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PALEOZOIC TRANSCURRENT CONJUGATE SHEAR ZONES IN THE CENTRAL APPALACHIAN PIEDMONT OF SOUTHEASTERN PENNSYLVANIA

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Abstract—Well-documented tectonic events in the central Appalachians of Pennsylvania are: (1) the early Paleozoic Taconian orogeny that occurred during convergence of Laurentian and the Chopawamsic–Wilmington complex magmatic arc over an east-dipping subduction zone, and resulted in intense metamorphism and deformation in the Piedmont, and (2) the late Paleozoic Alleghanian orogeny that resulted in the thrust and fold belt in the Valley and Ridge province and dextral shear zones in the Piedmont. Unlike the Paleozoic tectonic history for the northern and southern Appalachians, the north-central part of the orogen in Pennsylvania lacks evidence for Acadian deformation and metamorphism. The relative chronological order of deformation and metamorphic events in the eastern Piedmont of Pennsylvania, combined with published geochronology suggests the previously undocumented Acadian deformation possibly exists as a transcurrent conjugate shear zone pair.

The Rosemont shear zone is a dextral transcurrent shear zone that is the boundary between the type-section Wissahickon Formation of the Philadelphia structural block (to the southeast) and the West Chester and Avondale Grenvillian basement massifs (to the northwest). The Crum Creek shear zone is the sinistral antithetic structure to the Rosemont zone, and developed internal to the Philadelphia block. Geometric and metamorphic history similarities, opposing offsets, angular relationships, and relative timing of local deformation events supports a conjugate model for these shear zones. East–west oriented bulk shortening and north–south oriented bulk elongation directions are inferred from the conjugate geometry. The Rosemont–Crum Creek system cross-cuts and deforms regional Taconian structures and metamorphic zones. In turn, the Rosemont zone is truncated by the Alleghanian Pleasant Grove–Huntingdon Valley shear zone. The available geochronology brackets the movement on the Rosemont–Crum Creek system from Devonian to early Mississippian time. This timing correlates with the Acadian metamorphism in the central Appalachians, suggesting that the Acadian orogeny was manifest as a strike-slip shear system in the Piedmont of eastern Pennsylvania. The lack of regional thrusting and subsequent crustal thickening associated with transcurrent deformation could explain the lack of regionally extensive Acadian metamorphism in the Pennsylvania Piedmont.

INTRODUCTION

In the north-central Appalachian Piedmont of southeastern Pennsylvania (Fig. 1), the major regional structure and metamorphism that pervade the rocks are attributed to Taconian thrusting and nappe emplacement (Mackin, 1962;

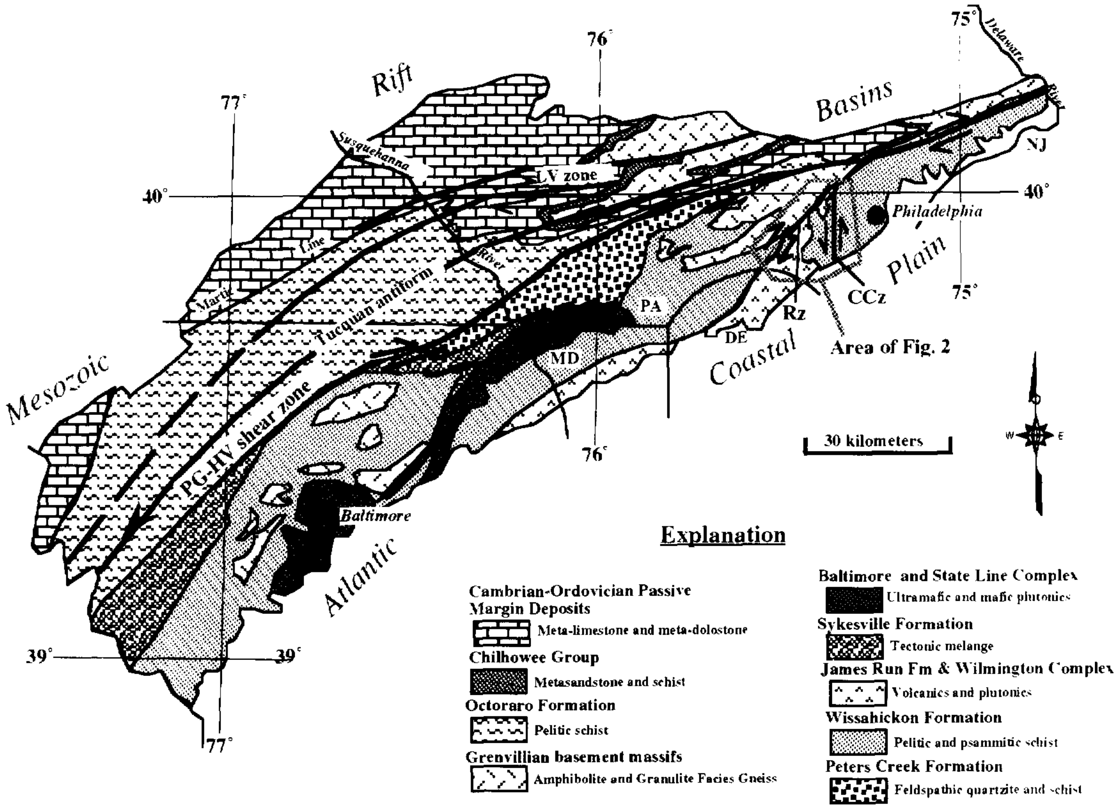


Fig. 1. Generalized tectonic map for the north-central Appalachian Piedmont (modified from Williams, 1980). Structure abbreviations: LV, Lancaster Valley zone; PG–HV, Pleasant Grove–Huntingdon Valley zone; Rz, Rosemont zone; CCz, Crum Creek zone.

Freedman *et al.*, 1964; Wise, 1970) during the convergence of Laurentia with the Chopawamsic–Wilmington complex magmatic arc (Crawford and Crawford, 1980; Crawford and Mark, 1982; Muller and Chapin, 1984; Wagner and Srogi, 1987; Wagner *et al.*, 1991). Recent studies have documented a consistent component of post-Taconian dextral strike-slip displacement on a number of shear zones in this part of the Piedmont (Hill, 1987, 1989; Valentino, 1990; Valentino and Hill, 1991; Valentino *et al.*, 1994). The impact of these later transcurrent displacements on the distribution of lithotectonic blocks, in southeastern Pennsylvania are of great significance to the construction of a tectonic history for the central Appalachians.

Wagner and Srogi (1987) presented a comprehensive tectonic model to explain the evidence of the Taconian orogeny now preserved in the crystalline rocks of the Piedmont between Philadelphia, Pa and Wilmington, Del. This model involves northwest-directed emplacement of nappes cored with Grenvillian basement, separated by thick sequences of a sedimentary melange of forearc basin sediments (the Wissahickon schist; for details of this tectonic model see Wagner and Srogi, 1987 and Wagner *et al.*, 1991). Thrust faults were considered the major structures between lithotectonic blocks. Also in the Piedmont there is evidence for lateral slip between lithotectonic blocks along Paleozoic strike-slip faults and shear zones (Valentino *et al.*, 1994). In the present investigation we use the results of detailed field mapping and petrographic analysis of oriented samples to document a strike-slip conjugate shear zone pair (the Rosemont and Crum Creek shear zones), located in the Philadelphia structural block of the eastern Piedmont (Figs 1 and 2). Relative chronology of geologic events and radiometric dating constrained the timing of offset for these Paleozoic shear zones. This paper focuses on the information that led us to interpret the Rosemont and Crum Creek zones as a strike-slip conjugate shear zone pair, and a review of regional geochronology is presented to place these shear zones in the context of Appalachian tectonics.

PREVIOUS RESEARCH AND GEOLOGIC SETTING

The structure described here as the Rosemont ductile shear zone was historically interpreted as a narrow, brittle fault (Bascom *et al.*, 1909), and in some current literature is still referred to as a fault or fault zone. However, some early workers recognized ductile deformation in Rosemont shear zone and many of their observations and interpretations are consistent with our results. Armstrong (1941) recognized a zone of mylonite associated with the Wissahickon Formation–West Chester massif contact (Figs 1 and 2) that is coincident with the shear zone. Wyckoff (1952) concluded that local retrograde metamorphism of the Wissahickon schist accompanied "crushing" or mylonitization. Ward (1959) described a gradational contact, not a fault, between the Wilmington complex and Wissahickon Formation in northern Delaware where the Rosemont "fault" was projected southwestward by Hagar and Thompson (1975).

Later workers submitted various hypotheses on the sense of the displacement across the Rosemont zone in order to explain features of the regional geology. Amenta (1974) suggested vertical displacement to explain the juxtaposition of Grenvillian basement gneiss with siliciclastic metasediments of the Wissahickon schist with kinematic analyses based primarily on the geometry of folds. Tearpock and Bischke (1980) recognized the broad zone of strain associated with the Rosemont zone, and proposed a suture zone to explain the presence of ultramafic bodies along the structure. Wagner and Srogi (1987) interpreted the Rosemont zone to be a northwest-directed Taconian thrust fault to explain metamorphic history and the distribution of lithologies along the western margin of the Wilmington complex.

In northern Delaware geophysical and geological investigations were conducted that resulted in the extension of the Rosemont zone to the southwest. Hagar and Thompson (1975) discussed the correlation of an air magnetic and topographic lineament coincident with the boundary between the James Run Formation and the Wissahickon Formation that is characterized by northeast–southwest striking and steeply-dipping zone of cataclastic and mylonitic foliation

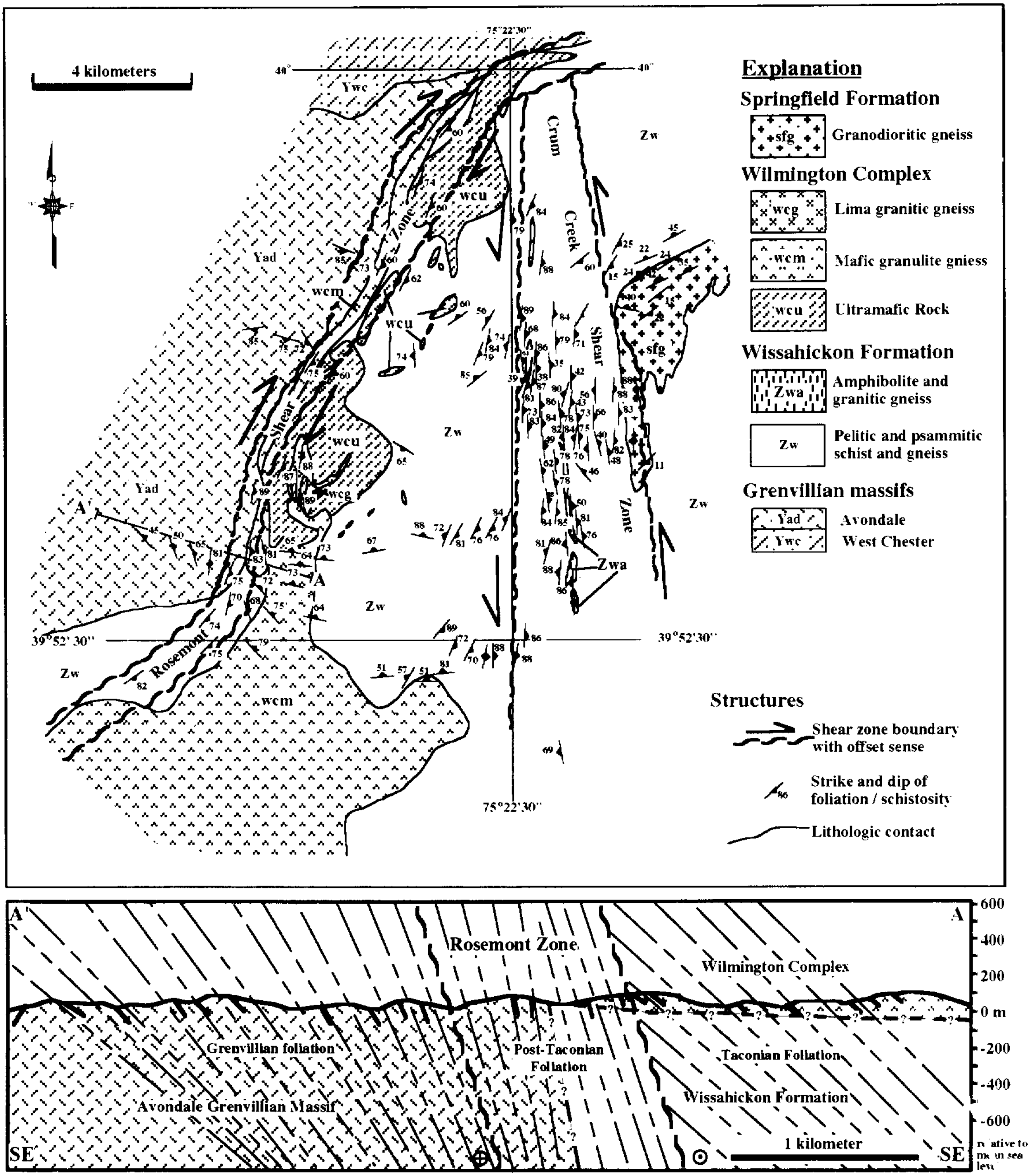


Fig. 2. Bedrock geologic map and structure map for the Crum Creek shear zone and southern segment of the Rosemont shear zone.

that developed during dextral shearing. They interpreted the lineaments and zone of cataclastic rock to be the southwestward extension of the Rosemont "fault" into northern Delaware.

West of Philadelphia, Pa, the Rosemont shear zone separates contrasting lithotectonic blocks of the Piedmont (Figs 1 and 2). The Grenvillian West Chester and Avondale massifs and Wissahickon Formation (Glenarm) lithologies lie to the northwest of the shear zone, the Wilmington complex and type-section Wissahickon Formation lithologies of the Philadelphia block lie to the southeast. Although the earlier workers recognized the significance of the Rosemont zone as a major regional structure, the extent of deformation, shear sense and magnitude of displacement were not addressed. We interpret the Rosemont shear zone to be a Paleozoic dextral transcurrent structure, with significant displacement that formed after the peak of regional early Paleozoic (Taconian) metamorphism. The Crum Creek shear zone (formally named here) occurs internal to the Philadelphia block southeast of the Rosemont zone and deforms the Wissahickon Formation and Springfield gneiss body (Fig. 2). We interpret the Crum Creek zone to have experienced Paleozoic sinistral displacement, and to be the antithetic conjugate of the Rosemont shear zone.

THE ROSEMONT SHEAR ZONE

The Rosemont shear zone in the region studied in detail is characterized by mylonitic fabric in portions of four lithologic units (Fig. 2): (1) the easternmost margins of the Grenvillian Avondale and West Chester massifs (previously referred to as Baltimore gneiss by Bascom *et al.* (1909) and workers that followed); (2) the pelitic and psammitic metasediments of the Wissahickon Formation in the Philadelphia block; (3) the western margin of the granulite and amphibolite facies metaigneous rocks of the Wilmington complex; and (4) a series of discrete ultramafic bodies.

The Avondale and West Chester basement massifs contain heterogeneous mafic and felsic high grade gneisses (Wagner and Crawford, 1975). Geologic mapping within the massifs is scant; therefore the detailed distribution of different gneiss lithologies is not known. However, the eastern margins of the Avondale and West Chester massifs contain mylonitic rock defining the Rosemont shear zone. The Avondale massif gneiss is compositionally layered on the centimeter, decimeter, and meter scale and are very coarse grained (individual crystals usually larger than 1 mm). Along the eastern margin, the Avondale massif consists of very fine grained felsic, mafic, and semi-pelitic gneiss. The felsic and pelitic rocks contain biotite, muscovite, polygonal quartz and feldspar aggregates, and small (1–2 mm) euhedral garnets. Mafic gneiss is composed of biotite, plagioclase and hornblende defining a medium to fine grained mylonitic foliation. The eastern margin of the West Chester massif is extremely fine grained with foliation defined by stringers of dynamically recrystallized quartz and K-feldspar, and parallel alignment of biotite and muscovite. Mylonitized

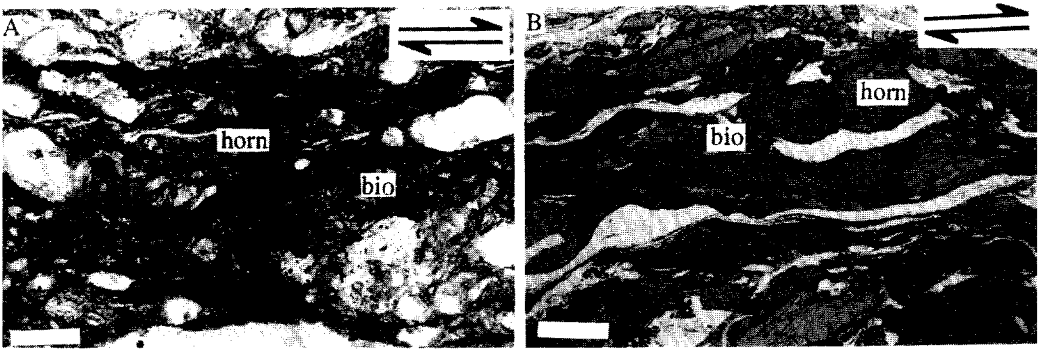


Fig. 3. Microstructural features for the Rosemont shear zone; (a) σ-type porphyroclast (Passier and Simpson, 1986) of hornblende (horn) with fine grained tails of retrograde biotite (bio) from the West Chester basement massif; (b) Type I S–C fabrics developed in amphibolite from the Wester Chester basement massif. The relative shear sense for these microstructures is dextral. Scale bar equals 1 mm on all photomicrographs.

mafic gneiss contains hornblende with reaction rims of biotite, some of which defined σ-type (Fig. 3a) microstructures (Simpson and Schmid, 1983; Passchier and Simpson, 1986). Quartz commonly occurs in thin ribbons (0.1 mm thick) of polygonal grains. Type I S–C mylonitic textures (Lister and Snoke, 1984) and shear bands (White *et al.* 1980) are pervasive in coarse grained amphibolitic gneiss (Fig. 3b). This is also true of coarse-grained felsic gneiss along the eastern margin of the West Chester massif.

The Wissahickon Formation of the Philadelphia area varies from garnet- and biotite-bearing pelitic schist to pelitic gneiss above the second sillimanite isograd near the Wilmington complex and Springfield gneiss (Wyckoff, 1952; Valentino and Faill, 1990). The Wissahickon Formation is in contact with the West Chester massif across the Rosemont shear zone. From southeast to northwest toward the contact with the adjacent West Chester massif, the schist progressively becomes dominated by the D2 structures of Tearpock and Bischke (1980), characterized by steeply southeast-dipping schistosity that is axial planar to meso-scale folds. Locally talc–chlorite–magnetic schist contains the same schistosity that is penetrative in the adjacent Wissahickon Formation. A small ultramafic body and granitic gneiss body contain Type I S–C mylonite with the C-surfaces parallel to the foliation in the adjacent Wissahickon Formation (Figs 4a and b). Biotite-fish microstructures (Eisbacher, 1970; Lister and Snoke, 1984) are also present in this deformed granitic gneiss body (Fig. 4c).

Shear sense analysis

On the regional-scale the Rosemont zone generally strikes 035–040° and dips 70–90° southeastward, although in detail the shear zone follows a more sinuous trace with the strike of the zone varying between 013 and 053° (Fig. 2). Near the intersection with the Crum Creek shear zone the Rosemont zone strikes 070°. The apparent bends in the strike of the Rosemont shear zone are attributed to younger deformation that is briefly discussed later in this paper. Mineral lineations defined by fibrolite nodules; in the Wissahickon Formation, and anthophyllite and serpentine needles in ultramafic bodies, are subhorizontal or plunge less than 8° southwestward. The combination of steeply dipping planar mylonitic fabric and shallow-plunging mineral elongation lineations suggest strike-parallel displacement.

The map of regional foliation shows map-scale dextral transposition of earlier structures into the Rosemont shear zone (Figs 2 and 5). Across this detailed transect, gneissic layering in the Wilmington complex and adjacent Wissahickon Formation strikes 280–300° and dips steeply 70–80° north and south. Clockwise rotation of the strike has occurred near the eastern limit of the Rosemont zone, and this positive rotation of the gneissic layering is most likely the result of dextral transposition. On the northwestern side of the Rosemont shear zone the gneissic foliation in the Avondale massif strikes 280–290°. Clockwise rotation or transposition has also occurred in the transition area between mylonitized and non-mylonitized rock. Strike lines plotted on the map show the curvature of earlier gneissic layering and foliation indicating map-scale dextral offset (Fig. 5).

The profiles of dextral Type I S–C structures in the ultramafic rock are best observed on subhorizontally oriented outcrop surfaces and thin sections (Fig.

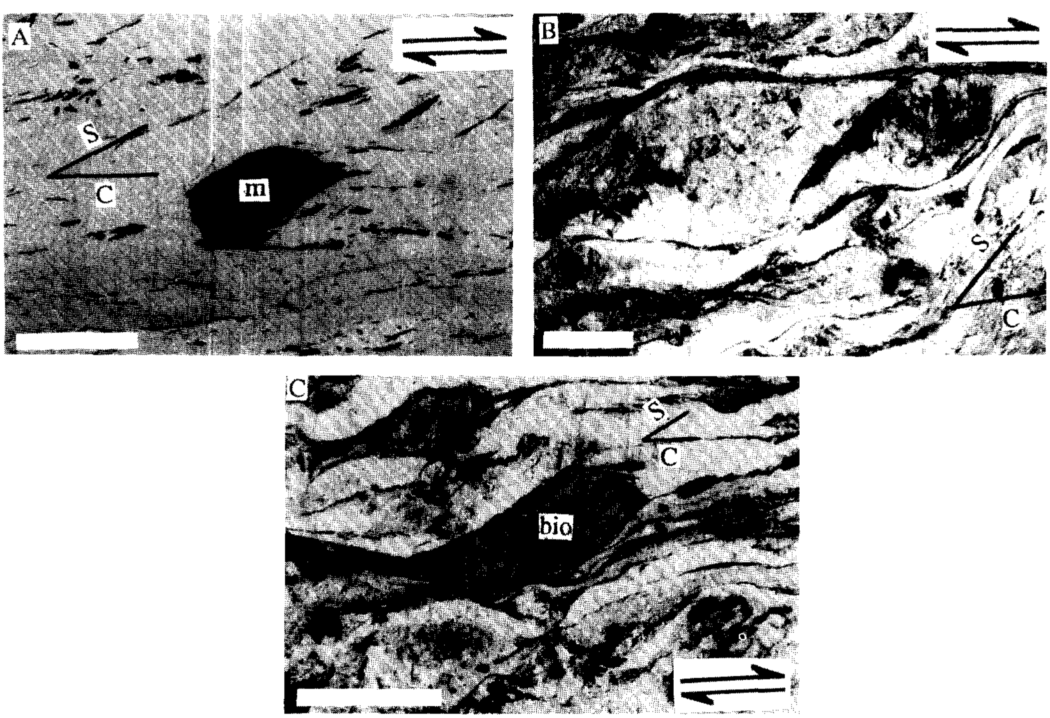


Fig. 4. Deformation features from the Rosemont shear zone; (a) Type I S–C mylonite developed in ultramafic rock (magnetite, m); (b) Type I S–C mylonite developed in deformed granite; (c) biotite (bio)-fish in deformed granite. Scale bar equals 1 mm on all photomicrographs.

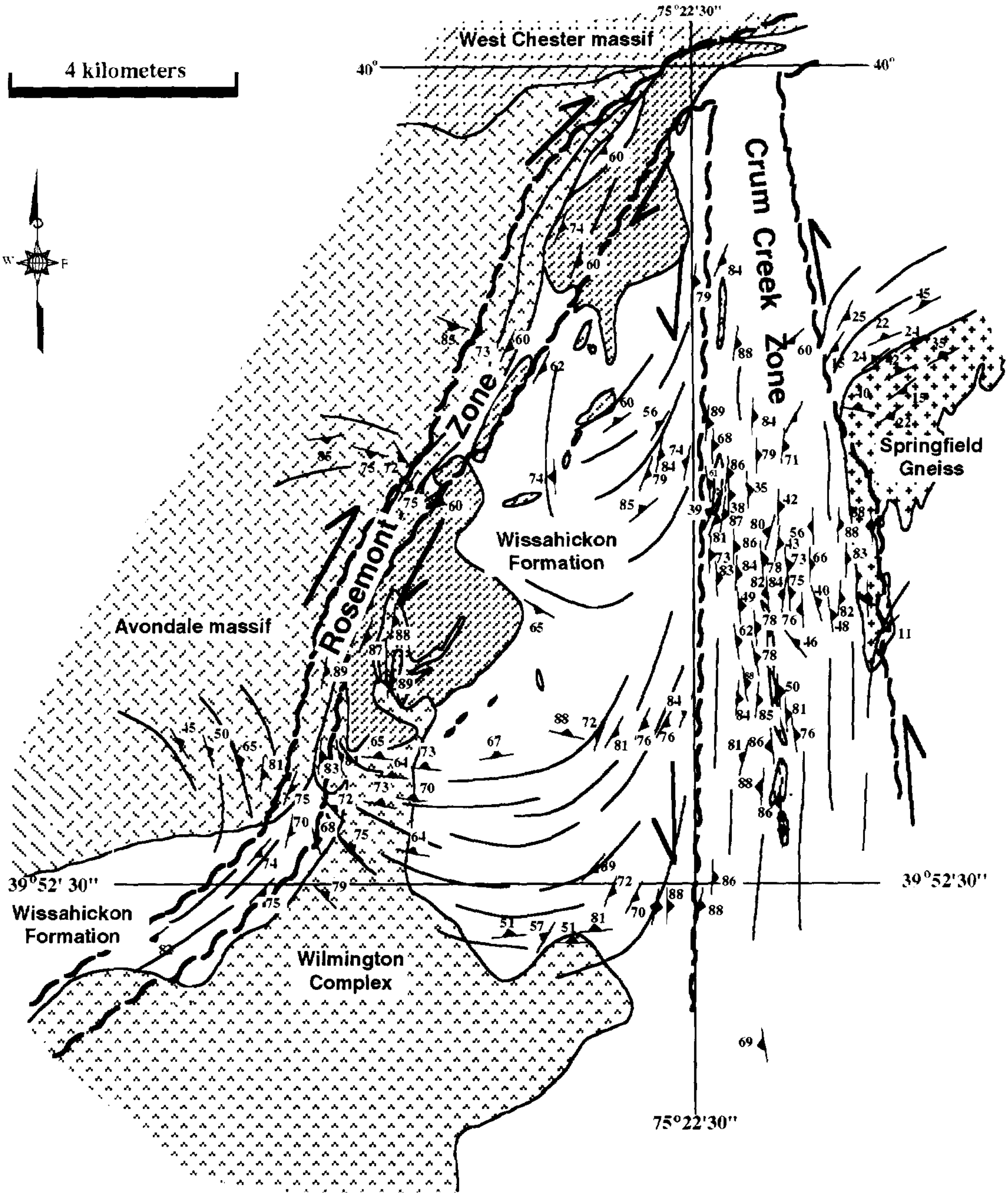


Fig. 5. Structure map for the Rosemont and Crum Creek shear zones with strike-lines showing the general trace of regional foliation into the shear zones defining large-scale "drag" folds. See Fig. 2 for explanation of lithology and structure symbols.

4a). Dextral Type I S–C mylonitic structures were also observed in amphibolite (Fig. 3b) from the West Chester massif and granitic gneiss from the Wissahickon Formation (Fig. 4b). σ-type porphyroclasts of hornblende with retrograde tails of fine grained biotite clearly indicate dextral shear (Fig. 3a). σ-type and δ-type porphyroclasts indicating dextral shear were observed in felsic gneiss from the Avondale and West Chester massif (Figs 6a and b). The conclusion drawn from the microstructural kinematic analysis is that the last displacement across the Rosemont shear zone was strike-slip and dextral.

The strike of the Rosemont zone traces in a clockwise orientation from 030° to 070°, in the vicinity of the Pleasant Grove–Huntingdon Valley shear zone (Fig. 1). (For a detailed discussion of the Pleasant Grove–Huntingdon Valley zone see Valentino *et al.*, 1994.) The Pleasant Grove–Huntingdon Valley zone is believed to have experienced late dextral offset accompanied by lower greenschist facies retrograde metamorphism (Hill, 1987; Valentino *et al.*, 1994). Clockwise rotation of the Rosemont shear zone in the vicinity of the Pleasant Grove–Huntingdon Valley zone is consistent with a model of large scale dextral shearing on the Pleasant Grove–Huntingdon Valley zone farther west (Valentino *et al.*, 1994).

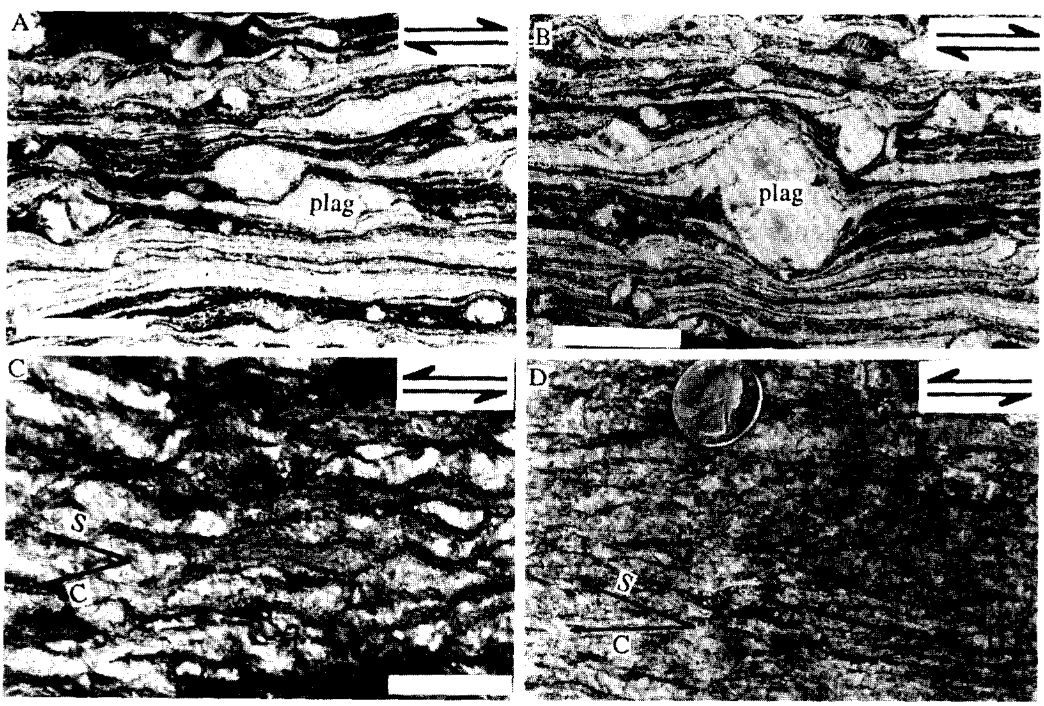


Fig. 6. Microscopic kinematic indicators from the Rosemont and Crum Creek zones; (a) σ-type and (b) δ-type porphyroclasts of plagioclase (plag) indicating dextral shear from felsic gneiss of the Avondale and West Chester basement massif within the Rosemont zone; (c) discrete shear zones in pelitic schist of the Wissahickon formation; (d) Type I S–C mylonite from the Springfield gneiss. Scale bar equals 1 mm on all photomicrographs.

THE CRUM CREEK SHEAR ZONE

The Crum Creek shear zone is defined by a 1–2 km wide zone of mylonite developed in mostly pelitic schist of the Wissahickon Formation and on the western margin of the Springfield gneiss body internal to the Philadelphia structural block (Fig. 2). The mylonite zone strikes 350–005° and dips 70–90° eastward, and shear sense was determined to be sinistral by means of detailed meso- and microscopic structural analysis similar to that applied to the Rosemont zone, and map-scale geologic features traceable across the zone.

The Wissahickon Formation locally contains interlayered pelitic and psammitic schist, and rare amphibolite layers. The Crum Creek zone developed at a high angle to the regional metamorphic isograds and schistosity as indicated by the shear zone crossing the Wissahickon Formation in the garnet zone in the north through the second sillimanite zone in the south. Within the Crum Creek zone the mylonitic foliation is defined by recrystallized muscovite, biotite, quartz and feldspar in the pelitic and psammitic lithologies, and recrystallized biotite and plagioclase in deformed amphibolite layers. the Springfield gneiss is a medium to coarse grained meta-granite and meta-granodiorite. Primary igneous textures are well preserved in regions that have experienced low amounts of strain. On the western margin of the Springfield gneiss (Fig. 2), within the Crum Creek shear zone, the rocks are dominated by a mylonitic foliation characterized by type I S–C fabrics, asymmetric feldspar augen, alignment of recrystallized biotite and muscovite, dynamically recrystallized plagioclase and K-feldspar, and ribbons of dynamically recrystallized quartz.

Shear sense analysis

Regional evidence exists for sinistral offset across the Crum Creek shear zone. The trace of the western contact between the Wissahickon Formation and the Springfield gneiss traces counter clockwise from outside to inside the shear zone near the western boundary (Fig. 2). This map pattern geometry suggests the contact was folded during sinistral shear. Similarly the geometry of Taconian metamorphic isograds within the Wissahickon Formation (Wyckoff, 1952; Valentino and Faill, 1990) mimic the folded contact. The map pattern of foliation parallels both the folded contact and isograds on the eastern side of the shear zone (Figs 5 and 7), and the western boundary of the Crum Creek shear zone exhibits a counter-clockwise movement of both the metamorphic isograds and the regional schistosity defining a fold at the margin of the shear zone (Figs 5 and 7). The geometry of these large-scale folds on the shear zone margins is consistent with sinistral shearing of pre-existing structural-metamorphic foliation in the transition regions of the mylonite zone. These map-scale observations demonstrate: (1) a consistent sinistral offset sense on both sides of the Crum Creek zone; and (2) the folding of earlier structures and metamorphic isograds during shearing, make the Crum Creek zone deformation to have occurred after the peak of regional metamorphism. The shear sense across discrete mesoscopic

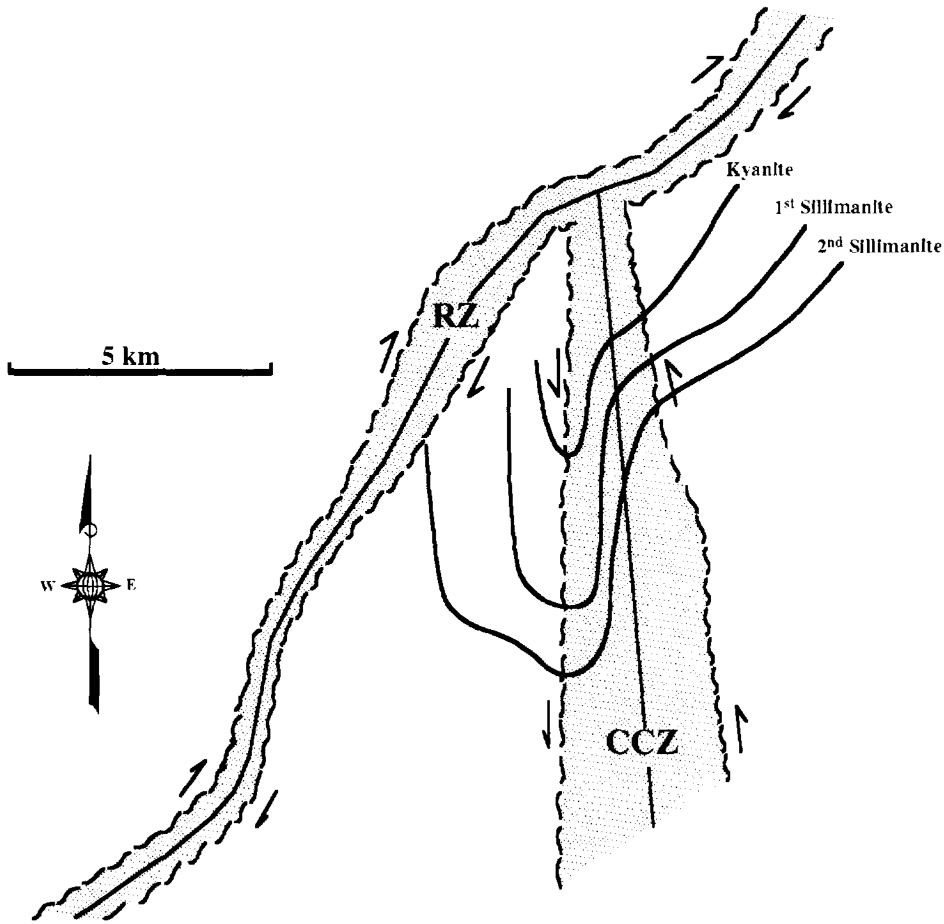


Fig. 7. Metamorphic isograd map from the area of the Crum Creek and Rosemont shear zones (modified from Wyckoff, 1952).

and microscopic shear surfaces in pelitic schist (Fig. 6c) is consistent with sinistral transcurrent displacement observed on a larger scale, as well as the shear sense deduced from the Type I S–C fabrics (Fig. 6d) in the Springfield granitic and granodioritic gneiss.

SHEAR ZONE INTERSECTION GEOMETRY

The Crum Creek shear zone intersects the Rosemont zone in the northern part of the study area (Figs 1, 2, 5 and 7), and this area has very limited bedrock exposure due to urban development. Bedrock geologic mapping revealed that the Rosemont zone continues through this intersection along the contact between the Avondale basement massif and Wissahickon Formation (Fig. 1). A "kink" or "job" in the trace of the Rosemont zone occurs in the intersection region between the two shear zones (Fig. 2), suggesting a complex structural relationship, but without better bedrock exposure it is difficult to model the true intersection geometry. The lack of Crum Creek zone fabrics in the Avondale basement massif immediately north of the intersection region clearly demonstrates that the Crum Creek zone terminates at this point. However, it cannot be ruled out that a hypothetical northern extension of the Crum Creek zone may exist in the West Chester basement massif or other units along strike, and was offset by dextral movements on the Rosemont zone. Mapping in the West Chester massif has yet to reveal the northern extension of the Crum Creek shear zone.

METAMORPHISM IN THE SHEAR ZONES

Deformation along the Rosemont and Crum Creek shear zones was accompanied by metamorphic reequilibration to the conditions at which the shear events occurred. Generally this metamorphic reequilibration resulted in mineral assemblages characteristic of middle to lower amphibolite facies. Rocks having diverse metamorphic histories were juxtaposed across the Rosemont shear zone, with the timing and grade of metamorphism varying from Grenvillian granulite facies (the West Chester massif; Wagner and Crawford, 1975) to the Barrovian sequence of metamorphism present in the Wissahickon Formation of the Philadelphia block (Wyckoff, 1952). The oldest rocks deformed in the Rosemont zone are the West Chester and Avondale massifs, metamorphosed to granulite and amphibolite facies, respectively, during the Grenvillian orogeny (Grauert *et al.*, 1973a, b; Wagner and Crawford, 1975). Wyckoff (1952) mapped metamorphic zones (garnet through second sillimanite) in the Wissahickon Formation with rocks above the second sillimanite isograd centered about the Springfield gneiss and Wilmington complex (Figs 2 and 7). These metamorphic zones are considered to represent Taconian metamorphism in the eastern Piedmont (Crawford and Crawford, 1980).

Metamorphic reactions accompanied mylonitization along the Rosemont and Crum Creek shear zones. Retrograde metamorphism occurred at different grades along the length of the Rosemont zone. In the south, hypersthene- and clinopyroxene-bearing rocks, such as the mafic gneiss of the Wilmington complex, show new growth of hornblende and biotite at the expense of primary pyroxenes. Mylonitic Wissahickon Formation above the second sillimanite isograd contains evidence for new growth of fibrolite and muscovite at the expense of prismatic sillimanite and K-feldspar. Further north fine-grained biotite is a retrograde reaction product that grew at the expense of primary hornblende in the West Chester (Figs 3a and b) and Avondale massifs. Recrystallized muscovite and biotite are the most common retrograde products in the Wissahickon Formation in the north. In the Crum Creek Zone the primary retrograde products are new biotite growth at the expense of primary hornblende in amphibolite layers, recrystallized biotite and muscovite in pelitic (Fig.

6c) and psammitic rocks, and new growth of muscovite from primary igneous K-feldspar in the Springfield gneiss. Biotite growth at the expense of primary hornblende was also documented for the Springfield gneiss.

CONJUGATE DUCTILE SHEAR ZONES

Ramsay and Huber (1987) summarized the following characteristics of conjugate ductile shear zones: (1) the conjugate zones develop during the same deformation event; (2) one shear zone offsets the other; and (3) the acute and obtuse angle bisectors between the zones lie in the direction of bulk stretching and bulk shortening respectively. Similarities in structural geometry and metamorphic history between the Rosemont and Crum Creek zones, along with the opposing shear sense, suggests these shear zones are a map-scale ductile conjugate set. Similar retrograde metamorphic mineral assemblages restricted to both the Rosemont and Crum Creek zones indicates that both shear zones were active during similar metamorphic conditions. Since there is no independent evidence that the region experienced separate metamorphic episodes, the observations suggest that the shear zones were active during the same metamorphic event.

In an investigation of meso-scale ductile conjugate shear zones in homogeneous rock, Lamouroux *et al.* (1991) demonstrated that geometric analysis of conjugate shear zones is greatly dependent on the plane of observation, and that plane should be orthogonal to the line defined by the intersection of the zones. A skeletal map of the Rosemont–Crum Creek conjugate pair was constructed looking down the plunge of the intersection line (Fig. 8). The approximate line of intersection is defined by the intersection of the average strike and dip of the shear zone boundaries for each zone. The down plunge view required only minor adjustments from the original structure map since the intersection line plunges 67° at a trend of about 175°. Based on the geometry, and angular relationship between the Rosemont and Crum Creek zones, assuming they are conjugate, the direction of bulk shortening was oriented approximately horizontal and trended west-northwest–east-southeast relative to the current orientation of the shear zones (Fig. 9a). More precisely the orientations of the principal bulk strains are: (1) maximum bulk shortening direction of 278° trend and 8° plunge; and (2) maximum bulk elongation direction of 13° trend and 21° plunge (Fig. 9b). The orientations of the bulk strain directions only applies to the local area including the shear zones, and a more regional interpretation is not implied.

The regional systematic variation of foliation in the acute angle between the zones defines a reclined map-scale fold (Figs 2 and 5), suggesting that the angle between the shear zones was modified by folding. Therefore, the present angular relationship between the Rosemont and Crum Creek zones does not reflect the original angle of intersection due to ductile deformation and modification of the wedge-shaped body of rock located between the zones. Since the angle of intersection was modified by folding the approximate orientations of the principal compressive stresses may not be directly related to the orientations of the axes of bulk strain (Ramsay, 1980; Ramsay and Huber, 1987).

CHRONOLOGY AND GEOCHRONOLOGY

Cross-cutting relationships reveal a relative chronology for the regional deformation and metamorphic episodes as discussed in previous sections and shown in Figs 2 and 5. The foliation associated with the Rosemont and Crum

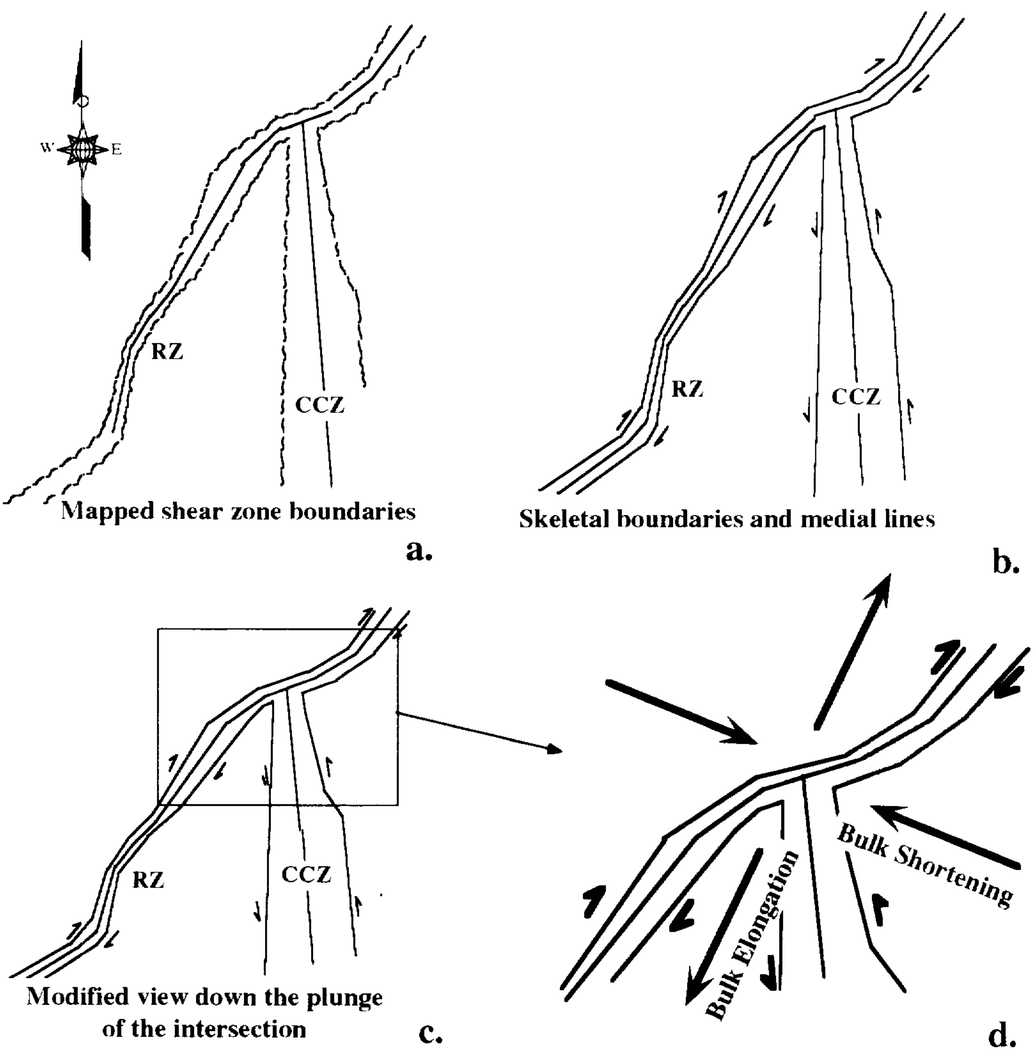
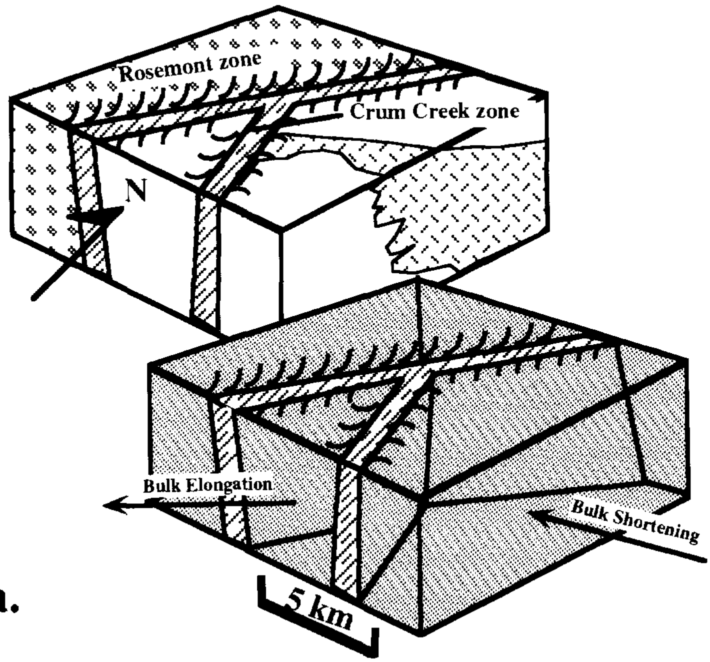
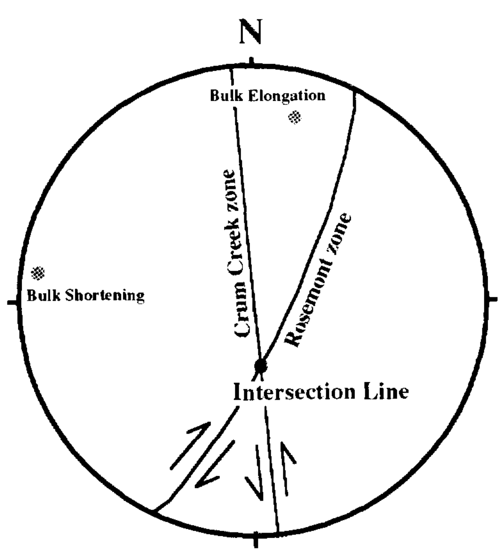


Fig. 8. Structure maps for the Rosemont and Crum Creek zones. (a) Shear zone boundaries; (b) skeletal shear zone boundaries with medial lines; (c) view of the shear zones down the plunge of the intersection between the two shear zones; (d) intersection region between the two shear zones with inferred orientations of the principal bulk strains.



a.



b.

Fig. 9. (a) Schematic block diagram showing the orientation of the Rosemont and Crum Creek zones and the approximate orientations of the principal bulk strains; (b) lower hemisphere stereographic projection of the average orientations of the Rosemont and Crum Creek zones with inferred orientations of the principal compressive stresses assuming the shear zones developed as a conjugate pair.

Creek shear zones developed synchronously during the same retrograde metamorphic episode, and by dating the shear zone metamorphism directly or by the dating of rocks cross-cut by the shear zones it is possible to bracket the age of shear zone deformation. Although the sum of published modern radiometric dates for the Pennsylvania Piedmont is not extensive, a compilation of dates for the region in conjunction with the relative order of structural events provides valuable information with respect to north-central Appalachian tectonics.

Foliation in the West Chester and Avondale basement rocks, Wissahickon Formation, and Wilmington complex are cross-cut and deformed by the Rosemont shear zone. These relationships place the Rosemont zone as having developed sometime after the peak of regional metamorphism. Similarly, the Crum Creek zone cross-cuts the Wissahickon Formation and Springfield gneiss foliations. The western contact between the two units is apparently transposed by the Crum Creek zone, and the trace of regional metamorphic isograds suggests sinistral offset across the zone. These relationships also place the Crum Creek zone development after the regional metamorphism and deformation that pervades the rocks of the Philadelphia structural block.

Tilton *et al.* (1960) inferred that the local basement rocks were metamorphosed during the Grenvilian orogeny from isotopic dating of zircons, and this was later confirmed by Grauert *et al.* (1973a, b). (A compilation of radiometric age determinations for the southeastern Pennsylvania Piedmont is included in Table 1 and Fig. 10.) Early geochronology using the Pb-α technique produced date ranges of 529–914 Ma and 215–480 Ma for the Wissahickon Formation and Springfield gneiss respectively (Jaffe *et al.*, 1959). The application of Pb-α systematics is obsolete, therefore the reported values are outdated. For the Wissahickon Formation an Rb/Sr muscovite age (Long and Kulp, 1962) of 353 ± 14 Ma was determined from a location at Neshaminy Falls north of Philadelphia (Fig. 10). This locality is in close proximity to the Pleasant Grove–Huntingdon Valley shear zone, and the rocks are strongly influenced by extensive grenschist facies shear zone-related retrogression (Hill, 1987; Valentino *et al.*, 1994). This age is consistent with K/Ar muscovite ages associated with late greenschist facies metamorphism that occurs primarily, but not exclusively, in and near the Pleasant Grove–Huntingdon Valley zone in the western Piedmont (Lapham and Basset, 1964). An $^{40}Ar/^{39}Ar$ age of 410 Ma for biotite from the Wissahickon Formation was reported from a locality south of the Rosemont zone (Sutter *et al.*, 1980), and an amphibolite within the Rosemont zone produced a hornblende $^{40}Ar/^{39}Ar$ age of 465 Ma. These dates were interpreted as cooling ages after the peak of metamorphism (Sutter *et al.*, 1980). U/Pb ages for zircons produced upper and lower intercepts of 441 and 1500 Ma respectively, for the Wilmington complex granulite facies metamorphism (Grauert and Wagner, 1975), and foliations associated with that metamorphism are cross-cut by the Rosemont zone. It was noted by Wagner and Srogi (1987) that the foliation is also cross-cut by a 502 ± 20 Ma pluton determined by whole rock Rb/Sr technique (Folland and Muessig, 1978). Folland and Muessig

Table 1. Compilation of published radiometric dates for the Piedmont of southeastern Pennsylvania (see Fig. 10 for the approximate locations)

Map No.	Formation	Technique	Date (m.y.)	Mineral	Reference
1	Honey Brook massif	$^{40}Ar/^{39}Ar$	880	hornblende	Sutter *et al.* (1980)
			850	biotite	Sutter *et al.* (1980)
			878	hornblende	W. Crawford—personal communication
			848	biotite	W. Crawford—personal communication
2	Honey Brook massif	$^{40}Ar/^{39}Ar$	889	hornblende	W. Crawford—personal communication
			731	biotite	W. Crawford—personal communication
3	Honey Brook massif	$^{40}Ar/^{39}Ar$	403	biotite	W. Crawford—personal communication
4	Mine Ridge massif	Rb/Sr	313	biotite	Kohn *et al.* (1993)
5	Octoraro	K/Ar	360 ± 18	muscovite	Lapham and Bassett (1964)
6	Octoraro	K/Ar	285 ± 14	muscovite	Lapham and Bassett (1964)
7	Octoraro	Rb/Sr	403	muscovite	Kohn *et al.* (1993)
8	Drumore Tectonite	K/Ar	330 ± 17	muscovite	Lapham annd Bassett (1964)
9	Peters Creek	K/Ar	330 ± 17	muscovite	Lapham and Bassett (1964)
10	Peters Creek	K/Ar	305 ± 15	muscovite	Lapham and Bassett (1964)
11	Peters Creek, Peach Bottom	K/Ar	320 ± 16	muscovite	Lapham and Bassett (1964)
12	Peters Creek	K/Ar	355 ± 18	mu/bio	Lapham and Bassett (1964)
13	Peters Creek	K/Ar	360 ± 18	muscovite	Lapham and Bassett (1964)
14	Peters Creek	K/Ar	395 ± 20	muscovite	Lapham and Bassett (1964)
			460 ± 23	muscovite	Lapham and Bassett (1964)
15	Wilmington complex	U/Pb	441	zircon	Grauert and Wagner (1975)
			1500	zircon	Grauert and Wagner (1975)
16	Wilmington complex	Rb–Sr	502 ± 20	whole rock	Foland and Muessig (1978)
			440	min. sep.	Foland and Muessig (1978)
17	Wilmington	Rb/Sr	275	biotite	Kohn *et al.* (1993)
18	Springfield	Pb-α	480	zircon	Jaffe *et al.* (1959)
19	Springfield	Pb-α	460	zircon	Jaffe *et al.* (1959)
20	Springfield	Pb-α	293	zircon	Jaffe *et al.* (1959)
21	Springfield	Pb-α	241	zircon	Jaffe *et al.* (1959)
21	Springfield	Pb-α	218	zircon	Jaffe *et al.* (1959)
22	Springfield	Pb-α	216	zircon	Jaffe *et al.* (1959)
23	Wissahickon	Pb-α	914	zircon	Jaffe *et al.* (1959)
24	Wissahickon	Pb-α	880	zircon	Jaffe *et al.* (1959)
25	Wissahickon	Pb-α	840	zircon	Jaffe *et al.* (1959)
26	Wissahickon	Pb-α	785	zircon	Jaffe *et al.* (1959)
27	Wissahickon	Pb-α	529	monazite	Jaffe *et al.* (1959)
28	Wissahickon	Pb-α	529	monazite	Jaffe *et al.* (1959)
29	Wissahickon	K–Ar	353 ± 14	muscovite	Long and Kulp (1962)
30	Wissahickon	$^{40}Ar/^{39}Ar$	410	biotite	Sutter *et al.* (1980)
31	Wiss. amphibolite (Rz)	$^{40}Ar/^{39}Ar$	465	hornblende	Sutter *et al.* (1980)
32	West Chester massif	$^{206}Pb/^{238}U$	1120	zircon	Tilton *et al.* (1960)
		$^{207}Pb/^{235}U$	1050	zircon	Tilton *et al.* (1960)
		$^{207}Pb/^{206}Pb$	1010	zircon	Tilton *et al.* (1960)
		K/Ar	550	biotite	Tilton *et al.* (1960)
		Rb/Sr	380	biotite	Tilton *et al.* (1960)
33	West Chester massif	U/Pb	980–1050	zircon	Grauert *et al.* (1973)
34	Avondale massif	$^{40}Ar/^{39}Ar$	375	hornblende	Sutter *et al.* (1980)
		$^{40}Ar/^{39}Ar$	375	biotite	Sutter *et al.* (1980)
35	Avondale massif	Rb/Sr	318	biotite	Kohn *et al.* (1993)
		Rb/Sr	358	muscovite	Kohn *et al.* (1993)

continued overleaf

Table 1—*continued*

Map No.	Formation	Technique	Date (m.y.)	Mineral	Reference
36	Avondale massif	Rb/Sr	270	biotite	Kohn *et al.* (1993)
		Rb/Sr	344	muscovite	Kohn *et al.* (1993)
37	Honey Brook massif	K/Ar	1010	biotite	Tilton *et al.* (1960)
		K/Ar	900	biotite	Tilton *et al.* (1960)
		Rb/Sr	630	biotite	Tilton *et al.* (1960)
		Rb/Sr	485	biotite	Tilton *et al.* (1960)
38	Honey Brook massif	Rb/Sr	567	biotite	Kohn *et al.* (1993)

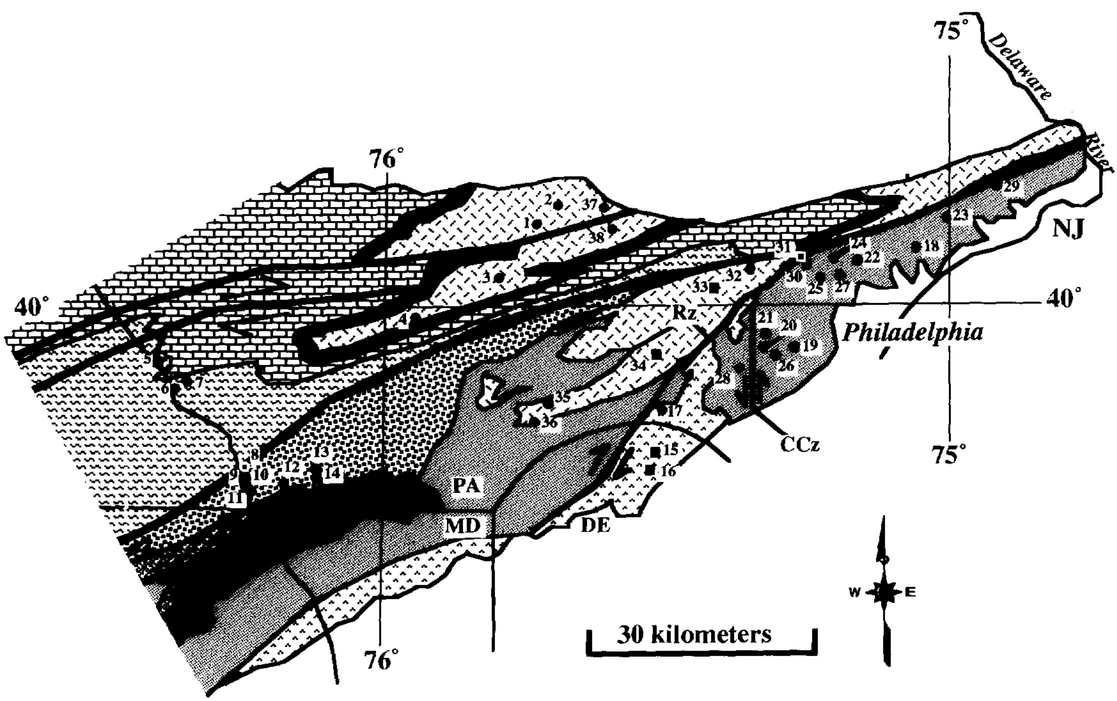


Fig. 10. Map of the north-central Appalachian Piedmont with the approximate locations for published radiometric dates (see Table 1 for the dates and Fig. 1 for explanation of lithotectonic units). Dark circles represent locations reported by earlier workers, and less specific locations are designated by a dark square within the given unit.

(1978) also arrived at an age of 440 Ma for the same pluton using Rb/Sr on mineral separates.

The 465 Ma hornblende date (Sutter *et al.*, 1980) for a locality within the Rosemont zone is probably not representative of the timing of deformation in the zone because Rosemont zone retrogressive metamorphism generally produced biotite at the expense of primary hornblende in sheared amphibolites. Biotite and muscovite was generally recrystallized in pelitic rocks in the northern part of the zone that includes deformed Wissahickon lithologies. This is also the case for the Crum Creek shear zone. The hornblende age probably represents a cooling date for the regional metamorphism, and this is consistent with earlier interpretations (Crawford and Crawford, 1980; Wagner and Srogi, 1987). The location for the 410 Ma biotite date (Sutter *et al.*, 1980) from the Wissahickon Formation south of the Rosemont zone is significant. If the biotite for this age was reset during shearing or directly associated with Rosemont zone retrogression, then this could possibly constrain the upper limit for the time of transcurrent shearing. If the biotite is primary and was not reset by the shear zone metamorphism, the 410 Ma age still represents an upper limit for the timing of Rosemont retrogression and deformation.

The Rosemont zone is deformed and cross-cut by the Pleasant Grove–Huntingdon Valley shear zone in the north (Figs 1 and 10). Although there is considerable variability in their data (Table 1), Lapham and Basset (1964) interpreted their muscovite K/Ar ages for the late greenschist metamorphism in the western Piedmont to be about 330 Ma. This metamorphism is associated with the Pleasant Grove–Huntingdon Valley shear zone (Valentino and others, 1994), and probably represents the cooling date for shear zone related muscovite. The same greenschist facies metamorphic episode occurs throughout the Pleasant Grove–Huntingdon Valley zone, and was also documented near the intersection with the Rosemont zone (Hill, 1987). Therefore, assuming that the Rosemont and Crum Creek zones developed as a conjugate pair relatively close in geologic time, they represent a phase of transcurrent shearing in the eastern Piedmont of Pennsylvania that occurred sometime in the Devonian to early Mississippian.

The timing of Paleozoic orogenic events were summarized for the central and southern Appalachians by Glover *et al.* (1983). They outlined three Paleozoic events: (1) the Taconic orogeny at 480–435 Ma, (2) the Acadian orogeny at 380–340 Ma, and (3) the Alleghanian at 320–230 Ma. In the north-central Appalachian Piedmont workers have recognized the effects of the Taconian orogeny and the Alleghanian orogeny evident in the various deformation phases and metamorphic episodes (Freedman *et al.*, 1964; Wise, 1970; Wagner and Crawford, 1975; Crawford and Crawford, 1980; Wagner and Srogi, 1987). Metamorphism and deformation associated with the Acadian orogeny has not been identified. Paleozoic transcurrent shearing in the central Appalachians is attributed primarily to the Alleghanian orogeny (Gates *et al.*, 1986; Gates, 1987), and the Pleasant Grove–Huntingdon Valley zone was interpreted to be in this category of central Appalachian transcurrent structures (Valentino *et al.*, 1994). The Rosemont and Crum Creek shear zones clearly pre-date the Pleasant Grove–Huntingdon Valley zone, and from the available geochronology, these shear zones were active between 410 and 330 Ma. This range of possible dates for the Rosemont and Crum Creek system suggests that they were active at about the time of Acadian orogeny (Glover *et al.*, 1983) in the central Appalachians. If the Acadian deformation was dominated by transcurrent faulting and shearing in the north-central Appalachians, the lack of thrusting and subsequent crustal thickening would account for the absence of Acadian metamorphism and deformation that is regionally pervasive in the northern and southern parts of the orogen.

SUMMARY

The Rosemont shear zone is a zone of ductile deformation approx. 1–1.5 km wide that separates the Grenvillian West Chester and Avondale massifs from the Wilmington complex and the Wissahickon Formation lithologies of the central Appalachian Piedmont near Philadelphia, Pa. The zone is characterized by steeply dipping mylonitic fabric which is nearly parallel to the boundaries of the zone. Dextral offset across the Rosemont zone is indicated by transposition of earlier structures, and microstructural analysis. The Crum Creek shear zone developed internal to the Philadelphia structural block, and is interpreted to be the antithetic conjugate structure to the Rosemont zone. Sinistral shear sense was deduced with microstructures, the geometry of map-scale folds at the shear zone margins, and displacement of regional metamorphic isograds across the zone. The conjugate geometry suggests that the approximate direction of bulk shortening was oriented east-west and subhorizontal, and the approximate direction of bulk extension was north-south and shallowly north plunging.

Relative chronology in the Philadelphia structural block places the Rosemont and Crum Creek shear zones to have developed after the peak of Taconian metamorphism and prior to dextral shearing on the Pleasant Grove–Huntingdon Valley shear zone. Available radiometric dates for the eastern Piedmont of Pennsylvania broadly constrain the Rosemont and Crum Creek system to have developed during the Devonian to early Mississippian. We suggest here that with the present data available, the Rosemont–Crum Creek conjugate shear system is possibly the result of Acadian deformation in the north-central Appalachian Piedmont. This hypothesis needs to be tested with additional geochronology, in conjunction with the knowledge we have concerning the sequence of deformation and metamorphic events in this part of the Appalachians.

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