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# Significance of the Deformation History within the Hinge Zone of the Pennsylvania Salient, Appalachian Mountains

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## ABSTRACT

Two competing models exist for the formation of the Pennsylvania salient, a widely studied area of pronounced curvature in the Appalachian mountain belt. The viability of these models can be tested by compiling and analyzing the patterns of structures within the general hinge zone of the Pennsylvania salient. One end-member model suggests a NW-directed maximum shortening direction and no rotation through time in the culmination. An alternative model requires a two-phase development of the culmination involving NNW-directed maximum shortening overprinted by WNW-directed maximum shortening. Structural analysis at 22 locations throughout the Valley and Ridge and southern Appalachian Plateau Provinces of Pennsylvania are used to constrain orientations of the maximum shortening direction and establish whether these orientations have rotated during progressive deformation in the Pennsylvania salient's hinge. Outcrops of Paleozoic sedimentary rocks contain several orders of folds, conjugate faults, steeply dipping strike-slip faults, joints, conjugate en echelon gash vein arrays, spaced cleavage, and grain-scale finite strain indicators. This suite of structures records a complex deformation history similar to the Bear Valley sequence of progressive deformation. The available structural data from the Juniata culmination do not show a consistent temporal rotation of shortening directions and generally indicate uniform, parallel shortening directions consistent with the single-phase model for development of the Pennsylvania salient.

## Introduction

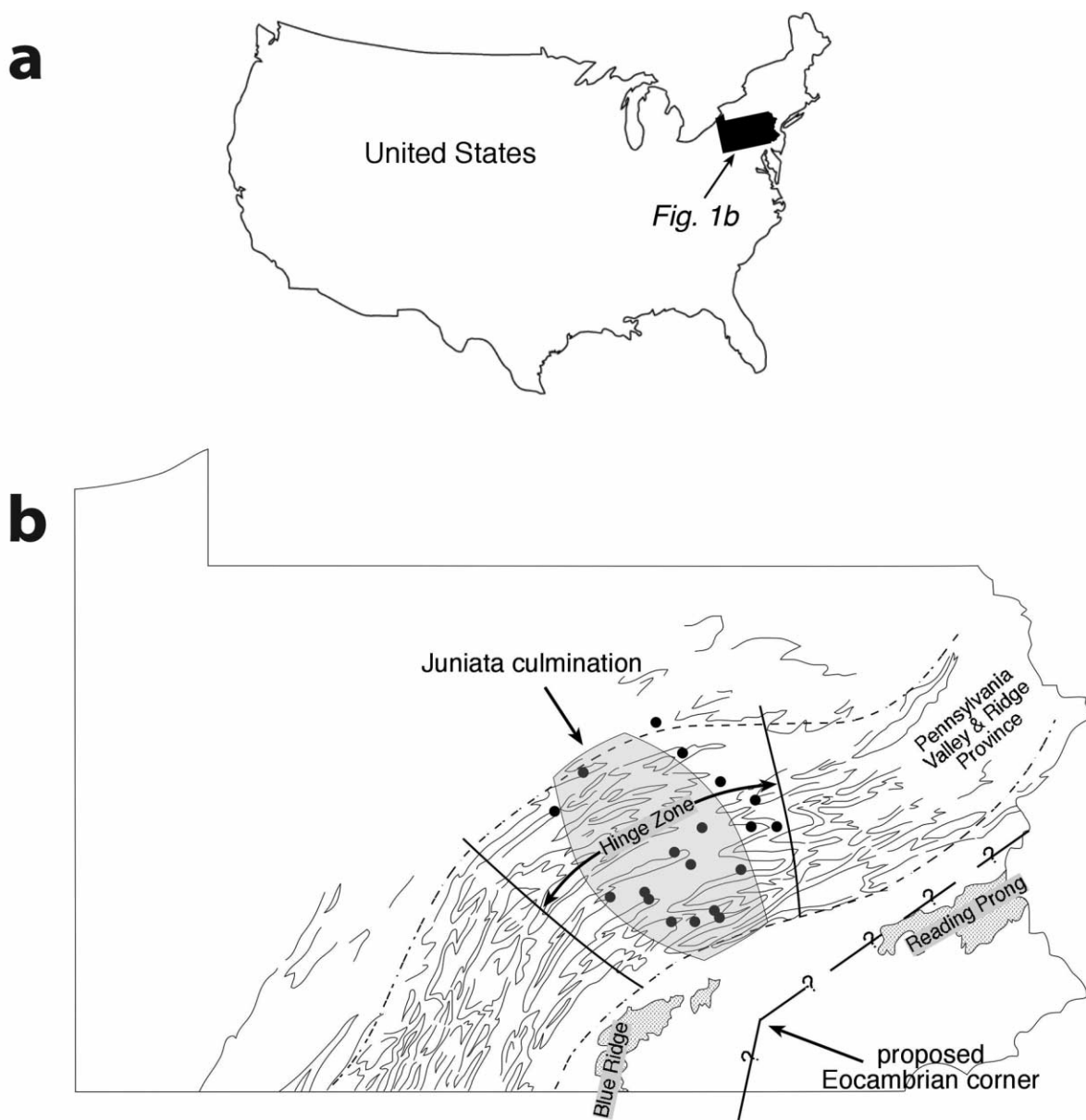
The Pennsylvania salient is one of the most prominent features in the Appalachian mountain system and has been extensively studied for more than 150 years (e.g., Dana 1866; Rogers 1958; Nickelsen 1963; Gwinn 1967; Thomas 1977; Ong et al. 2007). The structures in the Valley and Ridge Province are the result of tectonic shortening and thickening associated with the closure of the Iapetus Ocean, culminating in the Permian continent-continent collision of Gondwana with Laurentia during the Alleghanian orogeny (Rodgers 1949; Hatcher et al. 1989; Stamatakos et al. 1996; Faill 1998). In map view, the Pennsylvania salient forms a smooth arc with an interlimb angle of  $\sim 135^\circ$  (fig. 1). This arc links two relatively linear segments, the NNE-SSW-trending SW segment and the ENE-WSW-trending NE segment (fig. 1). The folds within the

SW segment plunge to the SW and record shortening directions that underwent a counterclockwise rotation through time (Nickelsen 1988, 2009). The folds in the NE segment plunge to the NE, and the shortening directions within these rocks preserve evidence of a temporal clockwise rotation (Nickelsen 1979; Geiser and Engelder 1983; Gray and Mitra 1993; Markley and Wojtal 1996; Zhao and Jacobi 1997; Younes and Engelder 1999). The segments of this salient meet in the hinge zone that contains a NW-trending structural high, the Juniata culmination (fig. 1b). The folds within the Juniata culmination are doubly plunging to the NE and SW. The hinge zone of the Pennsylvania salient encompasses the Juniata culmination and the area adjacent to it—it is defined as the area of maximum curvature, in plan view, of the Pennsylvania salient (fig. 1b).

Currently, two competing end-member kinematic models attempt to explain (1) the formation

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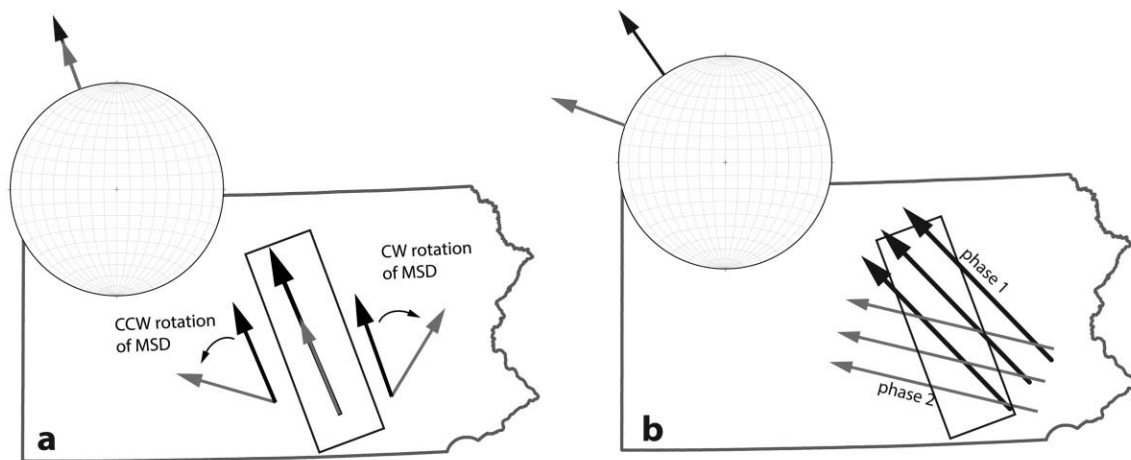
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**Figure 1.** *a*, Location of the study area; *b*, the Central Appalachian Salient, highlighting major lithologic contacts in the Valley and Ridge Province, the hinge zone, the Juniata culmination, internal crystalline thrust sheets comprising the Blue Ridge and Reading Prong, and location of study sites (black dots).

of the salient's arcuate pattern, (2) the temporal rotation of shortening directions within the salient, and (3) the formation of the Juniata culmination and general hinge zone (Gray and Stamatakos 1997; Wise 2004; Wise and Werner 2004). The first model is referred to here as the "single-phase" model and the second as the "two-phase" model (fig. 2). Both models assume that the shape and position of the Pennsylvania salient has been inherited from a pre-existing continental reentrant in the Iapetan rifted margin of eastern Laurentia (North America). This

guided and shaped the present-day geometry of the Pennsylvania salient during Alleghanian deformation (Thomas 1977, 2006; Beardsley and Cable 1983; Ong et al. 2007), such that major crystalline thrust sheets within the internides (e.g., Reading Prong and Blue Ridge) are also parallel to the segments of the reentrant (fig. 1b). In both of the models, the Juniata culmination forms at the corner of this Eocambrian reentrant (fig. 1b). Despite these similarities, the two models predict distinctively different progressive deformation paths, particu-



**Figure 2.** Schematic diagrams of the single-phase (*a*) and two-phase (*b*) models for Alleghanian tectonic shortening. Juniata culmination enclosed in rectangle. Black arrows = early-stage shortening directions, gray arrows = late-stage shortening directions. Stereonets show predicted maximum shortening directions in the Juniata culmination under each of the models. A color version of this figure is available online. MSD = maximum shortening direction.

larly within the hinge zone of the Pennsylvania salient.

While deformation paths on the salient segments differ, the single-phase model proposes a unidirectional transport toward the corner of the Eocambrian reentrant (fig. 2*a*; Stamatakos et al. 1996; Gray and Stamatakos 1997; Wise 2004). As a result, a single shortening direction, approximately parallel to the NW trend of the culmination, should be preserved within the salient's hinge (Gray and Stamatakos 1997). The two-phase model suggests that the salient formed by two separate shortening events, each directed approximately perpendicular to the salient's segments (fig. 2*b*; Geiser and Engelder 1983; Wise 2004; Wise and Werner 2004). If this model is valid, both phases should be represented by overprinting shortening directions within the salient's hinge.

In this article, we have compiled structural observations preserved at 22 locations within the hinge zone of the Pennsylvania salient—15 of these sites are within the Juniata culmination (fig. 1*b*). These structures are then compared to those predicted by the single- and two-phase models to determine whether the data are consistent with either of the models.

### Background

Fold-thrust belt culminations commonly form in salients and are topographic structural highs away from which the folds plunge (Boyer 1978; Elliott and Johnson 1980; Boyer and Elliott 1982). Cul-

minations often are a result of duplexing and/or basement uplift, possibly due to excess sediment in the original miogeoclinal package (Lageson 1984; DeCelles and Mitra 1995). Culminations may also reflect concentrated shortening resulting from pre-existing reentrants along convergent plate boundaries (Thomas 1977, 2006; Lageson 1980; Mitra 1997; Faill and Nickelsen 1999). These topographic highs are often the source for sediment shed into the adjacent foreland basin. Culminations may also help to maintain critical taper during fold-thrust belt evolution (DeCelles and Mitra 1995; Mitra 1997). In addition, culminations are key targets for oil and gas exploration (Lageson 1984).

The Juniata culmination, is a classic example of a fold-thrust belt culmination (fig. 1). We have conducted numerous small-scale structural studies of outcrops along roads, in quarries and stream cuts, within and around the culmination, with an eye to discerning kinematics. We have compiled the results of these studies and use the findings to test the viability of the single-phase and two-phase models. Each model is discussed in greater detail below.

**Single-Phase Model.** The single-phase model proposes that thrust sheets were transported toward 320°–340°, approximately parallel to the bisector of the Eocambrian cratonic corner (Gray and Stamatakos 1997; fig. 2*a*). The clastic wedge is stratigraphically thickest at the corner of this reentrant (Thomas 1977). As the excess sediment was shortened during Alleghanian deformation, a duplexed wedge-shaped culmination formed, which

**Table 1.** Structures Used to Determine Maximum Shortening Directions (MSDs)

Structural feature	Interpretation of MSD	Structural stage	
		Early	Late
Joints (mode I fractures) <sup>a</sup>	In plane of fracture and parallel to the strike of the fracture	X	X
Cleavage <sup>a</sup>	Normal to cleavage plane	X	X
Wedge faults	Parallel to the trend of slickenlines and fault poles	X	
Strike-slip faults <sup>b</sup>	Parallel to the strike of the acute planar bisector of conjugate faults	X	X
Folds (and parasitic folds)	Perpendicular to fold axes		X
Flexural-slip slickenlines	Perpendicular to fold hinge		X
Reverse faults	Parallel to the trend of slickenlines and fault poles		X

<sup>a</sup> Joints and cleavage are associated with both the early and late stages of deformation. A fold test is used to determine the temporal relationship between joint sets or cleavage and folding.

<sup>b</sup> Strike-slip faults are associated with both the early and late stages of deformation. Early strike-slip faults are characterized by slickenlines oriented parallel to bedding planes. Slickenlines associated with late-stage deformation are not folded by outcrop-scale folds.

was tapered toward the foreland and laterally away from the Juniata culmination. This model, compared to the two-phase model, suggests greater shortening within the corner culmination zone. This increased shortening and thickening eventually led to late-stage, radial gravitational spreading (Gray and Stamatakos 1997; fig. 2a). Because gravitational spreading was concurrent with shortening, this model does not require significant tangential extension around the arc of the salient. In other words, as the clastic wedge continued to thicken during transport and shortening, it provided a continual source of sediment that spread to the foreland, along the axis of the culmination, and laterally away from the culmination's axis. If the curvature postdated sediment deposition, then a significant amount of tangential extension would be required to form the salient's hinge.

Gravitational spreading combined with a unidirectional transport direction produced a shortening history with a clockwise sense of rotation in the northeast segment and a counterclockwise rotation in the southwest segment of the Pennsylvania salient (Gray and Stamatakos 1997; Wise 2004; fig. 2a). This rotation is preserved as secondary shortening directions toward 010° in the northeastern limb and 280°–290° in the southwestern segment (Gray and Stamatakos 1997). The proposed three-dimensional tapered wedge also helped to form the NE- and SW-plunging folds on either side of the culmination. Moreover, orientation patterns of characteristic and secondary paleomagnetic components in the strata exposed in the culmination are uniquely explained by this model alone (Gray and Stamatakos 1997).

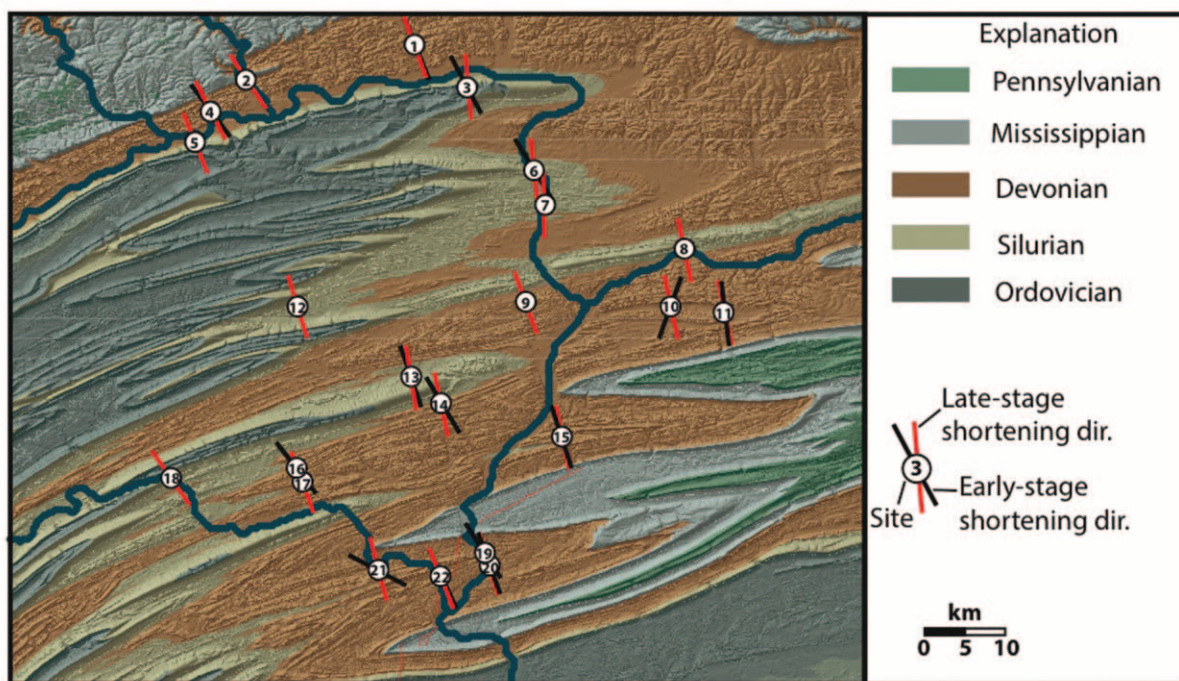
A variation to this single-phase model suggests that there was oblique convergence with the Laurentian craton (Ong et al. 2007). This model suggests that there was a single convergence direction

parallel to the Blue Ridge. The Reading Prong acted as a buttress, so most of the rotation took place in the salient's NE limb. With this variation, we would still expect to see only one shortening direction within the hinge of the salient, supporting a single-phase model (Ong et al. 2007). Although this model is not critical to our article, it is interesting to note that this approach would likely result in a similar suite of structures preserved throughout the hinge zone of the Pennsylvania salient as is suggested by our single-phase model.

**Two-Phase Model.** In the two-phase model, two successive stages of noncoaxial transport are used to explain the structures within, and the curvature of, the Pennsylvania salient (fig. 2b). An initial shortening event directed toward 325° is followed by a second shortening event directed toward 292° (Wise 2004; Wise and Werner 2004; fig. 2b). Each event is directed approximately perpendicular to the edges of a preexisting, corner-shaped continental reentrant (Thomas 1977; Geiser and Engelder 1983; Wise 2004; fig. 1b).

The linear Reading Prong and Blue Ridge basement uplifts trend perpendicular to the first and second transport directions, respectively (figs. 1b, 2b). The Reading Prong and the Blue Ridge delineate the NE and SW segments, respectively, of the Pennsylvania salient. These basement uplifts are proposed to be a result of each shortening event (Wise and Werner 2004). During both events, thrust sheet motion was impeded by the reentrant's corner, resulting in rotational drag (Wise 2004). This produced the observed clockwise rotation in shortening direction within the NE limb of the salient and counterclockwise rotation in the SW limb of the salient.

The change in direction of tectonic transport resulted in overprinting and duplexes piling up at the intersection of the two shortening directions, that



**Figure 3.** Geologic map draped over a shaded relief digital elevation model of the study area showing the locations of the 22 study sites and orientations of the early and late maximum shortening directions.

is, along the reentrant's corner, producing the Juniata culmination (Wise 2004). This type of salient is referred to as an intersection orocline because it is produced in a corner of a cratonic margin by more than one overlapping directions of tectonic transport (Marshak 2004; Weil and Sussman 2004). Based on this model, we should expect to see evidence of both the  $325^\circ$  and  $292^\circ$  shortening directions within the hinge zone of the Pennsylvania salient. And, similar to the one-phase model, this model does not require significant longitudinal extension around the arc of the salient.

### Methods

In general, the structural stages preserved throughout the Pennsylvania salient's hinge zone mimic those found in other parts of the Pennsylvania Valley and Ridge fold-thrust belt. Here, the deformation is due to the Alleghany orogeny. Nickelsen (1979) first unraveled a structural sequence of the Valley and Ridge Province from work done in the Bear Valley Strip Mine in Shamokin, Pennsylvania. The so-called Bear Valley sequence consists of five Alleghanian deformation stages (II–VI; Nickelsen 1979). These stages have since been recognized at other locations in the Valley and Ridge (e.g., Gray and Mitra 1993; Gray and Stamatakos 1997). Spiker

and Gray (1997) documented the Bear Valley sequence on the Appalachian Plateau along the Alleghany front in the vicinity of Williamsport, Pennsylvania. A similar sequence is also recognized by Gray and Mitra (1993) throughout the middle and southern Anthracite regions of Pennsylvania. Structures formed during the five-stage deformation sequence reported by Gray and Mitra (1993) are found in table 1 along with a brief explanation of how the orientations of these structures were used to establish mean shortening directions.

Following the methodology employed by Nickelsen (1979) and Gray and Mitra (1993), the stages of progressive deformation were established at each of the 22 sites incorporated into this study (fig. 3; table 2). Stages of deformation can be precisely defined by observing cross-cutting relationships among structures. In some cases it is possible to distinguish up to six stages of Alleghanian deformation. For the purposes of the regional compilation of multiple studies by different authors, it is most convenient to condense all progressive deformation into two general Alleghanian stages, early and late (Nickelsen 1963; fig. 4).

Early, or prefolding, structures are those that are clearly demonstrated to have been rotated on the limbs of folds (fig. 4). In the Valley and Ridge, these structures typically include features that accom-

**Table 2.** Locations of Field Sites and Orientation of the Maximum Shortening Directions

Site	Latitude (°N)	Longitude (°W)	Formation	MSD <sup>a</sup>		Source
				Early stage	Late stage	
1	41.2816	77.0649	Lock Haven	338°	340°	Spiker and Gray 1997
2	41.227	77.325	Lock Haven	326°	326°	Lunde 2012
3	41.2158	76.9833	Bald Eagle	332°	355°	Miller 1984
4	41.1829	77.3369	Lock Haven		323°	This study
5	41.1304	77.4047	Mifflintown	338°	338°	Miller 1984
6	41.0899	76.8807	Tuscarora	329°	354°	Nickelsen and Cotter 1983
7	41.0445	76.8506	Bloomsburg	358°	002°	This study
8	40.9663	76.6462	Bloomsburg/Mifflintown	348°	348°	Nickelsen and Cotter 1983
9	40.8836	76.8903	Keyser/Tonoloway		340°	Miller 1984
10	40.8759	76.6685	Mahantango	020°	348°	Miller 1984
11	40.8674	76.5858	Mahantango	353°	348°	Nickelsen and Cotter 1983
12	40.8738	77.2367	Bloomsburg	343°	342°	This study
13	40.7665	77.0697	Keyser/Tonoloway	341°	351°	Johnson 2000
14	40.7256	77.0239	Keyser/Tonoloway	329°	348°	Miller 1984
15	40.6748	76.8343	Keyser/Tonoloway	342°	348°	Bajak 1981
16	40.6241	77.2483	Keyser/Tonoloway	322°		Miller 1984
17	40.6066	77.2377	Mahantango	340°	340°	Miller 1984
18	40.6	77.4333	Tuscarora	325°	325°	Herbert 2009
19	40.4893	76.9543	Pocono	327°		Miller 1984
20	40.4715	76.9494	Irish Valley Mbr, Catskill Fm	340°	343°	Wills and Sak 2010
21	40.4674	77.1186	Irish Valley Mbr, Catskill Fm	298°	345°	Miller 1984
22	40.459	77.0252	Trimmers Rock	335°	338°	This study

<sup>a</sup> The maximum shortening direction (MSD) for the early and late phases of the Alleghanian orogeny were determined from field relationships. Absence of an MSD indicates insufficient data to support an interpretation. Mbr = Member, Fm = Formation.

plished layer-parallel shortening during the earliest stages of the orogeny such as joint sets, cleavage, wedge faults, and conjugate strike slip fault sets. Late-stage structures include folds and structures associated with folding, such as flexural-slip slickenlines, hinge extension fractures, fold-transecting cleavage, conjugate faults, and parasitic folds (fig. 4).

### Structural Data

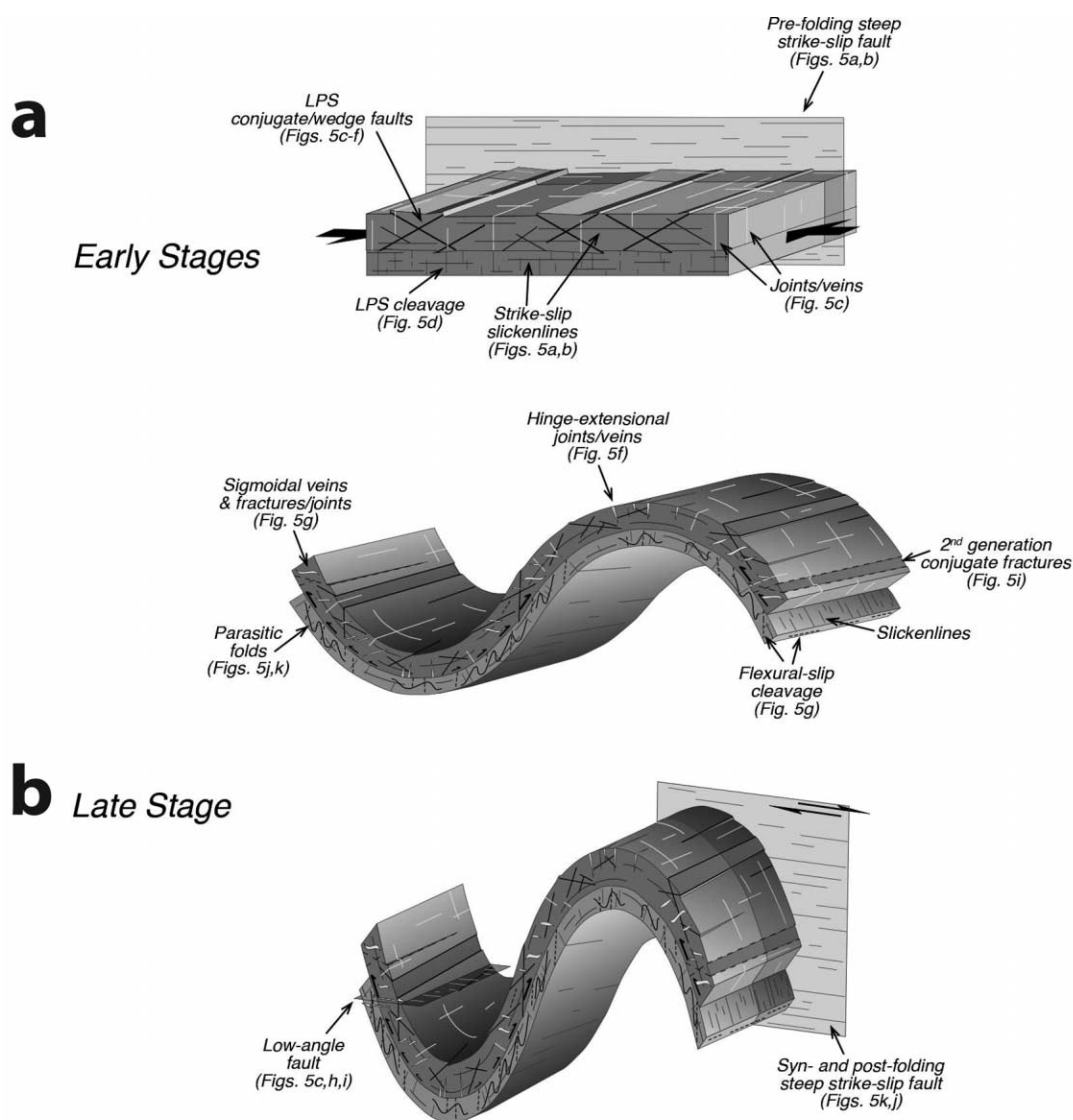
The rocks exposed in the Valley and Ridge Province range in age from the Ordovician to the Pennsylvanian and commonly form alternating layers of competent (e.g., quartz sandstone and quartz pebble conglomerate) and incompetent (e.g., shale and micritic limestone) beds. In this investigation, we focus on the folds and the structures found within the folds, throughout the 22 field sites (fig. 3). These structures are classified as either early or late stage and are described as either being primarily found in the competent or incompetent units (fig. 4; table 1). The sequence of the structures is determined from cross-cutting relationships.

**Early Stage.** The initial, prefolding, stages of deformation were accommodated by layer-parallel shortening structures (figs. 4, 5). In the competent units, this is primarily accomplished by conjugate

strike-slip ("wrench") and dip-slip ("wedge") faults. Joint sets perpendicular to the strike of bedding also formed (figs. 4, 5). The orientations of these joints suggest a similar shortening required to form the conjugate fault sets. Another set of joints, parallel to the strike of bedding, is also recognized in many of the competent layers. Both of these orthogonal joint sets are in orientations consistent with the J<sub>1</sub> and J<sub>2</sub> joints sets of Engelder et al. (2009), so both may have formed during the very early stages of folding.

In the incompetent layers, bed-perpendicular cleavage is most pronounced (figs. 4, 5). The cleavage orientation is consistent with the shortening directions required to form the structures preserved in the competent layers. This set is preserved as fanned cleavage, suggesting that it is passively rotated as the layers folded.

**Late Stage.** As the beds began to fold, younger conjugate fault sets formed in the competent layers (figs. 4, 5). The acute bisector of these younger conjugate sets is oriented subperpendicular to the hinge surfaces of the first-order folds, with a sub-horizontal bisector plane. Slickenlines plunge down the dip of these conjugate faults. Extensional fractures are preserved within fold hinge zones, accommodating tangential longitudinal strain (figs. 4, 5). Slickenfibers are commonly found on bedding



**Figure 4.** Representative structures used to determine maximum shortening directions in the Juniata culmination. *a*, Early-stage structures form before folding, in flat-laying strata; *b*, late-stage structures form during or after folding of strata. LPS = layer-parallel shortening.

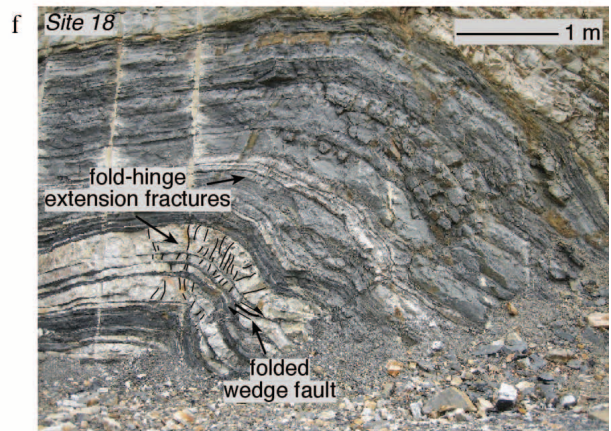
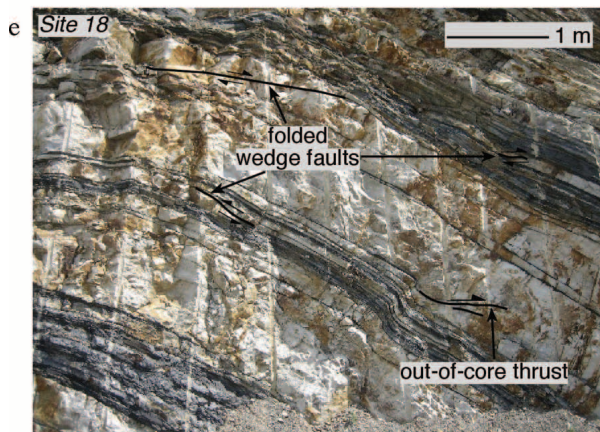
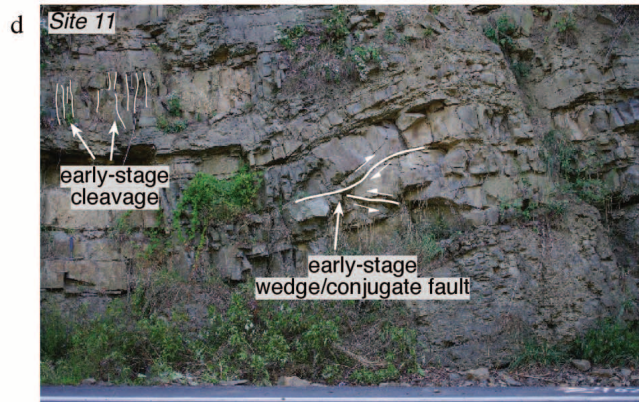
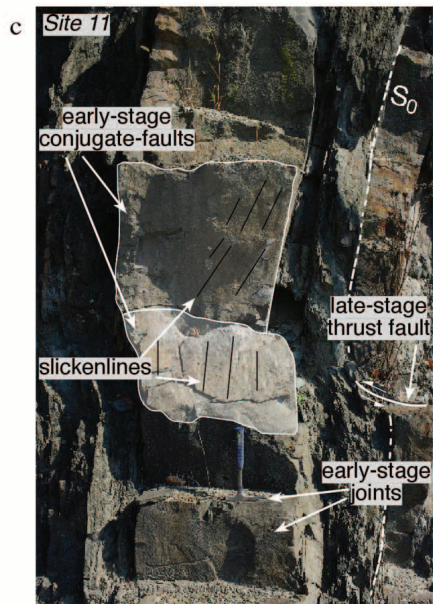
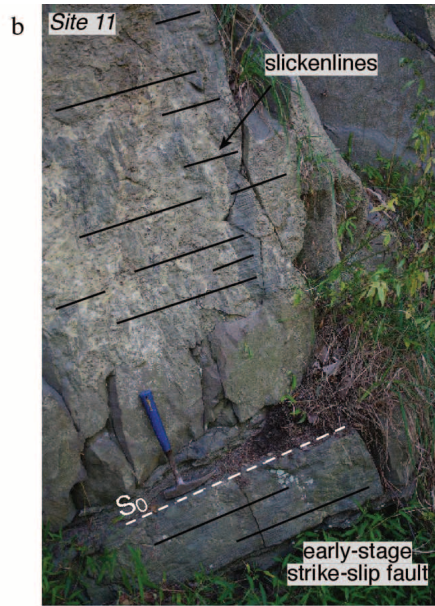
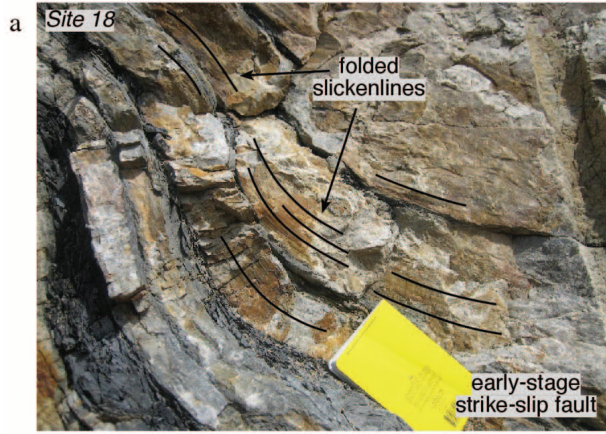
surfaces, with lineations perpendicular to the hinge and hingeward directed shear sense, suggesting bed-parallel flexural slip assisted folding. En-echelon fractures and sigmoidal veins are sometimes found in the competent layers in orientations consistent with bed-parallel, flexural slip. In the incompetent layers, higher-order parasitic folds and a second (or, third, in the Anthracite region) generation of cleavage surfaces further indicate bed-parallel flexural slip (figs. 4, 5). With continued folding, low-angle faults formed in the steep limbs. These faults propagated through the competent and incompetent layers (figs. 4, 5).

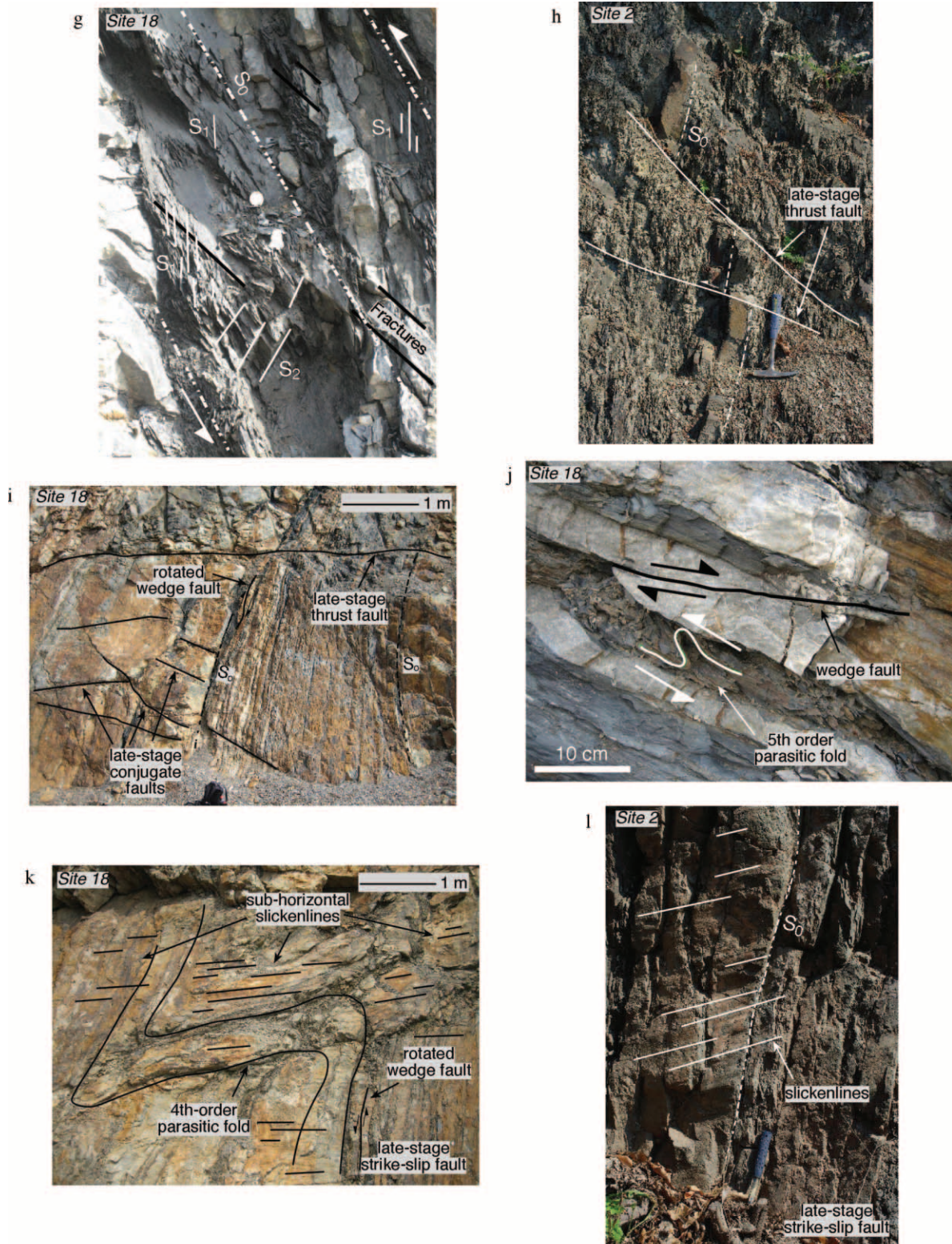
**Time-Independent Structures.** Subvertical strike-

slip faults that strike approximately perpendicular to the first-order fold hinges formed throughout the folding history, and cut through the competent and incompetent layers (figs. 4, 5). These strike-slip faults often form conjugate sets. Folded slickenlines indicate that the faults formed pre-folding, while other strike-slip faults overprint all the other structures, indicating that they are among the youngest structures formed. The strike of these faults supports a shortening direction comparable to the shortening direction that formed the other structures throughout the study sites.

**Data Summary.** Although the structures preserved at the 22 sites represent different stages in







**Figure 5.** Representative field examples of structures from early and late stages of deformation.

the deformation history of the Pennsylvania salient, they all suggest consistent shortening oriented  $320^{\circ}$ – $340^{\circ}$ , that is, subparallel to bisector of the Eocambrian cratonic corner (table 2). The stages temporally overlap, which is consistent with Nickelsen's (1979) observations from the Valley and Ridge Province. The clockwise and counterclockwise maximum shortening directions (MSDs) within the NE and SW segments, respectively, suggest that the deformation was continuous during rotation of the MSDs, which is consistent with the single-phase model (Gray and Mitra 1993). Both of these observations are critical in distinguishing this model from others that call for a pause in deformation between phases.

### Discussion

Early- and late-stage MSDs are consistently oriented to the northwest across the Juniata culmination (fig. 3; table 2). The mean orientations of the early-stage and late-stage MSD are  $336^{\circ} \pm 16.3^{\circ}$  ( $1\sigma$ ) and  $343^{\circ} \pm 8.5^{\circ}$  ( $1\sigma$ ), respectively (fig. 3; table 2). There are no systematic variations in MSD orientation as a function of position within the culmination. These findings differ from those reported by Wise and Werner (2004) to the southeast in the Piedmont province.

Discrepancies in the orientation of MSDs between the Piedmont and rocks exposed in the Valley and Ridge and southernmost Appalachian Plateau likely reflect the fact that the two regions expose rocks of different age, and consequently, record different deformational histories. Rocks in the Piedmont are older, ranging from Precambrian to Ordovician, whereas rocks exposed in the Valley and Ridge and southern Appalachian Plateau range in age from the Ordovician to Pennsylvanian. The older rocks of the Piedmont may have been deformed during the Taconic orogeny in the middle to late Ordovician as well as the during the Alleghany orogeny in the early Permian. This may complicate the Piedmont data, which are the basis for the two-phase model. However, the younger depositional age of the selected field sites in the Valley and Ridge and Appalachian Plateau strata preclude Taconic deformation. The deformation histories in these post-Taconic orogeny strata only record Alleghanian deformation, eliminating the potential complications produced by overprinting orogenies.

The variations in MSDs between the Piedmont and the Valley and Ridge and Appalachian Plateau provinces may also reflect the setting of the basement thrust sheets within the Piedmont. The Read-

ing Prong and Blue Ridge thrust sheets define a basement corner that is positioned south of the Juniata culmination in the Valley and Ridge and Appalachian Plateau provinces. The corner is projected to lie along a distinctive bend within the Blue Ridge. The axis of this bend trends parallel to the axis of the Juniata culmination. This basement corner likely served as a structural barrier within the Piedmont, thus establishing boundary conditions within the Piedmont that are distinctive from those in the Valley and Ridge and Appalachian Plateau Provinces.

It is important to note that while the data collected in the Valley and Ridge and Appalachian Plateau are consistent with the predictions of the one-phase model, the Piedmont may reflect a different history given the age of the rocks, their closer proximity to the core of the orogenic belt, and the location and orientation of the basement uplifts. Therefore, the kinematic histories are not expected to be similar across the entire salient, and so both models may be valid, but for different provinces.

Distinction between the single- and two-phase models is useful in classifying the Pennsylvania salient along the gradient of orogenic curves from primary arcs, which form in a curved shape from the onset of deformation, to secondary arcs, which are originally linear mountain belts that have later been bent by another deformation event. Because the Pennsylvania outer arc of the salient appears to have been produced by a single tectonic event, it is improbable that the salient is a secondary arc. However, rotation of MSDs with time implies that primary inheritance of curvature is also unrealistic. Most likely, the Pennsylvania salient is an intermediate between these primary and secondary end members and can be classified as a progressive arc, where curvature is acquired continuously throughout the evolution of the Alleghany orogeny (Marshak 2004).

The progressive arc model for the Pennsylvania salient was originally developed by Gray and Stamatatos (1997) and is sometimes referred to as a three-dimensional spreading wedge model (fig. 2a). In this model, shortening and gravitational spreading occur simultaneously under a single transport direction. It is a single-phase model that simply and elegantly integrates the structural and paleomagnetic data preserved throughout the Valley and Ridge Province of the Pennsylvania salient.

However, proponents of the two-phase model suggest that a progressive arc requires tangential extension around the arc (cf. Wise 2004). The Pennsylvania salient has a notable lack of tangential extension features, and this is used to argue that a

one-phase model is not possible. Nickelsen (1979) noted a few small late-stage cross-grabens on the "whaleback" anticline of the Bear Valley mine, and Fail (1981) reported a series of minor conjugate strike-slip faults just west of the Alleghany front, but these account for only a small fraction of the tangential stretching that some suggest would be required for progressive bending of the Pennsylvania salient (cf. Wise 2004). But, a progressive arc does not require tangential extension—it would be necessary only if shortening and gravitational spreading did not occur simultaneously.

Although a progressive arc does not require extension around the arc, it does not preclude that extension can take place and may help assist formation of the salient. Difficult-to-observe micro-scale processes, such as grain-boundary sliding and microscopic finite bulk strain (Sak et al. 2012), may have diffused extensional strain (Gray and Stamatakos 1997), and strike-slip faults common throughout the Pennsylvania salient (Nickelsen 2009) may assist curvature of the salient (Gray and Stamatakos 1997).

The consistent orientation of the MSD throughout the Alleghanian orogeny progressive deformation sequence in the Pennsylvania salient's hinge zone has implications for the construction of balanced geologic cross sections through the orogen. Couzens et al. (1993) argued that it is not possible to construct balanced geologic cross sections through the southern part of the central Appalachians because of the overprinting of at least two episodes on noncoaxial deformation. Because the Juniata culmination and overall hinge zone appear

to have been subjected to a single MSD, this is a suitable location through which to draw a balanced cross section oriented parallel to the direction of maximum shortening.

### Conclusions

Our analyses of progressive Alleghanian deformation in within the hinge zone of the Pennsylvanian salient permit us to draw four important conclusions: (1) All 22 field sites exhibit structures that have elements of the Bear Valley sequence (Nickelsen 1979) of progressive Alleghanian deformation. (2) In general, structures spanning the Alleghanian orogeny exhibit an MSD of  $\sim 340^\circ$  in, and adjacent to, the Juniata culmination, Pennsylvania salient. (3) The Gray and Stamatakos (1997) single-phase model agrees best with the data in the Pennsylvania Valley and Ridge. (4) It is possible that the MSD data from the Great Valley and Piedmont differ from those in the Valley and Ridge because some of the deformation in the internal portions of the salient likely predates the Alleghanian.

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