The discordant Doe Run thrust: Implications for stratigraphy and structure in the Glenarm Supergroup, southeastern Pennsylvania Piedmont

J. ALCOCK* *University of Pennsylvania, Philadelphia, Pennsylvania 19104*

ABSTRACT

Detailed mapping and ground magnetic surveys in the area of Doe Run, southeastern Pennsylvania Piedmont, show the Wissahickon Group to consistently lie above, and locally with angular contact upon, an overturned stratigraphic sequence of Grenville-aged (≈1 b.y. old) gneiss above Setters Formation above Cockeysville Marble. These discordant relations reflect the emplacement of the Wissahickon Group along the Doe Run thrust (redefined herein) across a previously folded footwall. Identifying the Doe Run thrust makes untenable the long-standing assumption of stratigraphic continuity throughout the Glenarm Supergroup of southeastern Pennsylvania.

INTRODUCTION

Multiple deformation and metamorphism of the Pennsylvania-Delaware Piedmont during early Paleozoic plate collision produced a complex regional structure that has proven difficult to interpret. Many geologists are familiar with the problems because the region has been used to demonstrate the down-plunge projection method of determining regional structure (Bailey and Mackin, 1937; Mackin, 1950; Ragan, 1984). The difficulties of interpretation were further demonstrated by the Mackin-McKinstry debate on the "Structure of the Glenarm Series . . ." (Mackin, 1962; McKinstry, 1961). Both McKinstry and Mackin were able to identify problems in the structural model of the other, but neither worker produced a model that accurately predicts field relations observed in the Doe Run area (D, Fig. 1).

Although limited structural relief and poor exposure in the area make interpretation difficult, more significant problems arise from the assumption that the Setters Formation, Cockeysville Marble, and Wissahickon Group metasediments of the Glenarm Supergroup originated as a conformable sedimentary sequence (Knopf and Jonas, 1923; Higgins, 1972; Crowley, 1976; among others). This assumption implies that the Wissahickon Group was placed on the underlimbs of early Paleozoic recumbent folds now exposed in basement-cored massifs. Detailed analysis of field relations at five locations near Doe Run shows that this assumption of stratigraphic continuity is not correct. Instead, the Wissahickon Group consistently lies above, and locally with angular contact upon, an overturned stratigraphic sequence of Grenville-aged (≈1 b.y. old) gneiss above Setters Formation above Cockeysville Marble, the vertical sequence commonly observed in the Doe Run area. This structural discordance, which is interpreted to reflect the tectonic emplacement of the Wissahickon Group, must be considered when interpreting regional structure because a single down-plunge projection cannot accurately model both the Doe Run thrust and prethrust structures in its footwall.

GEOLOGIC SETTING

Early Paleozoic deformation and regional metamorphism of the Pennsylvania-Delaware Piedmont are interpreted to result from a subduction-related collision that emplaced the Wilmington Complex arc-terrane on Grenville-aged gneiss and its metasedimentary cover (Crawford and Crawford, 1980; Crawford and Mark, 1982; Wagner and Srogi, 1987). Recent work in the area has begun to document the presence of at least three distinct tectonic units assembled during this event.

One unit is composed of rocks with possible Laurentian affinity, but which lie outboard of the pre-Taconian Laurentian margin (Rodgers, 1968). This unit includes Grenville-aged gneiss and its unconformable late Precambrian to early Paleozoic metasedimentary cover, the Setters Formation and Cockeysville Marble. (In this paper, the exposure of these units in southeastern Pennsylvania is referred to as the Brandywine terrane, after R. Faill, 1993, personal commun.) The Grenville-aged gneiss forms the core of several large anticlinal structures like the Avondale and West Chester massifs (Fig. 1). Although the Setters Formation and Cockeysville Marble are absent from the margins of the massifs in the east, they may reach a thickness of 100–200 m in the west near Avondale (Av in Fig. 1) (Bascom and Stose, 1932).

A second block, the Wilmington Complex (Fig. 1), includes granulite-facies gneiss, numerous small gabbroic plutons, and a norite-charnockite suite with a marked calc-alkaline affinity. It is considered to be the infrastructure of an early Paleozoic magmatic arc (Crawford and Crawford, 1980; Crawford and Mark, 1982; Wagner and Srogi, 1987).

The Wilmington Complex and the Brandywine terrane are separated by the third tectonic unit, pelitic to semipelitic schist and gneiss of the Wissahickon Group with associated amphibolites, metagabbros, and serpentinites. For many years, the Wissahickon Group has been considered a conformable member of the Glenarm Supergroup (Knopf and Jonas, 1923; Higgins, 1972; Crowley, 1976). In the last 10–15 years, however, additional data have led workers to question the stratigraphic relation of the Wissahickon Group to other members of the Glenarm Supergroup, especially in the area between the Wilmington Complex and Cream Valley fault (Fig. 1) (Crawford and Crawford, 1980; Wagner and Srogi, 1987; Alcock, 1989; Drake and others, 1989; Wagner and others, 1991).

*Current address, Pennsylvania State University, Ogontz Campus, Abington, Pennsylvania 19001.

Geological Society of America Bulletin, v. 106, p. 932–941, 8 figs., 1 table, July 1994.

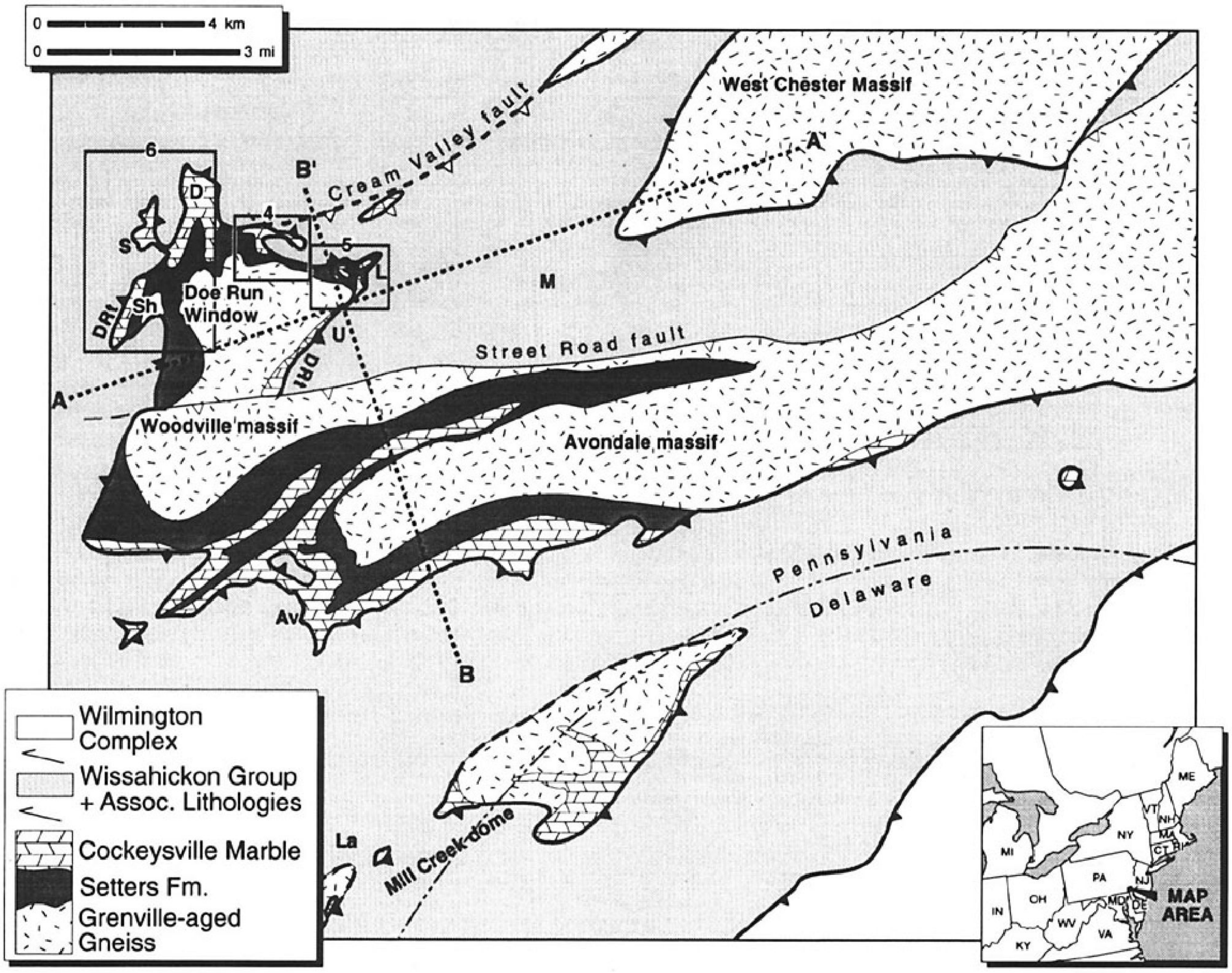

Figure 1. Geologic map of the Pennsylvania-Delaware Piedmont, after Bascom and Stose (1935) as revised by M. L. Crawford in Berg and others (1980). Additional revisions in areas of the Mill Creek dome (Higgins and others, 1973; Plank and Woodruff, 1991, personal commun.), the Cream Valley fault (Wiswall, 1990), and the Avondale and Woodville massifs and Doe Run window (Alcock, 1989, and unpub. data). Changes by the author include showing the base of the Wissahickon Group as a thrust, removal of a fault separating the Avondale and Woodville massifs, and the extension of the Street Road fault so that it entirely separates the Woodville massif from the Doe Run window. Pelitic schists north of the Doe Run window and Cream Valley fault are at distinctly lower grade and have uncertain relationship to other metapelites in the region.

Faults and/or ductile shear zones are indicated by heavy line; hanging wall, by triangles. Older and younger thrusts are indicated by solid and open triangles, respectively. Boxes 4, 5, and 6 locate Figures 4, 5, and 6. A–A′ and B–B′ are cross sections in Figure 3. Abbreviations: Av, Avondale; D, town of Doe Run; DRt, Doe Run thrust; L, Logan's quarry; La, Landenberg; M, Marlborough; S, Springdell; Sh, Shabatz Road; U, Upland. Southeast corner is at lat 39°45′N, long 75°32′W.

A metamorphic discontinuity at the Wissahickon Group–Cockeysville Marble contact near Landenberg (La, Fig. 1) is evidence that a thrust fault separates the Wissahickon Group from the Brandywine terrane south of the Avondale massif (Alcock, 1989; Wagner and others, 1991). There, higher-grade gneiss of the Wissahickon Group lies above lower-grade marble indicating emplacement of the Wissahickon Group after peak metamorphism. Metamorphic conditions affecting the marble are estimated to have been $T \approx 575$ °C, $P \approx 400$ MPa. Because systematic changes in mineral assemblages in the marble indicate that metamorphism resulted from emplacement of the Wissahickon Group, it follows that thrusting occurred at a depth of about 10 km.

THE DOE RUN THRUST

The Wissahickon Group near Doe Run is at staurolite-kyanite grade and cannot be shown to have experienced higher temperature or pressure than the Cockeysville Marble beneath it (Alcock, 1989). However, a major structural discordance occurs at the base of the Wissahickon Group in this area and is interpreted to be a thrust, termed here the Doe Run thrust, that separates the Wissahickon Group from a previously folded basement and cover sequence. The name, Doe Run thrust, was originally used by Bliss and Jonas (1916), but it was abandoned when they reinterpreted the Wissahickon Group to be conformable with the Cockeysville Marble (Knopf and Jonas,

TABLE 1. DESCRIPTION OF FOLDING

F_1	F_1 folds are isoclinal, recumbent folds along south- to southwest-trending axes with overturning to the northwest. These folds are found exclusively in Brandywine terrane rock and have not been found to include the Wissahickon Group in this area. ($F_{0\times1}$ in Wise, 1970.)
F_2	F_2 folds are northwest vergent, overturned to recumbent, and trending N60°E. F_2 folds deform the Brandywine terrane and the Wissahickon Group.
F_3	F_3 folds are generally open, upright to slightly overturned folds, plunging 10°–20° along S60°–90°W. (F_2 and F_3 are combined as $F_{0\times2}$ in Wise, 1970.)
F_4	A final stage of smaller folds, F_4, is found in and north of the Doe Run window. These folds trend north-south with nearly vertical axial planes and plunge gently to north or south. ($F_{0\times3}$ in Wise, 1970.)

1923; also, Bascom and Stose, 1932; Berg and others, 1980). The name is reintroduced here, but the thrust is reinterpreted to lie exclusively at the base of the Wissahickon Group exposed in the Doe Run area. Evidence for the Doe Run thrust and its relation to other faults in the region are discussed below.

OTHER REGIONAL STRUCTURES

The region has been deformed by multiple episodes of faulting and folding. Distinct sets of noncoaxial folds are recognized (for example, McKinstry, 1961; Wise, 1970; Wiswall, 1990). The fold sets are described in Table 1 and illustrated in simplified form in Figure 2. Faults other than those at the base of the Wissahickon Group include the Street Road fault (named here and identified in Fig. 1) and the Cream Valley fault. Both faults originated as northwest-directed thrusts that placed Brandywine terrane rock above the Wissahickon Group and were later reactivated with top-to-the-west or -southwest movement (Wiswall, 1990; Wagner and others, 1991; C. G. Wiswall, 1992, personal commun.).

FOLIATION

In the interior of the massifs, the Grenville-aged gneiss is either massive or foliated by compositional layering subparallel to axial planes of small F_1 folds. Near the margins of the massifs, the gneissic foliation is often replaced by a mylonitic fabric that parallels the margin.

Foliation in the Setters Formation and Cockeysville Marble tends to parallel bedding, except where it passes through the hinges of F_1 folds. Bedding and foliation were reoriented by F_3 folds to produce the N60°E regional strike visible in the trend of the massifs and by F_4 folds, especially near Doe Run.

The Wissahickon Group has multiple fabrics, defined primarily by micas and mineral segregations. Near the metapelites' basal contact with the Brandywine terrane, the dominant foliation tends to parallel that contact, generally following regional strike with gentle southeasterly dip. Away from this contact, however, the dip tends to

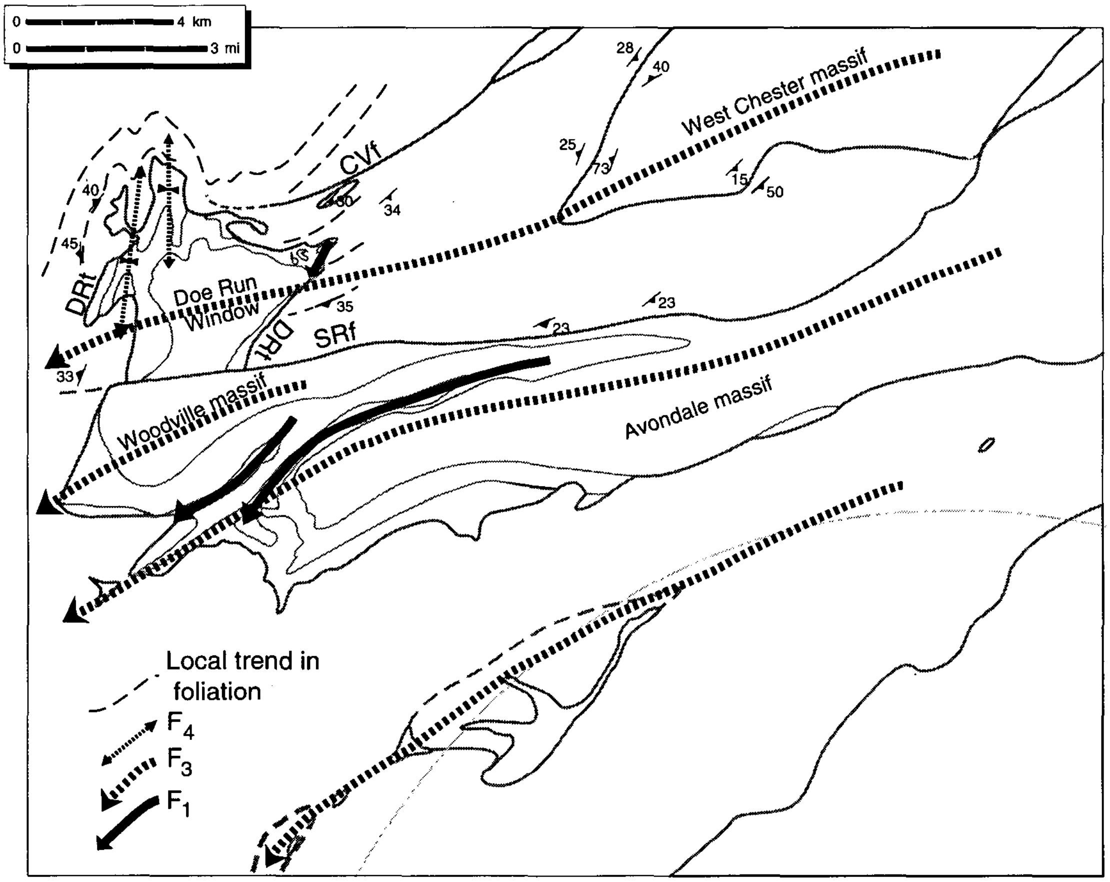

Figure 2. Schematic presentation illustrating relationships among three of four fold sets. Pattern of foliation near Doe Run window is after McKinstry (1961). F_1 folds between Avondale and Woodville massifs are tight, recumbent synclines. Abbreviations: CVf, Cream Valley fault; DRt, Doe Run thrust; SRf, Street Road fault.

become steeper, and the strike, more variable. This suggests that the foliation in the Wissahickon Group was reoriented parallel to its basal contact either when it was thrust onto the Brandywine terrane or by differential slip along its contact during later deformation.

EVIDENCE FOR THE DOE RUN THRUST

Evidence for the Doe Run thrust is best presented by comparing the structural models of Bailey and Mackin (1937; and Mackin, 1950, 1962) and McKinstry (1961), which assume a conformable stratigraphy throughout the Glenarm Supergroup, with an alternative model that includes the Doe Run thrust. The models are tested at five localities on the margin of the Doe Run window (named here and identified in Fig. 1) by comparing observed field relations to those predicted by the different structural models.

Bailey and Mackin (1937; Mackin, 1950, 1962) and McKinstry (1961) interpreted the Woodville structure to be a recumbent fold (or nappe) verging to the northwest (Figs. 3a and 3b). Differences in interpretation arise from the choice of fold axis used as a reference, with Bailey and Mackin projecting the structure down F_3, whereas McKinstry used F_4. Both the Bailey and Mackin and the McKinstry models assume that the Wissahickon Group is structurally concordant with the Brandywine terrane rocks and, therefore, *lies beneath the overturned limbs of the recumbent F_1 folds.*

The alternative model has the Wissahickon Group form the hanging wall above a thrust fault or ductile shear zone. Because emplacement of the Wissahickon Group occurred after recumbent folding (F_1) of the Brandywine terrane rocks in the footwall, the thrust is discordant to those structures (Figs. 3c and 3d), and *the Wissahickon Group everywhere lies above Brandywine terrane rocks exposed within the Doe Run window.*

FIELD RELATIONSHIPS

Detailed geologic maps (Figures 4, 5, and 6) were originally produced at a scale of 1:10,000. In the absence of outcrop, the position of a lithologic contact was estimated using float; the strike and dip of bedding planes in the Setters Formation and, to a lesser degree, in the Cockeysville Marble; topographic features such as ridges and sinkholes; and the occurrence of euhedral, centimeter-sized garnets typical of the Wissahickon Group in the soil. Descriptions of field observations at each locality are given in the appendix.

Direct structural measurement was limited by sparse outcrop. (See Figs. 4, 5, and 6 for representative data.) Additional evidence of structural relations was obtained from scattered well log reports and from ground magnetic surveys (Figs. 7 and 8). Magnetic data were collected using a proton precession magnetometer measuring total magnetic field at a height of 8 ft.

Detailed analysis of kinematic indicators has not been attempted because the event that is the focus of this paper probably precedes peak metamorphism in the Doe Run area and was succeeded by three additional deformations. Recognition of textures and indicators related solely to this early event would be difficult (Simpson, 1989).

The key relationship at each of the five localities is the position of the Wissahickon Group relative to the Brandywine terrane rocks. Because the Grenville-aged gneiss, Setters Formation, and Cockeysville Marble in the Doe Run window are commonly found in an inverted stratigraphic sequence, the position of the Wissahickon Group above or below the Brandywine terrane rocks becomes a test of the assumed stratigraphic continuity within the Glenarm Supergroup and, therefore, of the different structural models. For this reason, a series of heavy dashes drawn on each detailed map identifies the overlying unit at locations where this can be determined. Local cross sections contrast the model proposed here with the Bailey-Mackin and McKinstry

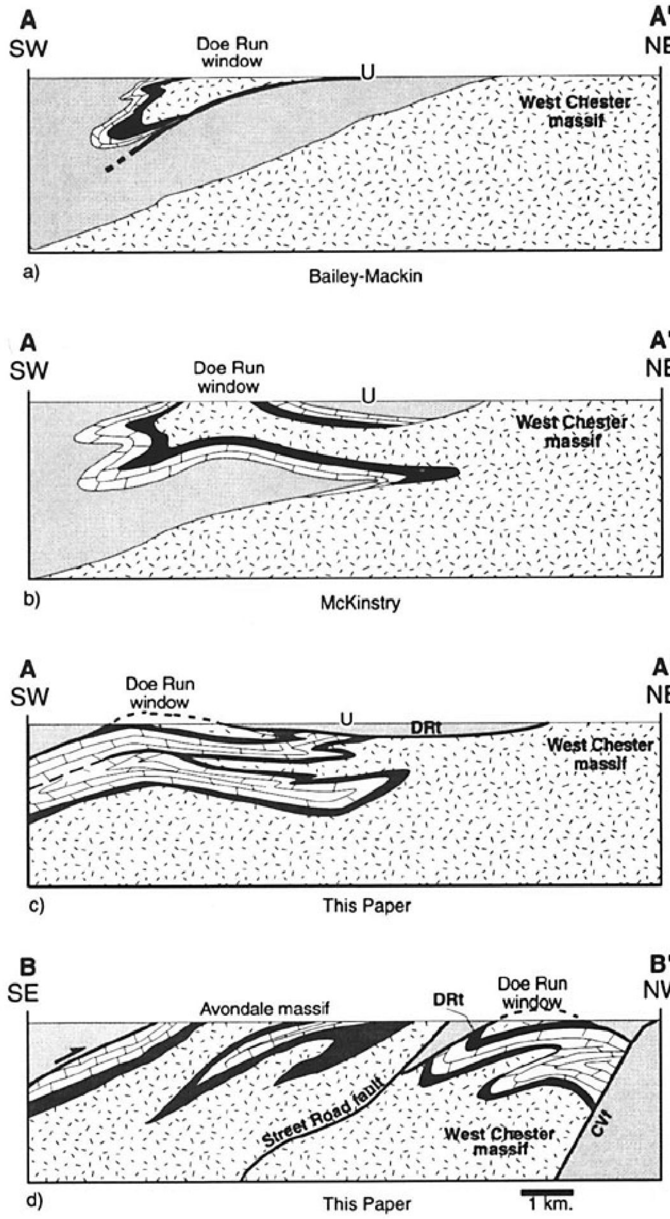

Figure 3. Contrasting longitudinal cross sections in a, after Bailey-Mackin (1937; Mackin, 1950, 1962), b, after McKinstry (1961), and c, the model proposed here, illustrating differences between structural models. Cross-strike view, d, illustrates post–Doe Run thrust deformation by Street Road fault and F_3. Note that in c and d the Wissahickon Group consistently lies above Brandywine terrane rocks exposed in the Doe Run window.

Lines A–A′ and B–B′ in Figure 1 locate sections. Patterns and symbols are same as in Figure 1. Abbreviations: DRt, Doe Run thrust; U, Upland. Total topographic relief along sections is <400 ft and cannot be shown at the scale of the drawing. Parts a, b, and c are at same scale as Figure 1. No vertical exaggeration.

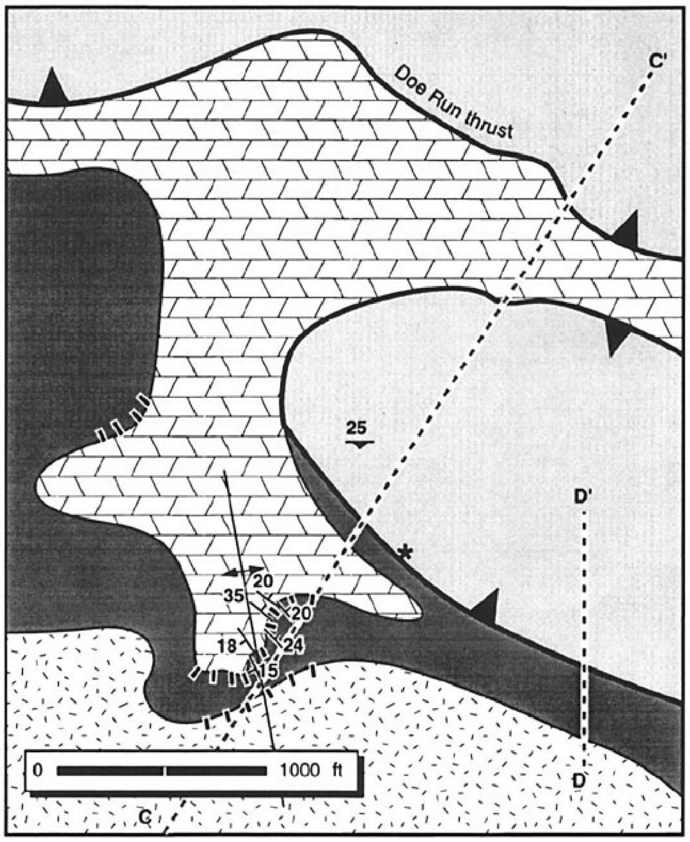

Figure 4a. Geologic map of Buck and Doe Run Farm area, box 4, Figure 1. Heavy dashes on lithologic contact are drawn into structurally higher unit where structural relations are clearly established in field. Asterisk indicates position of microcline-bearing gneiss and sheared Wissahickon Group schist discussed in appendix. F_4 trend is from field observation. D–D′ locates magnetic profile, Figure 7.

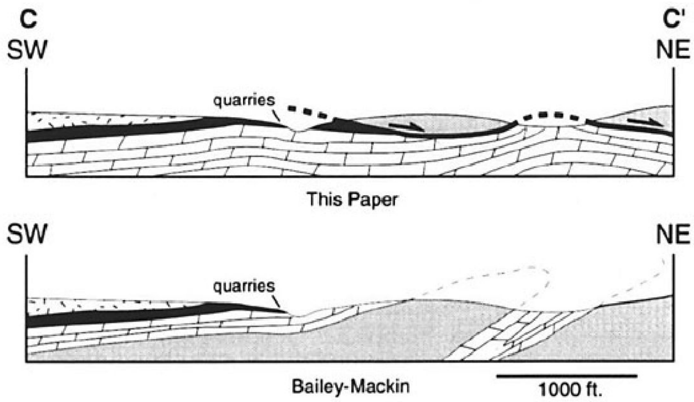

Figure 4b. Schematic cross sections along C–C′ (Fig. 4a) contrasting proposed structural model and Bailey-Mackin model (1937). View is to northwest. Note that the Bailey-Mackin model does not predict observed field relations. Symbols and patterns are same as in Figure 1. No vertical exaggeration.

models and compare the ability of the models to predict observed field relations.

Both field observations and ground magnetic surveys show the Wissahickon Group in the highest structural position at all five locations, independent of the vertical sequence of rocks within the window. These field relations identify a structural discontinuity, the Doe Run thrust, and establish the timing of emplacement of the Wissahickon Group along the Doe Run thrust as post-F_1 folding of the Brandywine terrane rocks.

POSTTHRUST DEFORMATION

The Street Road and Cream Valley faults cut the Brandywine terrane and the Wissahickon Group and, therefore, postdate the Doe Run thrust. Structural studies of the Street Road and Cream Valley faults indicate that northwest-directed thrusting and a later transpressional event that produced top-to-the-west-southwest movement occurred after peak metamorphism (Wiswall, 1990; Wagner and others, 1991; C. G. Wiswall, 1992, personal commun.). F_2 and associated fabrics may have formed with northwest-directed thrusting along the Street Road and Cream Valley faults. Replacement of sillimanite, garnet, and K-feldspar by kyanite, muscovite, and staurolite in the Wissahickon Group adjacent to the Street Road fault (Alcock, unpub. data) suggests a pressure increase consistent with this possibility. Transpression-related movement on the Cream Valley fault probably formed F_4 folds in the area of the Doe Run window, and it is refolding of F_3 by F_4 that lifts the window (McKinstry, 1961; Anderson, 1964; Wise, 1970; Wiswall, 1990).

Post–Doe Run thrust deformation is important to interpretation of a circular magnetic anomaly that is centered in Wissahickon Group east of Upland and continues into the Avondale and Woodville massifs (Fisher and others, 1979). This anomaly, similar to others in the Wissahickon Group, has been interpreted as evidence supporting the Bailey-Mackin structural model because it "shows" the Wissahickon Group passing beneath the massifs (Fisher and others, 1979). However, the Street Road fault places the Avondale and Woodville massifs above Wissahickon Group rock, so that the continuation of the anomaly into the massifs is expected. More important to the discussion here is what happens along the eastern margin of the Doe Run window. There, the anomaly becomes distinctly linear, suggesting that the Wissahickon Group is thinning and ending along the edge of the window.

APPLICATION OF DOWN-PLUNGE METHOD TO DISCORDANT SURFACES

Down-plunge reconstructions are possible in areas where structural surfaces are discordant. For example, in the nearby Martic area, Wise (1970) used multiple down-plunge projections to remove a later fold set before projecting down the plunge of early folds to show the original geometry of the Martic thrust.

In the Doe Run area, the problem is one of a discordant thrust that can produce distinct senses of plunge in hanging-wall and footwall rocks. Near the town of Doe Run, the Setters Formation lies in the core of a south-plunging synform (Fig. 6), but just to the west, the Wissahickon Group occupies a north-plunging syncline (see appendix for field descriptions). The plunges of the folds reflect the different prefold orientations of the surfaces being viewed, a southerly dip to bedding in the Setters Formation and Cockeysville Marble and the northerly dip of Doe Run thrust. In situations like this, one must be careful to separate the plunges before attempting a projection. For example, a cross section showing the Doe Run thrust (Fig. 6c) is

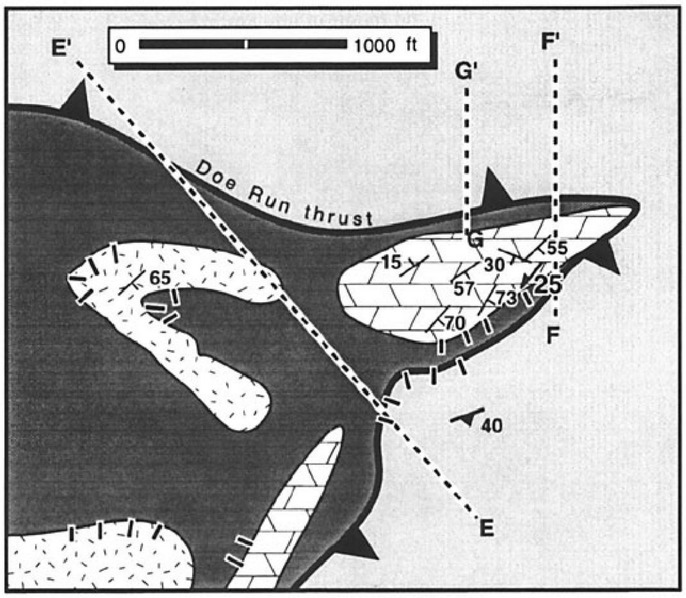

Figure 5a. Geologic map in area of Logan's quarry (box 5, Fig. 1). Heavy dashes on lithologic contact are drawn into structurally higher unit where structural relations are clearly established in field. Lines F–F′ and G–G′ give location of ground magnetic surveys shown in Figure 8.

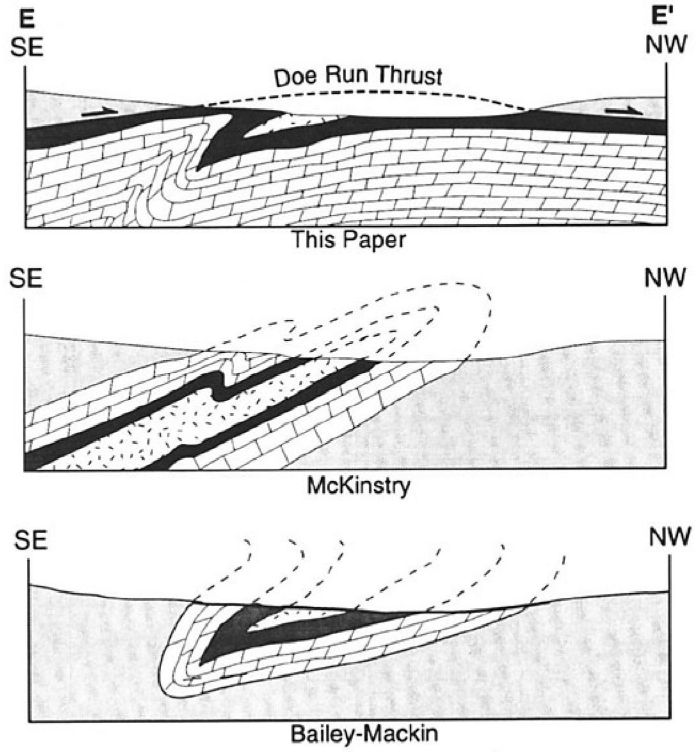

Figure 5b. Schematic cross sections along line E–E′ (Fig. 5a) contrasting three structural models. View is to southwest. Note that Doe Run thrust is consistent with field observations, but Bailey-Mackin (1937) and McKinstry (1961) models are not. Symbols and patterns are same as in Figure 1. Cross section is at same scale as Figure 5a. No vertical exaggeration.

projected down the plunge of F_4 folding of the thrust. Although one might expect Setters Formation from south of Springdell to project into the cross section, the Setters Formation–Cockeysville Marble contact here dips to the south as it does in the synform east of Doe Run. The Setters Formation, therefore, would project into the air above the projection along H–H′. A down-plunge projection along a line parallel to H–H′ but at Shabatz Road (Sh, Fig. 6) could be used to show Brandywine terrane structure so long as the Wissahickon Group to the north was excluded.

IMPLICATIONS FOR REGIONAL STRUCTURE

Recognition of thrust faults at the base of the Wissahickon Group leads to a new regional structural model in which the Wissahickon Group is separated from F_1 folds in the Brandywine terrane. One possibility is that the Doe Run thrust is regional in extent, and the Wissahickon Group between the Wilmington Complex and the Cream Valley fault was emplaced as a single sheet. The present gentle but irregular southwest dip of the thrust surface is not the original because the regional southwest plunge of F_3 results from postthrust deformation. Probably the thrust originally cut upsection from east to west as indicated by the position of the Wissahickon Group directly above Grenville-aged gneiss in the east (Fig. 1) but above the Setters Formation and Cockeysville Marble in the west. Emplacement at moderate depth (see above) would have allowed the thrust fault to follow zones of structural weakness such as shear zones or axial planes of folds that had already been established during recumbent folding of the Brandywine terrane, and the thrust could remain subhorizontal except where it ramped up from one décollement to another.

Alternatively, distinct packages within the Wissahickon Group may have been emplaced along multiple thrusts at different times and at different structural levels (Wagner and others, 1991). Serpentinite bodies are common in the Wissahickon Group near the West Chester massif but are rare elsewhere. It follows that the Wissahickon Group adjacent to the West Chester massif may have a distinctive origin as well. Further research is needed to clarify stratigraphic and structural relations within the Wissahickon Group of the Pennsylvania-Delaware Piedmont before it will be possible to determine if emplacement occurred along a single or multiple thrusts.

In either case, the Brandywine terrane is exposed in complex windows bounded by a thrust fault or faults at the base of the Wissahickon Group and by the later Street Road and Cream Valley faults. Prethrust recumbent folds are exposed within windows, and others may be hidden from view where the Wissahickon Group has not been removed by erosion (Figs. 3c and 3d). However, one result of recognizing the structural discordance of the Wissahickon Group is to make any attempt to define the structure of the Brandywine terrane rocks beneath the Wissahickon Group highly speculative.

Correlation of stratigraphy and structure in the Doe Run area to other regions in the Central Appalachian Piedmont is problematic. Although the presence of Grenville-aged gneiss and similar metasedimentary rocks in the massifs near Baltimore and in southeastern Pennsylvania has been used to correlate the two regions, significant differences exist. For example, amphibolites, metagabbros, and serpentinites are more common in the metapelites of southeastern Pennsylvania than they are in the Loch Raven Schist, the metapelitic basal unit of the Wissahickon Group in Maryland (for example, Crowley, 1976). The presence of the Wilmington Complex arc-terrane and the

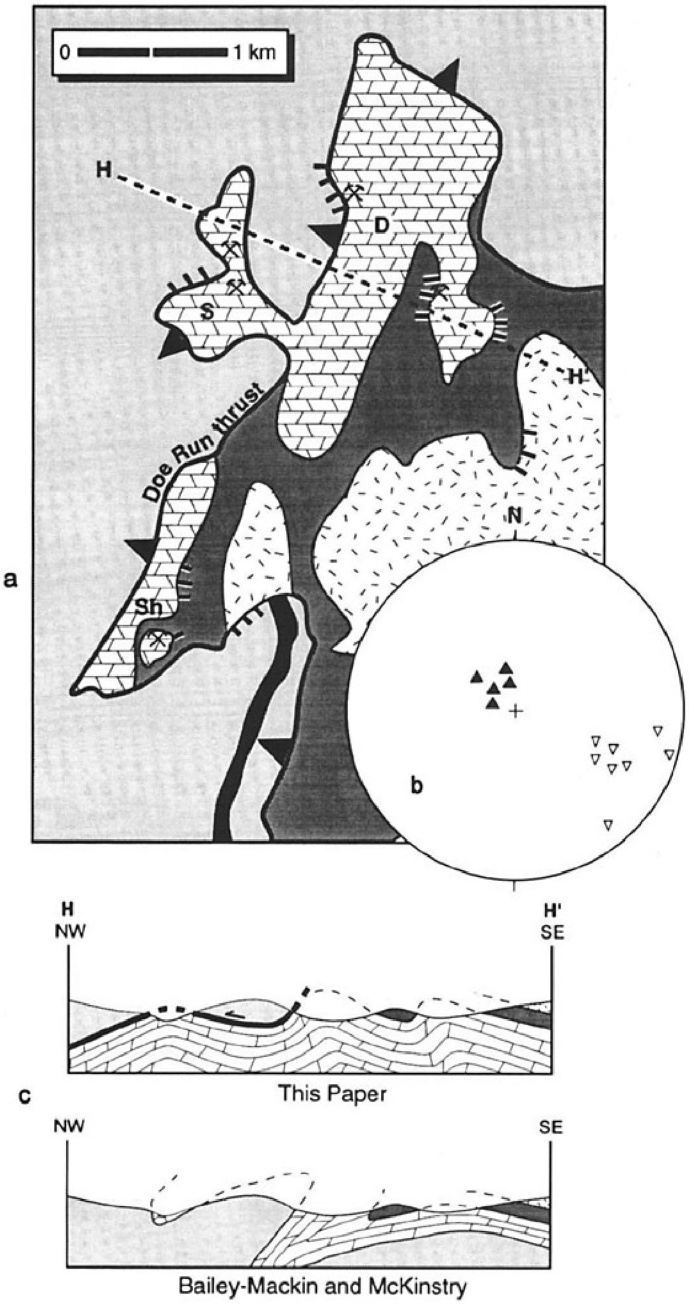

Figure 6. a. Geologic map along western edge of Doe Run window (Box 6, Fig. 1). Heavy dashes at contact are drawn into structurally higher unit if unambiguously determined in the field. D, Doe Run; Sh, Shabatz Road; S, Springdell. Patterns and symbols are same as in Figure 1, with amphibolite body near Shabatz Road shown as black. b. Lower hemisphere projection of poles to bedding (Cockeysville Marble) and foliation (Wissahickon Group) between Springdell and Doe Run indicates synformal nature of ridge of Wissahickon Group between two marble exposures. Data from east of ridge are shown as open triangles. c. Schematic cross sections along line H–H′ contrasting proposed model to models of Bailey and Mackin (1937) and McKinstry (1961). View is to northeast, down inferred plunge of synformal ridge. Note that the proposed model predicts the observed antiforms and synforms. Cross section is at same scale as Figure 6a. No vertical exaggeration.

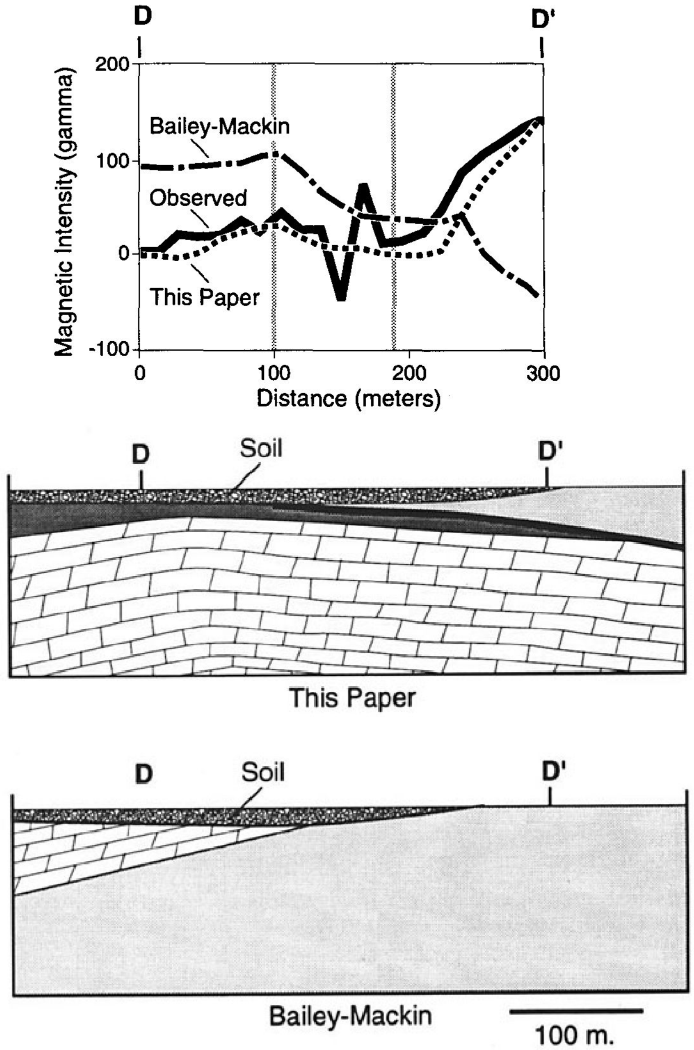

Figure 7. Results of ground magnetic survey and model anomalies along line D–D′ (Fig. 4a). Magnetic intensity is compared to arbitrary datum. Model anomalies were calculated with MacMagnetics (Malinconico and Larson, 1989). Assigned magnetic susceptibilities were .00002 emu/cm^3 for Cockeysville Marble and Setters Formation, and .0015 emu/cm^3 for Wissahickon Group (Fisher and others, 1979). Soil is assigned susceptibility of .0001 emu/cm^3. This assumes reduced susceptibility of oxidized Wissahickon Group. Topographic change modeled as change of thickness for surface lithology to maintain horizontal reference surface. Dashed lines give limits to location of lithologic contact between Wissahickon Group and Brandywine terrane rocks as constrained by field observations. Sharp anomaly within that zone occurs at Route 82 and is thought to be related to road. No vertical exaggeration in structural models.

higher grade of metamorphism in the Pennsylvania-Delaware Piedmont also suggest that this area and the Baltimore region may have distinct geologic histories. Recognition of the Doe Run thrust in contrast to the apparent conformable relations across the Cockeysville Marble–Loch Raven Schist contact in the Baltimore area (Crowley, 1976) raises additional concerns about the correlation of stratigraphy and geologic history between the two regions.

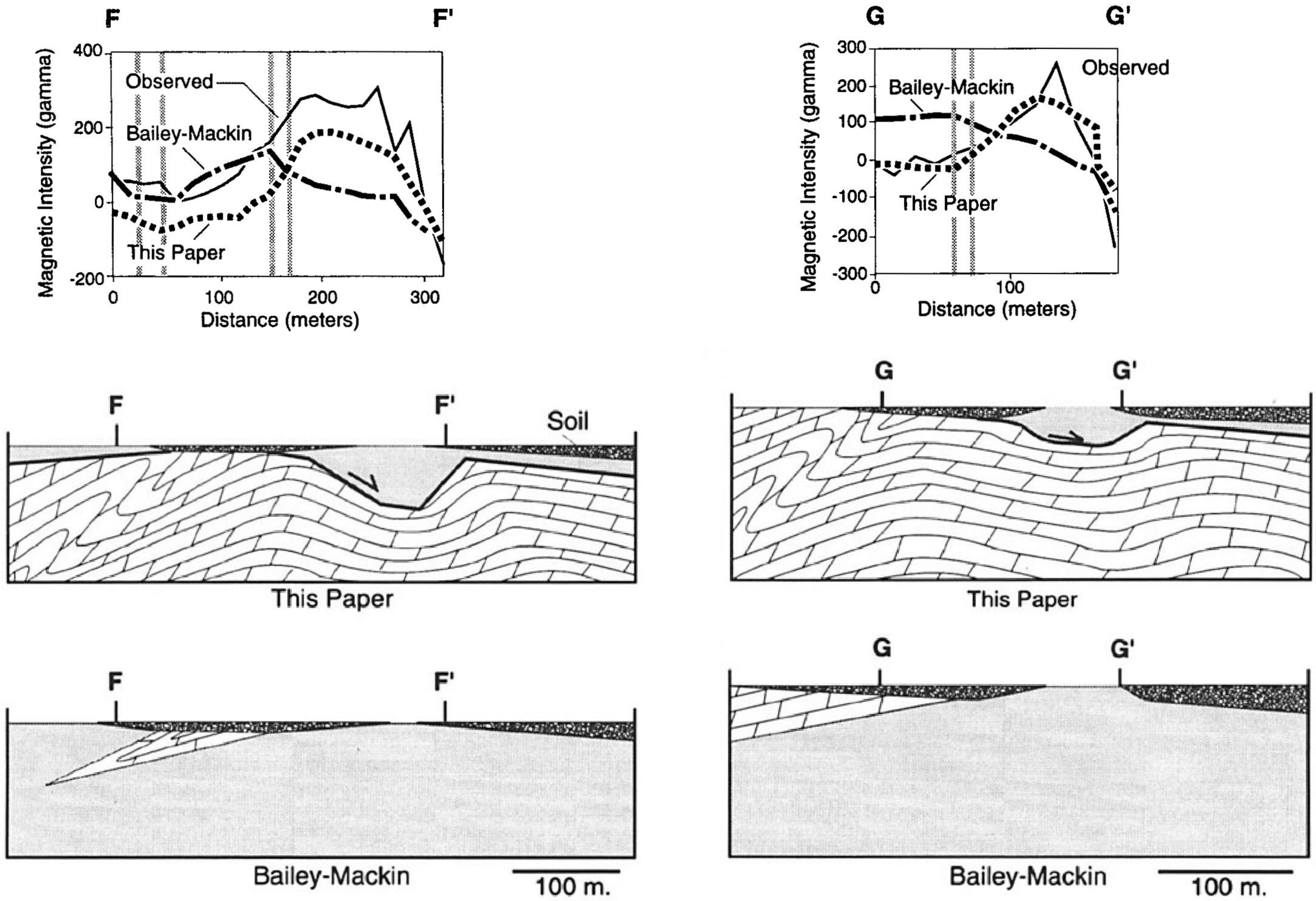

Figure 8. Observed and model magnetic anomalies for representative traverses in the area of Logan's quarry (Fig. 5a). Magnetic intensity is compared to arbitrary datum. Dashed lines indicate location of lithologic contact between Wissahickon Group and Brandywine terrane rocks as constrained by field observations.

Model anomalies were calculated as in Figure 7. Setters Formation is not included because its susceptibility is similar to Cockeysville Marble (Fisher and others, 1979). No vertical exaggeration in structural models.

CONCLUSION

Field relations in the area of Doe Run, southeastern Pennsylvania, can be used to recognize a significant structural discontinuity, the Doe Run thrust, that separates the Wissahickon Group from the Setters Formation and Cockeysville Marble. The discontinuity reflects the tectonic emplacement of the Wissahickon Group after recumbent folding of the Brandywine terrane including the Setters Formation and Cockeysville Marble in the thrust's footwall. It, therefore, makes untenable the longstanding assumption that the Glenarm Supergroup is a conformable stratigraphic package in the Pennsylvania-Delaware Piedmont. Recognition of the Doe Run thrust also implies that the assumed correlation of lithologies in this area with those found about the gneiss-cored massifs near Baltimore, Maryland, may be incorrect.

ACKNOWLEDGMENTS

Research reported here began as part of a doctoral dissertation under the direction of M. E. Wagner at the University of Pennsylvania. Additional support was given by Penn State University and by the Pennsylvania Department of Environmental Resources, Bureau of Geologic and Topographic Survey. I thank M. E. Wagner, L. Srogi, C. G. Wiswall, and M. L. Crawford, who helped me to clarify my thinking and writing; D. U. Wise, who reviewed an earlier version of the manuscript, for his suggestions and support; and R. Faill and G. W. Fisher for their thoughtful reviews of the manuscript as well. The advice and assistance of D. Dibiase, PSU Deasy GeoGraphics Lab, were invaluable.

APPENDIX: DETAILED DESCRIPTION OF FIELD RELATIONS

1. Upland: Southeast Corner of Doe Run Window

A well log from Upland (U, Figs. 1 and 3) reports passing out of a schist that can be identified in the field as Wissahickon Group and into marble at a depth of 30 ft. Soil type, float, and occasional outcrop also indicate that the Wissahickon Group is the structurally highest unit and lies above the Cockeysville Marble and Baltimore Gneiss at this location.

2. Buck and Doe Run Farm Quarry

Field relations near the Buck and Doe Run Farm quarry (Fig. 4) indicate that the Wissahickon Group lies above overturned Brandywine terrane rocks.

The overturned stratigraphic sequence is exposed in the Buck and Doe Run Farm quarries. There, Setters Formation lies above Cockeysville Marble brought to the surface by an open antiform (F_4) trending N10°W with a subhorizontal axis.

North of the quarries, coarse-grained Wissahickon Group muscovite-staurolite-garnet-kyanite schist holds up an east-west–trending ridge. The schist is found as float blocks, as weathered outcrop, and as saprolite. Foliation measured at a weathered outcrop strikes approximately east-west and dips ≈25° to the south. This foliation is similar to regional strike and is consistent with foliation in the Wissahickon Group near its contact with Brandywine terrane rocks throughout the region.

A zone of weathered, mylonitic schist and gneiss rich in microcline augen is exposed for about 100 m in a road bank (asterisk, Fig. 4). The presence of potassium feldspar can be used to identify these as Brandywine terrane rock. Both the Grenville-aged gneiss and the Setters Formation contain abundant microcline, and microcline is always more abundant than plagioclase in the Setters Formation. On the other hand, potassium feldspar has been found in only a single sample of the Wissahickon Group from the Doe Run area. This sample, which has abundant plagioclase, was taken from the contact of the Wissahickon Group with the Cockeysville Marble and may have been contaminated by the marble, which contains abundant potassium feldspar.

Highly sheared, garnetiferous Wissahickon Group schist is found directly above the microcline-bearing mylonite. This would seem to indicate that the Wissahickon Group originally lay above the mylonite, but it is possible that blocks of Wissahickon Group have slipped down-slope from the ridge to the north. However, although the relative position of the Wissahickon Group to the mylonite cannot be determined unequivocally in the road bank, it is clear that there is no room for the Cockeysville Marble between the Wissahickon Group and the mylonite as would be required if contacts were conformable.

A ground magnetic survey across this contact (Fig. 7) shows a small but distinct increase in magnetic intensity over the Wissahickon Group. Simplified structural models that assumed either a discordant Wissahickon Group thrust across the Doe Run window or a concordant Wissahickon Group passing under the window were used to compute model anomalies that were compared with the observed anomaly along the south-to-north traverse. Model anomalies were calculated using the program MacMagnetics (Malinconico and Larson, 1989).

Considerable uncertainty in the magnetic models arises from estimates of magnetic susceptibilities, thickness of soil cover, thickness of lithologies, and location of the contact. The size of the calculated anomaly is sensitive to changes in these variables. However, the shape of the anomaly is controlled by the relative position of the lithologic units and the dip of their contact. For example, whether the anomaly rises or falls across the contact is relatively insensitive to change in the variables listed above. Instead it depends on whether the Wissahickon Group lies above or passes under the Brandywine terrane rocks. The shape of the anomaly, therefore, can be used to determine relative position of the lithologies.

The observed increase in the magnetic anomaly over the Wissahickon Group (Fig. 7) is consistent with the Wissahickon Group lying above the overturned Brandywine terrane rocks. If the Wissahickon Group passed beneath the Brandywine terrane rocks, then the anomaly should peak south of the contact and decrease to the north after it is crossed.

3. Logan's Quarry: Northeast "Nose" of the Doe Run Window

Logan's quarry (Fig. 5) is cut into the Cockeysville Marble and exposes large (to >5 m) recumbent to Z-shaped folds (probably F_1) plunging 30° along S40°W. These folds are interpreted to be subsidiary folds on the overturned limb of the larger recumbent fold that creates the inverted stratigraphy of the Brandywine terrane rocks within the Doe Run window. However, because the sense of vergence of the folds does not fit a simple parasitic fold model, they may be drag folds formed during emplacement of the Wissahickon Group.

The axial planes of the F_1(?) folds have been refolded by both F_3 and F_4, so that bedding and foliation in the marble dip to the southeast on the southeast wall of the quarry but roll over to dip to the north in the quarry's northwest corner. The later folding, therefore, creates an antiform that lifts the marble in the quarry where it is exposed through the overlying Wissahickon Group.

In the area around Logan's quarry, the Brandywine terrane rocks exhibit an inverted stratigraphic sequence, although they are locally upright on the doubly overturned limbs of subsidiary folds. To the southeast of the quarry, Setters Formation lies above the Cockeysville Marble. To the west, in what would be the core of the F_1(?) folds exposed in the quarry, the Setters Formation is found both below and above Grenville-aged gneiss (Fig. 5).

Typical garnet-staurolite-kyanite Wissahickon Group lies to the southeast, dipping to the southeast, topographically above the overturned Brandywine terrane rocks (Fig. 5). Because they are on strike with the well at Upland (discussed above), they presumably are in the same structural position, above Brandywine terrane rock. This is also consistent with the southeast dip of bedding in the Cockeysville Marble exposed in the southeast wall of the quarry. It should be noted, though, that at Upland the Wissahickon Group apparently lies on Cockeysville Marble, whereas at Logan's quarry it is above Setters Formation.

North of the quarry, there is a continuation of the ridge found north of the Buck and Doe Run Farm quarries. Although there is no outcrop, soil along the ridge is very rich in mica, garnet, and flakes of garnetiferous schist, indicating a Wissahickon Group source. At the base of the ridge, float is predominantly a microcline-bearing schist similar to the mylonite found at the Wissahickon Group–Brandywine terrane contact near the Buck and Doe Run Farm quarries. The similarities between the two locations suggest that the Wissahickon Group lies above the Brandywine terrane rocks along the length of the ridge.

The pattern of magnetic anomalies in the area of the quarry supports this interpretation (Fig. 8). Magnetic intensity increases from a low over the Brandywine terrane rocks to a high above the Wissahickon Group north of the contact. Model anomalies were compared with the observed anomalies along two south-to-north traverses. It is possible to use the north-dipping contact predicted by the discordant structural model to obtain model anomalies that are similar in shape to the observed anomalies. However, calculated anomalies for the Bailey-Mackin (1937) model with the Wissahickon dipping beneath the Brandywine terrane rocks predict a decrease in magnetic intensity where the measured intensity increases (Fig. 8).

4. Shabatz Road, Southwest Corner of Doe Run Window

Near Shabatz Road (Sh, Fig. 6), the overturned stratigraphy of Setters Formation above Cockeysville Marble is exposed in two quarries. The position of the Wissahickon Group above these units can be established in the field using an extensive amphibolite body as a marker (Fig. 6). The amphibolite lies above the Setters Formation and within pelitic to semipelitic schists identified as belonging to the Wissahickon Group on the basis of rare garnet and the presence of plagioclase but not microcline. Typical garnet-staurolite-kyanite schist of the Wissahickon Group lies a few meters above the amphibolite.

5. Springdell

At Springdell (S, Fig. 6), the Wissahickon Group occurs as north-south–trending ridges to the east and west of two moderate-sized quarries in Cockeysville Marble. The structure here is dominated by F_4 folds. Marble is exposed at the surface where it has been lifted by F_4 antiforms, and the Wissahickon Group remains where it is dropped in a synform. A stereographic plot of poles to foliation and bedding on the east and west sides of the ridge to the east of the quarries clearly shows its synformal nature (Fig. 6b). The structural data, therefore, are opposite to relations predicted by the conformable models of Bailey and Mackin (1937; Mackin 1950, 1962) and McKinstry (1961) (Fig. 6c).

At the northern end of the Springdell quarries, irregularly shaped bodies of a graphite-rich, microcline-bearing schist occur in and above the uppermost layers of marble. The schist is probably Setters Formation, which would indicate an inverted stratigraphy similar to that found elsewhere within the Doe Run window, including directly on strike at Shabatz Road (see above) and a few hundred meters to the east where Cockeysville Marble dips west beneath the Setters Formation in another small quarry.

REFERENCES CITED

Alcock, J. E., 1989, Tectonic units in the Pennsylvania-Delaware Piedmont: Evidence from regional metamorphism and structure [Ph.D. thesis]: Philadelphia, Pennsylvania, University of Pennsylvania, 259 p.

Alcock, J. E., 1992, Windows and discordant thrusting, southern Chester County, Pennsylvania Piedmont: Alternative model for regional structure: Geological Society of America Abstracts with Programs, Northeastern Section, v. 24, p. 2.

Anderson, T. H., Drake, D. E., and Wise, D. U., 1964, Megapetrofabric of the Coatesville–Doe Run Area, Penna.: Proceedings of the Pennsylvania Academy of Science, v. 38, p. 174–182.

Bailey, E. B., and Mackin, H., 1937, Recumbent folding in the Pennsylvania Piedmont; preliminary statement: American Journal of Science, v. 33, p. 187–190.

Bascom, F., and Stose, G. W., 1932, Description of the Coatesville and West Chester quadrangles: U.S. Geological Survey Atlas, Folio 223, 15 p.

Berg, T. M., Edmunds, W. E., Geyer, A. R., Glover, A. D., Hoskins, D. M., and others, 1980, Geologic map of Pennsylvania: Pennsylvania Geological Survey, Fourth Series, Map 1.

Bliss, E. F., and Jonas, A. I., 1916, Relation of the Wissahickon mica gneiss to the Shenandoah limestone and the Octararo schist of the Doe Run and Avondale region, Chester County, Pennsylvania: U.S. Geological Survey Professional Paper 98-B, 34 p.

Crawford, M. L., and Crawford, W. A., 1980, Metamorphic and tectonic history of the Pennsylvania Piedmont: Journal of the Geological Society of England, v. 137, p. 311–320.
Crawford, M. L., and Mark, L. E., 1982, Evidence from metamorphic rocks for overthrusting, Pennsylvania Piedmont: Canadian Mineralogist, v. 20, p. 333–347.
Crowley, W. P., 1976, The geology of the crystalline rocks near Baltimore and its bearing on the evolution of the Eastern Maryland Piedmont: Maryland Geological Survey Report of Investigations No. 27, 40 p.
Drake, A. A., Jr., Sinha, A. K., Laird, J., and Guy, R. E., 1989, The Taconic orogen, *in* Hatcher, R. D., Jr., Thomas, W. A., and Viele, G. W., eds., The Geology of North America, Volume F-2, The Appalachian-Ouachita Orogen in the United States: Boulder, Colorado, Geological Society of America.
Fisher, G. W., Higgins, M. W., and Zeitz, I., 1979, Geological interpretations of aeromagnetic maps of crystalline rocks in the Appalachians, northern Virginia to New Jersey: Maryland Geological Survey Report of Investigations No. 32, 43 p.
Higgins, M. W., 1972, Age, origin, regional relations, and nomenclature of the Glenarm Series, Central Appalachian Piedmont: A reinterpretation: Geological Society of America Bulletin, v. 83, p. 989–1026.
Higgins, M. W., Fisher, G. W., and Zeitz, I., 1973, Aeromagnetic discovery of a Baltimore Gneiss dome in the Piedmont of northwestern Delaware and southeastern Pennsylvania: Geology, v. 1, p. 41–43.
Knopf, E. B., and Jonas, A. I., 1923, Stratigraphy of the crystalline schists of Pennsylvania and Maryland: American Journal of Science, 5th Series, v. 5, p. 40–62.
Mackin, H., 1950, Down structure method of viewing geologic maps: Journal of Geology, v. 58, p. 55–72.
Mackin, H., 1962, Structure of the Glenarm Series in Chester County, Pennsylvania: Geological Society of America Bulletin, v. 73, p. 403–410.
Malinconico, L. L., Jr., and Larson, T., 1989, MacMagnetics: An interactive modelling program: Carbondale, Illinois, Micro-innovations, Inc.
McKinstry, H., 1961, Structure of the Glenarm Series in Chester County, Pennsylvania: Geological Society of America Bulletin, v. 72, p. 557–578.
Rodgers, J., 1968, The eastern edge of the North American continent during the Cambrian and Early Ordovician, *in* Zen, E-An, White, W. S., Hadley, J. B., and Thompson, J. B., Jr., eds., Studies of Appalachian geology: Northern and maritime: New York, Interscience Publishers, p. 141–149.
Simpson, C., 1989, Methods of microstructural analysis: Geological Society of America, Northeast Section, Short-Course Notes, 35 p.
Srogi, L., 1982, A new interpretation of contact relationships and early Paleozoic history of the Delaware Piedmont: Geological Society of America Abstracts with Programs, v. 14, p. 85.
Valentino, D. W., and Wiswall, C. G., 1991, Post-Taconian deformation in the Pennsylvania Piedmont and the tectonic implications: Geological Society of America Abstracts with Programs, v. 23, p. 72.
Wagner, M. E., and Srogi, L. A., 1987, Early Paleozoic metamorphism at two crustal levels and a tectonic model for the Pennsylvania-Delaware Piedmont: Geological Society of America Bulletin, v. 99, p. 113–126.
Wagner, M. E., Srogi, L. A., Wiswall, C. G., and Alcock, J., 1991, Taconic collision in the Delaware-Pennsylvania Piedmont and implications for subsequent geologic history, *in* Schultz, A., and Compton-Gooding, E., eds., Geologic evolution of the eastern United States: Field Trip Guidebook, NE-SE GSA 1991, Virginia Museum of Natural History Guidebook 2.
Wise, D. U., 1970, Multiple deformation, geosynclinal translation and the Martic problem in Pennsylvania, *in* Fisher, G. W., Pettijohn, F. J., Reed, J. C., Jr., and Weaver, K. N., eds., Studies of Appalachian geology: Central and southern: New York, Interscience Publishers, p. 317–333.
Wiswall, C. G., 1990, Tectonic history of a terrane boundary based on structural analysis in the Pennsylvania Piedmont: Northeast Geology, v. 12, p. 73–81.

Manuscript Received by the Society March 12, 1993
Revised Manuscript Received August 31, 1993
Manuscript Accepted October 1, 1993

Printed in U.S.A.