics are also present (McEwen, 1997; Plank et al., 2001). Where contacts are exposed they are generally concordant with foliation and compositional layering in the metasedimentary rock (Blackmer, 2004a).

The White Clay Creek Amphibolite (WCCA) is characterized by high total Fe, moderate to high TiO_2, and high overall REE abundances. REE patterns are negatively sloped on chondrite normalized plots, and incompatible trace elements display a humped pattern on chondrite-normalized spider diagrams (Smith and Barnes, 1994, 2004; Plank et al., 2001). These patterns are characteristic of within-plate basalts from either a continental or oceanic setting (Pearce, 1983). Plank et al. (2001) favored an oceanic setting, while Smith and Barnes (2004) proposed a continental initial rift environment and correlate the WCCA with the Catoctin metabasalt.

Three geochemically distinct amphibolites – the Confluence Dikes, Bridgewater Amphibolite, and Smedley Park Amphibolite – occur within the Wissahickon Formation metasedimentary rocks in different geographic areas and possibly stratigraphic position (Bosbyshell, 2001; Bosbyshell et al., 2009). The Confluence Dikes occur in both the Wilmington Complex and Wissahickon Formation, near the contact between these units in the southern Media 7.5 minute quadrangle. The Bridgewater Amphibolite is found in the Fairmount member of the Wissahickon Formation in Philadelphia (Bosbyshell, 2008) and within and near the Chester Park gneiss (Bosbyshell, 2001, 2005a, 2005b) in a northeast-southwest trending belt along the Coastal Plain onlap. The Smedley Park Amphibolite is found within the Wissahickon Formation to the northwest of the Bridgewater Amphibolite. We note that the three Wissahickon Formation samples that were selected for detrital zircon analysis are from locations interlayered with a different amphibolite type: CC46-2 is associated with the Confluence Dikes; WISS-1N is associated with the Smedley Park Amphibolite; and WISS-2S is associated with the Bridgewater Amphibolite. This suggests that further subdivision of the Wissahickon Formation may be warranted, a discussion that is beyond the scope of the present investigation.

The Confluence Dikes are nearly identical to mafic layers in the Rockford Park Gneiss of the Wilmington Complex, and both are very similar to modern boninities, distinctive volcanic rocks found in the forearc regions of modern western Pacific island arcs (Hickey and Frey, 1982; Stern et al., 1991; Bloomer et al., 1995). Major element properties in the Confluence Dikes that are similar to boninites include Mg# (= Mg/Mg + Fe_{tot}) > 0.59, and TiO_2 < 0.35%, at SiO_2 content as high as 52.0%. Boninites are characterized by Mg# > 0.6, TiO_2 < 0.5%, and SiO_2 > 53.0% (Crawford et al., 1989; Taylor et al., 1994). The Confluence Dikes have very low abundances of LREE and concave up REE patterns with slight positive Eu anomalies. On chondrite-normalized trace element diagrams, the Confluence Dikes and Rockford Park Gneiss exhibit Nb and Ta anomalies and are enriched in incompatible elements relative to less incompatible, with abundances below typical MORB (Pearce, 1983) for all but the most mobile, incompatible elements. The patterns are consistent with those of modern boninites.

The Bridgewater Amphibolite occurs as 1 to 5 m thick layers that are concordant with foliation and compositional layering in surrounding rock. In many outcrops, the Bridgewater Amphibolite is distinctive for coarse (up to 0.5

cm) magnetite grains that are surrounded by a halo of plagioclase. The chemical composition is similar to highly-evolved Fe-Ti basalts and more closely resembles within-plate basalts than MORB or arc tholeiites (Bosbyshell et al., 2009).

The Smedley Park Amphibolite occurs in layers much thicker than the Bridgewater Amphibolite, such that both upper and lower contacts of individual layers are rarely exposed. Map relationships indicate thickness of greater than 20 m in many locations (Bosbyshell, 2001, 2004). The Smedley Park Amphibolite is characterized by REE patterns that show enrichment of LREE. Incompatible trace elements are enriched 10x relative to less incompatible trace elements which have abundances slightly less than MORB. Moderate Nb anomalies are present (Bosbyshell 2001; Bosbyshell et al., 2009). Based on these characteristics, the Smedley Park Amphibolite is very similar to modern back-arc basin basalt.

Pressure-temperature-deformation-time history.
The metamorphic and deformation histories of the WGMS and the Wissahickon Formation are distinct from each other, and within the WGMS, that of the Doe Run Schist differs somewhat from Mt. Cuba Gneiss. The Mt. Cuba Gneiss attained higher temperatures than the Doe Run Schist. The Doe Run contains evidence for an older period of metamorphism and widely-dispersed, locally-intense retrograde overprinting by hydrous fluids, that are absent from the Mt. Cuba. The dominant foliation in the Doe Run schist and much of the Mt. Cuba gneiss is shallow to moderately southeast-dipping and was defined as the regional S_2 by Blackmer (2004a, 2004b) and Wiswall (2005).

The Doe Run Schist contains an early fabric defined by aligned sillimanite preserved in microlithons – that may be Late Ordovician based on monazite core ages of ~450 Ma (Bosbyshell et al., 2007). Most samples contain one or more porphyroblasts – garnet, staurolite, kyanite – that indicate moderately high temperature and pressure of the amphibolite facies. The dominant foliation wraps around garnet and staurolite porphyroblasts, but staurolite also occurs parallel to foliation and in several samples is rimmed by fine sillimanite and small euhedral garnet (Fig. 4). Small euhedral garnet also cross-cuts the dominant foliation in some samples. These observations suggest that peak metamorphic conditions in the Doe Run Schist exceeded the high-T stability limit of staurolite (Fig. 5) and are post-kinematic relative to S_2 formation. Textures further indicate that some rocks may have experienced a small degree of partial melting (Srogi et al., 2007). Bosbyshell et al. (in preparation) utilize garnet isopleth thermobarometry to estimate peak conditions of approximately 700 ± 50°C at 550 ± 100 MPa in a sample in the footwall of the Street Road Fault (WG-216, Fig. 1). Monazite geochronology demonstrates that maximum temperatures were attained at ~410 Ma (Figs. 4 and 5). Infiltration of hydrous fluids caused variable retrogression of higher-temperature assemblages, ranging from partial rimming and replacement of porphyroblasts by fine-grained

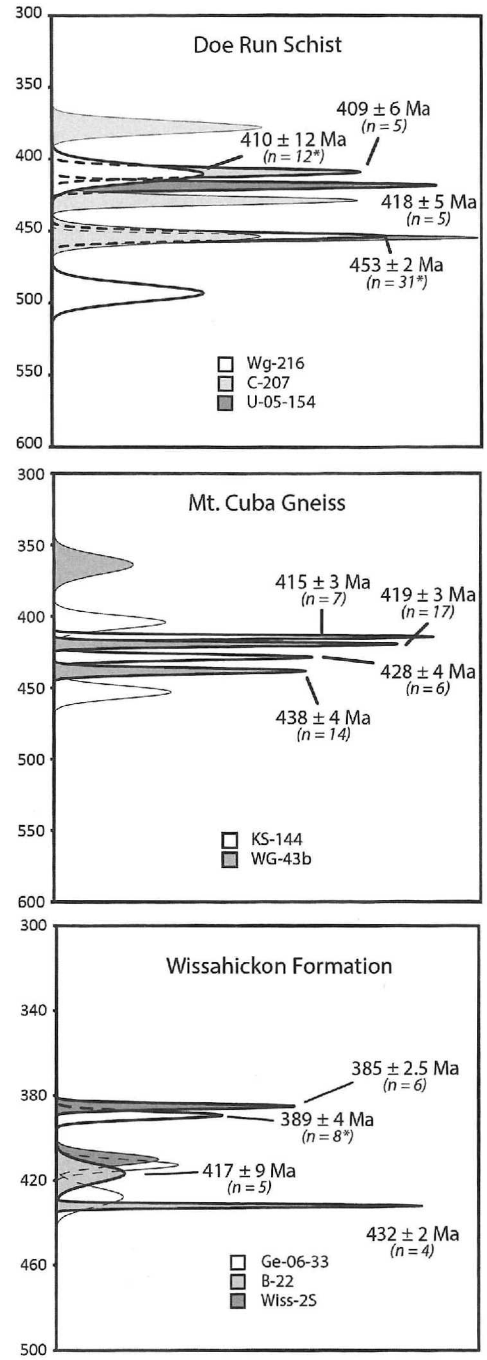

Figure 4. Results of in-situ EPMA U-Th-total Pb monazite geochronology. Labeled curves represent the weighted average age of multiple (n) compositional or age domains in monazite from a single sample. Unlabeled curves represent individual domains. Most analyses were performed at the University of Massachusetts Amherst following the procedures outlined by Williams et al. (2006, 2007). Results marked with an asterisk, samples WG-216 and Ge-06-33, were analyzed at Rensselaer Polytechnic Institute following Pyle et al. (2005). These results are the weighted average of n individual spot analyses.

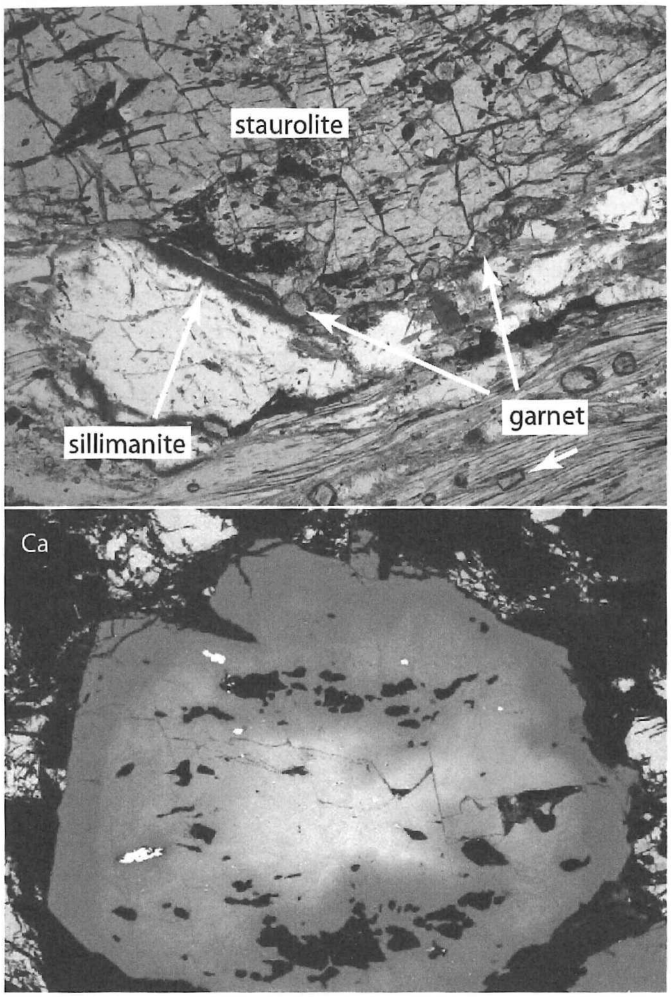

Figure 5. (A) Photomicrograph from location C-207, Doe Run Schist. Sillimanite and small garnet along the embayed rim of staurolite are interpreted as evidence for the high-temperature breakdown of staurolite. (B) Ca x-ray composition map of garnet in sample WG-216 of the Doe Run Schist. The abrupt step between the higher-Ca core and low-Ca rim is interpreted to be a hiatus in garnet growth during the formation of staurolite. The low-Ca rim formed as a result of the high-temperature demise of staurolite. Monazite inclusions in the low-Ca rim, which give ages as young as 410 Ma (Bosbyshell et al., 2006), constrain the maximum age of garnet growth.

muscovite or chlorite to complete replacement and recrystallization of foliated matrix biotite by mimetic chlorite. Retrograde metamorphism is most common, but not confined to, the Embreeville Fault.

In the Mt. Cuba Gneiss, Plank (1989) found that peak metamorphic conditions varied from 600 ± 50°C at 550 ± 100 MPa in southeastern-most Pennsylvania to 750 ± 50°C at 650 ± 100 MPa nearest the Wilmington Complex in Delaware; estimates which are supported by subsequent work (Alcock, 1989, 1994; Alcock and Wagner, 1995). In high-grade, migmatitic Mt. Cuba Gneiss, some leucosome contains biotite fish parallel to mesosome foliation while other leucosome contains randomly-oriented biotite. These high-temperature microstructures suggest syn- to post-kinematic partial melting with respect to S_2 foliation formation. The timing of maximum temperatures is constrained by monazite ages in two samples: monazite in the Mill Creek nappe (sample 44069) gives a Silurian age of 425 Ma (Aleinikoff et al., 2006), while monazite inclusions in staurolite from the hanging wall of the Street Road Fault in Pennsylvania (sample WG-43) must be no older than 415 Ma (Fig. 4). Alcock (1989) describes evidence for higher pressure metamorphism following peak temperature in the Mt. Cuba, inferred to reflect crustal thickening following thrust stacking. Recent unpublished results of 625 ± 50°C at 700 ± 100 MPa (Bosbyshell et al., in preparation), based on isopleth thermobarometry using the composition of garnet rims, agree well with Alcock's (1989) results.

The development of the regional S_2 foliation (Blackmer, 2004a, 2004b; Wiswall, 2005) is broadly synchronous with high temperature metamorphism (Alcock, 1989; Blackmer, 2004a, 2004b) in the WGMS, although the peak temperatures were attained at different times in the Mt. Cuba Gneiss and Doe Run Schist.

Two periods of metamorphism are well-documented in the Wissahickon Formation east of the Rosemont shear zone: early, high temperature – low- to moderate-pressure assemblages are variably overprinted by a second period of higher pressure metamorphism at 650 ± 50°C, 700 ± 100 MPa (Crawford and Mark, 1982; Bosbyshell et al., 1999; Bosbyshell, 2001). The temperature associated with the early metamorphism varies from west to east. Nearest the Wilmington Complex, peak conditions were likely in excess of 700°C at 500 ± 100 MPa while less than 10 km to the east, andalusite was part of the early assemblage, implying temperatures of approximately 500°C (Bosbyshell et al, 1999). In the type section of the Wissahickon Formation, the early metamorphism is largely absent, and the Barrovian-style metamorphism reflects the second period of metamorphism (Bosbyshell et al., 2007, Bosbyshell, 2008). Monazite ages (Bosbyshell, 2001; Pyle et al., 2006; Bosbyshell, 2008) constrain the early metamorphism to the Silurian (~430 Ma) and the high-pressure overprint to the Devonian (~385 Ma) (Fig. 4).

TECTONIC IMPLICATIONS

Origin of metasedimentary units. Several lines of stratigraphic and geochemical evidence, in addition to the detrital zircon data, point to a rift basin origin for the Doe Run Schist and Mt. Cuba Gneiss. Both of these units are in depositional contact with the Glenarm Group (Blackmer, 2004a, 2004b), which includes the Setters Formation (microcline gneiss, quartzite, and biotite-muscovite-quartz-garnet schist) and overlying Cockeysville Marble. Both the Setters Formation and Cockeysville Marble unconformably overlie the Baltimore Gneiss, which is assumed to be Laurentian basement. The previous model for the Glenarm Group, deposition of continentally-derived clastic sediments succeeded by carbonate on a continental platform, breaks down in the details (Blackmer, 2004c, 2005). Map-scale lenses and meter-scale layers of microcline gneiss are found within the Cockeysville Marble and the Mt. Cuba Gneiss, while map-scale lenses of marble are found in the Setters and the Mt. Cuba. This irregular stratigraphy suggests that the Glenarm Group and the Mt. Cuba Gneiss were deposited in a somewhat unstable environment capable of abrupt shifts between clastic and carbonate sedimentation. The Setters microcline gneiss has an unusually high (50-70%) microcline content. Geochemically, the gneiss plots in the rhyolite and trachyte fields on total alkali vs. silica diagrams. It has high K_2O (8-12 wt. %), low Na_2O (0.55-0.93 wt. %), and smoothly varying REE patterns consistent with an igneous parent. A literature search revealed that the best matches to this chemistry are hydrothermally altered volcanic or volcaniclastic rocks related to continental rifting or crustal extension (Blackmer, 2004b; Blackmer and Srogi, 2004). Both the Doe Run and Mt. Cuba host amphibolite bodies. The Doe Run has a few, small bodies of White Clay Creek Amphibolite, interpreted by Smith and Barnes (2004) as continental initial rift basalt. The much larger and more abundant amphibolite bodies in the Mt. Cuba include both WCCA and Kennett Square Amphibolite, interpreted as MORB (Smith and Barnes, 1994; Plank et al., 2001).

Taken together, these factors suggest that these rocks may represent early marine sediments deposited in an opening continental rift still floored by continental crust. The Setters Formation represents early clastic sedimentation in the new basin, including acidic tuffs or metasomatized arkoses (microcline gneiss). Carbonates formed as platforms on basement highs or as small reef caps. As the rift grew, the entire area was flooded by the aluminous sediments and interlayered basalts that became the Doe Run Schist, Mt. Cuba Gneiss, WCCA and KSA. Throughout the depositional history, shifting fault blocks and continued volcanism within the rift exerted local control on sedimentation and led to the interlayering of carbonate and clastic sediments in response to local changes in water depth and sediment source. The Mt. Cuba likely originated farther from the continent and closer to the developing ocean ridge, resulting in the higher volume of included amphibolite and MORB. The maximum depositional ages for the Doe Run and Mt. Cuba are younger than the nearby Catoctin rift activity.

High-temperature assembly. U-Th-total Pb monazite ages indicate that maximum temperatures in the Mill Creek nappe were attained in the late Silurian, prior to the highest temperatures in the structurally lower Avondale nappe. In turn, peak metamorphism in the structurally lowest unit, the Doe Run Schist in the West Chester nappe, is even younger – maximum temperatures were not reached until 410 Ma (early Devonian). We interpret this sequence to represent successive stacking of thrust sheets from southeast to northwest, with the warmer overriding sheets contributing to heating of the lower sheets. Deformation and metamorphism is interpreted to be the result of the Silurian collision of Ganderia in a sinistral transpressive tectonic regime (Hibbard et al., 2007; 2010). The New York promontory acted as a restraining bend and was the site of intense tectonism. The geometry of thrust sheets relative to the steeply dipping Pleasant Grove – Huntingdon Valley shear zone (PGHV) is consistent with such sinistral motion (Fig. 6). The most recent ductile deformation in the PGHV is thought to reflect dextral motion (Valentino et al., 1994, 1995); such motion could have transported the assembled nappes from a location nearer the New York promontory.

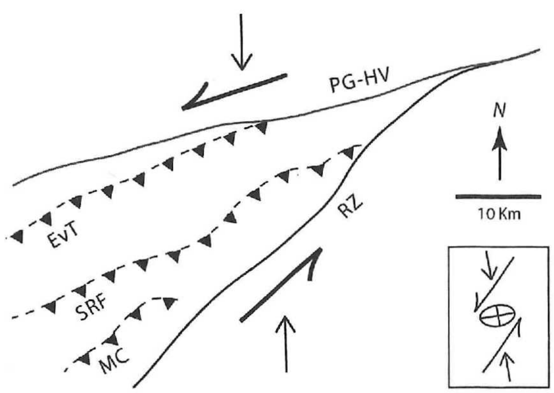

Figure 6. Simplified map showing geometry of thrust and steeply dipping shear zones consistent with sinistral transpression. PG-HV = Pleasant Grove Huntingdon Valley shear zone; RZ = Rosemont shear zone; EvT = Embreeville Thrust; SRF = Street Road Fault; MC = Mill Creek nappe.

The middle Devonian age of monazite for the Barrovian metamorphism in the Wissahickon Formation suggests crustal thickening during the Acadian orogeny, the accretion of Avalon in the northern Appalachians. Given the evidence for younger dextral transcurrent motion regionally on the Pleasant Grove – Huntington Valley and Rosemont shear zones (Valentino et al., 1994, 1995) and throughout the Appalachians, it is possible that the crustal block east of the Rosemont shear zone which contains the Wissahickon Formation and Wilmington Complex was originally located some distance to the north.

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Road log

Mileage From last	Cumulative	Directions/description
0.0	0.0	Leave Lancaster Marriott at Penn Square Hotel and go east on PA-462 E/E King St/Lincoln Hwy
1.9	1.9	Turn left, then right to proceed east on PA-340 E/Old Philadelphia Pike
3.8	5.7	Turn right onto PA-896 S /Eastbrook Rd
1.2	6.9	Turn left onto U.S. 30 E/Lincoln Hwy and travel east. East of Lancaster, Route 30 is underlain by Cambrian and Ordovician limestone of the Laurentian passive margin. The hill to the south of Route 30 is formed by the basal Cambrian Chickies Quartzite, on the north flank of the Proterozoic gneiss-cored Mine Ridge anticline. Route 30 climbs onto Mine Ridge on the east side of the village of Gap.
14.1	21.0	Intersection of U.S. 30 E/Lincoln Hwy and PA-10/Octorara Trail; continue east.
0.3	21.3	Bear right to continue east on U.S. 30 E Bypass. Small exposures of the Mine Ridge Proterozoic gneiss are visible along Route 30 here.
10.9	32.2	Exit onto US-322 E/Horseshoe Pike/Manor Ave
1.3	33.5	Turn left onto E Lancaster Ave
0.2	33.7	Turn right onto US-322 E/Brandywine Ave. The exposures along US-322 south of Downingtown are highly tectonized Octoraro Phyllite and Peters Creek Schist within the Pleasant Grove – Huntingdon Valley Shear Zone.
4.1	37.8	Turn right onto N Creek Rd
0.4	38.2	Turn right into parking area of Ingrams Mill Nature Area

STOP 1. Doe Run Schist at Ingram's Mill Nature Area, Unionville Quadrangle (Wiswall, 2005)

Interlayered psammitic and pelitic schist crops out for about 200 m along the east side of Creek Road, beginning about 100 m south of the parking area. The coarse-grained pelitic schist contains kyanite + garnet + biotite + muscovite ± staurolite + quartz + plagioclase. Very aluminous layers contain kyanite porphyroblasts 3-6 cm in length. Museum-quality clusters of blue kyanite have been found in this area.

The dominant foliation regionally, S_2, is shallow to moderately southeast dipping. In these outcrops, the S_2 foliation is folded by upright folds with variably-developed steeply-dipping foliation. The contact with Mesoproterozoic gneiss of the West Chester massif is just a few hundred meters south of this location. The contact with gneiss of the Poorhouse Prong is approximately 500 m to the north. Wiswall (2005) shows the Poorhouse Prong as rootless; his cross-section (Fig. 7) suggests that the base of the gneiss may be the Street Road fault.

Mileage		
0.0	38.2	Turn right out of parking area.
0.4	38.6	Turn right onto PA-162 W/W Strasburg Rd
0.1	38.7	Cross East Branch of Brandywine Creek and turn right onto Telegraph Rd.
0.4	39.1	Turn right on Waltz Rd
0.9	40.0	Park at end of guard rail

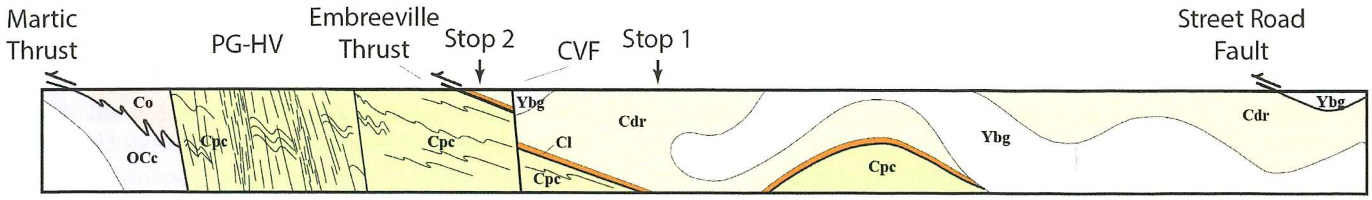

Figure 7. Cross-section of the Unionville 7.5 minute quadrangle modified from Wiswall (2005). PG-HV = Pleasant Grove-Huntingdon Valley shear zone, CVF = Cream Valley Fault. Position of A – A' is shown in Figure 1; along-strike positions of stops one and two are labeled.

STOP 2. Doe Run and Laurels Schist; Embreeville Fault, Unionville Quadrangle (Wiswall, 2005)

Walk approximately 200 meters east to a small outcrop at the bend in Waltz Rd. This is the Doe Run Schist, as seen at stop 1. The rock here contains garnet + biotite + muscovite + staurolite +quartz + plagioclase. The S_2 foliation dips southeast.

Return to the larger outcrops at the parking site. Here the rock is psammitic to semipelitic Laurels Schist, which contains the assemblage chlorite + muscovite + quartz + plagioclase + garnet. Wiswall (1994) describes three S-surfaces here, which he interprets as having formed sequentially. S1 is the oldest metamorphic foliation which is overprinted by S_2. Wiswall (1994) attributes the S_2 shear fabric to top to the northwest deformation (Fig. 8) associated with movement on the Embreeville Thrust, the contact between the Laurels Schist and the Peters Creek Schist, approximately 400m north Stop 2. He describes S_3 surfaces as southwest-dipping with asymmetry that indicates dextral and normal sense of motion. He associates S_3 with a younger period of strike-slip deformation on the Cream Valley Fault, the northern contact of the Poorhouse Prong, approximately 500m south of this location.

We suggest that the three fabrics described by Wiswall reflect a single thrust-related ductile strain regime. S_1 is an S surface formed by partitioning of the compressive component, S_2 is the C shear surface, and S_3 are C' shear bands. The fabrics in these outcrops are an expression of the Embreeville Thrust, which places the high-grade metamorphic rock to the southeast above greenschist facies rock to the northwest.

Mileage		
0.0	40.0	Proceed to Sugars Bridge Rd
0.1	40.1	Turn left onto Sugars Bridge Rd
0.8	40.9	Continue onto Telegraph Rd.
2.6	43.5	Continue onto Pa-162 W/Embreeville Rd. We've traversed the Poorhouse Prong, Mesoproterozoic (?) gneiss which underlies the hill which is now on the north side of Rt. 162. Outcrops along Rt. 162 are Doe Run Schist.
4.0	47.5	Turn left onto PA-82 S/PA-842 E/W Doe Run Rd.
0.7	48.2	At the roundabout, continue straight onto PA-82 S/Unionville Rd
3.6	51.8	Continue onto S Union St
0.5	52.3	Slight left onto Old Kennett Rd
0.9	53.2	Turn right onto PA-82 S/Creek Rd
200 ft		Take the 1st right to stay on PA-82 S/Creek Rd
		Continue to follow Creek Rd. Outcrops of Mesoproterozoic gneiss of the Mill Creek nappe on left.
2	55.2	Turn right onto Yorklyn Rd.
300 ft		Cross Red Clay Creek and turn left into Station Rd
0.1 mi	55.3	Park at railroad tracks.

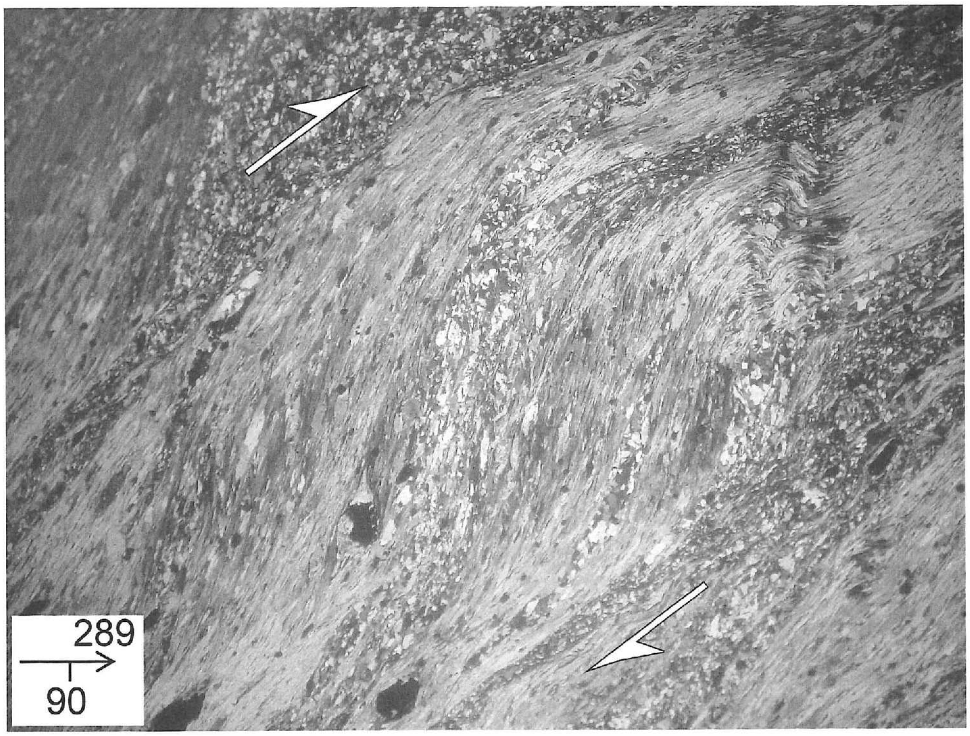

Figure 8. Photomicrograph of Laurels Schist at Stop 2 illustrating Embreeville Thrust fabric with top to northwest sense of shear.

STOP 3. Mt. Cuba Gneiss at Yorklyn, De., Kennett Square Quadrangle (Blackmer, 2004) Geological Map of Delaware (Plank et al., 2000)

Walk approximately 300 m northeast along tracks to railroad cut. The Mt. Cuba Gneiss experienced high temperature metamorphism and partial melting. The dominant foliation, regional S_2, dips SE, as it does throughout the Doe Run Schist and Mt. Cuba Gneiss from Stop 2 south to this location (Fig. 1). The gneiss is metatexite. Leucosome contains perthitic microcline, plagioclase and quartz. Melanosome is rich in garnet and biotite, but sillimanite occurs only as inclusions in plagioclase. No cordierite or orthopyroxene is observed. The mineral assemblage suggests partial melting at temperatures of 700-800°C and pressure of 550-800 MPa; i.e., within the sillimanite stability field at pressure above cordierite stability and at temperature below the appearance of orthopyroxene. Melting was likely the result of muscovite-breakdown followed by less extensive biotite-breakdown. The timing of metamorphism and partial melting here is constrained by SHRIMP and TIMS monazite ages of 426 ± 3 Ma and 424.9 ± 0.4 Ma, respectively (Aleinikoff et al., 2006).

The amphibolite interlayers present here are the White Clay Creek Amphibolite (Smith and Barnes, 1994, 2004), consisting of hornblende and plagioclase with minor quartz, titanite and magnetite. The trace element geochemistry of the White Clay Creek Amphibolite resembles continental initial rift basalt (Smith and Barnes, 1994, 2004).

Mileage		
0.0	55.3	Return to Yorklyn Rd.
0.1	55.4	Turn right onto Yorklyn Rd, cross Red Clay Creek and continue on Creek Rd.
1.4	56.8	Turn right onto Barley Mill Rd
0.3	57.1	Turn left to stay on Barley Mill Rd
0.9	58.0	Turn left into Mt. Cuba Center
0.4	58.4	Follow road to parking area at mansion.

STOP 4. Mt. Cuba Gneiss at Mt. Cuba Center - Hockession, De., Kennett Square Quadrangle (Blackmer, 2004) Geological Map of Delaware (Plank et al., 2000)

Please note that this is private property. If you have interest in visiting these exposures, please obtain permission from the Mt. Cuba Center before visiting.

Follow docent to outcrop, walking only where instructed. The enlargement of the Mt. Cuba Center Rock Wall garden began in 2011 after some successful excavation and approval from the Board of Managers. This garden was originally created from the blasting of an outcrop of existing mica gneiss to lay the Main Drive for the Copeland's estate. Upon completion of the driveway, Upper Banks Nursery designed and planted the new garden; it featured "planting pockets" to increase planting opportunities on the exposed rock face. During the 2011 expansion, forty dump truck loads of soil were removed, using a back-hoe, air-spade, and by hand, to create the exposure seen today. The entire area, approximately 3000 square feet, was pressure-washed at 3000 psi revealing this excellent outcrop of Mt. Cuba Gneiss in map view (Piatt, 2014, personal communication).

The Mt. Cuba Gneiss here is more pelitic than at Stop 3 and contains abundant sillimanite. Foliation within the outcrop trends N25-40E and is vertical or dips very steeply NW, similar to the general regional trend in this area of the Delaware Piedmont (Plank et al., 2000). The sub-vertical axial planes of folds trend N10E to N30E; fold axes plunge steeply NE. Sillimanite nodules parallel to axial planes (Fig. 9) demonstrate the high-temperature nature of deformation, but leucosome is folded. Therefore, the deformation, attributed to transpression near the western limit of the Rosemont shear zone, likely occurred subsequent to the attainment of maximum temperature. New, unpublished monazite ages from a sillimanite-bearing sample within the shear zone collected several miles along strike to the northeast suggest that the deformation could be as young as early to middle Devonian.

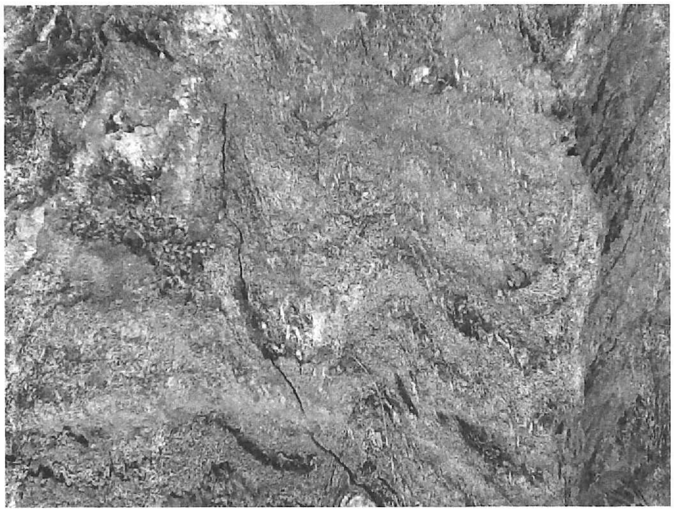

Figure 9. Photograph of Mount Cuba Gneiss at Stop 4. Note sillimanite-quartz nodules parallel to axial planes of folds.

Mileage		
0.0	58.4	Exit parking area
0.4	58.8	Turn left and Head northwest on Barley Mill Rd
0.9	59.7	Turn right to stay on Barley Mill Rd
0.3	60.0	Turn right onto Creek Rd
0.3	60.3	Slight left, then left onto Way Rd
1.6	61.9	Turn right onto Old Kennett Rd
0.1	62.0	Take the 1st left onto Owls Nest Rd
0.8	62.8	Turn right onto DE-52 S/Kennett Pike
0.2	63.0	Take the 1st left onto Center Meeting Rd
1.1	64.1	Continue onto Smiths Bridge Rd
1.6	65.7	Smiths Bridge Rd becomes Smithbridge Rd
6.6	72.3	Turn right onto Historic PA 261/Valleybrook Rd
325 ft		Take the 1st left onto Llewellyn Rd
0.5	72.8	Turn left onto Lenni Rd
1.2	74.0	Turn right onto Lungren Rd
0.2	74.2	Turn left onto Parkmount Rd
0.5	74.7	Cross PA-452/Pennell Rd; Parkmount Rd becomes Glen Riddle Rd
0.1	74.8	Turn right into parking lot for Tunbridge Apartments

STOP 5. Wissahickon Formation/Wilmington Complex contact, Aston Pa, Media 7.5 minute quadrangle

Please note that this is private property. If you have interest in visiting these exposures, please obtain permission from the King's Mill Banquet Facility before visiting. This stop examines the contact between the Confluence Gneiss and the Wissahickon Formation. Walk south along Chester Creek and ascend to the level of the railroad grade.

The first railroad cut exposes Confluence Gneiss with boninitic mafic layers, the Confluence Dikes. The mafic layers are concordant with and stretched parallel to the dominant metamorphic foliation in the host rocks; thus, they were present prior to the deformation that produced this foliation. Steeply dipping shear zones which cross-cut the dominant foliation are localized areas of high strain (local D_4, see below) associated with the Rosemont shear zone.

Continue south along the railroad tracks and descend towards the creek at the first valley. At the northwestern end of the next outcrop, (below tracks, just above creek level) is a small exposure of Confluence Gneiss. Though the contact is covered, pelitic gneiss of the Wissahickon Formation crops out just SE of this exposure. Four and possibly five S-surfaces can be discerned here. The dominant metamorphic foliation is defined by compositional layering of leucocratic, quartzo-feldspathic domains and micaceous domains consisting of aligned biotite and sillimanite, and garnet. This is the Silurian, high-temperature low-pressure metamorphic mineral assemblage. Because this dominant foliation is parallel to the axial planes of isoclinal folds it is termed S_2, a D_2 structural element. S_1 is the folded foliation that defines hinges of the isoclinal folds. These folds are in turn folded by close to tight and locally isoclinal F_3 folds; the axial planes of these folds are S_3.

The Confluence dikes are thin (<1 m thick) mafic layers present near the northwest end and in the center of this outcrop (Fig. 10). They are concordant with and attenuated within the S_2 foliation and folded by F_3 folds, demonstrating that the dikes can be no younger than the deformation responsible for the S_2 foliation. Since the boninitic layers are present in both the Wilmington Complex and Wissahickon Formation, it follows that the contact between these units also predates this deformation. The boninitic layers at this stop have not been dated directly, but assuming they are the same age as the geochemically-similar Rockford Park Gneiss, where geochemically similar boninitic rocks occur, then this contact can be no younger than the early Ordovician age of the Rockford Park Gneiss.

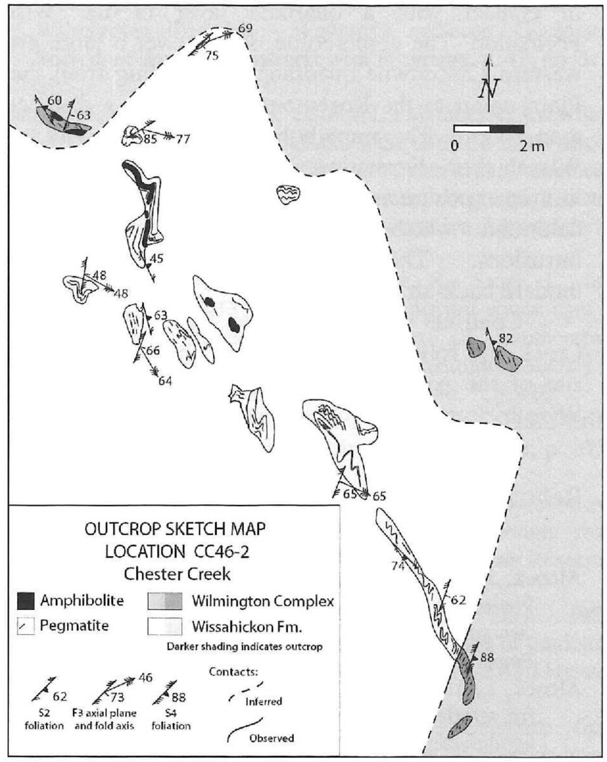

Figure 10. Sketch map of outcrop at Stop 5.

At the southeast end of the outcrop, all the structures described above are deformed by a sub-vertical, northeast trending shear zone. This shear zone is a D_4 structure; the shear zone foliation is S_4. Most of the pelitic gneiss here contains the Silurian high temperature mineral assemblage, but the shear zone contains the kyanite-bearing, higher pressure assemblage. The lighter-colored rock on the southeast side of the shear zone is the Confluence gneiss, thus the shear zone offsets the contact at this location. A crenulation elsewhere in this outcrop may be S_5 (and clearly younger crenulation will be seen at the next stop), but cross-cutting relationships are uncertain as the S_4 shear fabric is not crenulated.

Mileage		
0.0	74.8	Exit parking lot and turn right on Glen Riddle Rd
1.2	76	Turn left onto PA-352 N/S New Middletown Rd
0.1	76.1	Take the 1st right onto Elwyn Rd
1.0	77.1	Take the 1st right onto Baltimore Pike
2.5	79.6	Travel through Media, PA, past I-476 and turn left into Smedley Park on Paper Mill Rd
0.2	79.8	Cross trolley tracks and park on left.

STOP 6. Wissahickon Formation and Smedley Park amphibolite, Smedley Park, Media Pa. Lansdowne Quadrangle (Bosbyshell, 2005)

Walk north along Paper Mill Road from the parking area. The first outcrops expose the Smedley Park amphibolite in contact with a quartzite layer of the Wissahickon Formation. The amphibolite occurs over a large area in the western Lansdowne quadrangle, extending from the Coastal Plain onlap to the Rosemont shear zone, a distance greater than 10 km. The amphibolite is concordant with layering in Wissahickon Formation metasedimentary rocks, although limited exposure and intense deformation make it difficult to determine whether amphibolites originated as flows or intrusions. The Smedley Park Amphibolite resembles modern back-arc basin basalt.

Continue walking north on Paper Mill Rd., ford Crum Creek and follow the trail across an open field (the former site of the paper mill) and up a small rise to outcrops of Wissahickon Formation and continue to follow trail into an old quarry. The pelitic and psammitic lithologies are typical of the Wissahickon Formation along Crum Creek and east to the type section. They contain kyanite- and staurolite-bearing metamorphic mineral assemblages characteristic of Devonian intermediate pressure metamorphism. Exposures of the Wissahickon Formation along Crum Creek are unique in southeastern Pennsylvania due to the presence of rare andalusite (Gordon, 1922; Wyckoff, 1952; Heyl, 1980; Hess, 1981) and much more common kyanite and muscovite pseudomorphs after andalusite (Crawford and Mark, 1982; Bosbyshell et al., 1999). Pseudomorphs after andalusite are not present in Smedley Park, but can be seen in outcrops 1-2 km south of the park, in exposures on the campus of Swarthmore College. The andalusite is a product of Silurian high-temperature low-pressure metamorphism (Bosbyshell, 2001).

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