Vol. 46, No. 1

Pennsylvania Geology

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Folded wedge fault in the Tuscarora quartzite west of Macedonia, Pa. The wedge fault accommodated bed-parallel shortening when the beds were subhorizontal; it was then rotated during later folding (see article on page 4).

—Photograph by Zeshan Ismat

Deformation History Expressed Within the Juniata Culmination, Central Pennsylvania

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Introduction

Mountain belts (fold-thrust belts) are commonly curvilinear and vary in width along their length (Sussman and Weil, 2004). The number and size of the curves and degree of curvature may provide clues to the overall development of fold-thrust belts. Many of the current methods and terminology used today by geologists to understand the formation of mountains come from studies conducted in the Appalachian Mountains (e.g., Dana, 1866; Rodgers, 1963; Faill, 1973, 1999).

The Appalachian Mountains (Figure 1) extend from Newfoundland to central Alabama. Two of the chief distinguishing features of all fold belts, including the Appalachians, are (1) the prominent curves, termed salients, concave toward the foreland, that make up the entire mountain range, and (2) the patterns defined by thrusts and plunging folds. Our state is home to a distinctive salient—the Pennsylvania, or central, salient, within which are conspicuous plunging anticlines and synclines. These occur within the Ridge and Valley physiographic province.

The structural history of the Pennsylvania salient has been studied for more than 150 years (Dana, 1866; Rodgers, 1963; Gray and Stamatakos, 1997; Thomas, 1977, 2006; Faill, 1999; Wise, 2004; Ong and others, 2007; Sak and others, 2014) and still remains controversial. In map view, the Pennsylvania salient has a broad arcuate pattern with a central northwest-trending topographic high and structural culmination, the Juniata culmination. (A culmination is the highest part of a structural feature.) The "limbs" of the salient are composed of folds that plunge to the northeast and southwest on either side of the culmination (Faill, 1973) (Figure 1). The folds and thrusts within the salient formed during the Permian Alleghanian orogeny as the Laurentian and African cratons collided (Faill, 1999).

Currently, *two-azimuth* and *one-azimuth* models are used to explain the formation of the culmination and the adjacent plunging folds (Figure 2). Both models assume that the North American craton margin had a preexisting continental embayment, a ridge-transform corner, during the breakup of Rodinia and the opening of the Iapetus Ocean (Thomas, 2006), which guided and shaped the present geometry of the Pennsylvania salient during Alleghanian deformation. The limbs of the salient are defined by the Reading Prong and Blue Ridge. They are parallel to the flanks of the culmination. In both models, the Juniata culmination formed at the Eocambrian (latest Precambrian) reentrant's corner (Figure 1). Each model, however, predicts a different set of structures within the culmination.

The two-azimuth model suggests that the salient formed by two separate shortening directions, one directed approximately perpendicular to the Reading Prong and the other approximately perpendicular to Blue Ridge, and thus approximately perpendicular to the salient's limbs. Hence, the Juniata culmination formed as a result of the convergence of these two shortening directions (Figure 2) (Wise, 2004). The one-azimuth model, however, proposes a unidirectional northwest-directed transport toward the center of the salient (Gray and Stamatakos, 1997; Sak and others, 2014). In this case, the culmination formed

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Figure 1. A, Generalized map of the northern and central Appalachian Mountains showing major folds and topographic highs. B, Map of Pennsylvania showing folds in the Ridge and Valley physiographic province, the general area of the Juniata culmination, the proposed location of the Eocambrian craton's edge (dashed line and question marks), and the Blue Ridge and Reading Prong basement uplifts. The corner of the craton (also called the continental embayment or the reentrant's corner) is also indicated. The black dot marks the location of the field area.

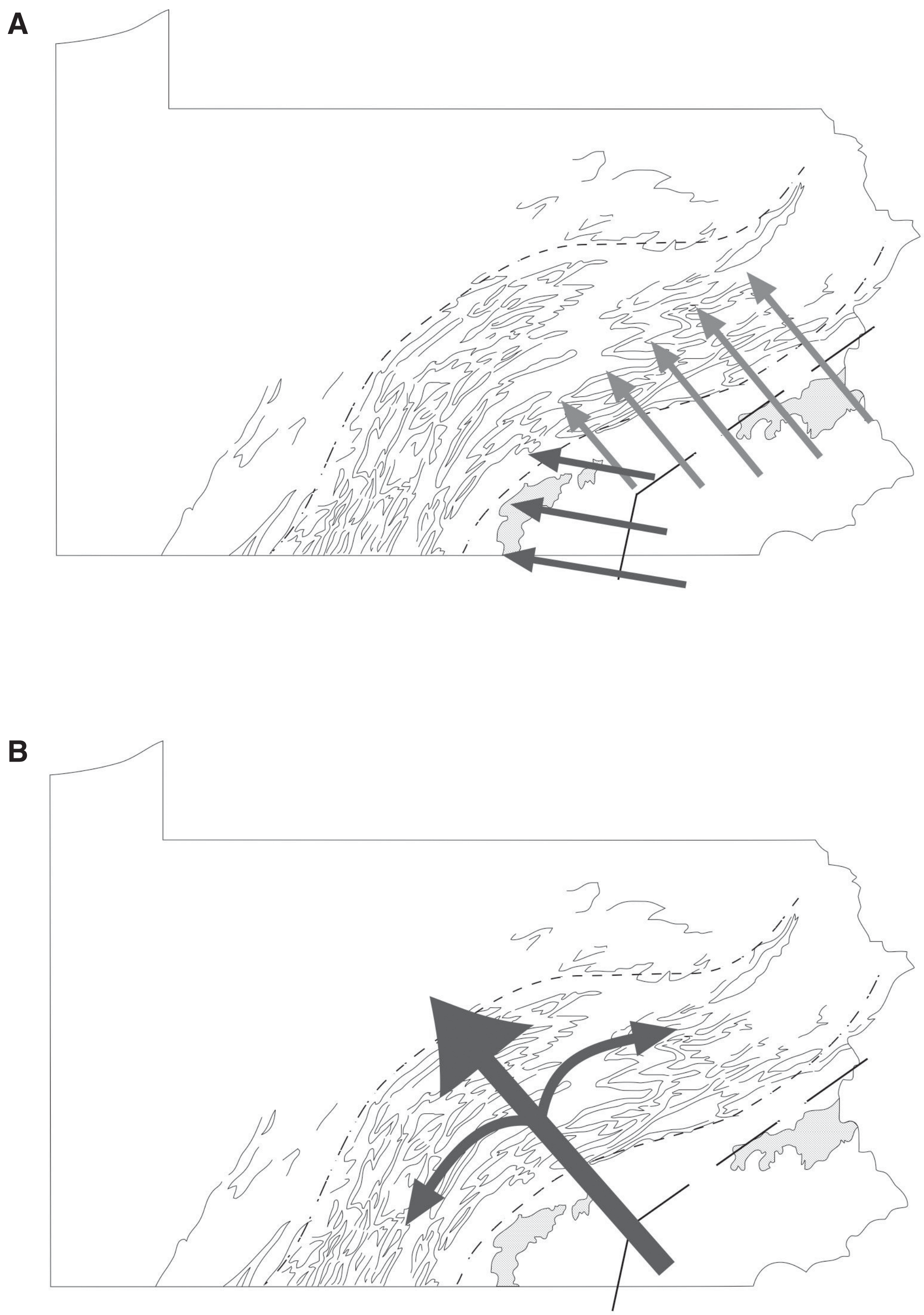


Figure 2. Generalized maps of the Ridge and Valley physiographic province showing the transport directions (arrows) in the two-azimuth (A) and one-azimuth (B) tectonic models. In A, the arrows lie at a high angle to the basement-cored uplifts (shaded).

as a result of concentrated shortening in a region where the sedimentary package was the thickest, specifically along the Eocambrian corner (Figure 2). Thus, the sediment "wedge" moved forward, forming the culmination, and flow occurred laterally, producing the plunging folds in the limbs—akin to an advancing angled snowplow.

One might expect that two overprinting sets of shortening directions should have been preserved in the culmination if the salient had been formed by the two-azimuth model. Alternatively, if the Pennsylvania salient formed according to the one-azimuth model, a single shortening direction, overall parallel to the Juniata culmination, should have been preserved.

Construction for the newly expanded U.S. Route 22/322 approximately 4 miles east of Lewistown has exposed a transect through the Juniata culmination. In our study, we examined structures preserved along this transect and analyzed the shortening directions defined by several generations of structures that are present. The intent was to determine the overall shortening history within the Juniata culmination. We examined the salient's two limbs in order to determine which model, if either, is appropriate. The new exposures provide a resolution to the choice of models.

Solving this puzzle may help us understand the role of preexisting sedimentary packages and the shape of the preexisting craton to mountain-belt formation. Also, culminations are commonly regions for natural resource exploration; therefore, understanding the formation of this one may provide clues for potential exploration locations. Finally, this area may provide another model for mountain-belt formation.

Location of Study Area and General Structure

The transect is located in the central region of the Juniata culmination, along the newly expanded U.S. Route 22/322 (Mannino, 2010), west of Macedonia, Pa. (Figure 3). The new roadcut trends northwest-southeast and exposes a cross section approximately perpendicular to the first-order fold hinges, providing a view of a profile plane for study. Therefore, the geometry of the structures is not distorted.

The transect lies within the first-order Shade Mountain anticlinorium (Figures 3, 4, and 5). The Shade Mountain anticlinorium is composed of two second-order anticlines, Shade Mountain and Blue Mountain, which form an en echelon fold pair (Figures 3 and 4). The transect is on the northwest limb of Blue Mountain and consists of three third-order asymmetric folds and smaller higher order folds throughout (Figures 4 and 5).

Stratigraphy

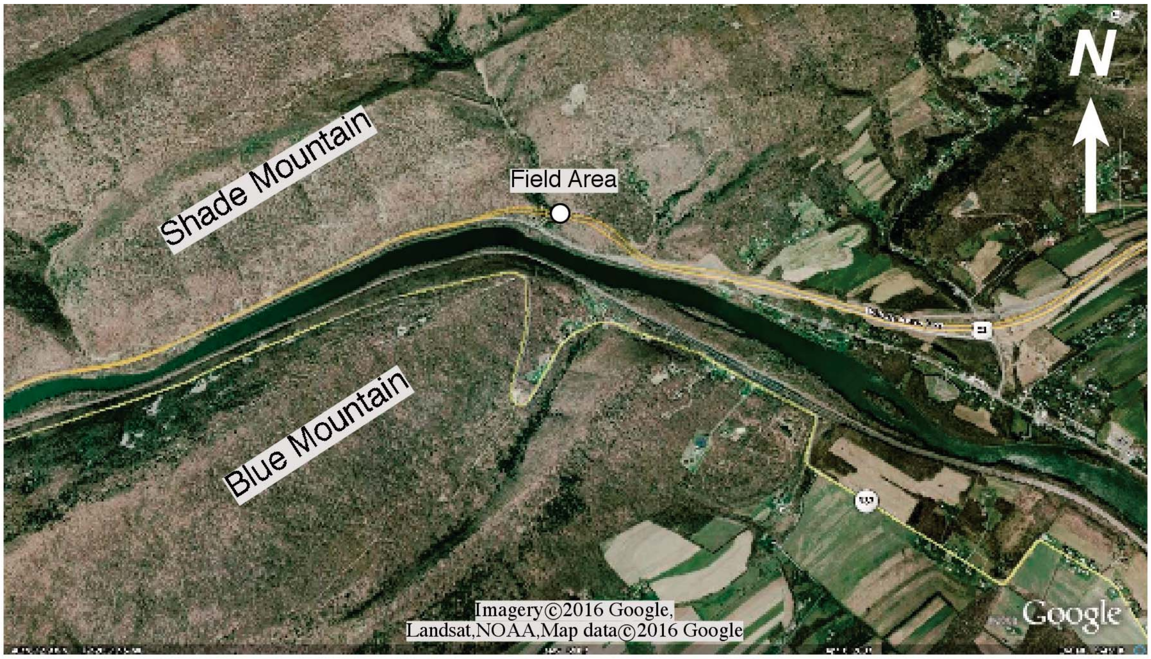
The contact between the Silurian Tuscarora quartzite and the Silurian Rose Hill shale is exposed in the study area (Figures 5 and 6). The Tuscarora beds on the northwest side of the outcrop are massive (1 to 14 meters thick), composed of about 80 percent quartzite and thinner interbedded shale layers. The southeast end of the cross section is thin bedded (a few centimeters to a few meters thick) and has repeated layers of equal amounts of shale and quartzite.

The geometry of the folds reflects the lateral bed-thickness changes along the transect (Figures 5 and 7). At the northwest end, where the quartzite beds are significantly thicker, the folds are more open and have rounded hinges. At the southeast end, the folds are much tighter and form kink folds.

Fold Data

The first- and second-order folds are upright, and their hinges are oriented approximately 55°/235° (that is, they plunge 55° toward 235°). The two main third-order folds plunge 4°/238°, with a hinge surface dipping 75° toward 333° (Figure 8). The fourth-order fold plunges 7°/231° and its hinge surface dips 64° towards 317°(Figure 8). These fold orientations indicate an average shortening directed toward the northwest (325°), perpendicular to the fold hinges and parallel to the trend of the Juniata culmination. The data support a one-azimuth model.

A



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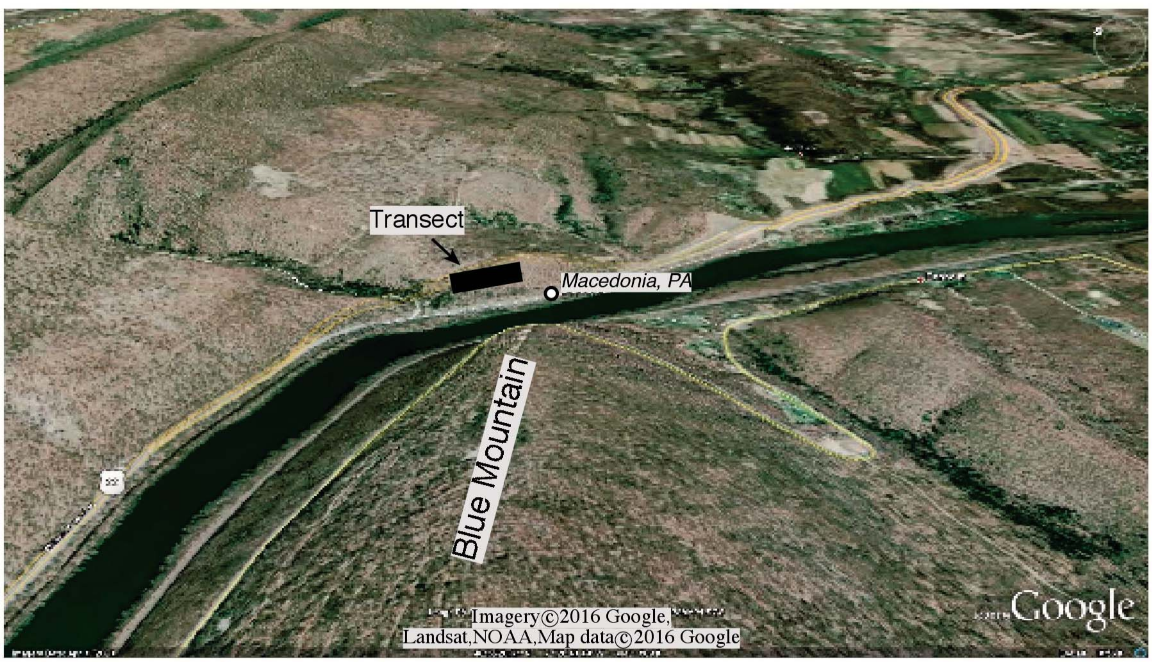


Figure 3. High-angle (A) and oblique (B) views of the field area (from Google Maps). The black box in B marks the location of the transect.

Deformation History

In order to more clearly track the deformation history, detailed outcrop-scale (mesoscale) data were collected across the third- and fourth-order folds. The deformation features were then separated into three generations, based on cross-cutting relationships.

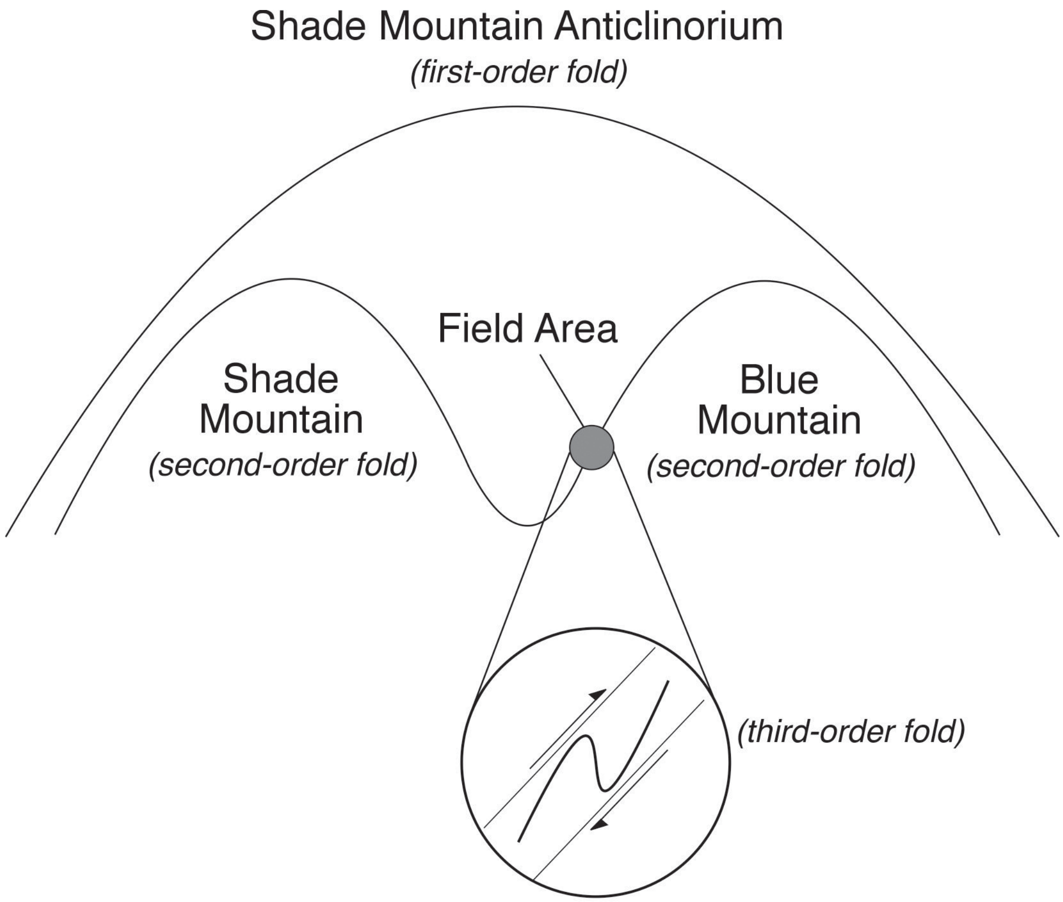


Figure 4. Schematic cross section of various fold orders in the region near the field area.

First Stage. The first stage of deformation is preserved as layer-parallel shortening structures, specifically low-angle wedge faults in the quartzite layers (see cover photograph) and a cleavage set oriented perpendicular to bedding in the subhorizontal shale layers (Figures 7A and 7B). Near the hinge regions of the third-order folds, the wedge faults are folded, and on the steep limbs (>60° dip), the wedge faults are passively rotated (Figures 7A, 7B, 7C, and 7D). Both relationships indicate that wedge faulting took place when the beds were subhorizontal and were deformed by later folding. Assuming that the shortening direction is parallel to the dip direction of the faults and perpendicular to the cleavage surfaces, these first-stage structures suggest a single shortening direction toward the northwest.

Second Stage. Extensional faults formed in the hinge regions to accomodate outer-arc lengthening (Figures 7E and 7F) during the second, or folding, stage of deformation. In the shale layers, two cleavage sets (S_1 and S_2) are preserved in the steeper dipping (>30°) beds (Figure 7G). The gently dipping cleavage surfaces (S_1) are cross cut by the younger second set of steeply dipping cleavages (S_2). We interpret the older set (S_1) as having been rotated during flexural slip folding. The younger, steeper set (S_2) then formed as the folds became tighter. Both cleavage sets dip toward the southeast, which indicates a shortening direction in plan view toward the northwest (Figure 7G). Distorted primary sedimentary structures suggest layer-parallel slip during folding (Figure 7H).

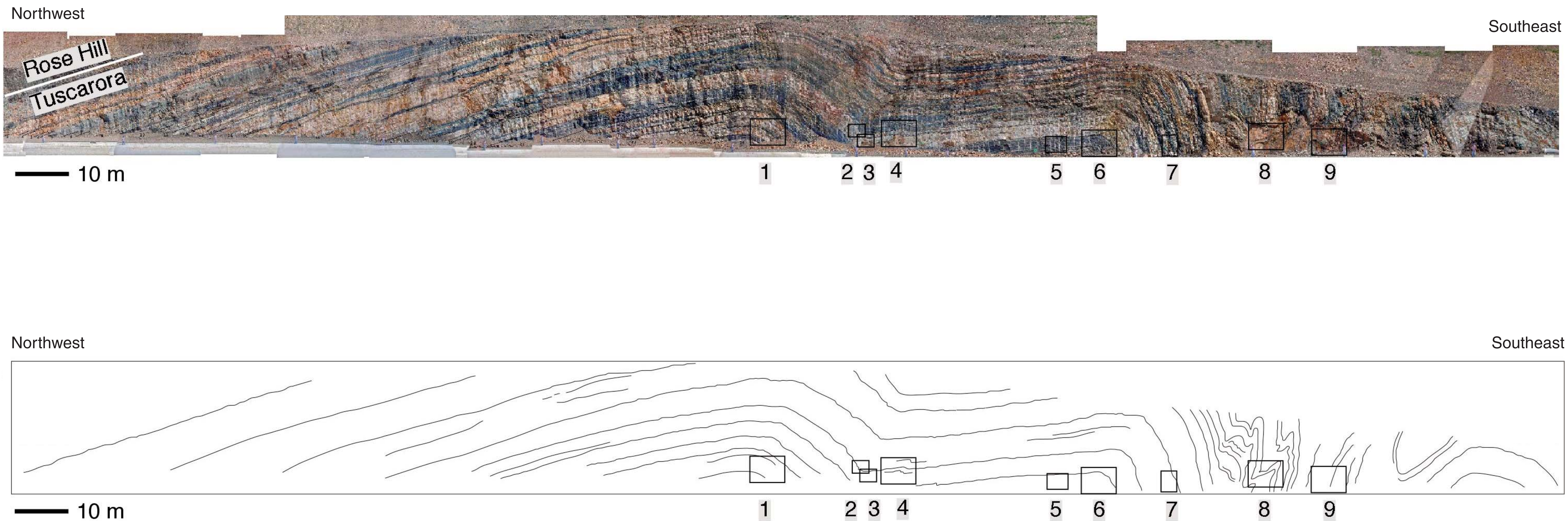


Figure 5. Photomosaic and sketch of transect. Areas in boxes are enlarged in the photographs in Figure 7.

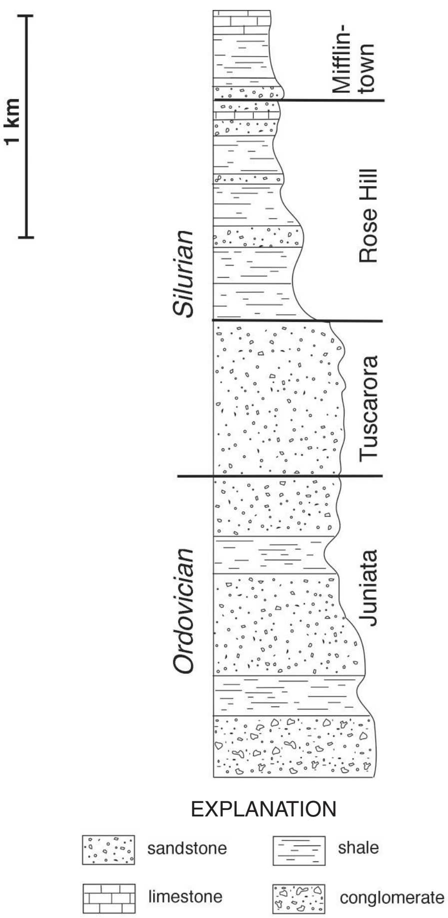


Figure 6. Stratigraphic column showing the two formations exposed in the transect (Tuscarora and Rose Hill), as well as one formation above and one below.

Third Stage. The third and final stage of deformation took place after the folds became tighter (limb dips >60°). Low-angle (conjugate) thrust faults cut across steep limbs of the third-order folds (Figures 7B and 7D). These faults are approximately perpendicular to the third- and fourth-order fold hinges, which suggests a shortening direction toward the northwest.

Subvertical faults that strike approximately parallel to the transect (325°) also are preserved (Figure 7C). These faults formed during the entire deformation history, and their orientations indicate displacements toward the northwest. Two examples are relevant. One such fault preserves almost horizontal slickenlines ("a lineation on a fault surface, defined by grooves, ridges, and/or striations" [Nueuendorf and others, 2005]); it is crosscut by stage 3 low-angle faults, indicating that it formed between stage 2 folding and stage 3 faulting. Another subvertical fault displays folded slickenlines, suggesting that the fault formed prior to stage 2 folding (Figure 7I).

Conclusions

The stages of deformation preserved throughout the Pennsylvania Ridge and Valley province, specifically layer-parallel shortening, main folding (Faill, 1973), and fold modification including low-

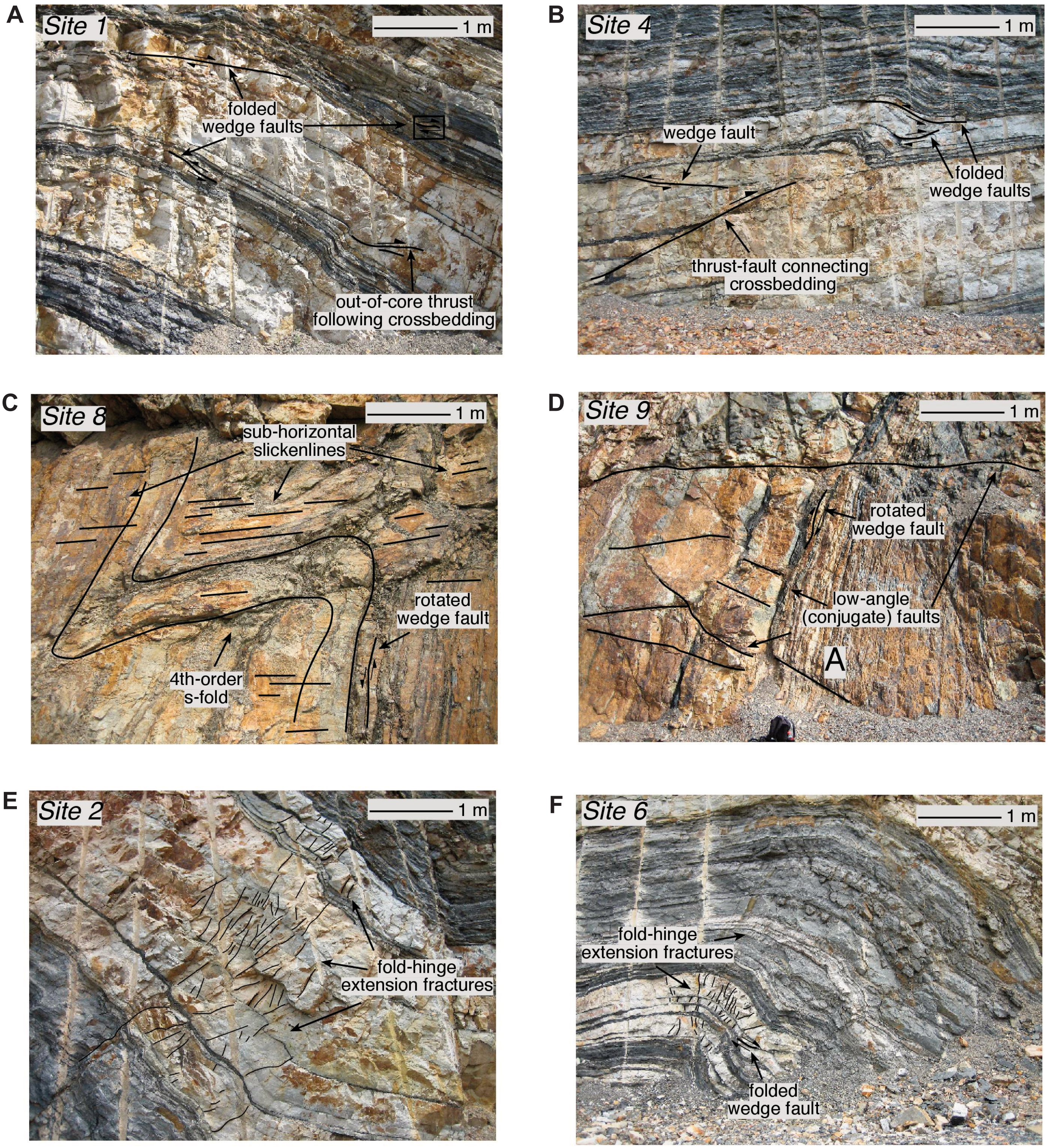
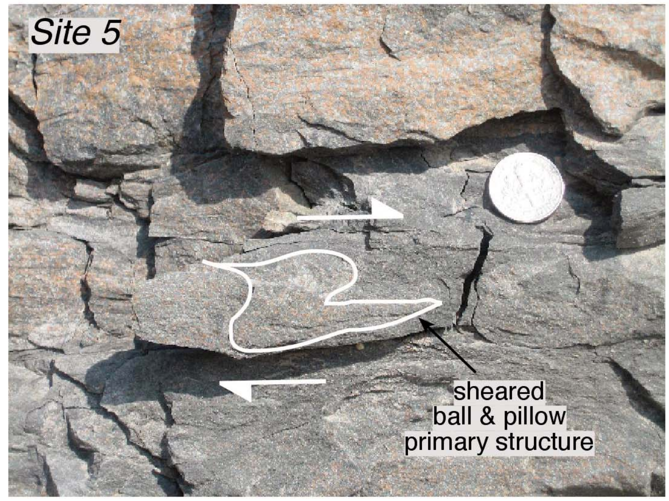


Figure 7. Photographs showing highlighted secondary features. All photographs are toward the northeast and are referred to in the text along with explanations. See Figure 5 for site locations.

G

H



I

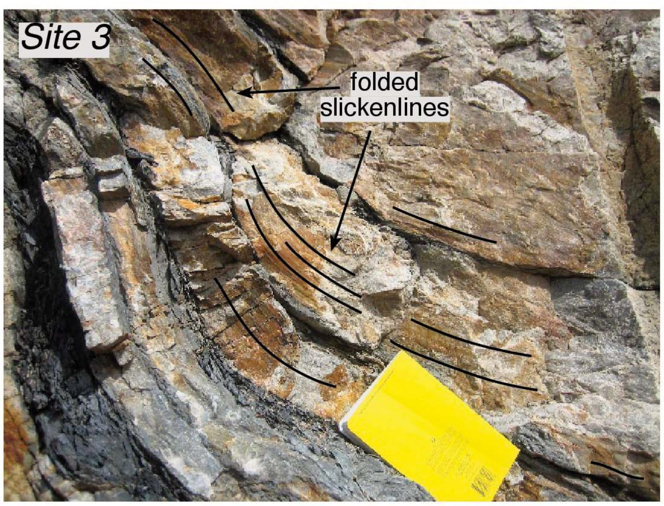


Figure 7. (Continued).

angle thrust faulting (Nickelsen, 1979), are preserved as well in the Juniata culmination. The various stages of deformation preserved throughout the transect define a consistent shortening direction toward the northwest (320°–330°). Structural data suggest that a single transport direction, parallel to the proposed Eocambrian cratonic corner (Thomas, 1977), assisted in the development of the Juniata culmination (Figures 1 and 2). The Pennsylvania salient fits the one-azimuth model (Gray and Stamatakos, 1997; Sak and others, 2014).

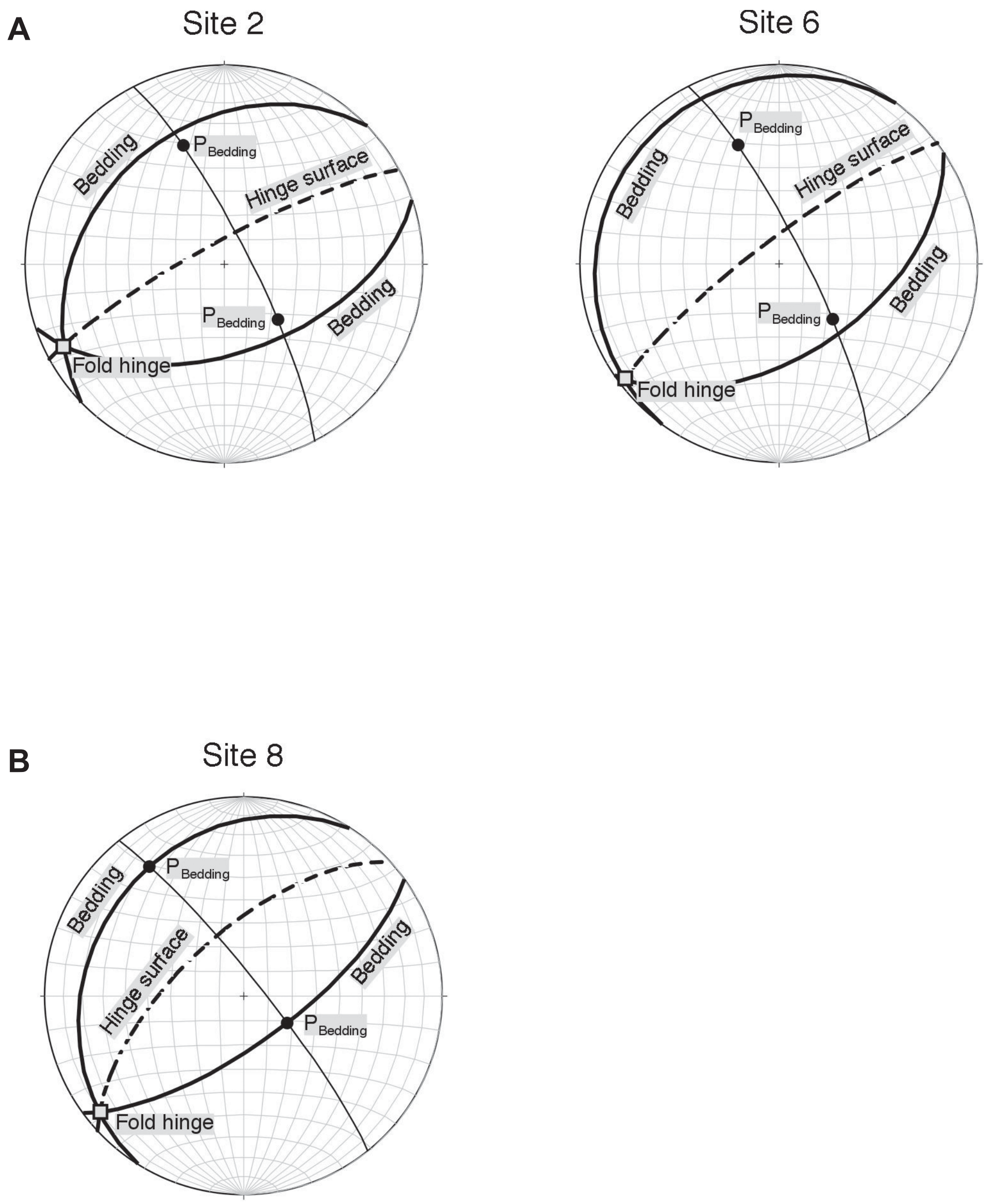


Figure 8. A, The orientations of the fold hinges from third-order folds exposed at sites 2 and 6. B, The orientation of the fold hinge from a fourth-order fold exposed at site 8. See Figure 5 for site locations.

Acknowledgments

We thank the Committee on Grants at Franklin and Marshall College for funding this research. We also thank Noel Potter, Peter Sak, and Robert Walter for helpful comments on Justin Herbert's senior thesis, on which this paper is based. We also thank two anonymous reviewers for their helpful comments, and Anne Lutz for her patience and thoughtful suggestions.

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