# The Piedmont: Old Rocks, New Understandings

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## ABSTRACT

The results of recent geochronological investigations in the central Appalachian Piedmont of southeastern Pennsylvania and northern Delaware have prompted a reevaluation of the tectonic history of rocks in the high grade metamorphic core of this portion of the orogen. Monazite results reveal that major metamorphism and deformation in the Piedmont occurred in the Silurian and Devonian and.is not related to the Taconic orogeny. The West Grove Metamorphic Suite and Wissahickon Formation lie on opposite sides of the Rosemont Shear Zone. Distinct differences in metamorphic history and detrital zircon provenance between these units demonstrate that the Rosemont Shear Zone is a significant tectonic boundary. Detrital zircon results further show that the Chester Park Gneiss likely originated in a peri-Gondwana basin and may be correlative with the Moretown Terrane in the New England Appalachians.

## INTRODUCTION

This field trip focuses on the high-grade metamorphic rocks in the central Appalachian Piedmont of southeastern Pennsylvania and northern Delaware (Fig. 1). Metamorphism and deformation in the rocks of the area have long been interpreted to be products of the Taconic Orogeny: the Ordovician collision between a peri-Laurentian volcanic/magmatic arc and the Laurentian margin (Wagner and Srogi, 1987; Aleinikoff et al., 2006; Wise and Ganis, 2009; Sinha et al., 2012). The importance of younger transcurrent deformation, that likely translated the Taconic hinterland from its original location within the orogen, has also been recognized (Valentino et al., 1994; Wise and Ganis, 2009). Monazite results (Bosbyshell, 2001, 2004, 2008; Pyle et al., 2006; Bosbyshell et al., 2014, 2016) show that, while there is evidence for middle to late Ordovician, Taconic-aged, metamorphism in some rocks, the bulk of the metamorphism is Silurian through mid-Devonian in age. Thus, the Salinic and Acadian orogenies, which mark the accretion of Gondwanan terranes Gander and Avalonia, respectively, in the Northern Appalachians played a significant role in Piedmont tectonics. These results also underscore the importance of transcurrent deformation in the assembly of the Piedmont and demonstrate that today's configuration is the result of tectonism that spanned a significant portion of the Paleozoic Era and not merely the Ordovician.

In addition to monazite geochronology, detrital zircon analysis has also been important in reshaping our understanding of the bedrock geology and the provided key evidence in support of defining a new lithodeme in the lower Paleozoic metasedimentary rocks. Bosbyshell et al. (2014) cite differences in detrital zircon provenance, geochemistry of interlayered amphibolite, and metamorphic history between units that have historically been considered part of the Wissahickon Formation. They proposed a new lithodeme, the West Grove Metamorphic Suite (WGMS), for the portion of the Wissahickon formerly known informally as the "Glenarm Wissahickon." Detrital zircon results (Bosbyshell et al., 2014; 2015) further reveal that the Wissahickon Formation, *sensu stricto*, likely received sediment from a Gondwanan source in addition to a Laurentian (Grenville-aged) source. The Chester Park Gneiss, which outcrops along the Coastal Plain onlap (Fig. 1), contains relatively few Grenville-aged detrital zircon and

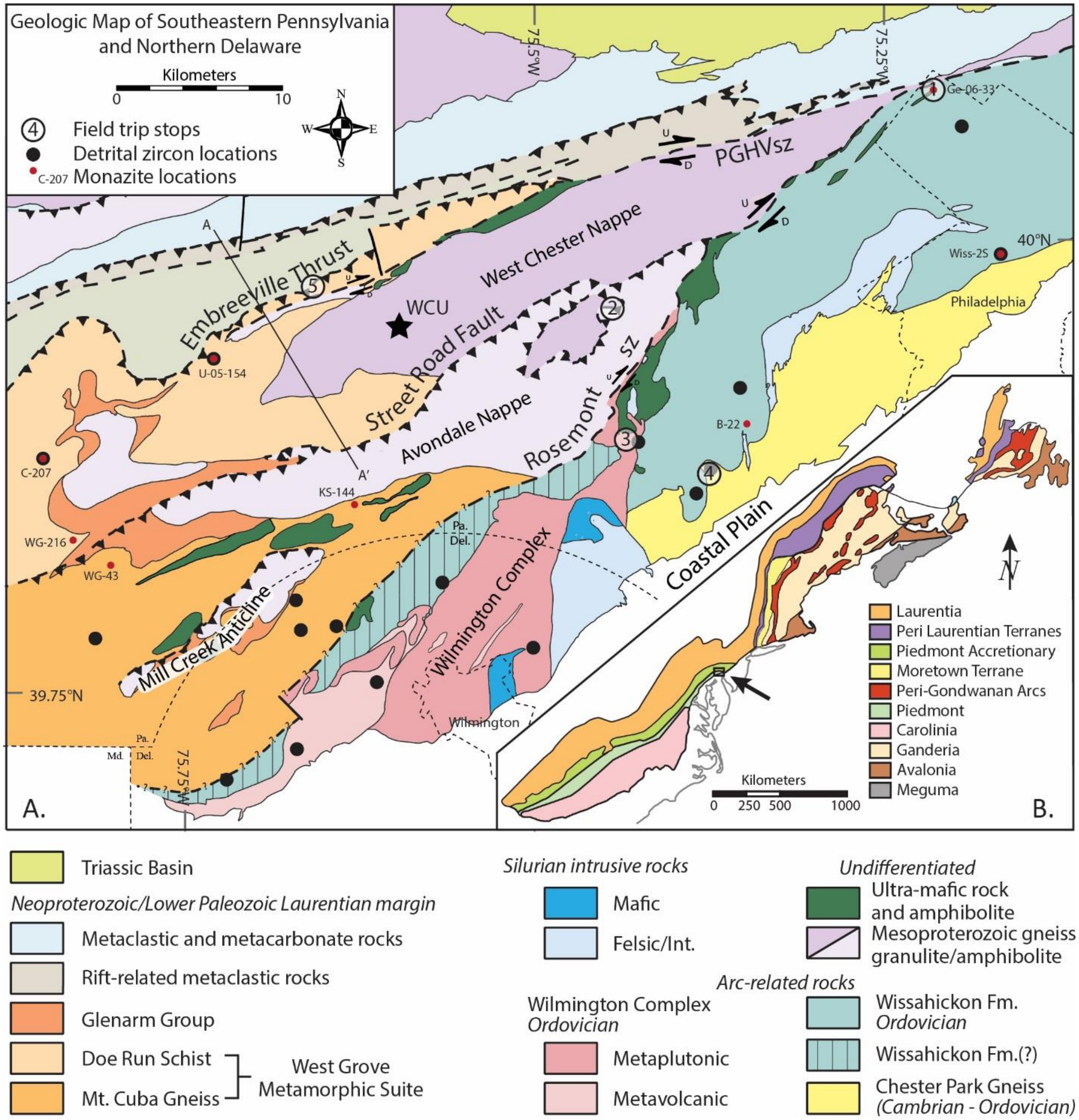


**Figure 1.** (a) Geologic map of southeastern Pennsylvania and northern Delaware, modified after Blackmer (2005) and Schenck et al. (2000). PGHVsz = Pleasant Grove and Huntingdon Valley shear zone. Cross-section A-A' is shown in Figure 2. (b) Map of Appalachian orogen after Hibbard et al. (2006) as modified by Macdonald et al. (2014), arrow indicates location of map (A).

was apparently deposited in a basin adjacent to a Gondwanan terrane. This unit may be correlative with, or is possibly a fragment of, the Moretown Terrane (Macdonald et al., 2014) in New England.

## GEOLOGIC SETTING

The bedrock geology of southeastern-most Pennsylvania and northern Delaware in the area of the field trip (Fig. 1) consists of two main lithotectonic elements: rocks of the Laurentian margin, including

Mesoproterozoic basement gneiss and a lower Paleozoic cover sequence, and an early Ordovician magmatic/volcanic arc and associated metasedimentary rocks, including the Wilmington Complex and Wissahickon Formation. Silurian-aged intrusive rocks are present in the arc terrane, but are not found in the Laurentian rocks. The Rosemont Shear Zone (RSZ) is the boundary between arc rocks and the Laurentia margin.

**Laurentian margin rocks**

Rocks of the Laurentian margin include the Mesoproterozic-aged Baltimore Gneiss, which occurs in the West Chester nappe, the Avondale nappe, the Woodville dome and the Mill Creek anticline, and cover rocks including the Glenarm Group and West Grove Metamorphic Suite (Fig. 1). The basement gneiss is among the least studied rock in the Appalachian orogen. Granulite facies metamorphism in the West Chester gneiss was investigated by Wagner and Crawford (1975) and Wagner and Srogi (1987). Limited geochronologic data for the gneiss (Grauert et al., 1973, 1974) is consistent with the Mesoproterozoic age obtained from zircon results in Baltimore gneiss domes (Aleinikoff et al., 2004). An age of 1075 +/- 9 Ma was from zircon in the Woodville Dome (John Aleinikoff, unpublished data). Zircon results for gneiss of the Avondale massif (Grauert et al., 1974) are quite discordant and indicate a large component of Paleozoic zircon growth.

The lower Paleozoic cover sequence which unconformably overlies the gneiss consists of the Glenarm Group: the Setters Formation and Cockeysville Marble; and the recently named West Grove Metamorphic Suite (WGMS) (Bosbyshell et al., 2014). The WGMS consists of rock historically known as Wissahickon Formation (Bascom, 1902, 1905; Bascom et al., 1909). Named for exposures along Wissahickon Creek in Philadelphia, Pennsylvania, the Wissahickon Formation once extended throughout the mid-Atlantic Piedmont, from New Jersey into Virginia (a full discussion of the evolution of Wissahickon nomenclature is given by Schenck, 1997). Differences between the Wissahickon Formation east of the Rosemont Shear Zone, including the type locality in Philadelphia, and the metasedimentary gneiss and schist 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). The informal nomenclature associated with lithologic units within the terranes evolved, but the name "Wissahickon" was retained for rocks in both terranes (e.g. Blackmer 2005). Bosbyshell et al. (2014) outlined differences in the detrital zircon populations, geochemistry of interlayered amphibolite, and metamorphic history between the western and eastern rocks and proposed the WGMS, to encompass amphibolites and metasedimentary rock west of the RSZ and above the Glenarm Group.

The West Grove Metamorphic Suite consists of rock formerly mapped as "Glenarm Wissahickon" (Blackmer 2004a, 2004b, 2005) and includes metasedimentary rock of the Mt. Cuba Gneiss, Doe Run Schist, and Laurels Schist as well as metavolcanic rock of the White Clay Creek Amphibolite and Kennett Square Amphibolite (Smith and Barnes, 1994, 2004; Plank et al., 2001). Detrital zircon results, discussed further below, suggest that the depositional age of the WGMS is most likely early to middle Cambrian.

Mt. Cuba Gneiss consists of interlayered pelitic gneiss and pelitic schist. Small bodies of granitic pegmatite appear to be locally-derived products of partial melting. 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 Delaware (Plank et al., 2000; Schenck et al., 2000) uses the older formal nomenclature and the unit is shown as Wissahickon Formation.

Doe Run Schist is silvery to dark gray pelitic schist dominated by medium-grained muscovite giving the rock a spangled appearance. Locally, quartz and feldspar content is sufficient to make the rock psammitic. The Doe Run Schist is in the hanging wall of the Embreeville Thrust (Fig. 1), 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.

The geochemistry of amphibolites in the WGMS, the White Clay Creek Amphibolite (WCCA) and Kennett Square Amphibolite (KSA), resemble modern basalt. Smith and Barnes (2004) suggest that the WCCA resembles continental initial rift basalt and correlate the WCCA with the Catoctin metabasalt. The KSA is very similar to modern mid-ocean ridge basalt (MORB) (Smith and Barnes, 1996, 2004; Plank et al., 2001). The cover sequence including the Glenarm Group and WGMS is interpreted to have been deposited along the rifting Laurentian margin in the latest Neoproterozoic to Cambrian (Blackmer 2004c, 2005; Bosbyshell et al., 2014).

## Arc-related rocks: the Wilmington Complex and Wissahickon Formation

The Wilmington Complex has been studied for well over a hundred years (Chester, 1890; Bascom et al., 1909), and was defined by Ward (1959) to include the igneous and metamorphic rocks across northern Delaware from Cecil County, Maryland, to Chester, Pennsylvania. Detailed geologic mapping (Plank et al., 2000; Schenck et al., 2000), geochemical analyses of mafic units (Plank et al., 2001), and ages determined by Sensitive High-Resolution Ion Microprobe (SHRIMP) U-Pb isotopic analysis of zircons from felsic gneisses (Aleinikoff et al., 2006), were used to re-define the lithodemic units of the Wilmington Complex and constrain the age and tectonic affinity. Geochemically, metavolcanic and metaplutonic units resemble modern subduction related igneous rock (Plank et al., 2001). Zircon result demonstrate that they are early Ordovician in age, 475 to 485 Ma; the relatively undeformed Arden pluton is Silurian, 434 ±5 Ma (Aleinikoff et al., 2006).

The Wissahickon Formation consists of fine- to coarse-grained pelitic schist interlayered with psammitic granofels and quartzite. Pelitic schist is composed of quartz, plagioclase, biotite, muscovite, garnet, and local sillimanite, kyanite, and/or staurolite. Psammitic layers are composed of quartz, plagioclase, biotite, and muscovite with rare garnet. Also present are thin layers of granofels, composed of plagioclase, quartz, hornblende and epidote, with or without garnet and/or dolomite. These may have originated as marl or other calcsilicate. This interlayered lithology alternates at the map scale with massive to layered, medium- to coarse-grained psammitic to semipelitic schist. Throughout the Wissahickon Formation, metasedimentary rock is interlayered with amphibolite, up to 20 m thick. The Wissahickon Formation contains detrital zircon as young as 475 Ma (Bosbyshell et al., 2012; 2014) and is host to the 427 ± 3 Ma Springfield granodiorite (Bosbyshell et al., 2005). Thus, the depositional age of the Wissahickon Formation is most likely middle to late Ordovician.

## Structural Geology

Here we present an overview of the deformation history of rocks. Different generations of foliation (S) and folding (F) are number sequentially, but these are not correlated across the Rosemont Shear Zone. A “W” or an “E” is appended to the subscript (e.g., $S_{2W}$) to indicate west (within the WGMS) or east (Wissahickon Formation) of the RMZ.

We adopt a structural framework that is based on relatively recent mapping by the Pennsylvania and Delaware geological surveys (Schenck et al., 2000; Blackmer, 2004a, 2004b, 2005; Wiswall, 2005;

Blackmer et al., 2010). To the west of the RSZ, the Embreeville Thrust (Fig. 1) is the lowest structure in a series of nappes composed of basement gneiss and metasedimentary cover. From structurally lowest to highest, these include the West Chester nappe, Avondale nappe, and Mill Creek (Hockessin-Yorklyn) anticline (Schenck et al., 2000). The dominant, $S_{2W}$, foliation in this area dips shallowly to moderately to the southeast (Blackmer 2004a, 2004b, Wiswall, 2005), and is axial planar to overturned to recumbent outcrop scale folds, which exhibit top to the northwest asymmetry (Alcock, 1994; Blackmer, 2004a). This foliation is also parallel to thrust-sense shear zones at the base of the nappes (Bosbyshell et al., 2006a). The $S_{2W}$ foliation, therefore, likely formed as a result of thrust emplacement. The $S_{2W}$ foliation is deformed by upright folds (Fig. 2), especially in the northwestern- and southeastern-most rocks (Alcock, 1994; Blackmer, 2004a; Wiswall, 2005). This upright folding is attributed to younger, transpressive deformation in the Pleasant Grove-Huntingdon Valley and Rosemont shear zones (Valentino et al., 1994, 1995).

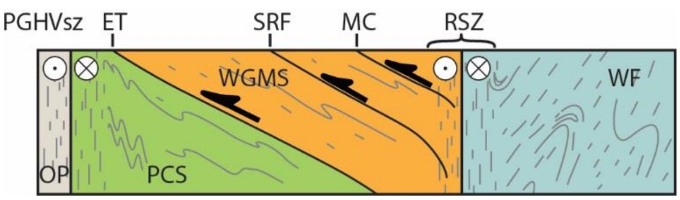


**Figure 2.** Schematic cross section of field trip area. PGHVsz = Pleasant Grove/Huntingdon Valley shear zone; ET = Embreeville Thrust; SRF = Street Road Fault; MC = base of Mill Creek nappe; OP = Octoraro Phyllite; PCS = Peters Creek Schist; WGMS = West Grove Metamorphic Suite; WF = Wissahickon Fm. Basement gneiss and Wilmington Complex not shown. Modified from Bosbyshell et al. (2016).

The nappes and associated southeast dipping fabrics are truncated to the southeast by the steeply dipping RSZ (Valentino et al., 1995; Bosbyshell 2005a, 2005b), the western boundary of the arc terrane, which includes the Wilmington Complex, Wissahickon Formation, and Chester Park gneiss (Figs. 1,2). Detailed structural analyses in the Wissahickon Formation (Amenta, 1974; Tearpock and Bischke, 1980; Bosbyshell 2001, 2008) describe similar deformational histories, involving five recognizable stages. Different generations of structures are preserved to varying degrees at the map or even outcrop scale, depending on local metamorphic history (Amenta, 1974; Bosbyshell, 2001). The oldest deformation is recognized as an early foliation present in the hinges of $S_{2E}$ folds and as transposed $F_{1E}$ hinges rarely preserved within the $S_{2E}$ schistosity. The regional schistosity, the $S_{2E}$ foliation, is axial planar to $F_{2E}$ isoclinal folds and generally dips moderately to steeply to the northwest. $S_{2E}$ and $F_{2E}$ folds are in turn folded by $F_{3E}$, close to tight, upright to recumbent folds associated with a variably developed sub-vertical to moderately northwest-dipping axial planar foliation. $S_{4W}$ fabrics are associated with the RSZ and cross cut $F_{3E}$ folds (Amenta, 1974; Bosbyshell, 2001). The youngest ductile fabrics include sub-horizontal crenulation ($S_{5E}$) and associated outcrop scale open folds which are variably developed throughout the area (Amenta, 1974; Tearpock and Bischke, 1980; Valentino and Gates, 2001; Bosbyshell, 2008).

Gneissic fabrics in metaigneous rock of the Wilmington Complex are sub-vertical to steeply northwest dipping along the northwest margin of the Complex, approaching the RSZ, and dip moderately to the northwest elsewhere (Schenck et al., 2000). The pattern is similar to that in the Wissahickon

A note on terminology: Nappe is a structural geology term equivalent to thrust sheet. Historically, the West Chester and Avondale nappes have also been referred to as massifs. Here we use the term massif to refer to the body of gneiss within the thrust sheet. Massif has many definitions, but usually refers in some way to a fault-bounded mountain. The gneissic lithologies in the Piedmont tend to be more resistant to weathering than metasedimentary cover rocks and tend underlie higher elevations, hence our usage (though clearly they are not mountains!).

Formation to the northeast of the Wilmington Complex and contrasts with the shallow to moderate southeast dips in rocks to the northwest throughout the WGMS.

## COMPARISON OF WEST GROVE METAMORPHIC SUITE AND WISSAHICKON FORMATION

Bosbyshell et al. (2014) provide a detailed comparison of the WGMS and Wissahickon Formation in support of separating the WGMS as a distinct unit. They describe distinct differences in detrital zircon population, amphibolite geochemistry, and metamorphic pressure-temperature-deformation-time (P-T-D-t) paths between these units. The P-T-D-t histories are further detailed by Bosbyshell et al. (2016). These differences are summarized below.

### Detrital zircon geochronology

The results of recent detrital zircon analysis (Bosbyshell et al., 2012, 2014, 2015) demonstrate significant differences in the source regions for metasedimentary rocks of the WGMS and 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. 3). Doe Run samples contain Archean zircon, which is absent in the Mt. Cuba. The youngest zircon in the Doe Run Schist 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 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. 3). Two samples from the Wissahickon Formation, including one from a location intruded by arc-related magmatic rock near the contact with the Wilmington Complex, contain sizable populations of zircon with late Neoproterozoic ages which likely indicate a Gondwanan source. Most other Wissahickon samples, including those in a belt along the western side of the Wilmington Complex, yield zircon of this age although it is much less abundant. A meta-volcaniclastic unit adjacent to the Wilmington Complex also contains a small number of zircon grains of this age. 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.

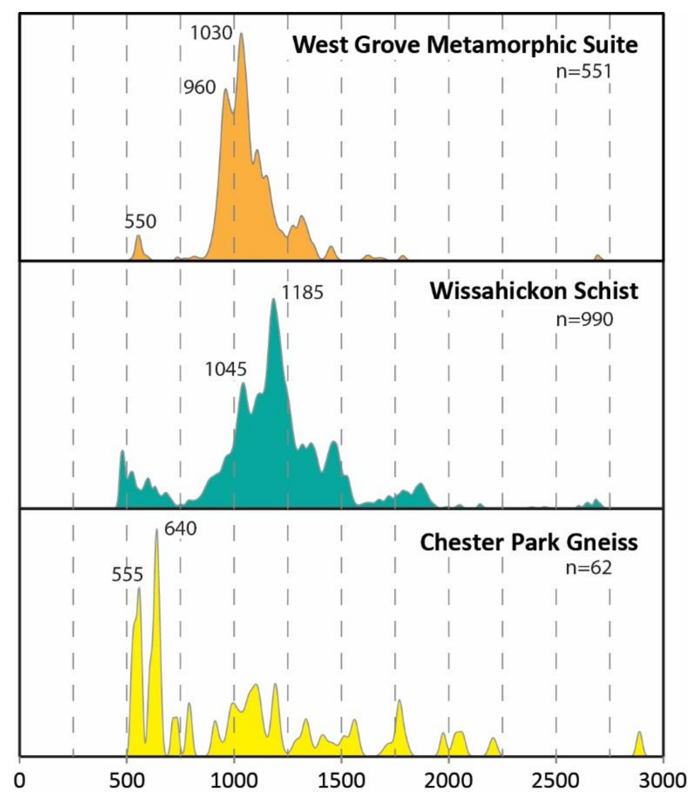


**Figure 3.** Detrital zircon results. The Wissahickon Schist results include the Windy Hills Gneiss (Aleinikoff et al., 2006), a volcanic clastic unit along the western margin of the Wilmington Complex, and two additional metaclastic samples within the Wilmington Complex. Note that the Chester Park Gneiss results from a single sample.

The detrital zircon population of the Chester Park Gneiss is dominated by

Neoproterozoic ages (peaks at 555 Ma and 640 Ma), that are likely derived from a peri-Gondwanan source, and a small number of grains of Mesoproterozoic, Paleoproterozoic and Archean age. Voluminous Neoproterozoic arc magmatism of is well known in peri-Gondwanan terranes (Nance et al., 2008) and similar detrital zircon signatures are present in sedimentary and metasedimentary rocks derived from these terranes in New England (Macdonald et al., 2014; Connard et al., 2015) and the Canadian maritime provinces (Fyffe et al., 2009). The Chester Park gneiss detrital zircon population is very similar to that of the Moretown terrane in New England (Macdonald et al., 2014).

Cawood et al. (2012) examined the detrital zircon signature of rocks deposited in different tectonic settings. They suggest that in rocks deposited in an extensional tectonic environment, the age of fewer than five percent of detrital zircons is within 150 Ma of the depositional age of the rock (cumulative probability curves will pass below the blue star in Fig. 4). In contrast, rocks deposited in a convergent tectonic setting contain a significant proportion of zircon grains (>30%) with ages within 100 million years of the depositional age of the rock (curves pass to the left of the red star). A "collisional" setting is inferred for rocks between these endmembers. Following this analysis (Fig. 4), an extensional depositional environment is inferred for the West Grove Metamorphic Suite, while Wissahickon Schist samples plot mainly in the collisional field with two samples nearly meeting the convergent criteria. The Chester Park Gneiss was likely deposited in a convergent tectonic setting.

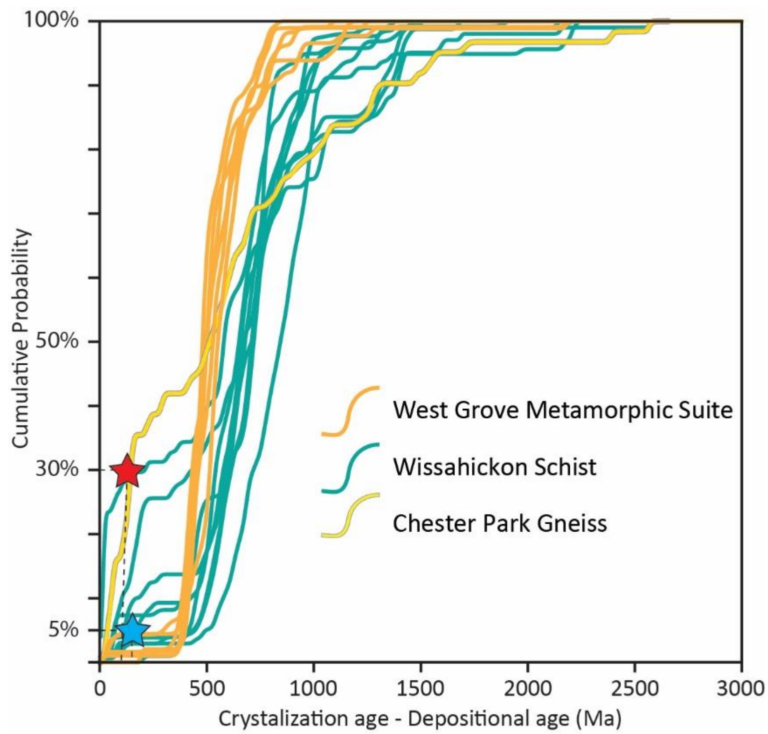


**Figure 4.** Cumulative probability plot of the difference between zircon crystallization ages and the depositional age of study area samples, after Cawood et al. (2012). The plot was prepared using estimated depositional ages of 520 Ma for the WGMS, 500 Ma for the Chester Park Gneiss and 480 Ma (or the age of the youngest zircon, whichever is younger) for the Wissahickon.

**Amphibolite geochemistry**

The West Grove Metamorphic Suite includes the Kennett Square Amphibolite (KSA) and White Clay Creek Amphibolite (WCCA). 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 as map-scale bodies up to 10 km long in a belt along the southern portion of the Avondale nappe (Fig. 1). 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).

The White Clay Creek Amphibolite is interlayered within the Mt. Cuba Gneiss and less commonly within Doe Run Schist (Blackmer, 2004b). WCCA is characterized by high total Fe, moderate to high TiO2, and high overall REE abundances. The REE patterns are characteristic of within-plate basalts from either a continental or oceanic setting. 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 in different geographic areas and possibly stratigraphic position (Bosbyshell, 2001; Bosbyshell et al., 2014, 2015). These amphibolites are described in detail by Bosbyshell et al. (2105). 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 (Stop 3). The Bridgewater Amphibolite is found 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.

The Confluence Dikes are nearly identical to mafic layers in the Rockford Park Gneiss of the Wilmington Complex (Bosbyshell et al., 2015), 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; Bloomer, 1987; Stern et al., 1991). 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 diameter) 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. The Smedley Park Amphibolite occurs in layers thicker greater than 20 m in many locations (Bosbyshell, 2001, 2004). Geochemically the Smedley Park Amphibolite is very similar to modern back-arc basin basalt (Bosbyshell et al., 2015).

**Pressure-temperature 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 (Plank, 1989; Alcock and Wagner, 1995; Bosbyshell et al., 2016). The Doe Run contains evidence for an older period of metamorphism and widely-dispersed, locally-intense retrograde overprinting by hydrous fluids (Moore, 2007), that are absent from the Mt. Cuba.

The older period of metamorphism in the Doe Run Schist is present as an early fabric defined by aligned sillimanite preserved in microlithons within the dominant foliation. This fabric may be late Ordovician based on monazite core ages of ~450 Ma (Bosbyshell et al., 2016), but no direct textural evidence links the monazite cores to older fabrics. The dominant foliation, $S_{2W}$, wraps around garnet and staurolite porphyroblasts, but staurolite also occurs parallel to this foliation. In several instances staurolite is rimmed by fine sillimanite and small euhedral garnet which cross-cut foliation. These observations suggest that peak metamorphic conditions in the Doe Run Schist exceeded the high-T stability limit of staurolite and that peak temperatures were attained subsequent to formation of $S_{2w}$ foliation. Bosbyshell et al. (2016) utilized 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 (Fig. 5). Infiltration of hydrous fluids caused variable retrogression of higher-temperature assemblages, ranging from partial rimming and replacement of porphyroblasts by fine-grained muscovite or chlorite to complete

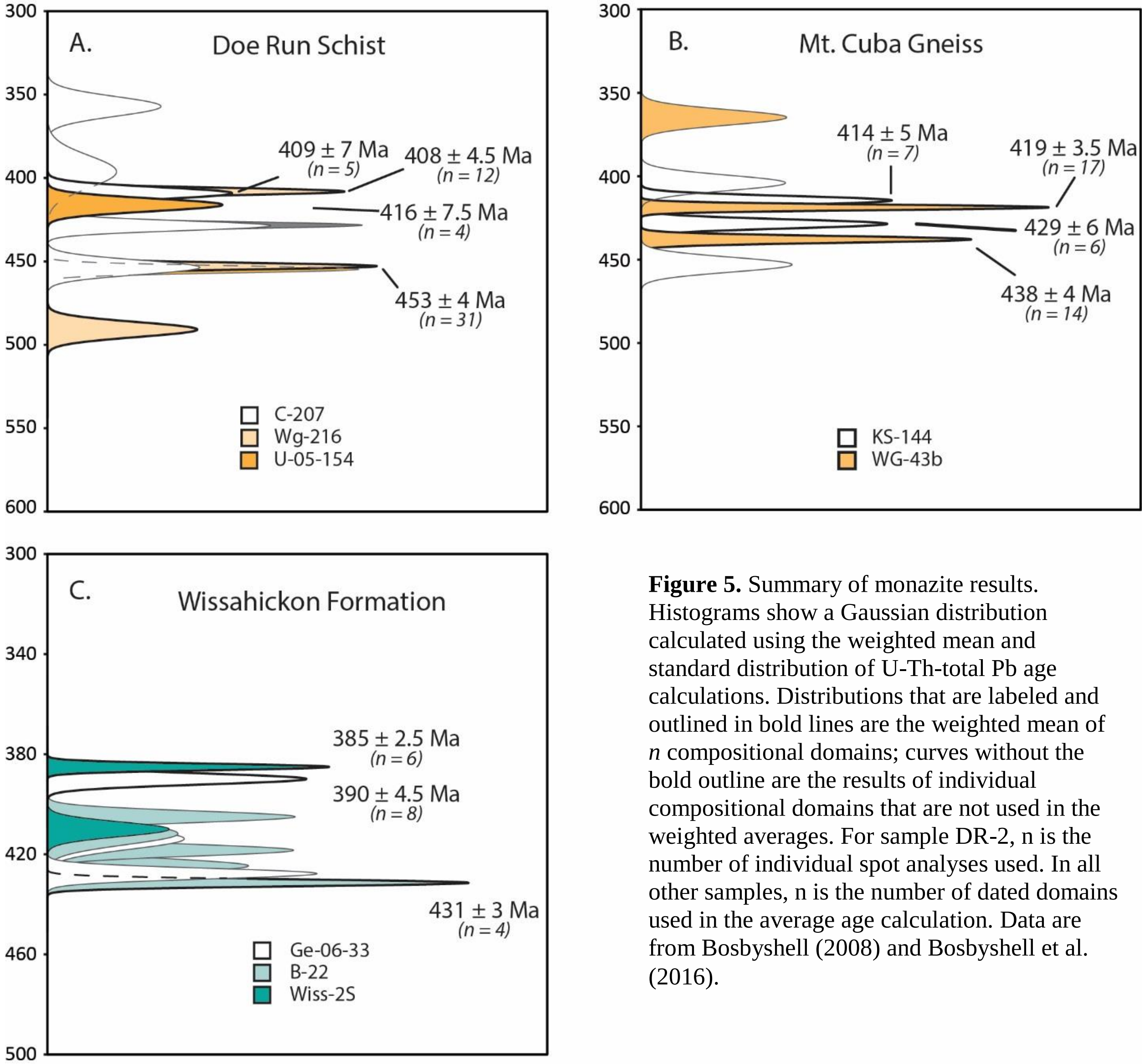


**Figure 5.** Summary of monazite results. Histograms show a Gaussian distribution calculated using the weighted mean and standard distribution of U-Th-total Pb age calculations. Distributions that are labeled and outlined in bold lines are the weighted mean of *n* compositional domains; curves without the bold outline are the results of individual compositional domains that are not used in the weighted averages. For sample DR-2, n is the number of individual spot analyses used. In all other samples, n is the number of dated domains used in the average age calculation. Data are from Bosbyshell (2008) and Bosbyshell et al. (2016).

replacement and recrystallization of foliated matrix biotite by mimetic chlorite. Retrograde metamorphism is most common near the Embreeville Fault (Moore et al., 2007).

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; Bosbyshell et al., 2016). 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 $S_{2w}$ 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); an age of 415 Ma for monazite inclusions in staurolite from the Avondale nappe provide a maximum age for peak metamorphism there (Fig. 5). Alcock (1989) describes evidence for higher pressure metamorphism following peak temperature in the Mt. Cuba, inferred to reflect crustal thickening following thrust stacking.

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 present only near Silurian intrusions and the Barrovian-style moderate pressure metamorphism evident there reflects the second period of metamorphism (Bosbyshell et al., 2016). Monazite ages (Bosbyshell, 2001; Pyle et al., 2006; Bosbyshell, 2008; Bosbyshell et al., 2016) constrain the early metamorphism to the Silurian (~430 Ma) and the high-pressure overprint to the Devonian (~390 Ma) (Fig. 5). Metamorphism in the Wissahickon Formation is further described below (Stop 1.5).

**TECTONIC IMPLICATIONS**

Tectonism in the field trip area has long been interpreted to be the result of the Taconic Orogeny: the Ordovician collision between a peri-Laurentian volcanic/magmatic arc and the Laurentian margin (Wagner and Srogi, 1987; Aleinikoff et al., 2006; Wise and Ganis, 2009; Sinha et al., 2012). Constraints on the timing of metamorphism described above require revision of this model. Bosbyshell et al. (2016) propose that Silurian to earliest Devonian metamorphism in the WGMS is the result of the accretion of a peri-Gondwana terrane, Ganderia (Fig. 6) in the dominantly sinistral transpressive tectonic regime thought to be present at that time (Hibbard, 2000; Hibbard et al., 2007; 2010). Hibbard et al. (2007) suggest that the New York promontory acted as a restraining bend in this transpressive setting and was

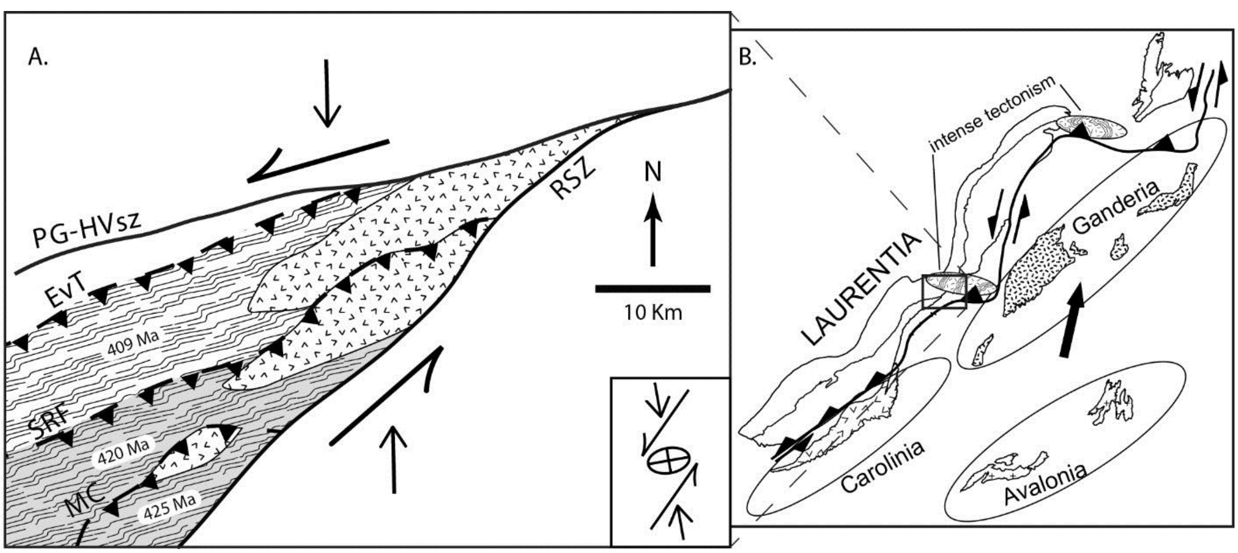


**Figure 6.** Schematic geologic map illustrating that the geometry thrust sheets in relation to the vertical shear zones is consistent with a sinistral transpressive regime. The age of metamorphism, with peak temperatures attained in the structurally lowest block subsequent to those in higher sheets, is interpreted to be the result of successive stacking of thrust sheets from southeast to northwest with the warmer overriding sheets contributing to the thermal budget of lower sheets. (b) Plate tectonic reconstruction for the Silurian modified from Hibbard et al. (2007) illustrating approach of Ganderia in sinistral transpression. Rectangle shows possible location of deformation shown in A. PGHVsz = Pleasant Grove and Huntingdon Valley shear zone; EvT = Embreeville Thrust; SRF = Street Road Fault; MC = unnamed fault below Mill Creek anticline; RSZ = Rosemont shear zone. From Bosbyshell et al. 2016.

the site of intense tectonism at this time. Bosbyshell et al note that in the Mill Creek anticline, the structurally highest nappe, peak metamorphism is older (425 Ma) than in the lower Avondale nappe (415 Ma). In turn, metamorphism in rock at the lowest structural level, the Doe Run Schist in the West Chester nappe, is even younger (409 Ma). They interpret this sequence to represent successive stacking of thrust sheets from southeast to northwest (present geography) with the warmer overriding sheets contributing to heating of the lower sheets. They suggest that the geometry of the thrust slices containing the Doe Run Schist and Mt. Cuba gneiss in relation to the steeply dipping shear Pleasant Grove-Huntingdon Valley shear zone is consistent with the sinistral restraining bend proposed by Hibbard et al. (2007).

The middle Devonian age of monazite suggests that metamorphism in the Wissahickon Formation is the result of crustal thickening during the Acadian orogeny, the accretion of Avalon in the northern Appalachians. Previously, the effects of the Acadian orogeny in southeastern Pennsylvania were the subject of reasoned inference (Amenta, 1974; Valentino et al., 1995) or were considered to be absent (Faill, 1997). Metamorphism of this age is well known in southern New England (Lanzirotti and Hanson, 1996; Robinson et al., 1998; Lancaster et al., 2008). 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 (e.g., Dennis, 2007; Hibbard and Waldron, 2009) Bosbyshell et al. (2015, 2016) proposed 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.

In the northern Appalachians, the Taconic Orogeny has also been modeled as the result of arc-continent collision involving a peri-Laurentian volcanic/magmatic arc (e.g. Stanley and Ratcliffe, 1985). Recent U-Pb detrital zircon geochronology (Macdonald et al., 2014) demonstrates that the Moretown terrane, upon which the bulk of the Taconic Shelburne Falls arc (Karabinos et al., 1998) is built, is Gondwana-derived. In a reevaluation of the Taconic orogeny, Macdonald et al. (2014) suggest that the Moretown terrane was the first of several rifted Gondwanan terranes – analogous to, but distinct from, Carolinia in the southern Appalachians and Ganderia in the northern Appalachians – to collide with the Laurentian margin. Metasedimentary rock structurally below the Moretown terrane, the Rowe belt, are Laurentian-derived, while rock above the Moretown, the Hawley belt (including the Cram Hill formation in Vermont), contains zircon from both Laurentian and Gondwanan sources (MacDonald et al., 2014; Connard et al., 2015) and is also host to arc-related metaplutonic and metavolcanic rocks (Kim and Jacobi, 1996).

There are many similarities between the rocks described here and arc-related rocks in New England. In the central Appalachian Piedmont, the Wilmington Complex at 476 to 483 Ma (Aleinikoff et al., 2006) is the same age as the Shelburne Falls arc, where the main magmatic pulse is 475 Ma (MacDonald et al., 2014). The Wissahickon Formation, like the Hawley belt in New England, is host to boninitic amphibolites (Kim and Jacobi, 1996); geochemical characteristics of the Smedley Park amphibolite are very similar to the Group IV, BABB-like amphibolite of Kim and Jacobi (1996). Detrital zircon age spectra of the Wissahickon Formation have similar peaks to the Hawley belt, including Gondwanan peaks (Connard et al., 2015) and Grenville-aged peaks that are distinctly different from those in adjacent Laurentian rift-related metasediments (the WGMS in the Central Appalachians, the Rowe belt in New England). The distinct lithological character of the Chester Park gneiss is very similar to the "pinstripe" granofels of the Moretown terrane (MacDonald et al., 2014). The detrital zircon age spectra obtained from the Chester Park gneiss is very similar to the Moretown terrane. As in the Moretown Terrane, deformed tonalitic rock is present in the Chester Park gneiss.

Bosbyshell et al. (2015) proposed that the arc-related rocks described above may have originally been part of the Taconic arc in New England that were translated by strike-slip deformation to their present location. In the Piedmont, middle to late Paleozoic transpressive deformation with a significant strike-slip component is associated with the Pleasant Grove – Huntingdon Valley shear zone (PGHV) (Valentino et al. 1994, 1995) and the RSZ (Valentino et al., 1995; Bosbyshell, 2001). As much as 150 km of dextral displacement has been proposed for the PGHV, based in part on similarities between rock in Manhattan, N.Y. and Baltimore, Md. (Valentino et al. 1994). A Devonian age (384 ± 6 Ma) was determined for syn-tectonic monazite in the RSZ (Bosbyshell, 2001) and fabrics related to deformation in the RSZ crosscut Devonian-aged (390 ± 4.5 Ma) mineral assemblages at stop one (Bosbyshell et al., 2016). These results suggest that deformation in the Rosemont is associated with the Acadian orogeny. Final emplacement is likely the result of younger movement in the PGHV shear which was active into the Pennsylvanian-Permian Alleghenian orogeny (Valentino and Gates, 2001; Blackmer et al., 2007).

## FIELD TRIP OVERVIEW

This year's trip visits five locations which highlight recent research and new insights into the tectonic evolution of rock underlying Philadelphia, Delaware and Chester counties of southeastern Pennsylvania. At stop one we will examine the Wissahickon Schist, associated ultramafic rocks and highly sheared rock at the margin of the West Chester massif. Detrital zircon data reveal that the Wissahickon Formation may be derived in part from sediment eroded from a peri-Gondwanan terrane (Bosbyshell et al., 2015). The main period of metamorphism is now known to be Devonian (~390 Ma) in age (Bosbyshell et al., 2016). Kerrigan et al. (this volume) suggest that the ultramafic rock is most likely a differentiate derived from an arc-related magma system, supporting the inference that the depositional setting of the Wissahickon Formation is a basin adjacent to a volcanic arc. Stop two will afford us the opportunity to view Laurentian basement gneiss of the Avondale nappe. Recent research here has focused on an outcrop along the eastern edge of the nappe, adjacent to the Rosemont Shear Zone, which contains evidence for possible ultra-high temperature or pressure metamorphism (Trice et al., 2014; Noble et al., 2015). The Wilmington Complex, the remains of a volcanic/magmatic arc that formed along the Laurentian margin in the Ordovician will be seen at stop three before visiting the Chester Park Gneiss at stop four. Detrital zircon from this unit reveals that the sediment source is peri-Gondwanan (Bosbyshell et al., 2015) and that these rocks may be correlative with, or even a fragment of, the Moretown Terrane in New England (MacDonald et al., 2104). At stop five, we return to the West Chester area and Laurentia. Here we will view the Doe Run Schist and Laurels Schist, which are part of the early Paleozoic metasedimentary cover sequence, formerly known as "Glenarm Wissahickon," now the West Grove Metamorphic Suite (Bosbyshell et al., 2014).

## ROAD LOG

The trip departs from M-lot, West Chester University.

| *Mileage* | *Cum. mileage* | *Description* |
|---|---|---|
| 0.0 | 0.0 | Exit M-lot and turn right onto S. Matlack St. |
| 0.6 | 0.6 | Turn left at light onto US-202 N |
| 17.1 | 17.1 | Follow signs for I-76 E |
| 18.6 | 18.6 | Merge on I-76 (Schuylkill Expressway) |
| 22.2 | 22.2 | Take exit 331B to merge onto I-476N (toward Plymouth Meeting) |
| 25.0 | 25.0 | Take exit 18A toward Conshohocken |
| 25.4 | 25.4 | Merge onto Ridge Pike |
| 29.1 | 29.1 | Turn left onto Bells Mill Rd. (after Northwestern Ave and Ayrdale Rd) |
| 30.0 | 30.1 | Parking lot on right. |

## STOP ONE: BELLS MILL ROAD ULTRAMAFIC BODY AND WISSAHICKON SCHIST

This stop is within Wissahickon Valley Park, a 1,800 acre park in Philadelphia, PA that follows Wissahickon Creek approximately 1 km north of this location and 10 km south to the confluence of Wissahickon Creek and the Schuylkill River. The area offers excellent exposure of the Wissahickon Schist and Bells Mill Road ultramafic body. Exposures along Wissahickon Creek comprise the type section of the Wissahickon Formation, first described by Bascom (1905). Crawford (1987) provides details of the traverse from just north of our present location south to the mouth of Wissahickon Creek.

The walking/biking path along Wissahickon Creek, known as "Forbidden Drive (Fig. 7)," offers several outcrops that characterize that lithologies present within the ultramafic body and Wissahickon Schist. This stop is an excellent location for teaching exercises in igneous and metamorphic petrology due to the presence of the ultramafic body surrounded by the Wissahickon Schist and a small quarry within a granodioritic body where tectonized contacts with schist are visible. The northern most exposures along the creek provide a view of Mesoproterozoic gneiss which exhibits a mylonitic texture, evidence of intense deformation in the Rosemont Shear Zone (RSZ).

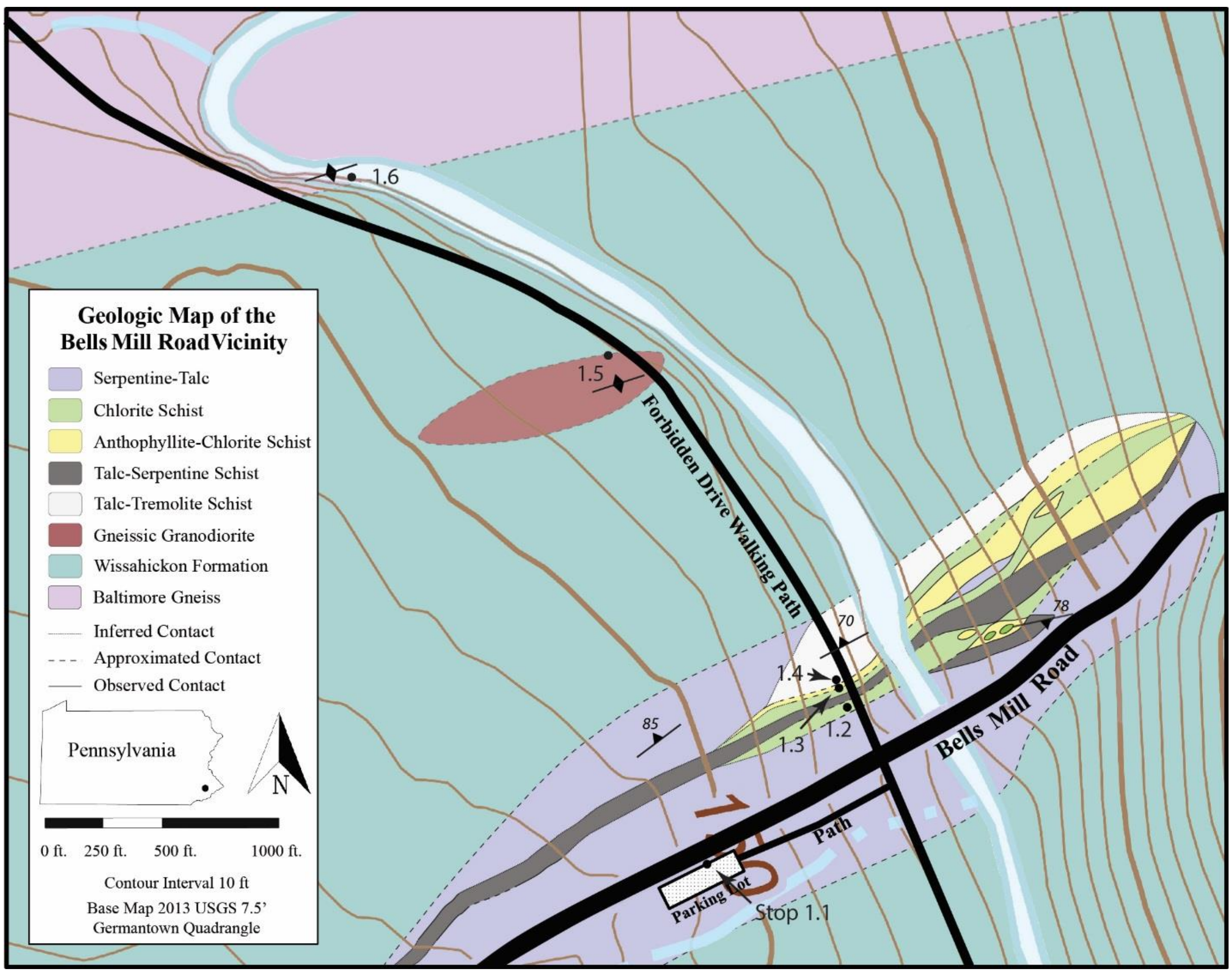


**Figure 7:** Geologic map of the Bells Mill Road ultramafic body showing the field trip stops. The lithologic zones of alteration are defined as: serpentine-talc, talc-tremolite, anthophyllite-chlorite schist, chlorite schist, and talc-serpentine schist (modified after Simboli et al., 2017)

**STOP 1.1 - Serpentine Talc Rock**

In the parking lot there is a large boulder of a serpentine-talc rock observed which encompasses the majority of the ultramafic body. The serpentine-talc rock is the largest of all lithologic units exposed at the Bells Mill Road ultramafic body. The rock has oblong, sub-rounded inclusions of serpentine surrounded by a talc-anthophyllite-magnesite matrix. The rock is matrix-supported and throughout the rock there are scattered oxides, mostly magnetite and chromite.

Walking from STOP 1.1 to STOP 1.2 follow a path leading from the parking lot to the main walking path of the Wissahickon Valley Park, Forbidden Drive. Along the short path from the parking lot there are numerous boulders scattered on the side of the path which show some of the diversity of the serpentine-talc rock. Some inclusions can reach up to 10 cm in diameter. Further discussion of the petrology and geochemistry each of these lithologies is contained in the accompanying paper in this volume.

**STOP 1.2 - Chlorite Schist**

Walking approximately 20 meters northwest from Bells Mill Road along the walking path, Forbidden Drive, there is an outcrop of the chlorite schist. The chlorite schist at this location is approximately 20 meters thick. The rock is dominated by chlorite (~90%) with scattered talc, anthophyllite, tremolite, magnesite, and magnetite. The northwestern end of the unit exhibit abundant magnetite up to 1 cm in diameter and some with nice octahedral crystal habit. Within this unit there are locations where the density of magnetites is so high that Brunton compasses are often thrown out of alignment by the magnetic pull of the minerals.

**STOP 1.3 - Anthophyllite-Chlorite Schist**

Approximately 20 meters northwest from STOP 1.2 there is an outcrop of the anthophyllite-chlorite schist. The anthophyllite-chlorite schist at this location is approximately 5 meters thick. Point counting analysis of the anthophyllite-chlorite schist reveals approximately 42% anthophyllite, 34% chlorite, 17% talc, 5% orthopyroxene, 1% magnesite, and 1% opaques. The orthopyroxene are observable only in thin section and may be relic from the protolith. Anthophyllite exhibits a bladed to acicular texture sometimes radially orientated.

**STOP 1.4 - Talc-Tremolite Schist**

Approximately 20 meters northwest from STOP 1.3 along the walking path, there is an outcrop of the talc-tremolite schist. The talc-tremolite schist at this location is approximately 20 meters thick and appears to pinch-out to the southwest and increase in width to the northeast. The rock is massive and mainly talc (~49%) with tremolite (27%), anthophyllite (15%), serpentine (6%) and orthopyroxene (3%). On fresh surfaces stringers of tremolite are visible helping to define the foliation. The outcrop is dense rock with wavy foliation.

Continue north along the trail, examining outcrops of Wissahickon Schist. A small abandoned quarry is found approximately 500 meters north of STOP 1.4.

**STOP 1.5 - Small quarry exposing granodioritic gneiss and Wissahickon Schist**

In an investigation of metamorphism along the entire Wissahickon Creek transect, Bosbyshell et al. (2007; 2016) prepared x-ray composition maps of garnet from 12 samples. With the exception of one sample, from this quarry at the contact with the granodiorite, all garnet along the transect shows relatively simple zoning indicative of prograde metamorphism. Garnet from this outcrop exhibits distinct small very low-Ca, high-Mn cores indicative of two stages of metamorphism (Fig. 8). Pelitic schist here contains the

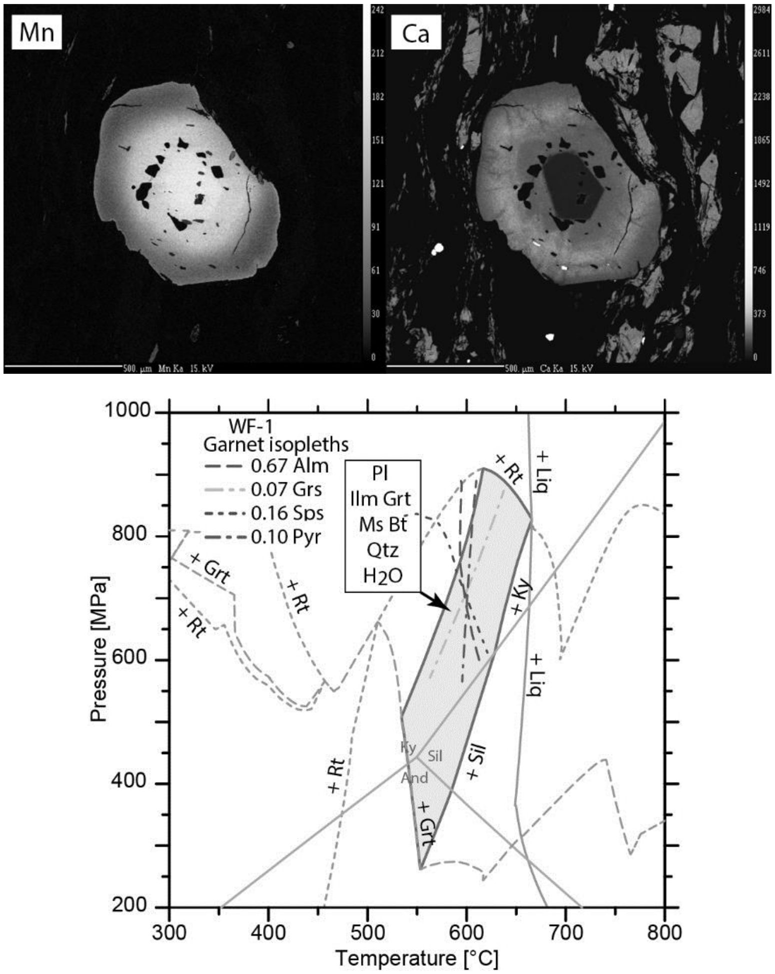


**Figure 8.** (a) X-ray composition maps of garnet from Stop 1.5, note well defined high-Mn, low-Ca core, which we infer is the result of contact metamorphism at the time of granodiorite intrusion. (b) Estimated metamorphic conditions calculated with outer garnet composition using Theriak-Domino (de Capitani and Petrakakis, 2010). From Bosbyshell et al. (2016)

assemblage muscovite + biotite + garnet + quartz + plagioclase + ilmenite with minor staurolite and kyanite. Bosbyshell et al. (2016) estimated metamorphic conditions of approximately 600°C and 700 MPa based on garnet isopleth thermobarometry calculated with Theriak-Domino (de Capitani and Petrakakis, 2010).

Bosbyshell et al. (2016) report EPMA U-Th-total Pb results of monazite from this location. The age of metamorphism, based on analysis of eight monazite grains, is 390 ± 4.5 Ma (Fig. 5). Devonian monazite ages have been reported in the Wissahickon Formation from the sillimanite zone in Philadelphia (Bosbyshell, 2008) and in rock along strike approximately 15 km to the southwest (Bosbyshell, 2001). Slightly discordant Devonian monazite ages from a nearby sample and from the sillimanite zone downstream were previously obtained using thermal ionization mass spectrometry (TIMS) (Bosbyshell et al., 1998). The age of the igneous protolith of the granodioritic gneiss here is unknown, but a larger intrusion of similar composition, the Springfield granodiorite (Fig. 1), yielded a U-Pb zircon age of 427 ± 3 Ma (Bosbyshell et al., 2005). One monazite grain in the Bosbyshell et al. (2016) study contained a core which yielded an indistinguishable age of 428 ± 4.5 Ma. They suggest that the monazite core and the small low-Ca garnet core likely formed during a period of contact metamorphism related to the granodiorite intrusion.

Nearest the Wilmington Complex (stop two), rock of the Wissahickon Formation contains Silurian-aged, high-T low-P mineral assemblages, with Devonian kyanite-bearing assemblages present only in shear zones, where fluids likely facilitated metamorphic recrystallization (Bosbyshell et al., 1999; Bosbyshell, 2001; Pyle et al., 2006). Bosbyshell et al. (1999) describe a metamorphic gradient in the early assemblage – from west to east over a distance of less than 10 km, sillimanite + k-feldspar assemblages give way to sillimanite + muscovite and andalusite-bearing assemblages. The younger kyanite overprinting becomes pervasive as the grade of the early metamorphism decreases. Here, and along the remainder of Wissahickon Creek, the early metamorphism is found only in rock adjacent to intrusions. Thus, the early metamorphic gradient identified by Bosbyshell et al. (1999) continues to the east. This suggests that the Wissahickon Formation in the type section is higher and relatively younger than the deeper and likely older portion of the Wissahickon Formation that is exposed near the Wilmington Complex.

Continue walking north along Forbidden Drive. Descend to creek level approximately 150 meters northwest of STOP 1.5 to examine outcrops in the bank of Wissahickon Creek.

**STOP 1.6 – Mesomylonite in the Rosemont Shear Zone**

The term mylonite is used for rock that has experienced a high degree of dynamic recrystallization in a ductile fault or shear zone, resulting in significant grain size reduction. The rock here is mesomylonite, so named because the grain size reduced matrix comprises 50 to 90% of the rock (if a rock consists of >90% matrix it is termed ultramylonite). The highly foliated rock in this outcrop consists of plagioclase feldspar, epidote, clinozoisite, and possibly alkali feldspar porphyroclasts which range from 0.25 – 0.5 mm diameter. Pyroxene porphyroclasts are also present in very low abundance. These are largely replaced by amphibole and epidote and can be as large as 1mm. The matrix consists of micron to tens of microns scale grains of plagioclase, biotite, quartz and epidote. Quartz also occurs as mm-scale polycrystalline ribbons. Texturally late epidote, which overgrows mylonitic foliation is also present. The presence of pre-, syn- and post-tectonic epidote suggests that deformation occurred under conditions corresponding to the epidote-amphibolite metamorphic facies, similar to, or at slightly lower temperature than, the conditions estimated for Devonian metamorphism in the nearby Wissahickon Formation. Fabrics in schist indicate that shear zone deformation occurred subsequent to the growth of garnet and staurolite porphyroblasts.

Return to vans and proceed to stop two.

| *Mileage* | *Cum. mileage* | *Description* |
|---|---|---|
| 0.0 | 30.1 | Exit the parking lot turning left on Bells Mill Rd. |
| 1.1 | 31.2 | Turn right onto Ridge Ave. |
| 3.8 | 33.9 | Slight right onto I-476 S access ramp |
| 4.0 | 34.1 | Merge on I-476 S |
| 13.8 | 43.9 | Take exit 9 to merge onto PA-3 W |
| 20.5 | 50.6 | Turn left onto N. Sandy Flash Dr. (<0.5 mi from Providence Rd.) |
| 21.4 | 51.5 | Turn right into parking lot of Colonial Plantation |

**STOP TWO: THE AVONDALE MASSIF IN RIDLEY CREEK STATE PARK.**

Most of the land which is now Ridley Creek State Park was the former site of the estate of Walter Morrison Jeffords, Sr., a Philadelphia businessman and prominent Thoroughbred racehorse owner and breeder in the first half of the twentieth century. The park encompasses some 2600 acres and is underlain by gneiss that has historically been mapped as the Mesoproterozoic Baltimore Gneiss of the Avondale nappe (Bascom et al., 1909), although mapping and preliminary geochronology cast doubt on this association (Bosbyshell et al., 2006b). Recent research (Trice et al., 2014; Noble et al., 2015) has focused on an outcrop some two miles east of our present location, along Bishop Hollow Road near the eastern entrance to the park, where a unit informally referred to as the Sycamore Mills formation is exposed (Fig. 9). However, given the small size of the outcrop, parking considerations, and the number of participants on this trip, we will view gneiss of the Avondale massif here, near the Colonial Plantation.

On the east side of the park, the Bishop Hollow Road outcrop exposes a rare pelitic lithology in the Avondale massif, informally designated the Sycamore Mills formation. The presence of garnet with crystallographically oriented inclusions of rutile needles (Trice et al., 2014; Noble et al., 2015) makes this

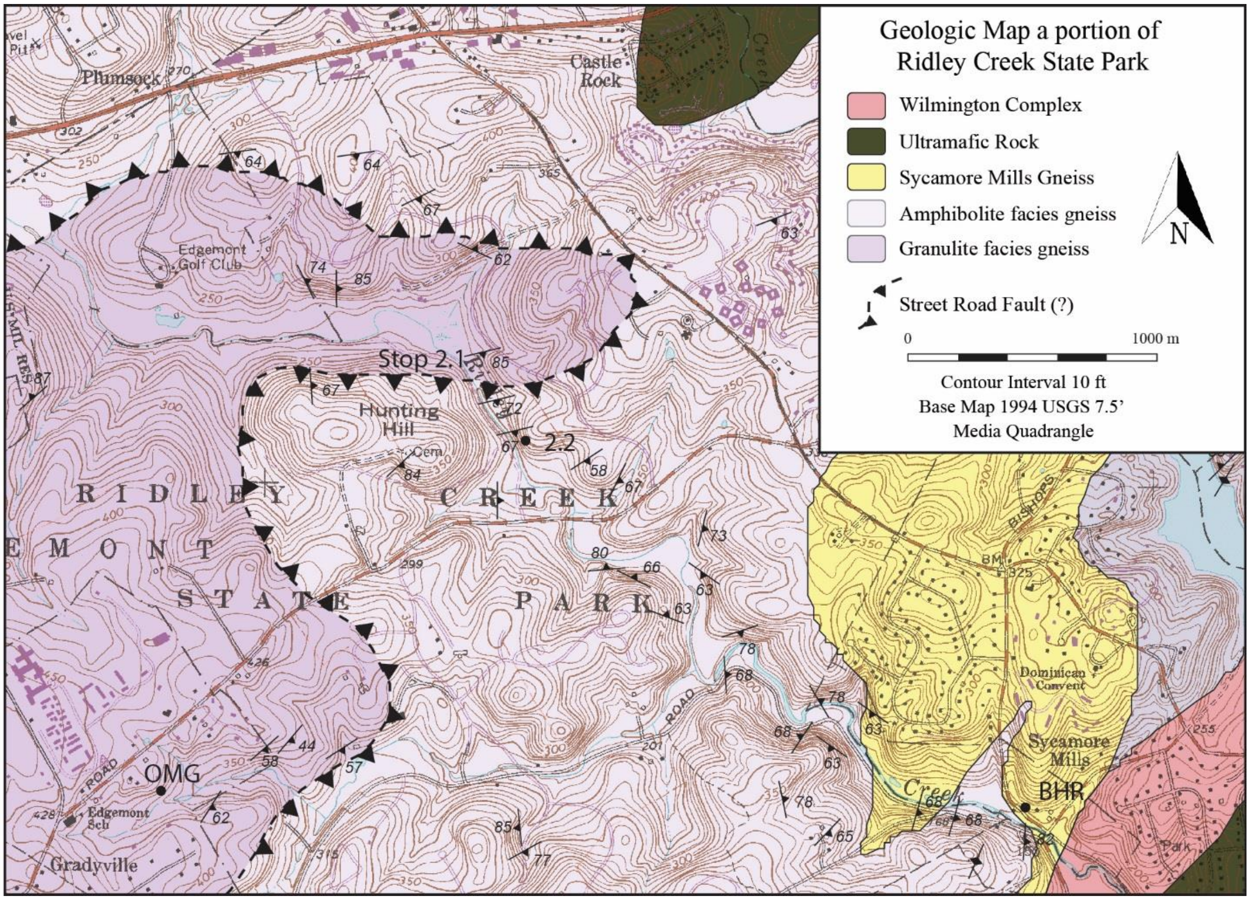


**Figure 9**. Geologic map of a portion of Ridley Creek State Park and the surrounding area, showing locations of Stops 2.1 and 2.2, Bishop Hollow Road (BHR) and olivine metagabbro (OMG) outcrops described in text.

rock especially interesting. The oriented rutile is possibly indicative of ultrahigh-temperature (UHT) and/or ultrahigh-pressure (UHP) metamorphism (e.g., Ague and Eckert, 2012). The rock is medium- to coarse-grained migmatitic gneiss composed of the middle to upper amphibolite facies assemblage garnet + biotite + sillimanite + quartz + plagioclase + alkali feldspar with accessory ilmenite. In addition to rutile needles, garnet cores contain inclusions of kyanite and coarsely exsolved antiperthitic plagioclase feldspar. An equilibrium assemblage diagram calculated using Theriak-Domino (de Capitani and Petrakakis, 2010) indicates minimum pressure of approximately 1100 MPa (or burial to a depth of ~35 km) for kyanite + rutile bearing assemblages. Using the Tomkins et al. (2007) calibration of the Zr in rutile thermometer, Trice et al. (2014) estimated metamorphic temperatures of 775 °C at this pressure. Noble et al. (2015) reintegrated the composition of antiperthitic plagioclase inclusions and estimated temperatures in excess of 1000 °C.

Outer portions of garnet also contain quartz inclusions which are surrounded and separated from garnet by plagioclase-$Al_2SiO_5$ intergrowths (Fig. 10). This texture suggests that plagioclase formed from garnet, indicating rapid decompression from this depth while still at high temperature (Whitney, 1991). The age of the early high T, high P metamorphism remains poorly constrained, but rapid decompression in the Sycamore Mills formation likely took place in the early Devonian (Bosbyshell, unpublished data). These plagioclase coronas against garnet contrast markedly with textures in the granulite facies rocks at Stop 1.2, described below, which are indicative of crustal thickening, or tectonic burial of the rocks.

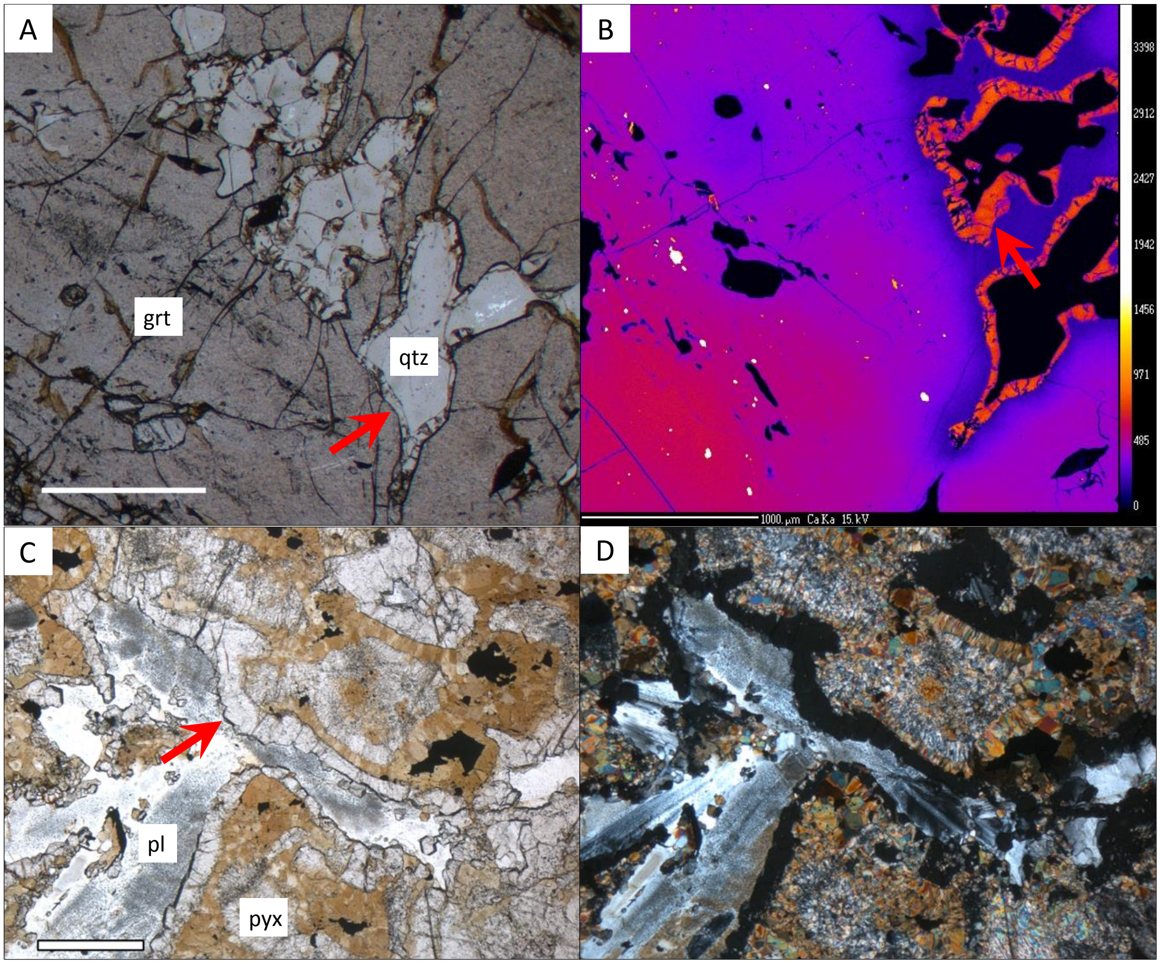


**Figure 10.** Textures in rocks of the Avondale massif indicating opposite P-T histories – but the time of their formation is unknown. A. Garnet (grt) from the Bishop Hollow Rd. outcrop (BHR, Fig. 9) in which quartz inclusions exhibit plagioclase coronas (arrow) against garnet, indicative of high temperature decompression. Fine inclusions in the garnet core are rutile. B. Ca-x-ray of garnet in C showing plagioclase coronas (orange). The highest-Ca inclusions (white spots) are apatite. C and D (crossed polarizers). Olivine metagabbro from the granulite zone (OMG, Fig. 9) exhibiting garnet coronas (arrow) on plagioclase (pl) against complex amphibole coronas on pyroxene (pyx), indicating an increase in pressure during metamorphism. Scale bars in A and C are 0.5 mm.

Walk down the trail to an outcrop approximately 10 m north of the trail.

## Stop 2.1 – Granulite facies gneiss – a window through the Street Road Fault?

The rocks here are heterogeneous, massive to moderately foliated and lineated, medium to coarse grained, granulite facies gneiss. Felsic to intermediate compositions predominate in the Avondale massif, but cm- to m-thick mafic layers and larger metagabbro bodies are present (although not at Stop 2.1). Gneissic fabric is defined by cm- to m-scale compositional layering; some felsic rocks are characterized by lineated fabric defined by aligned mafic minerals and 2-5 cm quartz ribbons. These rocks are composed of plagioclase, quartz, orthopyroxene, clinopyroxene, garnet, hornblende and biotite. Coronas of garnet and amphibole or clinopyroxene are present between plagioclase and orthopyroxene in all granulites examined. Metagabbro is medium grained with a sub-ophitic texture and consists of olivine, orthopyroxene, clinopyroxene, and plagioclase. As in the granulite gneiss, garnet coronas are present between pyroxene and plagioclase. Massive to lineated amphibolite grade gneiss consisting of plagioclase, hornblende, garnet, and quartz is also present locally. These rocks are similar to the eastern granulites in the West Chester massif, described by Wagner and Crawford (1975) and are interpreted to be Proterozoic in age, though the metagabbro is clearly younger than the host gneiss.

Granulite facies gneiss in the Avondale massif contains evidence for two periods of metamorphism: an older high temperature episode, which produced the granulite facies assemblages; and a younger metamorphic episode that resulted in the formation of garnet coronas and complete re-equilibration to amphibolite facies assemblages in some rocks. Olivine metagabbro retains undeformed igneous subophitic textures, but does exhibit evidence for the second metamorphism in the form of garnet coronas. Coronal textures in granulite facies rocks have been interpreted to be the product of a single prograde metamorphic episode in some areas (Harley, 1989), including metagabbro in the Adirondack highlands, a Grenville gneiss terrane (Whitney and McLelland, 1973). However, the relationships described above are identical to those involving diabase dikes and host granulite gneiss of the West Chester massif previously described by Wagner and Crawford (1975) and Wagner and Srogi (1987). The authors reasoned that because cross-cutting, undeformed diabase dikes exhibit coronal textures, metamorphism of the diabase must be younger than that in rocks which are crosscut, and that coronal textures in granulite gneiss also formed during this younger, post-Grenville, metamorphic episode. Like the diabase dikes in the West Chester massif, gabbro likely intruded sometime subsequent to granulite facies metamorphism but prior to amphibolite facies metamorphic overprinting.

Garnet coronas likely formed by reactions of the general form:

orthopyroxene + anorthite → garnet + clinopyroxene + quartz (1)

or if fluid is present:

orthopyroxene + anorthite + $H_2O$ → garnet + amphibole (2).

Reaction (1) has a positive slope in pressure-temperature space (Green and Ringwood, 1976), with the garnet-bearing assemblage on the higher pressure, lower temperature side of the curve. The position and slope of reaction (2) depends on lithostatic pressure and on $pH_2O$ (Essene et al., 1970), so the significance of reaction (2) is difficult to assess without additional data. Wagner and Srogi (1987) estimated that corona formation in the West Chester massif reflected metamorphic conditions of ~650 – 700 °C at pressures of 9 – 11 kb.

While most of the rock in the West Chester massif is at the granulite facies, granulite facies gneiss is only present within a relatively small area of the Avondale massif (Figs. 1, 9). The distinct lithologic difference between the granulite facies gneiss, as seen here at Stop 2.1, and amphibolite facies gneiss throughout the remainder of the Avondale massif (Stop 2.2) led Bosbyshell et al. (2006a) to propose that the area of granulite facies rock is actually gneiss of the West Chester massif exposed in a window through the Street Road Fault.

**Stop 2.2. Folded amphibolite facies gneiss.**

Follow the trail along Ridley Creek until you come to a large boulder at the edge of the stream. Take a narrow trail up into the woods to an outcrop of folded amphibolite facies gneiss. The rock consists of hornblende, plagioclase, biotite and quartz. If the speculation of Bosbyshell et al. (2006a) is correct, we have crossed the Street Road Fault. The outcrop illustrates the complexity of folding in the Avondale massif. An outcrop-scale synformal hinge is visible on the uphill end of the exposure; this is likely a second generation fold. On the long side of the exposure up-right folds which arch the older synform are evident.

Return to buses, proceed to Pavilion 14 for lunch.

| *Mileage* | *Cum. mileage* | *Description* |
|---|---|---|
| 0.0 | 51.5 | Exit Colonial Plantation parking lot and turn right on Sandy Flash Dr. |
| 1.1 | 52.6 | Turn right onto Gradyville Rd. |
| 1.8 | 53.3 | Turn left into the main entrance to the park, Sandy Flash Dr. |
| 3.3 | 54.8 | Turn left into parking area of Pavilion 14 |

**Lunch.** After lunch, return to buses and proceed to Stop 3.

| *Mileage* | *Cum. mileage* | *Description* |
|---|---|---|
| 0.0 | 54.8 | Exit parking lot and turn right on Sandy Flash Dr. |
| 1.5 | 56.3 | Exit park turning left on Gradyville Rd. |
| 2.8 | 57.6 | Turn left at light onto PA-352 S/Middletown Rd. |
| 5.3 | 60.1 | Turn right onto PA-452 S/Pennell Rd. |
| 7.1 | 61.9 | Turn left onto Mount Rd., Stop 3, Novotni Bros., is on left |

## STOP THREE: CONFLUENCE GNEISS AT NOVOTNI BROTHERS PAVING COMPANY

This stop (Fig. 11) examines an old quarry in the Confluence Gneiss, a unit that is part of the Wilmington Complex. The Confluence Gneiss is heterogeneous gneiss, consisting of hornblende plagioclase quartz biotite granofels, interlayered mafic, felsic, and intermediate orthogneiss, and several large amphibolite bodies (Bosbyshell, 2001). This unit is contiguous with the Brandywine Blue gneiss of the Wilmington Complex (Schenck et al., 2000), but shares many characteristics with the Rockford Park Gneiss (also part of the Wilmington Complex), including the scale of layering and the boninitic affinity of some mafic rocks. Zircon in this unit yielded an age of 476 ± 4 Ma (Bosbyshell et al., 2015), identical to zircon ages of the Brandywine Blue Gneiss (476 ± 6 Ma), Rockford Park Gneiss (476 ± 4 Ma) (Aleinikoff et al., 2006) and Springton Tonalite (476 ± 4 Ma), which crops out along the trend of the Rosemont Fault approximately 7 km from Stop 3 (Bosbyshell et al., 2006b).

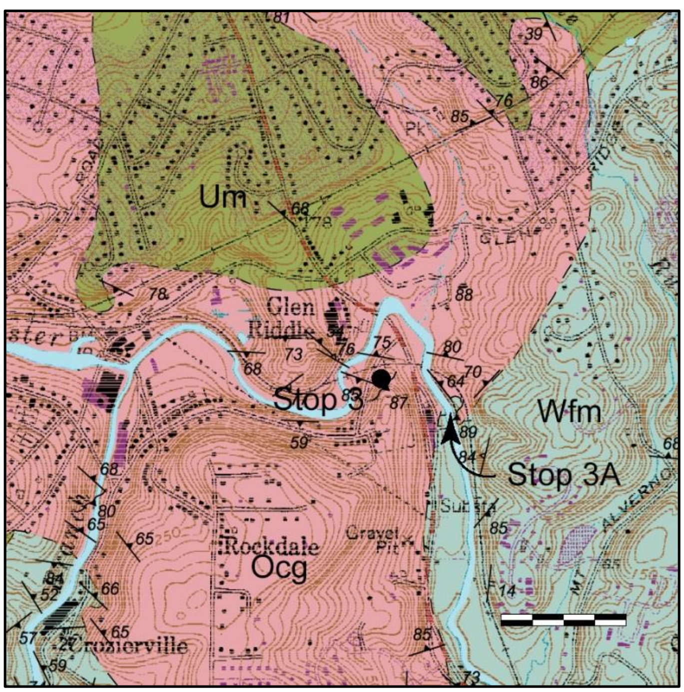


**Figure 11.** Geologic map of a portion of the southern Media quadrangle showing location of Stop 3. Contact between Wilmington Complex (Ocg = Confluence gneiss) and Wissahickon Fm. is exposed at Stop 3A. Scale bar is 400 m.

Geochemically, the Confluence Gneiss is similar to modern volcanic arc rocks. Intermediate gneiss resembles andesite or the intrusive equivalents, diorite, tonalite or granodiorite. Mafic layers are basaltic, and some are geochemically similar to modern boninites, rocks that occur almost exclusively in fore arcs. Boninitic amphibolite layers are also present in the Wissahickon Formation, at the contact with the Confluence Gneiss in an outcrop approximately 400m from the

Novotni Brothers quarry on the opposite side of Chester Creek. These boninitic amphibolites are collectively referred to as the Confluence Dikes.

Unlike much of the Wilmington Complex, which experienced granulite facies metamorphism, the Confluence Gneiss contains mineral assemblages characteristic of the amphibolite facies: hornblende + plagioclase ± quartz ± biotite ± garnet ± epidote. Orthopyroxene is present in some rocks to the west of Stop 3 in outcrops along the West Branch of Chester Creek, suggesting that granulite facies conditions were achieved at least locally in the Confluence Gneiss. Three zircon grains with equant morphology, indicative of a metamorphic rather than magmatic origin, yielded an age of 427 ± 7 Ma (Bosbyshell et al., 2015), indistinguishable from zircon and monazite ages from other Wilmington Complex rocks (~428 Ma; Aleinikoff et al., 2006).

Multiple episodes of deformation are evident here. A large synform is visible on the NE-SW trending quarry face (parallel to Mount Rd.). This fold and the many related minor folds deform an older metamorphic foliation and so are part of at least the second episode of deformation to have affected these rocks. The dominant foliation here strikes approximately east-west and is parallel to the axial planes of these folds. Close inspection of the folds indicates that some degree of refolding has occurred, with the axial surface of the younger folds approximately parallel to that of the first. Whether this represents progressive deformation during a single deformation event or discreet deformation episodes cannot be determined. On the horizontal surface at the north end of the quarry wall doubly closed folds suggest sheath fold geometry.

Several shear zones, which cross cut the fold set and dominant foliation described above, are visible in the other quarry wall (Fig. 12), though recent mass wasting has significantly degraded the exposure. Many similar shear zones occur along the Rosemont Shear Zone. The shear zones are characterized by a moderately to steeply plunging lineation defined by aligned hornblende crystals and sheath fold axes. Folded foliation at shear zone margins and fabric asymmetry indicate east-side down motion with a dextral strike-slip component (Bosbyshell, 2001; Kellogg et al., 2001).

At first glance, the shear zones may appear to be brittle structures, due to intense weathering of the well-defined, planar, shear zone foliation. However, petrographic analysis of mylonitic shear zone rock reveals microstructures which are characteristic of deformation under amphibolite facies conditions. Similar shear zones in metapelitic rock contain kyanite, indicating that deformation was synchronous with Devonian moderate pressure metamorphism.

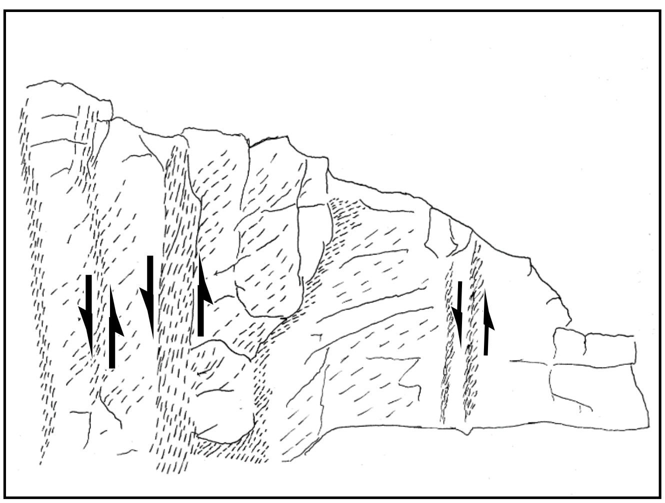

**Figure 12.** Sketch of shear zones in northeast facing quarry wall before recent mass wasting (Kellogg *et al.*, 2001).

As mentioned above, the contact between the Confluence Gneiss and the Wissahickon Formation, where boninitic layers/dikes are present in both units, is exposed just across Chester Creek, approximately 400m from the Novotni Brothers facility (Stop 3A in Fig.11). Unfortunately, these outcrops cannot accommodate a group of this size, so we will not visit them. The location is described in detail in the 2004 Field Conference of Pennsylvania Geologists guidebook (http://fcopg.org/wp-content/uploads/2014/06/69th2004.pdf) and more recently by Bosbyshell et al. (2015), in a guidebook prepared for the Geological Society of American Annual Meeting in Baltimore, Md. If you have interest in visiting these exposures please note it is private property; obtain permission from King's Mill banquet facility before visiting.

Return to buses.

| *Mileage* | *Cum. mileage* | *Description* |
|---|---|---|
| 0.0 | 61.9 | Turn left onto PA-452 N |
| 0.2 | 62.1 | Turn right onto Glen Riddle Rd. |
| 1.6 | 63.5 | Turn right at light onto PA-352 S/Middletown Rd. |
| 4.3 | 66.2 | Turn left onto E Brookhaven Rd. |
| 4.6 | 66.5 | Turn right onto Waterville Rd. |
| 5.2 | 67.1 | Waterville Rd. becomes Chestnut Parkway |
| 5.3 | 67.2 | Turn right onto Chester Park Drive |

## STOP FOUR: CHESTER PARK GNEISS IN CHESTER PARK: A PERI-GONDWANAN TERRANE?

Chester Park, one of the oldest municipal parks in Delaware County, is owned and maintained by Chester City. It consists of 71 acres along the banks of Ridley Creek. The rock exposed in Chester Park is medium to coarse grained, quartzo-feldspathic biotite gneiss and schist designated the Chester Park Gneiss. New detrital zircon results (Fig. 3) from a sample at this location (Fig. 13) indicate that the Chester Park Gneiss is derived from a Gondwanan source, the first exposure of peri-Gondwanan rock to be recognized in this portion of the Appalachian orogen.

Some portions of the Chester Park Gneiss are sufficiently micaceous to be called schist. Garnet, fibrolitic sillimanite, replaced by kyanite blades at some locations, and cordierite, replaced to varying degrees by intergrowths of pale-green low-Ti biotite with either kyanite or sillimanite (Crawford and Mark, 1982; Bosbyshell et al., 2005), are also present in more aluminous domains. Accessory minerals include Fe-Ti oxides, apatite, monazite, and zircon. Alkali feldspar is present only in pegmatite pods and lenses. This lithology can be mapped from southern Darby Creek, where it is host rock to the Springfield granodiorite, south to Marcus Hook Creek, where it hosts the Arden pluton. It may be equivalent to the Fairmont member of the Wissahickon Formation in Philadelphia (Bosbyshell, 2008). Portions of the Chester Park Gneiss were originally mapped by Bascom et al., (1909) in the Philadelphia Folio as both Granitic Gneiss and Wissahickon Gneiss. Bascom et al.'s (1909) contacts were incorporated into the 1960 geologic map of Pennsylvania, but on the most recent state map (Berg et al., 1980) the area of granitic gneiss decreased and portions were mapped as gneiss of the Wilmington Complex.

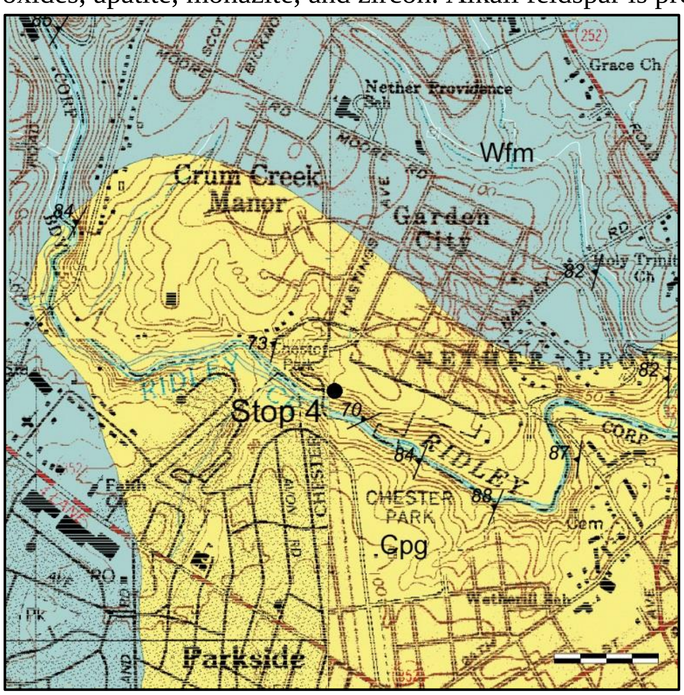


**Figure 13.** Geologic map of Stop 4, junction of Media, Bridgeport, Marcus Hook and Lansdowne 7.5 min quadrangles. Scale bar = 400m.

A sedimentary protolith is inferred for much of the Chester Park gneiss, based the quartz rich nature of some rock, the aluminous character of other rock and the rounded, detrital morphology of zircon grains (Bosbyshell et al., 2008). Compositional layering is present at some locations, but is generally not well developed. Other rock may have an igneous protolith. This rock frequently has a massive appearance and contains irregularly shaped and elongate, biotite-rich enclaves (xenoliths?), that vary in size from a few centimeters to several meters long, suggesting a possible intrusive igneous origin.

| *Mileage* | *Cum. mileage* | *Description* |
|---|---|---|
| 0.0 | 67.2 | Turn left onto Chestnut Parkway/Waterville Rd. |
| 0.7 | 67.9 | Turn left onto Brookhaven Rd. |
| 1.0 | 68.2 | Turn right onto PA-352 N/Edgemont Ave. |
| 11.7 | 78.9 | Turn left onto PA-3 W/PA-352 N/West Chester Pike |
| 14.9 | 82.1 | Use the right lane to merge onto US-202 N/US-322 W |
| 15.7 | 82.9 | Take the US-322 W exit toward Downingtown |
| 18.6 | 85.8 | Turn right to stay on US-322 W |
| 20.9 | 88.1 | Turn left onto Sugars Bridge Rd. |
| | | Turn left onto Waltz Rd. |

### STOP FIVE: DOE RUN AND LAURELS SCHIST; EMBREEVILLE FAULT: INVERTED METAMORPHISM

At this stop (Fig. 14) we will view the Doe Run and Laurels Schist, two units in the West Grove Metamorphic Suite which, together with the Mt. Cuba Gneiss, were formerly known as the "Glenarm Wissahickon." This area is within a zone of very complex deformation (Fig. 15) involving the Pleasant Grove-Huntingdon Valley Shear Zone, the Embreeville Thrust and the Cream Valley Fault (Wiswall,

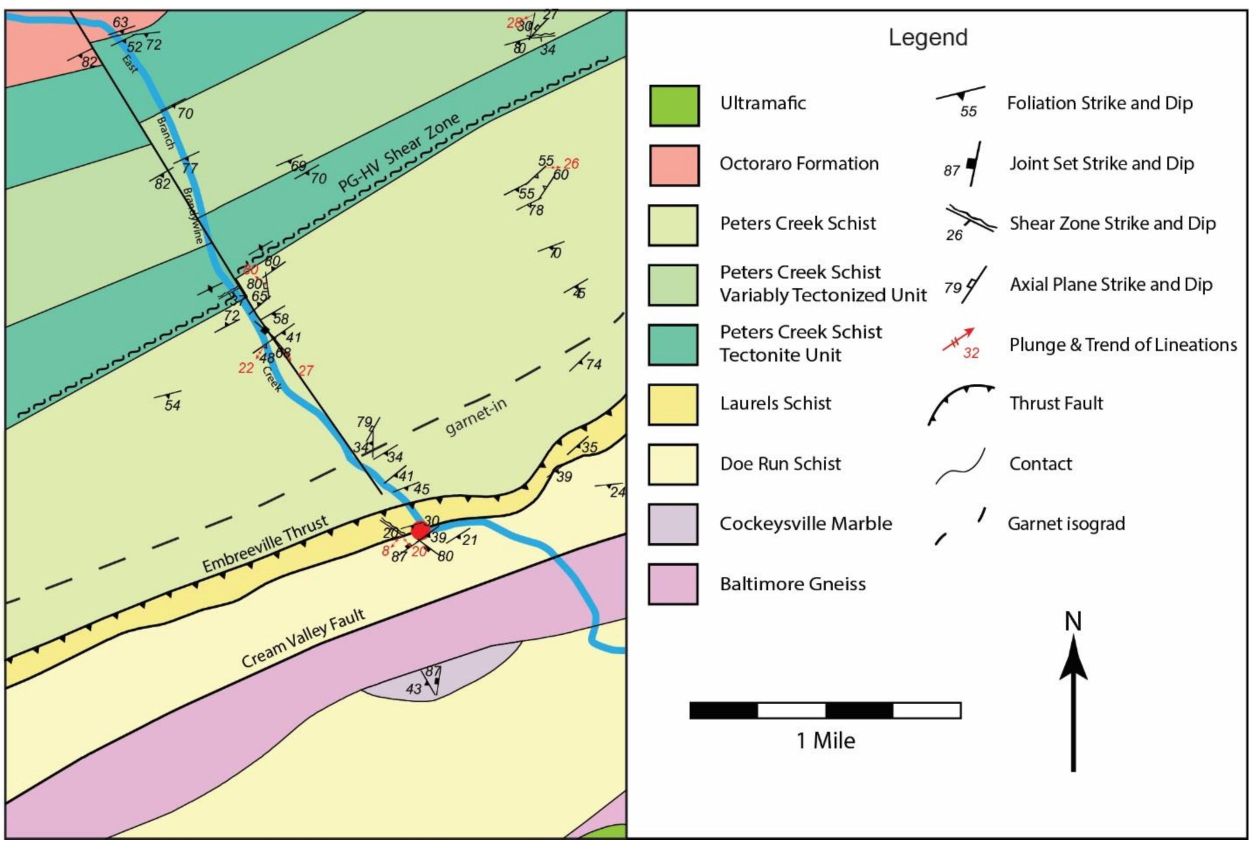


**Figure 14.** Geologic map of the vicinity of Stop 5 (red dot) modified from Wiswall (2005).

1990, 2005). Here the fabrics are an expression of the Embreeville Thrust, a ductile shear zone at the base of the West Chester nappe, which places amphibolite facies metamorphic rocks above rocks at the greenschist facies (Fig. 15).

Walk east to a small outcrop at the bend in Waltz Rd. This is the Doe Run Schist in the hanging wall of the Embreeville Thrust. The rock here contains garnet + biotite + muscovite + staurolite + quartz + plagioclase. The dominant foliation dips southeast.

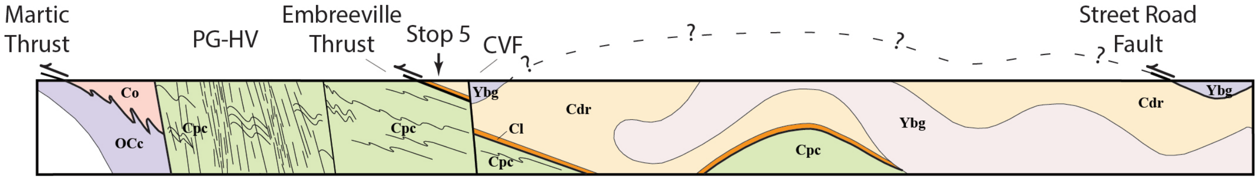


**Figure 15.** Cross-section of the Unionville 7.5 minute quadrangle modified from Wiswall (2005). PG-HV = Pleasant Grove-Huntingdon Valley shear zone, CVF = Cream Valley Fault. Section corresponds to A – A' in Figure 1; relative along-strike position of stop five is shown.

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. The complex fabric in these rocks is an S/C mylonite. Three distinct surfaces can be discerned: an S surface formed by partitioning of the shortening component of strain, the dominant SE-dipping foliation is C, the shear surface, the third are more steeply dipping C' shear bands. The fabrics in these outcrops are an expression of the Embreeville Thrust, we are in the highest strain portion of the shear zone.

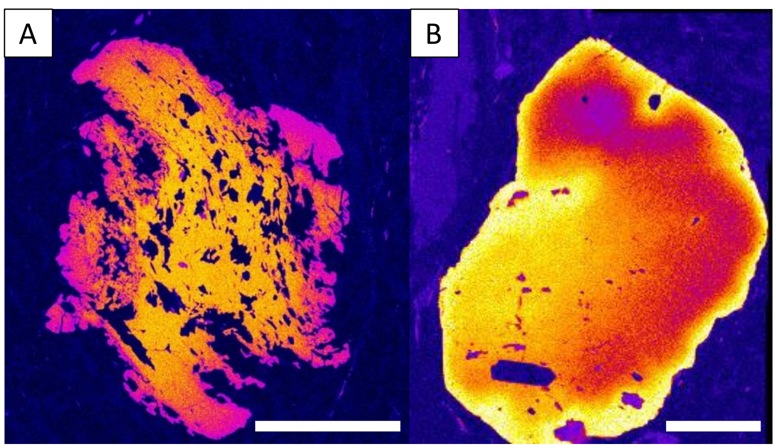


**Figure 16.** Mn x-ray maps of garnet. A. Syntectonic garnet from Peters Creek Schist in footwall of Embreeville Thrust. Core to rim decrease is indicative of prograde growth. B. Garnet from hanging wall (from outcrop at bend in Waltz Rd.). Sharp increase of Mn in rim indicates some degree of garnet resorbtion.

The garnet-in isograd occurs in the Peters Creek Schist approximately 300m northwest of our present location. Garnet in the Peters Creek Schist exhibits curved inclusion trails suggesting syn- to post-kinematic garnet growth (Ford and Bosbyshell, 2015). Garnet core compositional isopleths intersect at 520 C and 600 MPa, which likely indicates considerable over-stepping of the garnet-in reaction. Prograde garnet zoning (Fig. 16) suggests that maximum temperatures were somewhat higher. Peak metamorphic conditions in the Doe Run Schist in the hanging wall are estimated to have been in excess of 600 C at approximately 700 MPa based on the presence of staurolite and kyanite. Garnet in the hanging wall exhibits a sharp increase in Mn content at the rim (Fig. 16), indicating some degree of garnet dissolution which we interpret as the result of retrograde metamorphism driven by fluids released from the footwall during thrusting.

The timing of peak metamorphism in the Doe Run Schist is constrained by monazite ages, including monazite inclusions in garnet and staurolite, which range from 394 ±8.6 to 409 ±5.2 Ma

(Bosbyshell et al., 2016). Here at Stop five, monazite within relatively coarse-grained microlithons within the shear zone yields a somewhat older age, 424 ±10.6 Ma. Elongate, asymmetric, likely syntectonic monazite is younger at 387 ±6 Ma (Bosbyshell and Ford, 2017). Based on these observations, Bosbyshell and Ford (2017) suggest that emplacement of the Doe Run Schist drove prograde metamorphism in the structurally lower Peters Creek Schist.

Return to West Chester University. I hope you've enjoyed the trip!

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