KINEMATIC ANALYSES OF DISCFOLDS IN DEVONIAN MILLBORO FORMATION IN THE CENTRAL-SOUTHERN APPALACHIAN JUNCTION ZONE

by

John Latham Stubbs, Jr.

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APPROVED:

Dr. W. D. Lowry, Chairman

Dr. R. K. Bambach

Dr. C. G. Tillman

Dr. R. L. Wheeler
Adjunct Committee Member
West Virginia University

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Blacksburg, Virginia

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INTRODUCTION

This study applies a method of kinematic analysis of discfolds (as defined by Hansen, 1971, p. 157-162; see discussion in text under "Discfolds") in metamorphic rocks to mesoscopic discfolds within several contorted zones in the lower part of the section of fissile, dark gray shales of the Middle Devonian Millboro Formation. The planar preferred distribution of the hinge lines of the discfolds and their style elements (asymmetric, disharmonic folds, between similar and concentric in geometry) suggest the discfolds are the result of drag in shear zones within this unit (Wheeler, 1975, 1977b). The hinge line, axial surface, and sense of asymmetry were measured for as many folds as possible for each of the outcrops (29) throughout the study area. For each outcrop, a comparison of the kinematic analysis of the discfolds as a whole and the overall attitude of the bedding provided one or more solutions to the type of movement that caused the shear. The orientation of the plane of shear (slip plane) and the orientation of the direction of relative movement within the slip plane (slip line) were also determined for each outcrop.

The study area is the junction zone and adjacent segments of the Central and Southern Valley and Ridge Province in southwest Virginia and southeast West Virginia (Fig. 1, Plate 1). The junction zone is a narrow belt at a latitude (approximately $37^{o}30'$N) that runs through Buchanan, Virginia. This recess (concave toward the craton)

Figure 1. Location map of the study area with outcrops where disc-folds were measured indicated by solid squares. The study area is shown on the small index map by the open-square pattern.

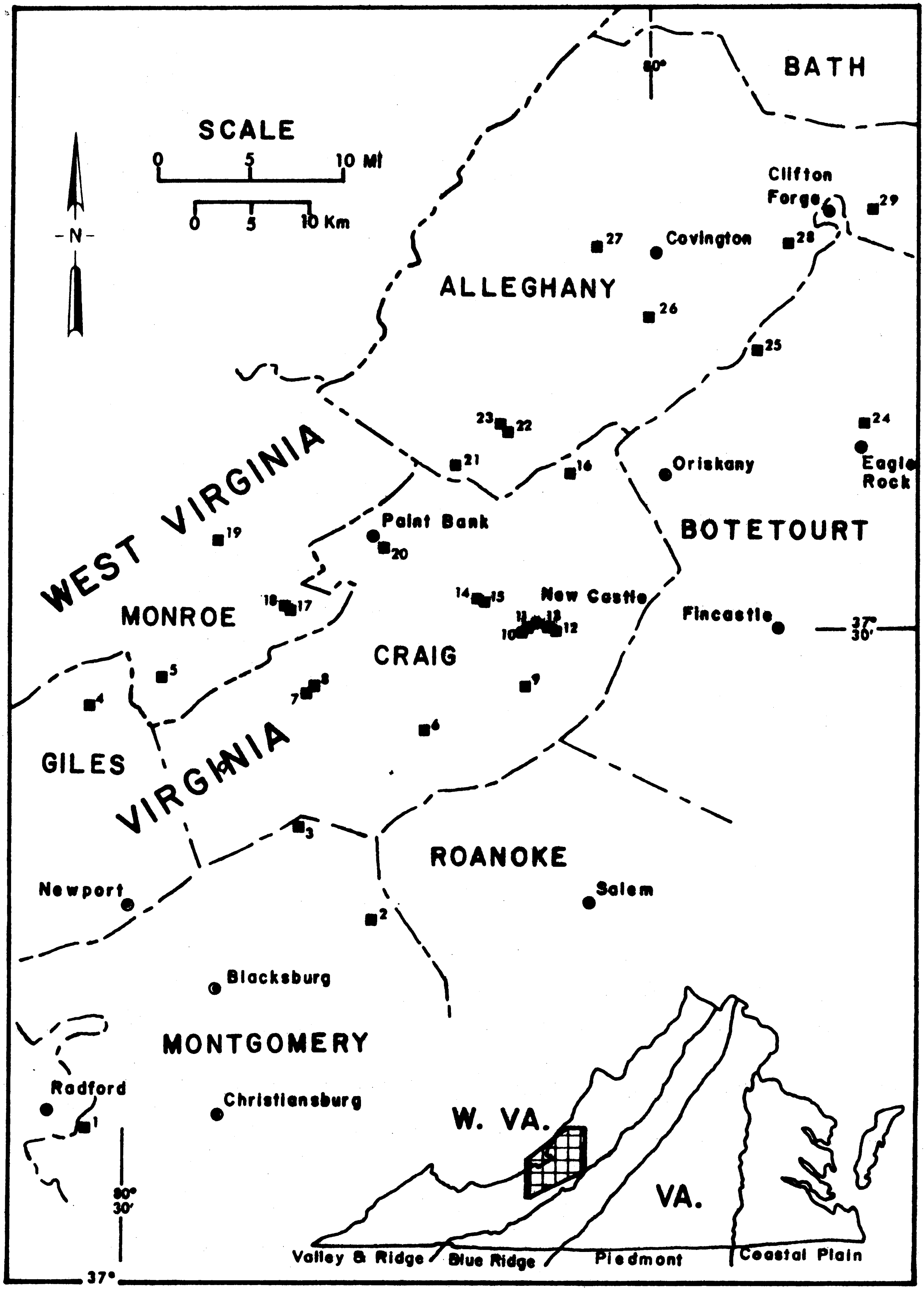

SCALE
0 5 10 Mi
0 5 10 Km
N
80°
BATH
Clifton Forge
Covington
ALLEGHANY
WEST VIRGINIA
Oriskany
Eagle Rock
Paint Bank
BOTETOURT
New Castle
MONROE
Fincastle
37° 30'
CRAIG
GILES
VIRGINIA
ROANOKE
Newport
Salem
Blacksburg
MONTGOMERY
Radford
Christiansburg
W. VA.
VA.
80° 30'
37°
Valley & Ridge
Blue Ridge
Piedmont
Coastal Plain

Plate 1. ERTS photo of study area (modified from NASA ERTS photos E-1172-15310-7 - E-1172-15312-7; refer to Figs. 1,8 for physical and structural setting for the photo and see discussion in text under "Structure" for complete discussion of the changes in topography and structure that occur in the area shown by this photo). The recess or transition zone between the Central and Southern Appalachian system occurs in the zone running approximately east-west across the center of the photo. The nose of the Sinking Creek anticline and the northern terminus of the Saltville fault are almost directly in the center of the photo. The edge of the Appalachian Plateau Province is at the northwestern edge of the photo and the Blue Ridge Province, here represented by Poor Mountain directly below Roanoke, is shown in the southeast corner of the photo.


SCALE
0 3Mi
0 3Km
N

marks the strongly contrasting topography, structural and topographic trends, and style of deformation of surface structures between not only the central and southern segments of the Valley and Ridge Province but also between those of the Appalachian Plateau Province and between those of the Blue Ridge Province.

The primary objective of this study is to test the usefulness of this method of kinematic analysis in sedimentary rocks, which may enable structural geologists to accurately determine movement directions within major structures. Examination of the kinematic analyses through the study area by visual inspection and comparison of the analyses for the two segments of the Valley and Ridge Province by nonparametric statistical tests provides needed information on the nature, geometry, and evolution of the central and southern segments of the Valley and Ridge Province and their anomalous junction.

GEOLOGIC SETTING

Stratigraphy

The stratigraphic nomenclature (Fig. 2) of the Middle Devonian black shale interval is complicated by the complex facies relationships of the shales. The stratigraphy of the black shales was first studied in detail in New York state where the shales were named the Hamilton Group. There, the black shale interval extends from the top of the Onondaga Limestone to the base of the Tully Limestone and is represented by the Marcellus (at the base), Skaneateles, Ludlowville, and Moscow Formations (Rickard, 1964; Dennison and Hasson, 1974). Recent work has helped to resolve the stratigraphy in Pennsylvania and the northern parts of Virginia and West Virginia (Dennison, 1961; Dennison and Textoris, 1971; Dennison and Hasson, 1976). In these areas, the underlying Onesquethaw Stage is represented by the Needmore Shale (in the northeast), the Huntersville Chert, or the Onondaga Limestone (in the southwest). These units are separated from the Hamilton Group by a thin unit, the Tioga Metabentonite (Dennison, 1961). The Hamilton Group (Erian Group in West Virginia, Woodward, 1943) is represented at its base by the grayish black, thinly laminated, fissile Marcellus Shale, which includes 15 to 30 m (50-100 ft) of interbedded calcareous shale and limestone (Purcell Member) approximately 30 m (100 ft) above its base. Overlying the Marcellus Shale is the Mahantango Formation that is made up of thickly laminated, silty shale and interbedded siltstone and some limestone (Dennison and Hasson, 1976). The Hamilton Group is overlain in Pennsylvania and the northern parts of Virginia and West Virginia by the Tully Limestone, which is represented to the south by limestone concretions at the base of the Brallier Formation (Dennison and Hasson, 1976).

In the study area, Cooper (1939) and Butts (1940) discussed the Middle Devonian black shales. Here the Hamilton Group interval was described and renamed the Millboro Formation southwest of Shenandoah County, Virginia, and the formation has not been divided into smaller mappable units (Butts, 1940; Fig. 2). Dennison and Textoris (1971) reported the Tioga Metabentonite at the base of the Millboro Formation. The metabentonite was not seen in contact with the Millboro Formation at any of the localities where discfolds were measured, although the writer did examine this thinly laminated, mica-bearing unit at other localities. Underlying the Millboro Formation and the metabentonite are the non-fissile, buff-yellow, calcareous shales of the Needmore Shale or the black chert and glauconite-bearing sandstone beds of the Huntersville Chert (Butts, 1940; Woodward, 1943; Dennison and Hasson, 1976). These two facies interfinger, with the chert facies becoming more prevalent in the southwest part of the study area (Dennison, 1961; C. G. Tillman, personal communication, July, 1977). They are underlain by the medium-coarse grained, friable, quartz arenite beds of the Ridgeley Sandstone (Butts, 1940; Lesure, 1957). Several formations are

Figure 2. General stratigraphic column for the study area (modified after Butts, 1940; Woodward, 1943; Lesure, 1967; Dennison, 1961; Bowen, 1967; Berry and Boucot, 1970).

AGE		FORMATION	THICKNESS (meters)
Devonian	Upper	Chemung Formation	150-760
Devonian	Upper	Brallier Formation	380-610
Devonian	Middle	Millboro Formation	180-350
Devonian	Middle	Tioga Metabentonite	.5-4.5
Devonian	Lower	Needmore Shale / Huntersville Chert	4-15
Devonian	Lower	Ridgeley Sandstone (Oriskany)	0-7.5
Devonian	Lower	Licking Creek Limestone	18-37
Devonian	Lower	Healing Springs Sandstone	7.5
Devonian	Lower	New Creek Limestone (Coeymans)	6
Devonian	Lower	Keyser Limestone	21-37
Silurian	Pridoli	Tonoloway Limestone	43-61
Silurian	Pridoli	Wills Creek Formation	12-31
Silurian	Ludlow / Wenlock	Keefer Sandstone	61-76
Silurian	Llandovery	Rose Hill Formation	61-82
Silurian	Llandovery	Tuscarora Sandstone	21-37

represented in an incomplete manner in the southeastern section of the study area, i.e., in the Salem synclinorium relative to their appearance to the north and west. These formations include the Lower Devonian formations of the Helderberg Group and the Silurian Rochester, McKenzie, Wills Creek, and Tonoloway formations. These Silurian formations are probably represented in part in the Salem synclinorium by the "Keefer" sandstone interval (Tillman, 1963). Lack of good exposure has discouraged detailed stratigraphic studies, and the writer did not attempt to work out details of the stratigraphy.

Overlying the Millboro Formation are the interbedded greenish brown shale, siltstone, and sandstone beds of the Brallier Formation with the number of sandstone beds increasing upward (Butts, 1940; Lesure, 1957). The contact between the Millboro and Brallier Formations is gradational and difficult to establish. As seen from the stratigraphic relations given above, the Millboro Formation is over- and underlain by more competent strata.

The Millboro Formation is best known at its type section at Millboro Springs, Bath County, Virginia, which is northeast of the study area. The unit consists of dark gray to black, carbonaceous, fissile, thin to thickly laminated (upward) mud-shale that weathers into light gray to grayish yellow chips (Butts, 1940; Lesure, 1957; refer to Blatt, Middleton, and Murray (1972) for terminology used in this study). Unweathered Millboro Shale may contain as much as 10 percent fine-grained, subhedral to euhedral pyrite (Lesure, 1957).

The unit is fossiliferous (marine) although the fossils tend to be concentrated in several, usually calcareous zones. Numerous nodules and concretions occur within a few zones and range in diameter from a few centimeters to more than a meter; they are ovoid, with shortest dimensions perpendicular to bedding. According to Woodward (1943), most of the zones of concretions are concentrated 15 to 23 m (50-75 ft) above the base of the Millboro Formation. They are found as both hollow nodules filled with clay and very fine grained quartz particles and as septarian concretions containing pyrite, calcite, dolomite, selenite, marcasite, iron sulfide, and/or radiating barite crystals (Woodward, 1943; Lesure, 1957; J. Renton, oral communication, June, 1974). Most of the concretions are calcareous, and some have fossil nuclei. Lesure (1957) recorded that these zones of concretions commonly grade laterally into zones of thick-bedded argillaceous limestone.

The thickness of the highly incompetent Millboro Formation is variable and difficult to measure. The formation is usually poorly exposed. Evidence, which includes numerous faults and highly contorted and sheared bedding, of tectonic thickening or thinning of the formation is present at most outcrops (J. Renton, oral communication, 1974). Butts (1940) reported a thickness of at least 305 m (1000 ft) for the unit at its type section. At the northern end of the study area, Lesure (1957) reported 180 to 350 m (600-1150 ft) of Millboro shale. At Drapers Mountain, just southeast of the study area, Cooper (1939) reported a thickness of 274 to 305 m (900-1000 ft), and along the northwestern edge of the study area in West Virginia (Hampshire and Hardy Counties), Woodward (1943) recorded a thickness of 213 to 259 m (700-850 ft).

The Millboro Formation is at the base of a thick Devonian clastic sequence that increases in thickness and grain size toward the source areas on the east. This sequence progrades west-northwestward and culminates in the large Catskill Delta complex (Colton, 1970). The dark color, abundant pyrite, and type of marine fossils of the Millboro shales support the idea that these shales represent the "deeper" water, basinal facies of the Devonian clastic sequence.

The Millboro Formation is currently being studied in the subsurface as a possible zone for the injection of liquid waste and more importantly as a possible reservoir for natural gas (Dennison, 1971; Patchen, 1976; Wheeler and others, 1976; Wheeler, 1977b).

Although minor, mesoscopic folds are found in several formations in the study area, only those in the Millboro Formation were studied. The study was restricted to this formation for the following reasons: 1) the minor, shear folds are abundant and well developed in the lower part of the Millboro shale, 2) largely because of different erosion levels between the Central and Southern Valley and Ridge Province, the Millboro Formation is the only unit that exposes discfolds, whose hinge lines are planar distributed throughout the length of the study area, and 3) the restriction of the study to one formation and one lithologic rock type allows a comparison of the orientation patterns of the minor folds of the

Central and Southern Valley and Ridge Province without having to include controls caused by different rock types, different burial depths, and/or different adjacent formations.

Structure

The marked change in the topography, structural and topographic trends (Plate 1, Fig. 8), and style of deformation of surface structures between the Southern and Central Appalachians occurs along a zone less than 16 km (10 mi) wide. This zone trends approximately east-west (lat 37°30'N) and extends across the entire Appalachian Mountain system, although its nature and importance in the Piedmont Province are uncertain (Plate 1).

The Blue Ridge Province northwest of Roanoke, Virginia is a single ridge that is 10 to 20 km (5-10 mi) across and trends N30-35° E. Southwest of Roanoke, the province broadens into an upland as much as 100 km (60 mi) across and trends N60-65°E (Rodgers, 1970).

The changes across the junction zone are not as apparent in the Appalachian Plateau Province except for the abrupt change in the orientation of the higher amplitude folds along the southeastern side of the province, i.e., along the "High Plateau" (Gwinn, 1964). The structures of the northwestern side of the Plateau Province tend to be irregular and very low in amplitude. Their irregular nature and similarity to structures of the Midcontinent region suggest that they are largely controlled by basement tectonics (Rodgers, 1970).

The study area lies entirely within the Valley and Ridge Province, and most of the outcrops studied were in the northwestern half of the province. It is within this province that the differences between the Southern and Central Appalachians are the most apparent. Perhaps the most striking contrast is the marked change in the topographic and structural trends of N30-35^{o}E for the central segment to N60-65^{o}E for the southern segment. In general, the folds of the Valley and Ridge Province of the Central Appalachians tend to be gently curving, doubly plunging, more open, and less asymmetrical than those of the southern segment (Gwinn, 1964; Lowry, 1971). High-angle, southeast-dipping reverse faults as well as back-thrusts are located on the majority of the northwest as well as on some southeast limbs of the anticlines in the central segment (Lesure, 1957; Cardwell, Erwin, and Woodward, 1968; Bick, 1972, 1973; J. Renton, personal communication, June, 1974). The use of geophysical and well data has shown that these faults are usually splays of deeper detachment or sole faults (Rodgers, 1963; Gwinn, 1964, 1970; Perry, 1975; Perry and Rader, 1976).

Southwest of the junction zone, six major thrust faults are exposed in the Valley and Ridge Province in southern Virginia and two of these faults extend some 600 km (370 mi) to the southwest (Rodgers, 1970). The St. Clair, Narrows, Saltville, and Salem thrusts all lose stratigraphic throw, increase in dip, and terminate either at the junction zone or barely penetrate the central segment. The Pulaski-Staunton and Max Meadows thrusts extend a good deal farther into the central segment, although they do undergo changes in character and strike (Spencer, 1968; Rodgers, 1970; W. D. Lowry, personal communication, February, 1977).

Cloos (1971) reported the results of an extensive study of principally the strained state of ooids in Cambro-Ordovician carbonates along the southeastern side of the central segment of the Valley and Ridge Province. Lowry (personal communication, February, 1977) stated that Cloos was surprised to find that the ooids in the Cambrian carbonates exposed on the overturned northwest limb of the Christiansburg anticline (Fig. 8) and in the adjacent Pulaski thrust sheet (southern segment) are relatively little deformed, reflecting less penetrative deformation in this region.

Unlike the southern segment, intrusives occur in the Valley and Ridge Province of the Central Appalachians. Numerous examples include the felsitic and basaltic dikes and sills located along deep fractures transverse or highly oblique to the Appalachian trend in Highland County, Virginia and the kimberlites at Mt. Horeb, Rockbridge County, Virginia (Kettren, 1970; Johnson, Milton, and Dennison, 1971; Sears and Gilbert, 1973). Bollinger (1973) reported that the Southern Appalachian belt of earthquake epicenters is offset to the east along an east-west trending zone, and this zone strongly parallels the Central-Southern Appalachian junction zone.

Although there are other zones where the Appalachian "trend" changes its strike, only along the Central-Southern Appalachian junction zone is the belt so narrow and angular, and the changes in topography, structural and topographic trends, and style of deformation of surface structures so apparent (Rodgers, 1953). Gwinn (1964) stated that the difference in the style of deformation between the Southern and Central Valley and Ridge Province is only one of erosion as the thrust faults of the central segment are covered by a blanket of younger strata. This may be true in part, but a difference in erosion alone cannot explain all the abrupt contrasts, such as the marked change in structural and topographic trends, found across the junction zone.

DISCFOLDS

Previous Work

The facies concept has been used recently to analyze some mesoscopic folds in metamorphic rocks (Hansen, Scott, and Stanley, 1967; Howard, 1968; Hansen and Scott, 1969; Scott and Hansen, 1969; Wheeler, 1973). Mesoscopic (size of an outcrop to hand sample) folds are classified by their geometric styles and fabric relationships into different strain facies and each facies is interpreted to have formed under a different strain environment (Hansen, 1971). The discfold facies (Hansen, 1971, p. 157-162) comprises asymmetric, disharmonic folds, between similiar and concentric in geometry, with coplanar hinge lines. They have been reported in experimentlly deformed media and in sedimentary rocks (Hansen, Porter, and Hall, 1961; Scott, 1969; Gevirtz and Hansen, 1973; Hall, 1973; Henderson, 1973; King, 1973; Moore and Wheeler, 1975; Wheeler, 1975, 1977b). Several analyses have provided solutions that closely match the movement directions determined by other means (Hansen, 1967, 1971; Scott and Hansen, 1969; Gevirtz and Hansen, 1973; Hall, 1973). One such example is Hansen's (1967, 1971) kinematic analysis of the mesoscopic folds developed in a tundra landslide on a slope in Trollheimen, Norway (Figs. 3, 4). There, Hansen was able to measure folds across the entire sheared mass. The plane of shear was taken to be parallel with the contact between the soil and

Figure 3. Map (1) and cross section (2) of a tundra landslide in Trollheimen, Norway (modified from Hansen, 1971, Fig. 15). The linear arrows represent the trends of the horizontal projections of the hinge lines of the folds with the plunge angle given beside them. The asymmetry (as determined looking down the plunge of the folds) of each fold is indicated by a clockwise or counterclockwise curved arrow. Horizontal and vertical scales are equal. Note that the tundra pulled apart at the top of the slide and that the folds were developed primarily at the toe of the slide where the tundra was compressed the most.

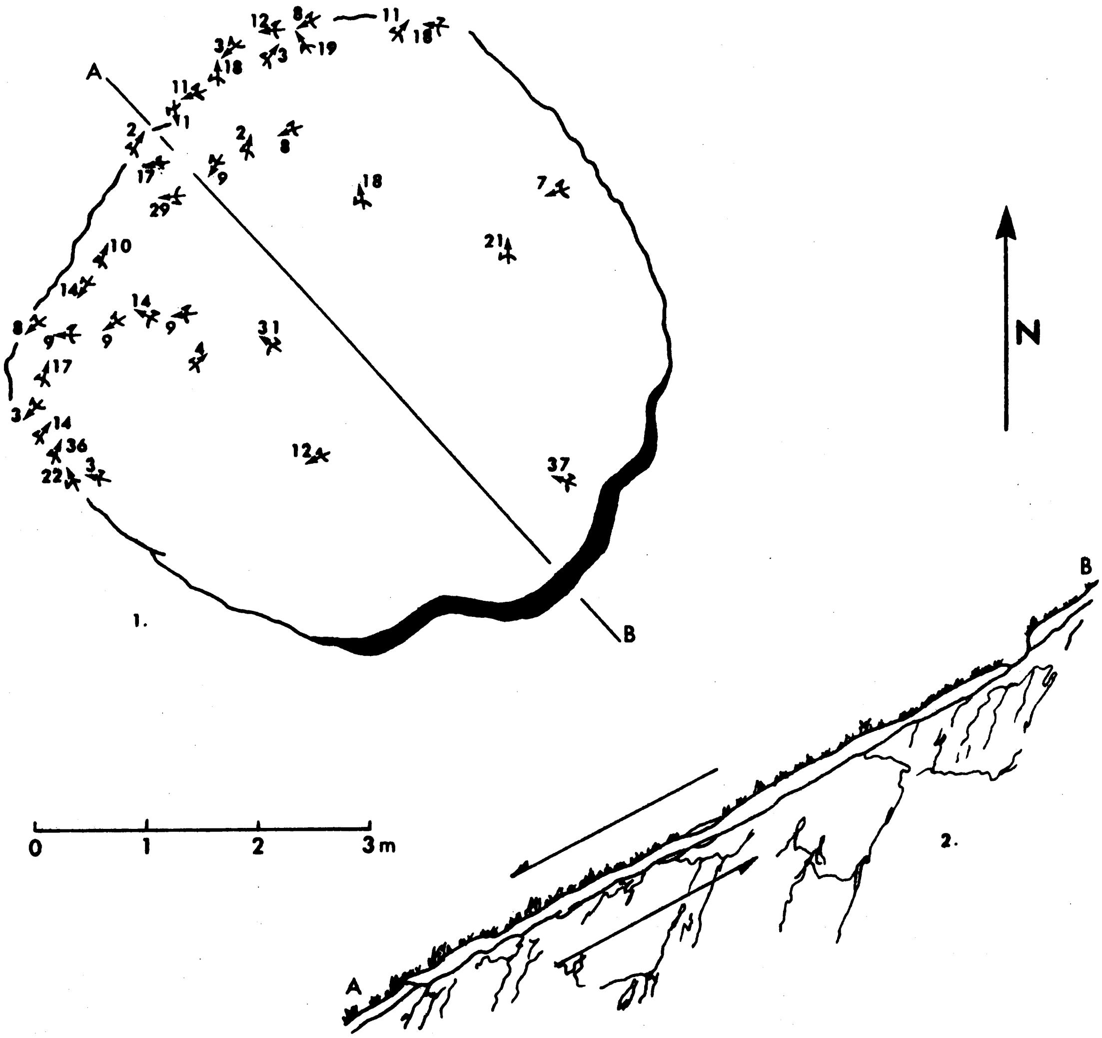
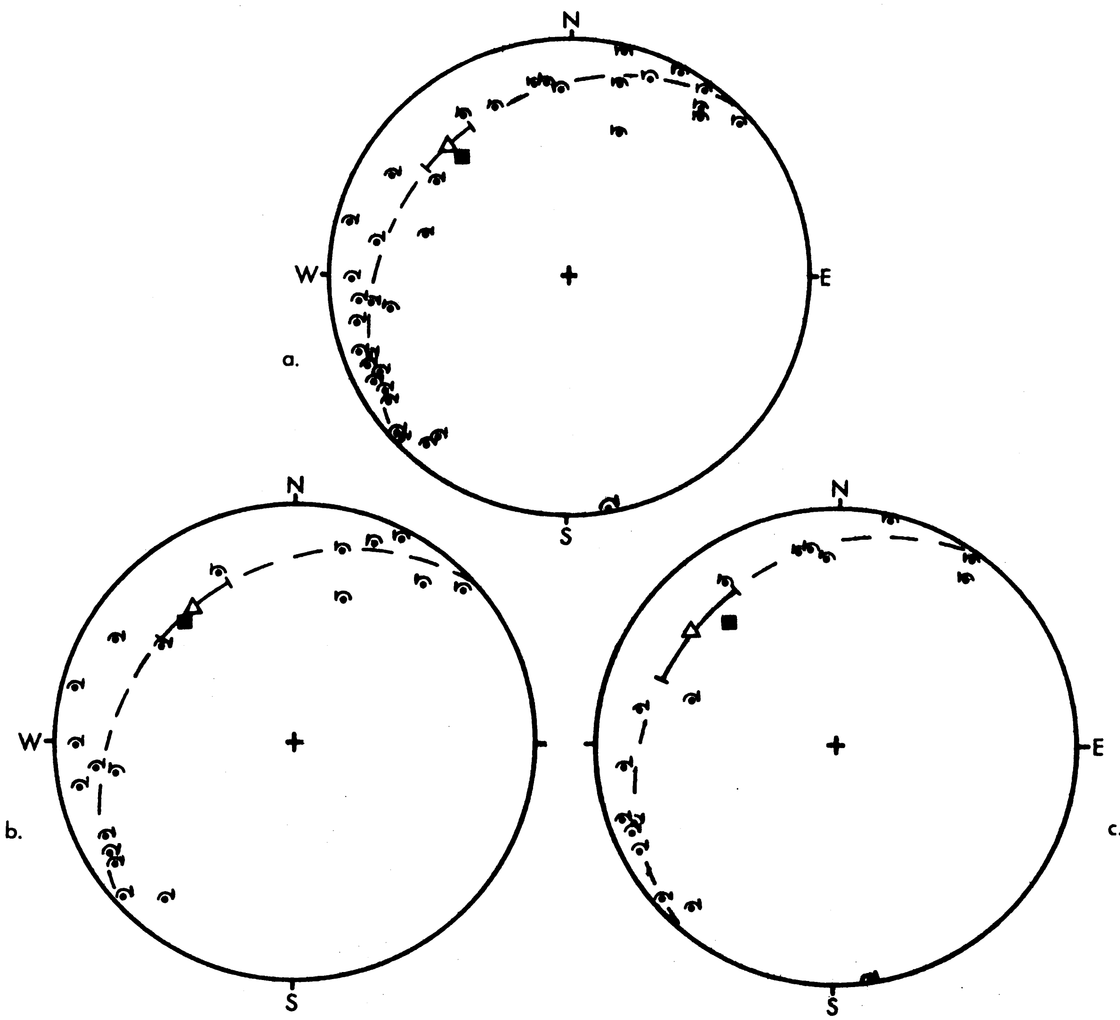

A
B
N
0
1
2
3m
1.
2.

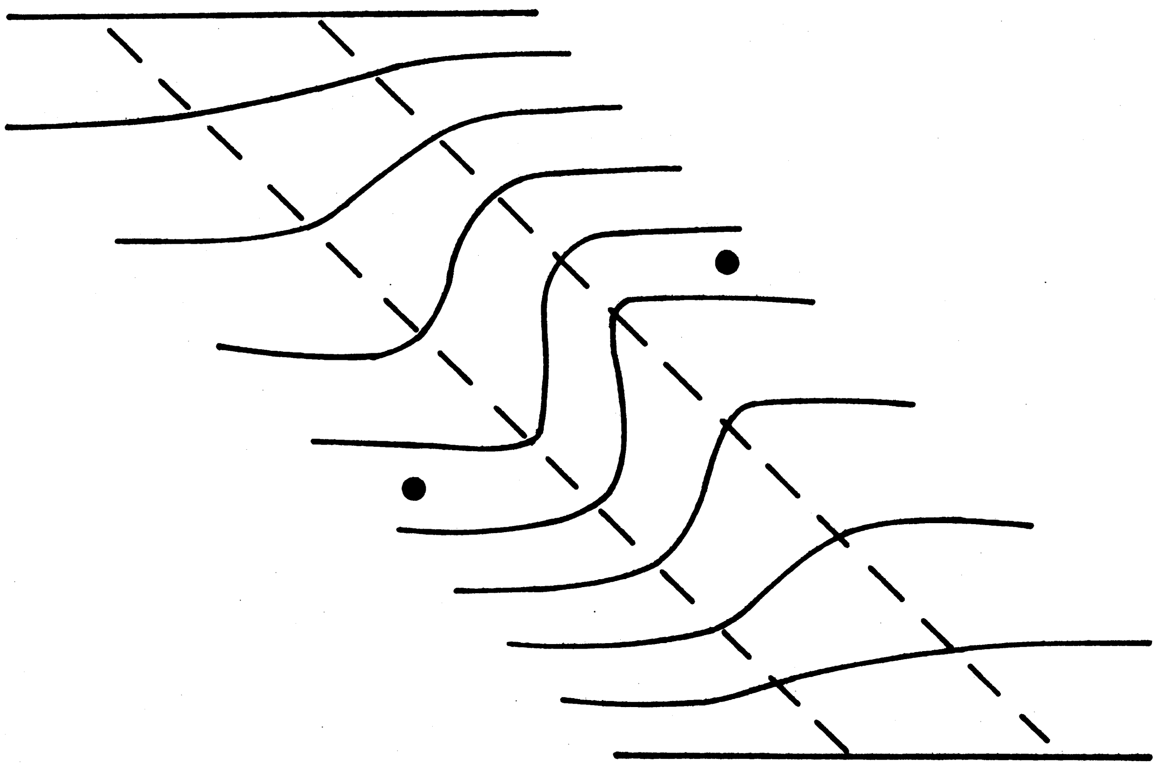
Figure 4. Lower-hemisphere spherical projections of planar distributed hinge lines (dots) and asymmetries (semicircular arrows) of the folds in the tundra landslide (modified from Hansen, 1971, Fig. 17). Separation angles are shown by the solid arc segments on the slip planes (dashed arcs). Separation lines (midpoint of the separation arc) are indicated by open triangles and the mean downslope directions by solid squares. Composite diagram (a). Partial diagram (b) of folds southwest of line AB (Fig. 3). Partial diagram (c) of folds northeast of line AB.


N
W
E
S
a.
N
W
S
b.
N
E
S
c.

bedrock as the slide was of the same thickness throughout. The mean downslope direction was determined by averaging some downslope directions of the surface of the tundra within and around the land-slide since the slide had moved downslope under the influence of gravity (Hansen, 1971). When the orientations of the hinge lines (Fig. A2) of the discfolds were plotted on a map of the slide (Fig. 3), it was clear that the discfolds were oriented at diverse angles to the mean slip line and that folds of both northern and western plunges were located throughout the slide. When the orientations of the hinge lines of the mesoscopic folds and their senses of asymmetry were plotted on a spherical projection (Fig. 4), the folds with northern plunges were found to be of dominantly counterclockwise (sinistral, as determined looking down the plunge of the fold) asymmetry and those with western plunges were primarily of clockwise asymmetry (dextral). The hinge-line orientations were planar distributed, i.e., the hinge lines in spherical projection do not form a cluster of points but instead form a curved girdle of points to which a great circle can be fit. The great circle that was fit to the plot of hinge lines was subparallel to the previously determined plane of shear. The planar angle that separated the folds into two groups by their opposite asymmetries was the separation arc. It is within the separation arc that "the direction of displacement between the flexing layers as a mass and their surroundings" (i.e., slip line) is located (Hansen, 1971). Hansen (1971) also constructed spherical projections of the discfolds by using data from only parts of the slide. The movement directions (separation arcs and separation lines, Fig. 4) determined from these plots closely matched the mean downslope direction (Fig. 4) and the movement direction determined from the plot of the data across the whole slide. This last result showed that a study of only a limited exposure of a sheared zone can accurately determine the movement direction of the whole domain (Hansen, 1971).

The minor, mesoscopic folds in the Millboro Formation north of the area of this study have been analyzed by Wheeler (1977b) using a modification of Hansen's (1971) method of style elements. The folds are in highly contorted zones and appear to be chaotic in terms of orientations, sizes, and styles (Wheeler, 1977b). Numerous small faults and areas of intense shearing have produced some folds with isolated hinge lines and zones with little clearly visible bedding. Wheeler's (1977b) study of the style elements has quantitatively described and reduced the fold geometries to a meaningful classification and shown that the folds are examples of discfolds as originally defined by Hansen (1971, p. 157-162). The majority of the discfolds are between similar and concentric (1C geometry, Fig. A1; Ramsay, 1967) with gently to moderately curved hinge lines and limbs (Fig. 5). The interlimb angles of these asymmetrical folds averaged 83 degrees. Most of the folds are disharmonic and commonly both ends of the axial surfaces are exposed (Wheeler, 1977b). The fold styles suggest that the folds were formed by a flexural mechanism (Donath and Parker, 1964; Wheeler, 1977b). Wheeler (1977b)

Figure 5. Schematic profile section of typical discfold of the Millboro Formation (from Wheeler, 1977b, Fig. 3). Style elements were evaluated along the layer indicated with dots, and the traces of axial surfaces are represented by dashed lines. The fold has the most common or medium values of seven style elements: 1C geometry, gently to moderately curved hinges and limbs, height/spacing = 0.8, depth/spacing = 6.9, disharmonic, interlimb angle approximately 83°.



attributed this flexural mechanism to a tectonic origin although mesoscopic, planar distributed folds can develop from sedimentary processes as seen by Hansen's (1971) analysis of folds developed in a tundra landslide and Hall's (1973) analysis of slump folds in turbidites. Evidence for the tectonic origin of the discfolds in the Millboro Formation includes the presence of slickensides on most of the folded surfaces, the fact that the slip planes of northwest limbs of anticlines cut across otherwise undisturbed bedding, and the previous knowledge that the Millboro Formation is commonly a zone of tectonic detachment.

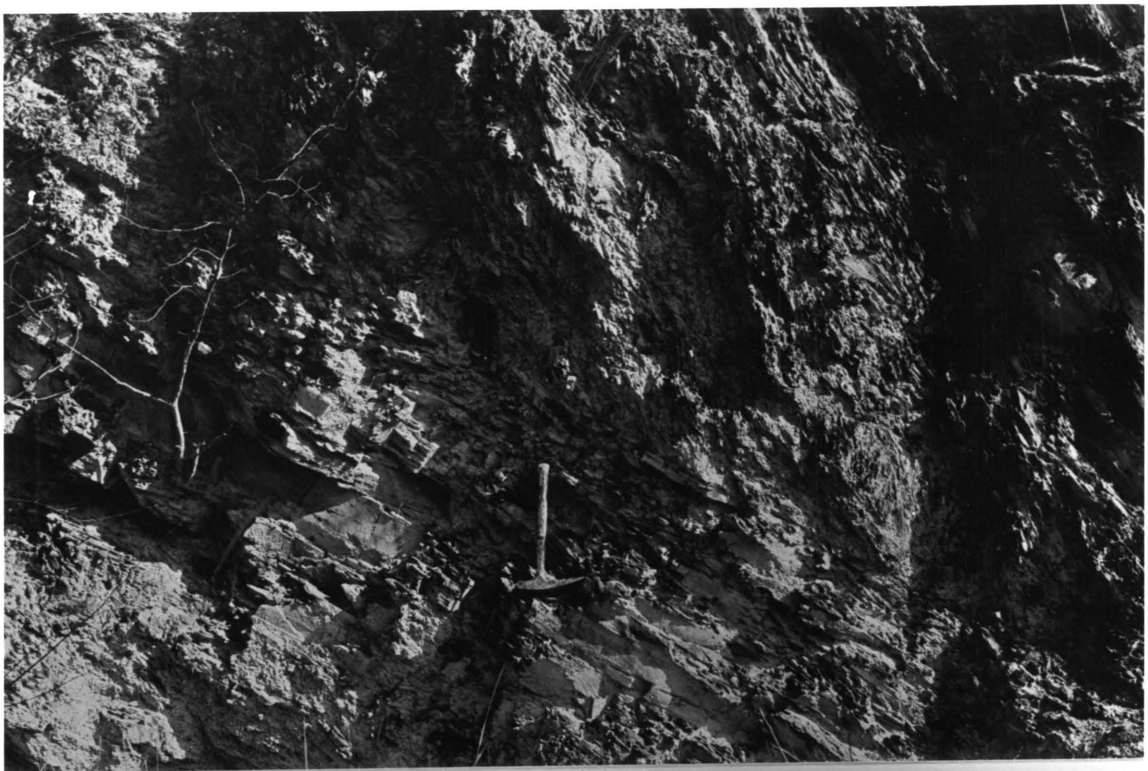
Wheeler's testing of the geometric style elements of the discfolds with nonparametric statistical methods did not detect any significant differences between outcrops on different limbs of the anticline studied, i.e., that the outcrops on different limbs did not form "under different physical, chemical, or spatial conditions of lithology or orogenic history, or at different times" (Wheeler, 1977b). Wheeler (1977b) concluded from his kinematic analyses of the discfolds that the folds were the result of shear during the growth of the major anticline. The cause of the shear on the northwest limb of the anticline was southeast-dipping reverse faulting and that on the southeast limb was either large-scale flexural flow or southeast-dipping reverse faulting. These shearing movements have been suggested by other workers in the region and have been documented in several places (Wheeler, 1977b).

Discfolds of the Study Area

In the study area, the discfolds in the Millboro Formation are in irregular shear zones from 5 cm (2 in) to at least 7.5 m (25 ft) thick, measured perpendicular to bedding (Plate 2). Commonly several of these zones of various thicknesses in an outcrop are separated by unfolded, less fissile shale. The majority of the shear zones contain abundant discfolds, although the abundance of the folds is usually not constant throughout the zone, i.e., the folds are found in heavier concentrations in irregular zones throughout the shear zone. The folds are not concentrated along the contacts of the shear zone with the uncontorted, less fissile bedding. The shear zones also contain smaller shears that have destroyed the original planar bedding within the zones but have not affected the general trend of the unsheared intervals.

The overall geometries of the discfolds were observed at the outcrops, in slabs, and in thin sections (Plates 2,3,4), and the geometries agree with those reported by Wheeler (1977b). This study did not include the quantitative measurement of the geometric style elements of the folds since Wheeler (1977b) had already determined that the folds were discfolds (Hansen, 1971), and he did not detect any significant differences in the style elements of folds of outcrops in different structural positions. The majority of the discfolds are upright, open, noncylindrical, asymmetrical folds of Ramsay's (1967) 1C geometry, as the folds have more curvature toward

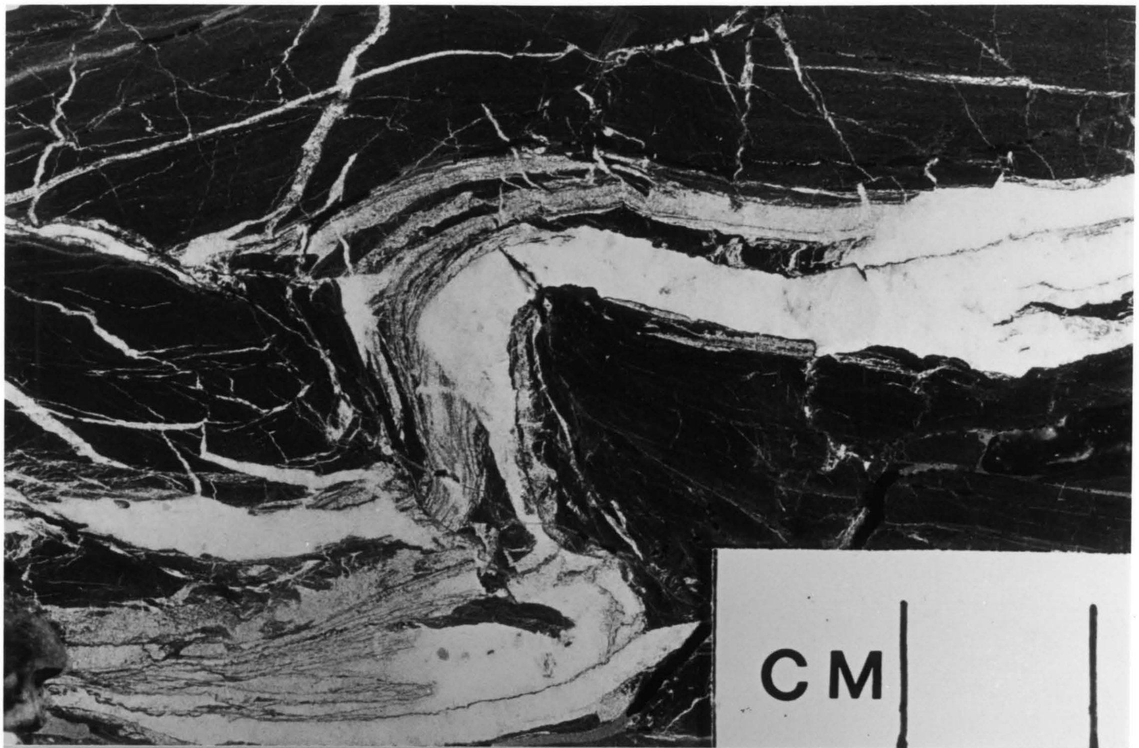
Plate 2. Examples of shear zones in the Millboro Formation (hammer for scale). Note the abundance of the discfolds throughout the shear zones and the lack of any increase in the number of folds at the contacts of the shear zones with the zones of uncontorted, less fissile bedding (photo A is from outcrop 8, which is on the southeast limb of an anticline (Fig. 8), and photo B is from outcrop 23, which is on the northwest (?) limb of an anticline).



A

B

Plate 3. Examples of discfolds from the Millboro Formation, which are pictured in order to point out some of the features of discfolds but not to suggest that all the discfolds in the Millboro Formation are of the same geometry and nature as these folds (refer to Fig. 5 for line sketch of a discfold drawn with the most common or median values of the style elements of the folds in the Millboro Formation). The pair of folds in photo A have folded a calcite seam. Note the presence of a small reverse fault on the steep limb of the anticline in A (A from outcrop 23, which is on the northwest (?) limb of an anticline). The pair of folds in B are not as asymmetrical as those in A, and the bedding within the folds is harder to follow due to the presence of numerous, small shears within the limbs (B from outcrop 11 (Fig. 1), which is on the northwest limb of the nose of Sinking Creek anticline).



A

B

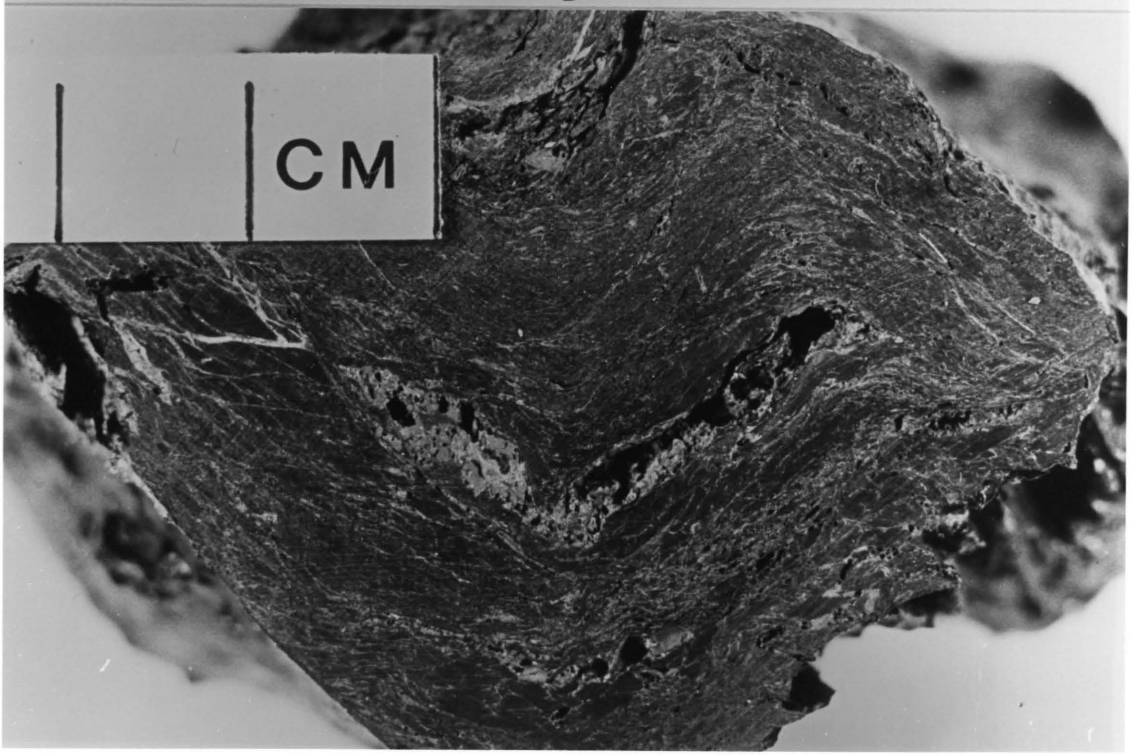
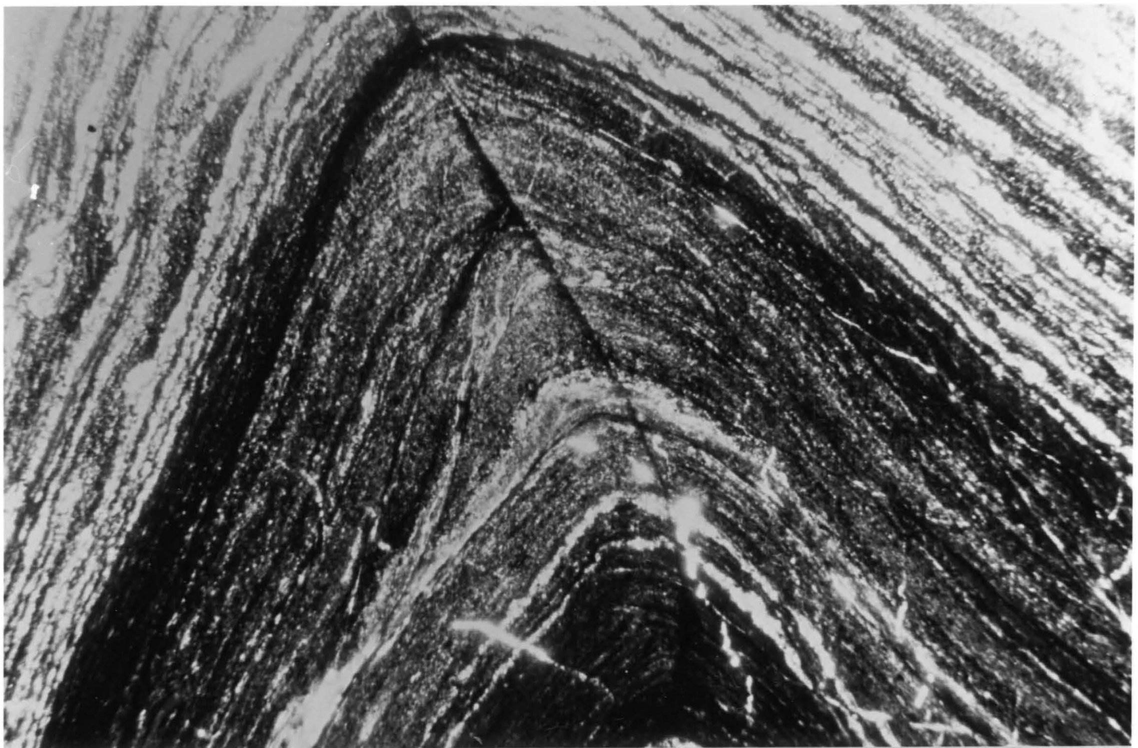


Plate 4. Photomicrographs (5X) of discfolds from the Millboro Formation that are examples of discfolds with somewhat straighter limbs and that are less open as compared to the folds in Plate 3. Both of the folds have a moderate amount of flowage into the hinge areas and both have small reverse faults on one or both of their limbs (these folds were taken from outcrop 23, which is on the northwest (?) limb of an anticline, Fig. 8).



A 2mm

B 2mm

the inner part of the fold and there is very little flow toward the hinges (Figs. A1,A2,A3). The problem of lack of space in the cores of the concentric discfolds is commonly resolved by the presence of small reverse faults (Plate 4) on one or both limbs of the folds in a manner suggested by Gwinn (1964). Commonly, the bedding surfaces are slickensided as most of the slip is confined to the bedding planes with only a slight amount of flow toward the hinge zones of the folds. These observations suggest a flexural mechanism of formation. The discfolds are closest to Donath and Parker's (1964) flexural slip class. The hinge lines and poles of the axial surfaces of the folds have planar preferred orientations and the shear senses (asymmetries) of the folds show a common sense of overturning. Hansen and Scott (1969) interpreted folds with geometries very similar to the discfolds in the Millboro Formation to have been formed as a result of compression in a triaxial stress field with subsequent drag and/or flattening into their present forms under the influence of the resolved shear stresses on the layer(s).

Assumptions

Scott and Hansen (1969), Hansen (1971), and Wheeler (1977b) reported several conditions or assumptions that have to be met in order to kinematically analyze discfolds.

1) The discfolds are the result of a flexural mechanism. As discussed in the previous section "Discfolds of the Study Area",

the discfolds are flexural slip folds.

2) As deformation starts, the intermediate stress axis parallels the beds that are to be folded. Wheeler (1977b) stated that this is a valid assumption for discfolds as they are a type of flexural fold.

3) The discfolds were developed in planar shear zones. The folds are found in somewhat irregular, though planar, contorted zones, and numerous field and laboratory tests have shown that this assumption is certainly a reasonable working hypothesis (Wheeler, 1977b).

4) The discfolds belong to a single generation. No folded folds were observed, and Wheeler (1977b) has shown that this assumption would not be violated if early formed discfolds were tightened, folded, rotated, or destroyed by the later stages of the same shear movement. The continued movement would "blur" the pattern of the orientations of the folds somewhat, but if the shear direction and sense were constant, the assumption would still be valid. The amount of "blurring" that possibly has occurred was estimated using nonparametric statistical methods as described by Wheeler (1977a,b) and discussed later in this text (see "Consistency Tests of Discfold Vergences").

5) The discfolds belong to the same order. The presence of lower order folds is difficult to detect in the shear zones of the Millboro Formation because the bedding in the zones is highly contorted. Wheeler (1977b) has shown how this assumption may not

have been violated in the Millboro Formation, and again, statistical testing of the data provide measurements on the validity of this assumption.

6) "The discfolds occur between two adjacent axial surfaces of the next-lower-order folds of the same fold generation" (Wheeler, 1977b). The discussion of assumption 5 also pertains to this assumption.

7) The layers that were deformed were planar before folding. The bedding in the uncontorted intervals is planar.

8) If there were other episodes of folding, the discfolds postdated them in the rock volumes analyzed. Both the sheared and the uncontorted intervals in the Millboro Formation have evidence of only one episode of deformation.

METHODOLOGY

Field Work

Discfolds found in 29 outcrops (Fig. 1) were measured throughout the summer months of 1976. Because of the incompetency and high susceptibility to weathering of Millboro shale, good exposures of the formation are confined largely to roadcuts, fill quarries, and a few stream cuts. The outcrops studied occur on both limbs of the major folds in the study area as well as along several major reverse faults. Where possible, the outcrops chosen for study occur away from the noses of the major folds. The outcrops ranged from 1 m (3 ft) to approximately 0.4 km (0.25 mi) in length. In the larger outcrops, the measurements for a given analysis were restricted to a small part of the outcrop. Outcrops of various orientations were studied, although discfolds in outcrops oriented perpendicular to the strike of the shales are easiest to measure. The structural position of each outcrop was determined from published geologic maps of the area and by field checks.

Only discfolds with the overall geometries and orientations previously discussed were measured (see "APPENDIX A" for detailed methodology and fold criteria). Minor chevron folds were sometimes developed in the shear zones, but they were not studied. The hinge line (trend of its horizontal projection and plunge), axial surface (strike and dip), and sense of asymmetry (clockwise or counterclockwise as determined looking down the plunge of the fold) were measured for as many folds as feasible for each outcrop (Figs. A2, A3). The general attitude of the shear zone and that of the surrounding, uncontorted shale were recorded as well as the thickness of the shear zone, measured perpendicular to bedding.

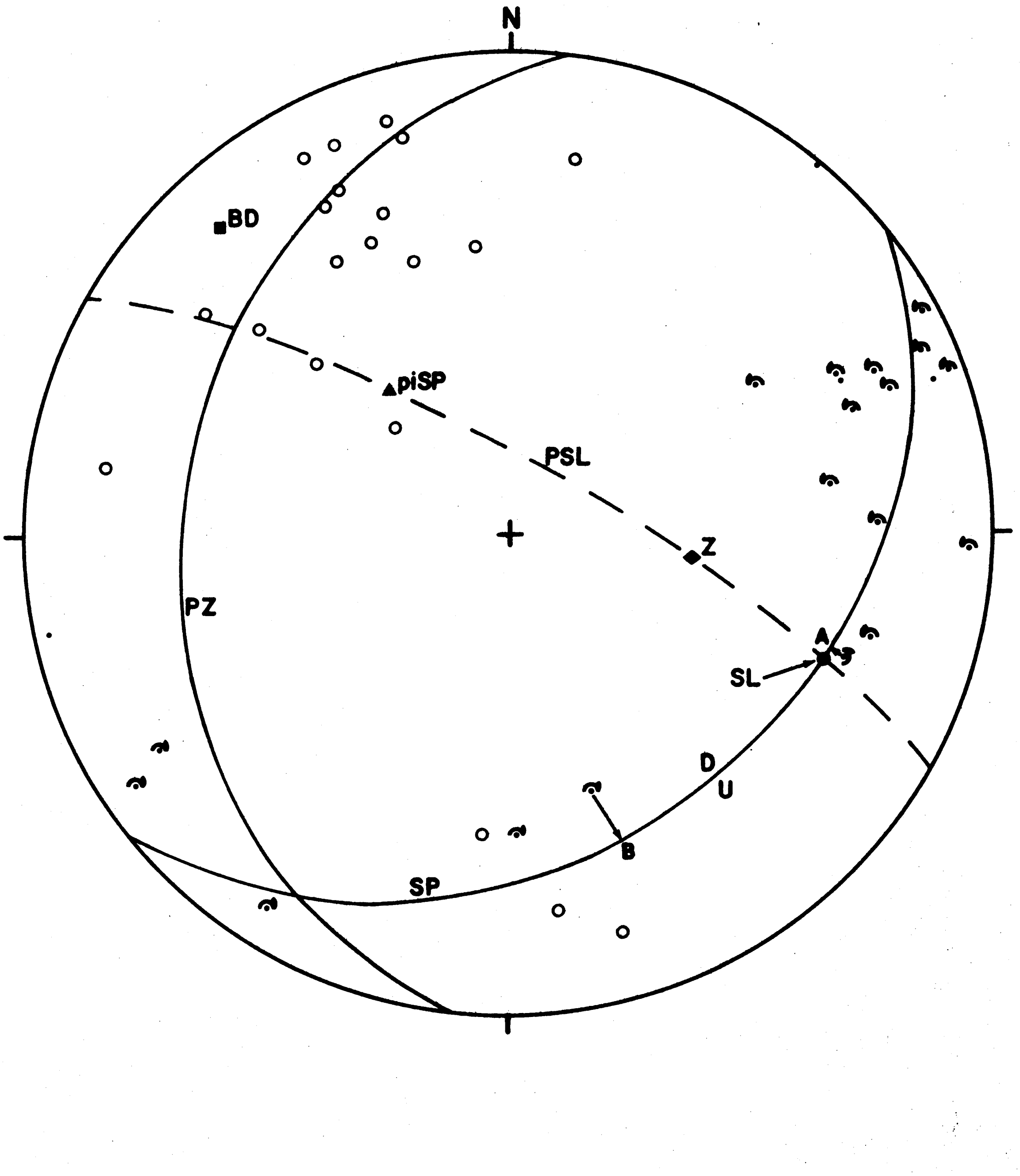
Kinematic Analysis

Hansen (1967, 1971) discussed two related methods for the kinematic analysis of the data. The better known separation-arc (SA) method provides the attitude of the planar shear zone (slip plane), the sense of relative movement between the strata on each side of the slip plane, and the separation arc. The separation arc contains the "direction of relative movement within the slip plane" (slip line), but this method alone cannot resolve the exact orientation of the slip line itself (Wheeler, 1977b). The second method, called the axial-surface fabrics (ASF) method, combines techniques used in the first method with the attitudes of the axial surfaces of the minor folds in order to determine the slip line exactly (Hansen, 1963; Hansen, 1967; Scott and Hansen, 1969; Hansen, 1971). In this study, both methods were used.

These methods first involve plotting the points that represent the hinge-line orientations (i.e., the trend of the horizontal projection of the hinge line and its plunge) on a lower-hemisphere spherical projection from an equal area (Schmidt) net with the asymmetry of each fold (as determined looking down the plunge of the fold) shown by a clockwise or counterclockwise arrow (Fig. 6). The great circle (SP of Fig. 6) that is fit to the girdle of these points represents the slip plane (SP), and the sense of movement along this plane is determined by observing the asymmetries of the folds. The planar angle that separates the two domains of asymmetry is the separation arc. In order to derive the slip line, a plane (PZ of Fig. 6) with its pole (Z) is then fit to the girdle of the poles to the axial surfaces. The point Z is thus a pi-axis fit to the axial surfaces, i.e., it is an estimate of a line that is the most common to the axial surfaces (Scott and Hansen, 1969). Another plane (PSL) is constructed so that it contains the pole (piSP) to SP and Z. The intersection of this plane with SP is the slip line. This line should fall within or very close to the separation arc (Wheeler, 1977b).

The slip plane and the plane fit to the poles of the axial surfaces were initially fit by hand. The planes were later fit by a Fortran IV program that Wheeler (1977b) has written using a least-squares method described by Ramsay (1967, p. 18-19). The latter method does not work well in fitting planes or pi-axes that are very close to horizontal, but this problem can be overcome by fitting after the data have been rotated as described in a later section (see "APPENDIX A") or by using the planes that were fit by hand. Differences in the results of fitting the planes by hand and by the computer program are very small. The results of the computer

Figure 6. Lower hemisphere spherical projection of the hinge line (solid dots) and axial surface (poles of which are shown as open circles) data of the discfolds from outcrop 24 (see "APPENDIX B" for listing of the data) on an equal area (Schmidt) net, constructed using the separation-arc (SA) and axial-surface fabrics (ASF) methods. Terminology and symbols: asymmetry of each fold (as determined looking down the plunge of the fold) is indicated by the short, curved counterclockwise (ccw) or clockwise (cw) arrows (lack of arrows indicates the asymmetry could not be determined for that fold); slip plane (SP, N51E/33SE for this outcrop) is the great circle fit to the plot of the hinge lines (horizontal projection of the trend of the hinge line and its plunge, Fig. A2); slip line (SL, N68W/30SE); pole to SP (piSP); pole to the great circle (PZ) that was fit to the poles of the axial surfaces, i.e., the pi-axis of axial surfaces, is Z (N82W/58SE); plane that contains piSP and Z and is used to determine SL is PSL; pole to the attitude of the uncontorted bedding (BD). The movement along SP is indicated by U, D (U for upthrown and D for downthrown block). A and B are the points that were constructed by the projection of the two folds (shown by arrows; refer to "Kinematic Analysis" in APPENDIX A for methodology) onto SP in order to determine the separation arc. Thus, the kinematic analysis of this data indicates a NE-SW striking, SE-dipping slip plane, with an overall vergence toward the northwest as indicated by the orientation of the slip line and the asymmetry of the folds.


N
BD
piSP
PSL
Z
PZ
A
SL
D
U
B
SP

program fits were used for the majority of the analyses to remove any possible operator bias.

Uncertainties in the orientations of the planes (SP and PZ) arise from possible inaccurate measurements of data, plotting of data, and in reading the Brunton compass. The total uncertainty for any given plane or line should not exceed ± 3-4 degrees.

Consistency Tests of Discfold Vergences

As previously discussed in the "Assumptions" section, there are several assumptions (notably 4, 5, 6) that can not be entirely substantiated. Some discfolds are encountered that have asymmetries that are not consistent with the overall sense of movement as determined from the majority of the folds. Wheeler (1977b) has reported several factors that can cause a fold to have an inconsistent asymmetry: 1) local perturbations can occur within the shear zone, 2) unobserved underthrusting can occur in a shear zone of overall overthrusting, 3) certain types of convergent, locally irregular flow can cause the hinge lines of a few discfolds to cross the separation arc, 4) discfolds that formed early in a shear movement can be destroyed, rotated, tightened, or unfolded by later phases of the same shearing movement, 5) several unusual conditions may cause a slip line to fall outside the separation arc (Hansen, 1971, p. 40-42). Because all of these factors have to be considered, the data from all of the outcrops were tested with nonparametric, binomial statistical tests that have been described by Wheeler (1977 a,b; see Siegel, 1956 for detailed methodology of the tests). These tests resulted in a significance level or p-value for the consistency of both the asymmetries of the folds and the orientations of the axial surfaces of the discfolds for each outcrop. The p-values represent the probability that the overall vergence as deduced from the spherical projection of the discfold data was produced by chance, i.e., the question that is being asked is "whether the vergences of the consistent and inconsistent discfolds differ significantly from what they could be if the measured discfolds were drawn from a population in which consistently and inconsistently verging discfolds were equally common" (Wheeler, 1977b). Therefore, a small p-value indicates that the overall vergence of the shear zone is real. No results were drawn from data that had p-values over 0.085 (Table 2), which means that each of the accepted exposures has less than 1 chance out of 11 of having overall asymmetry patterns or vergences that are chance occurrences. Actually, the majority of the accepted exposures have p-values much lower than 0.085 and no accepted exposures have mean p-values over 0.042 (Table 2).

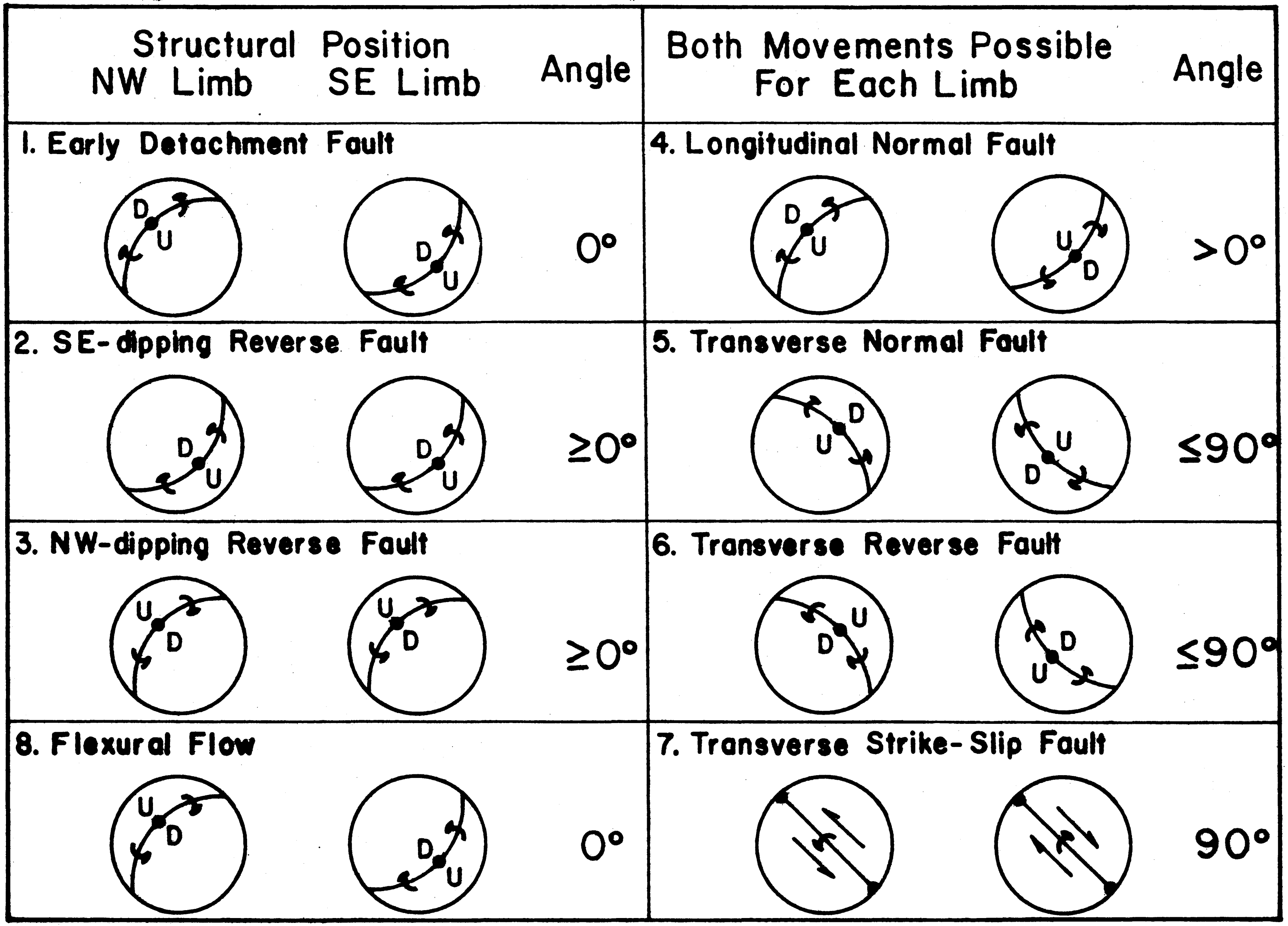
INTERPRETATION OF DATA

The discfolds in the Millboro Formation are the result of a flexural mechanism produced by drag within shear zones as the more competent units moved past one another. The kinematic analysis of the minor folds (Fig. 6) can reveal the type of tectonic movement that caused the drag for a given outcrop since, according to Wheeler (1975; 1977b), each type of shearing movement produces a different combination of slip-plane orientation, slip-line orientation, distributions of shear sense (direction of movement along the slip line), and angle between uncontorted bedding and the slip plane.

Possible Types of Shear Movements

Wheeler (1975, 1977b) described eight possible different types of tectonic movements that are consistent with the regional geology and which could have produced shear zones in the Millboro Formation (Fig. 7): 1) early, nearly horizontal, bedding-parallel detachment faults or overthrusts that had northwestward movement of the top block and that were additionally folded to give either higher southeast dips or northwest dips as suggested by Rodgers (1963), Gwinn (1964), and Jacobeen and Kanes (1975), 2) southeast-dipping reverse faults that are splays off deeper detachment faults and formed up the southeast limbs of the anticlines or on the northwest limbs as the beds steepened to a high angle to the plane of

Figure 7. Kinematic signatures of the eight possible types of map-scale, tectonic shearing movements in the study area, as they would appear on limbs of anticlines (modified from Wheeler, 1977b, Fig. 4). The lower-hemisphere spherical projections represent the general orientations of the slip planes (great circles) and slip lines (solid dots) for each of the tectonic movements discussed in the text under "Possible Types of Shear Movements". The directions of movement along the slip planes are represented by the symbols: U (upward movement; d (down); ⇆ (left-lateral); and ⇄ (right-lateral). The sense of movement can also be determined by observing the clockwise and counterclockwise curved arrows, which represent their respective asymmetry fields along the slip plane. The number of degrees that would be expected between the average attitude of nearby uncontorted bedding and the slip planes are listed under the heading, Angle. The actual degree of dip of the slip planes can vary from those shown.


Structural Position
NW Limb
SE Limb
Angle
Both Movements Possible For Each Limb
Angle
1. Early Detachment Fault
D
U
D
U
0°
2. SE-dipping Reverse Fault
D
U
D
U
≥0°
3. NW-dipping Reverse Fault
U
D
U
D
≥0°
8. Flexural Flow
U
D
D
U
0°
4. Longitudinal Normal Fault
D
U
U
D
>0°
5. Transverse Normal Fault
D
U
U
D
≤90°
6. Transverse Reverse Fault
U
D
D
U
≤90°
7. Transverse Strike-Slip Fault
90°

maximum shear stress (Gwinn, 1964; Cardwell, Erwin, and Woodward, 1968; Perry, 1975; Perry and Rader, 1976), 3) northwest-dipping reverse faults or backthrusts trending parallel to strike as suggested by Gwinn (1964), 4) high-angle, northwest- and southeast-dipping normal faults trending parallel to the regional strike, 5) normal, 6) reverse, and 7) strike-slip faults that are nearly vertical, cut across strike at high angles, and probably post-date the major period of folding (Gwinn, 1964; Cardwell, Erwin, and Woodward, 1968), and 8) map-scale flexural flow of the lower Millboro shale that was produced by layer parallel shear between less ductile, over- and underlying units as the major folds developed.

All of these tectonic movements are consistent with the regional geology in some part of the study area although some types of movement are more prevalent in the southern or central segment of the study area. Indeed, overthrusts play an important role near or at the surface in the southern segment of the Valley and Ridge Province, and these thrusts have been folded to horizontal and northwestern dips in several places.

RESULTS

The kinematic analyses of the discfolds from 20 outcrops were accepted (Table 1) after the data from all 29 of the outcrops studied were checked by consistency tests (Table 2). The results for the other 9 outcrops were not used because of the presence of too many discfolds with inconsistent vergences and/or an indication that the ASF method had broken down (refer to text under "Consistency Tests of Discfold Vergences" for discussion of the significance levels of the tests and causes of inconsistent data, and to "Factors that Indicate the ASF Method has Broken Down" in "APPENDIX A"). The majority of the outcrops whose results were rejected had fewer than 15 measured discfolds.

For the majority (18) of outcrops the kinematic analyses show northeast-striking, southeast-dipping (17-84^{o}) slip planes with reverse movement to the northwest (Fig. 8, Table 1). Most (17) of the slip lines trend northwest-southeast. The overall vergences of 17 outcrops are directed toward the northwest, which indicates top-over-bottom movement from the southeast. For all (20) of the analyses the overall vergences indicated by the separation-arc method are consistent with those determined by the axial-surface fabrics method. All of the slip lines lie in or within a few degrees of the separation arc.

Table 1. Summary of the kinematic analyses for the 20 outcrops used in the final analysis. Symbols: Otc No (outcrop number); N (total number of folds measured); Slip Plane (attitude); e(SP) (average of the angular deviations of the hinge lines from the SP); Slip Line (trend and plunge); e(Z) (average of the angular deviations of the poles of the axial surfaces to PZ); Ver (overall vergence of the exposure); SA (separation arc); Ang (angle in degrees between SP and the attitude of the uncontorted bedding); Str Pos (position of the outcrop on the major anticline or fault); NW (northwest limb of anticline); SE (southeast limb of anticline); F (located along major fault; ? indicates that the writer is not certain of the structural position).

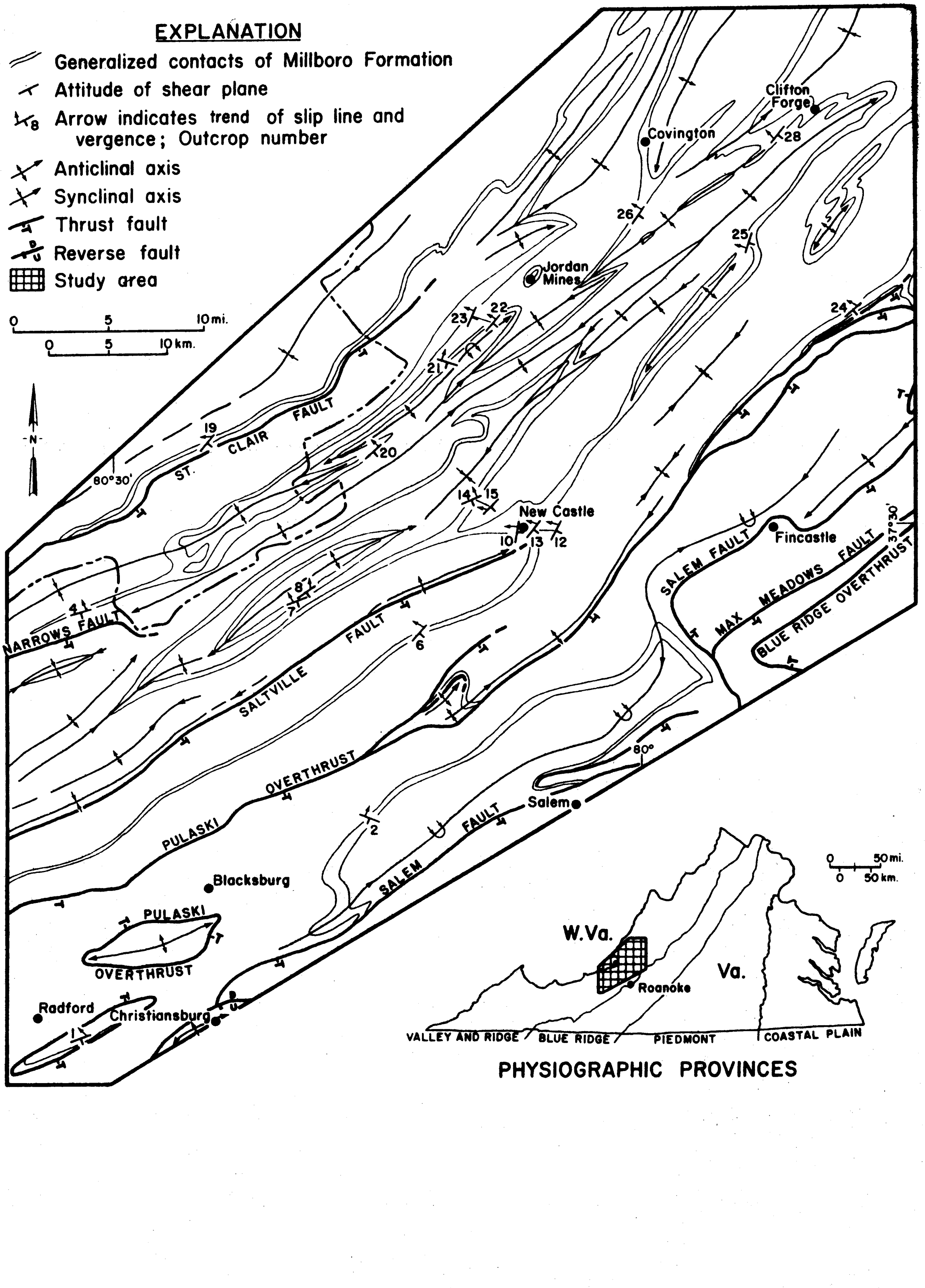
Otc No	N	Slip Plane	e(SP)	Slip Line	e(Z)	Ver	SA	Ang	Str Pos
1	22	N68E/26SE	11	N46W/25SE	20	NW	110	49	NW
2	20	N70W/27SW	11	N26E/27SW	10	NE	108	27	SE
4	25	N74E/80SE	8	N24W/80SE	12	NW	50	26	NW?
6	24	N42E/68SE	13	N59W/68SE	11	NW	59	17	SE
7	13	N68E/25SE	10	N24W/26SE	12	NW	108	13	SE
8	23	N59E/25SE	8	N05W/23SE	10	NW	107	20	SE
10	15	N08E/24SE	5	N89W/24SE	6	NW	2	24	NW
12	18	N27E/39SE	8	N71W/39SE	13	NW	100	15	NW
13	16	N39E/52SE	13	N77W/49SE	11	NW	2	43	NW
14	11	N71E/51SE	10	N28W/51SE	8	NW	78	21	NW?
15	21	N46E/27SE	17	N69W/25SE	9	NW	82	68	NW?
19	20	N40E/54SE	9	N83E/44NE	12	SW	119	45	F
20	27	N50E/78SE	11	N51W/78SE	13	NW	58	2	SE
21	14	N71W/23SW	13	N21E/24SW	16	NE	87	44	NW?
22	22	N41E/36SE	15	N64W/36SE	10	NW	32	18	NW?
23	24	N25E/34SE	8	N69W/34SE	20	NW	94	23	NW?
24	22	N51E/33SE	9	N68W/30SE	14	NW	43	44	F
25	11	N17E/51SE	8	N74W/51SE	11	NW	54	25	SE?
26	14	N34E/84SE	8	N54W/84SE	12	NW	92	17	NW?
28	22	N38E/17SE	14	N35W/17SE	10	NW	121	27	SE?

Table 2. Summary of significance test results for all outcrops studied. Symbols: Otc No (outcrop number); N (total number of folds measured); n(HL) (total number of folds whose asymmetry could be determined); Asym ratio (ratio of the number of discfold asymmetries consistent (see Wheeler, 1977a,b) with the overall vergence of the exposure, to the number of inconsistent, to the number of indeterminate consistency); Asym p-val (exact significance level of consistent: inconsistent ratios from the preceding column); n(AS) (total number of axial surfaces measured); AS ratio (ratio of the number consistent, to inconsistent, to indeterminate axial surfaces), using slip-line method of Wheeler (1977a,b); AS p-val (exact significance level of preceding column); Mean p-val (mean of Asym p-value and AS p-value). Use (indicates whether or not the kinematic analysis was accepted or rejected). The analyses were rejected if the significance levels of the consistency tests were too high or as in the case of outcrops 5 and 18, the separation arc was too large.

Otc No	N	n(HL)	Asym Ratio	Asym p-val	n(AS)	AS Ratio	AS p-val	Mean p-val	Use
1	22	12	11:1:10	0.003	19	18:1:0	0.0	0.002	yes
2	20	17	17:0:3	0.0	18	18:0:0	0.0	0.0	yes
3	18	16	11:5:2	0.105	18	7:11:0	0.760	0.433	no
4	25	23	20:3:2	0.0	24	16:8:0	0.076	0.038	yes
5	11	10	9:1:1	0.011	11	9:2:0	0.033	0.022	no
6	24	23	23:0:1	0.0	24	24:0:0	0.0	0.0	yes
7	13	12	11:1:1	0.003	11	9:2:0	0.033	0.018	yes
8	23	23	23:0:0	0.0	19	18:1:0	0.0	0.0	yes
9	13	11	7:4:2	0.274	13	13:0:0	0.0	0.137	no
10	15	13	12:1:2	0.002	15	14:1:0	0.004	0.003	yes
11	14	11	7:4:3	0.274	12	9:3:0	0.073	0.174	no
12	18	18	18:0:0	0.0	16	15:1:0	0.002	0.001	yes
13	16	16	14:2:0	0.002	16	12:4:0	0.038	0.020	yes
14	11	11	11:0:0	0.0	11	11:0:0	0.0	0.0	yes
15	21	20	17:3:1	0.001	21	20:1:0	0.0	0.001	yes
16	11	10	6:4:1	0.377	11	8:3:0	0.113	0.245	no
17	14	11	8:3:3	0.113	14	14:0:0	0.0	0.057	no
18	22	22	21:1:0	0.0	20	16:4:0	0.006	0.003	no
19	20	19	18:0:1	0.0	20	19:1:0	0.0	0.0	yes
20	27	26	26:0:1	0.0	26	17:9:0	0.084	0.042	yes
21	14	13	11:2:1	0.011	12	11:1:0	0.003	0.007	yes
22	22	21	21:0:1	0.0	22	20:2:0	0.0	0.0	yes
23	24	24	21:3:0	0.0	24	19:5:0	0.003	0.002	yes
24	22	19	19:0:3	0.0	20	17:3:0	0.001	0.001	yes
25	11	10	10:0:1	0.0	10	10:0:0	0.001	0.001	yes
26	14	12	11:1:2	0.003	14	11:3:0	0.029	0.016	yes
27	12	10	1:9:2	0.989	12	5:7:0	0.613	0.801	no
28	22	17	17:0:5	0.0	20	20:0:0	0.0	0.0	yes
29	9	7	3:4:2	0.500	8	5:3:0	0.363	0.432	no

Figure 8. Map showing results of the kinematic analyses of discfolds in the Millboro Formation in the study area (contacts of Millboro Formation are modified after Butts, 1933: and Cardwell, Erwin, and Woodward, 1968; refer to Fig. 1, Plate 1 for physical setting of the map). The outcrops are numbered starting at the base of the map, and only the 20 outcrops whose analyses were accepted are shown on this map.

MAP SHOWING RESULTS OF KINEMATIC ANALYSES OF DISCFOLDS IN THE MILLBORO FORMATION IN THE STUDY AREA



Tectonic Movements that Produced the Shear Zone

The majority (18) of the analyses indicate slip planes with discfold vergences consistent with top over bottom movement along southeast-dipping planar shear zones (Table 1, Fig. 8). The kinematic signatures of the shear zones are different in some aspects between outcrops located on different (NW or SE) limbs of the major anticlines in the study area. These differences are primarily in the angles between the attitudes of the slip planes and the uncontorted bedding. A large angle indicates that the slip plane and uncontorted bedding are not subparallel and a small angle means that the two surfaces are subparallel. Before one can decide if the angle is large enough to indicate that the planes are not subparallel, the angle has to be compared to the average angular deviation of the hinge lines of the discfolds from the great circle (SP) that was fit to them, i.e., to the measure of uncertainty of the slip plane (e(SP) of Table 1; refer to discussion in APPENDIX A under "Kinematic Analysis of Data"). Excluding outcrops 2 and 21 (Fig. 8) whose slip planes are transverse to regional strike, most outcrops on the southeast limbs of the major anticlines (outcrops 6,7,8,20, 25,28) have much smaller angles (Table 1) between the slip planes and uncontorted bedding than do outcrops (1,4,10,12,13,14,15,19,22, 23,24,26) on the northwest limbs.

Thus, the kinematic signatures of the outcrops on the southeast limbs are consistent with three of the eight possible types of tectonic movements that could have produced the shear zones in the Millboro Formation (refer to Fig. 7 and discussion in text under "Possible Types of Shear Movements"): 2) early, bedding-parallel, detachment faults that have been folded by the growing anticlines, b) southeast-dipping, bedding-parallel reverse faults located on the southeast limbs of anticlines, and c) flexural flow within the rising southeast limbs of the anticlines. If the shear zones were produced by early (pre-major folding) detachment faults, then northwest-dipping shear zones with apparent normal movement should be found on the northwest limbs of the anticlines since the early detachment faults would have been rotated by the major stage of folding. No shear zones of that nature were detected in this study. This decreases the likelihood of such faults, but still, the possibility of such faults can not be ruled out completely without more analyses. The other two types of tectonic movements are both consistent with the kinematic signatures of the shear zones and the regional geology (Lesure, 1957; Gwinn, 1964; Cardwell, Erwin, and Woodward, 1968; Jacobeen and Kanes, 1975; Perry, 1975). The existence of a few outcrops (25,28) on southeast limbs that have angles between bedding and slip planes that are marginal between being "large" or "small" suggests that at least some of the outcrops may be due to southeast-dipping reverse faults that are oriented at a small angle to the bedding.

The majority of the outcrops (1,4,10,12,13,14,15,19,22,23,24, 26; excluding outcrop 21 whose slip plane is oriented transverse to regional strike) on northwest limbs of anticlines have angles between bedding and slip planes that indicate the two are not subparallel (Table 1). The kinematic signatures (Figs. 7,8) of the slip planes for all of these outcrops match only those of a southeast-dipping reverse fault. The attitude of the uncontorted bedding in all of these outcrops is steeply dipping to the southeast because of the rotation of the beds by second order folds, or more likely, rotation by drag along the faults or by actual overturning of the beds by first order folds. For the majority of these outcrops, the slip plane is dipping southeast at a lesser angle than the bedding. These types of reverse faults match those already mapped in more competent strata or postulated by other workers (Lesure, 1957; Cardwell, Erwin, and Woodward, 1968; Jacobeen and Kanes, 1975; Wheeler, 1977b). Several of these outcrops, in particular outcrops 1,14, and 26 (Fig. 8), have an angle between the attitude of the uncontorted bedding and slip plane that is marginal between "large" or "small" (Table 1). The bedding in these outcrops dips 67-75^{o} southeast. These relationships suggest that the reverse faults that produced the shear in these outcrops are bedding-parallel faults. The steep nature of these faults suggests that they are the toes of reverse faults that probably flatten with depth to gentler dips and cut across bedding (Gwinn, 1964; Jacobeen and Kanes, 1975).

Several outcrops (2,10,12,13,19,21) have slip planes that are oriented transverse to regional strike or whose slip lines do not trend NW-SE (Fig. 8). All of these outcrops, except outcrop 2, are located in the junction or recess between the central and southern segments of the Valley and Ridge Province. Outcrop 2 (Fig. 8, Table 1) has a slip plane that suggests a low-angle, oblique fault. The slip line trends NE-SW and its vergence indicates reverse movement toward the northeast. Such a fault can not be substantiated because of the lack of detailed mapping in the area; however, a gap and offset in the mountain, which can be seen on the topographic maps and on the high altitude photo (Plate 1), occur in line with the outcrop and numerous oblique faults have been mapped farther southwest. The kinematic signatures of the shear zones in the five other outcrops (10,12,13,19,21; Fig. 8) indicate shear movement toward the northeast or southwest, i.e., movement directed parallel to the regional strike of the Millboro shales. In particular, those of outcrops 10,12, and 13 (Fig. 8) suggest that the shales were sheared up the nose of the Sinking Creek anticline and therefore away from the recess. The large angle between the attitude of the uncontorted bedding and the slip plane for each of these outcrops (Table 1) and the southeastern dips of the uncontorted beds suggest that the shear zones were not produced simply by flexural flow up the nose of the structure. The shearing probably reflects the results of movement of material out of the junction along a fault associated with the Saltville fault. This movement of material out of the junction should be expected since the southern and central segments are converging into the area and a space problem develops in the recess.

Outcrop 19 is on the overturned southeast limb of the Hurricane Ridge syncline with the St. Clair fault just southeast of the outcrop (Fig. 8). The slip plane strikes about 15^{o} more northerly than the general trend of the St. Clair fault and it dips approximately the same amount to the southeast as the fault; however, the slip line trends east-west and the overall vergence indicates shear movement almost due west along the St. Clair fault or a fault associated with it. This result is another indication of movement of material out of the junction.

Outcrop 21 is on the northern side of the junction zone (Fig. 8). Again, it indicates a shearing movement away from the recess (here, along a southeast-dipping oblique fault), but the movement is toward the northeast, possibly reflecting the movement of material out of the recess on the other side of the zone.

Timing of the Shear Movements

In general, the discfolds in the Millboro Formation appear to have developed during the later stages of the growth of the major folds and the initiation of faulting. The southeast-dipping reverse faults on the northwest limbs of the anticlines could not have formed before the major period of folding as they would have been rotated to horizontal and/or northwestern dips. These faults were probably produced as the northwest limbs of the folds steepened to a point where the bedding was at a high angle to the plane of maximum shear stress and the beds were beginning to undergo layer-parallel extension. At this point, further northwestern translation of material could be achieved only by faulting or shearing, resulting in southeast-dipping reverse faults that are typical of the region (Cardwell, Erwin, and Woodward, 1968; Jacobeen and Kanes, 1975; Wheeler, 1977b).

The orientations and kinematic signatures of the shear zones that produced the discfolds on the southeast limbs of the anticlines do not restrict the formation of the discfolds to any particular stage in the growth of the anticlines; however, the age of the Millboro Formation alone restricts their development to post-Middle Devonian. The discfold geometries, uniform intensity of the discfolds within the shear zones, and lack of an increase of folds at the contacts of the shear zones and uncontorted bedding, suggest that the deformation within the shear zones occurred at high confining pressure (W. D. Lowry, oral communication, June, 1977). This observation indicates that several thousand feet of younger rock overlay the Millboro Formation during the development of the discfolds.

Also, as discussed in a previous section, the southeast-dipping reverse faults on the southeast limbs of the anticlines were probably not early detachment faults. The faults were probably developed as the fold grew to a point where the rock could no longer undergo purely ductile deformation, and the faults allowed further northwestern translation of material up the conveniently oriented southeast limbs (Wheeler, 1977b).

Contrasts in the Analyses Across the Recess

There are marked differences in the orientations of the slip planes and slip lines between the central and southern segments of the Valley and Ridge Province (Fig. 9), although the writer did not detect any difference in the style or density of the discfolds, in the nature of the shear zones, or in the types of tectonic movements that produced the shear zones in the Millboro Formation across the recess (Fig. 8).

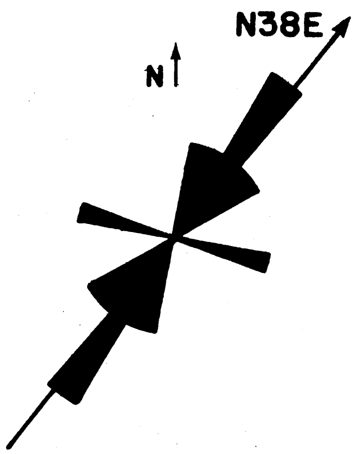
In general, the strikes of the slip planes (Fig. 9) are subparallel to the regional strikes for the central and southern segments. The regional strike of the southern segment is N60-65°E and the median value of the slip planes is N68°E, whereas the regional strike for the central segment is N30-35°E and the median slip-plane strike is N38°E (Fig. 9). The median values of trends of the slip lines (Fig. 9) indicate that the slip lines are oriented roughly perpendicular to strikes of the slip planes (N24°W for southern segment; N64°W for central segment). At least by visual comparison, the orientations of the slip planes, slip lines and therefore the tectonic movements that produced the shear zones in the central and southern segments are at different orientations to one another, i.e., the two segments converge at the recess.

The relationships discussed above were also checked by nonparametric statistical tests (R. L. Wheeler, written communication,

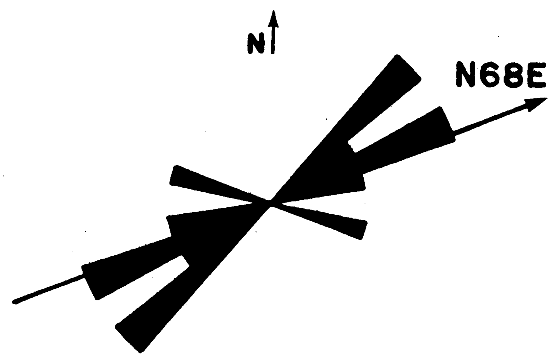
Figure 9. Rose diagrams of the strikes of the slip planes and trends of the slip lines (lines were plotted in the quadrant of overall vergence) for the central and southern segments of the Appalachian Valley and Ridge Province. The median value (actual value given beside arrows) for each diagram is indicated by the straight arrow. The diagrams were made using only those outcrops (1,2,4,6,7,8,19,21, 22,23,24,25,26,28) that could be assigned clearly to either the central or southern segment.

SLIP PLANES

CENTRAL

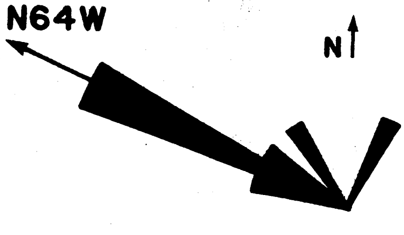


SOUTHERN

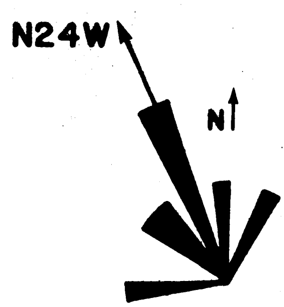


SLIP LINES

CENTRAL



SOUTHERN



June, 1977), notably the Kruskal-Wallis (K-W) test and the randomization test (Table 3; refer to Siegel, 1956, p. 152-159, 184-194 for methodology). Nonparametric tests were used because the tests are designed for small sample sizes and for data that is not necessarily normally distributed about any average value(s). The K-W test was used when the samples being compared (central versus southern segments) had more than 5 observations per sample and the randomization test when one or both samples had fewer than 5 observations per sample. The comparison between the central and southern segments was made using only the results from outcrops (1,4,6,7,8,22,23,24,25,26,28) that could be assigned clearly to either the central or southern segment, excluding those outcrops (2,19,21) whose slip planes are oriented transverse to regional strike or whose slip lines do not trend NW-SE (Fig. 8). The strikes of the slip planes and trends of the slip lines of these outcrops were compared in three groups, the results of which are shown in Table 3. A comparison of the slip planes and slip lines between: 1) the 6 outcrops of the central segment to the 5 of the southern segment, 2) those outcrops of the central segment that are the result of flexural flow or bedding-parallel reverse faults to the same type of outcrops of the southern segment, 3) those outcrops of the central segment that are the result of fault or fault zones to those same types of outcrops of the southern segment.

The comparison shows a significant difference (low p-value) between the orientation of the slip planes for the southern and

Table 3. Summary of the comparison tests of the kinematic analyses of the discfolds between the central and southern segments (central outcrops: 22,23,24,25,26,28; southern: 1,4,6,7,8; Fig. 8) of the Appalachian Valley and Ridge Province. The comparison excluded those outcrops (2,19,21) whose slip planes are oriented transverse to regional strike or whose slip lines do not trend NW-SE (Fig. 8). Symbols: Data (the result being compared; SP is slip plane, SL is slip line); Movement (the comparisons were made on 3 groups: Combined means comparing the results of all the outcrops that can be assigned to either the central or southern segment; Flex-Fl? means comparing the results for the outcrops whose discfolds were the result of flexural flow and/or southeast-dipping, bedding-parallel faults; Fault means comparing the results of discfolds produced by southeast-dipping reverse faults that cut across bedding); N is the total number of analyses compared; Test is the statistical test used (K-W is the Kruskal-Wallis Test, Rand is the randomization test); p-value is the significance level for the comparison made in each row; Southern is the median value of SP or SL (refer to Data and Movement column) for the outcrops in southern segment; Central is the median values of SP or SL for the outcrops in central segment.

Data	Movement	N	Test	p-value	Southern	Central
SP	Combined	11	K-W	0.01	N68E	N36E
SP	Flex-Fl?	5	Rand	0.10	N59E	N28E
SP	Fault	6	Rand	0.07	N71E	N38E
SL	Combined	11	K-W	0.03	N24W	N66W
SL	Flex-Fl?	5	Rand	0.20	N24W	N54W
SL	Fault	6	Rand	0.07	N35W	N66W

central segment (Table 3). The slip planes of the southern segment strike more to the east. A significant statistical difference (Table 3) was also detected between the directions of the slip lines for the "Combined" and "Fault" data but not for the "Flex-Fl?" data. Still, the results for the "Fault" data are the most significant since these shear zones record movements that cut across bedding and are more likely to record movement related to the major detachments that caused the major folds. The shear zones produced by flexural flow may be of a smaller scale, and therefore the slip lines recorded by them will have more scatter and may not relate as directly as the faults to the major movements that produced the major structures (R. L. Wheeler, written communication, June, 1977).

CONCLUSIONS

1) This study provides another field test of a method of kinematic analysis of mesoscopic folds developed by Hansen (1971) and modified by Wheeler (1977b). Although the detailed relationship between this method and strain theory is not yet clear, numerous field and laboratory tests, including this study, have shown the method to be reliable and valid. The application of this quantitative and unbiased method to the discfolds in the Millboro Formation has provided results that shed some light on the evolution of the central and southern segments of the Appalachian Valley and Ridge and their anomalous junction.

2) The discfolds in the Millboro Formation are the result of flexural folding within planar shear zones. The fold geometries, uniform intensity of the folds within the shear zones, and lack of an increase of folds at the contacts of the shear zones and uncontorted bedding, suggest that the deformation within the shear zones occurred at high confining pressures.

3) The discfolds for any given shear zone are of a single generation.

4) The results of the analyses of the discfolds by the separation-arc and axial-surface fabrics methods are consistent with one another.

5) The kinematic analyses of the discfolds have provided the orientations of the slip planes and slip lines and the directions

of overall vergence for 20 exposures. The majority of the analyses indicate NE-SW striking, southeast-dipping slip planes, NW-SE trending slip lines, and reverse movement along the slip planes.

No differences in the intensity or geometries of the discfolds or in the sizes of the shear zones were found between outcrops located on opposite (NW or SE) limbs of the major anticlines. A difference was detected however in the type of tectonic movements that produced the shear zones on the different limbs of the anticlines.

6) The shear zones on the southeast limbs of the anticlines were produced by flexural flow of the ductile Millboro shales as the anticlines grew and/or by southeast-dipping, bedding-parallel, reverse faults that cut up the back limbs of the anticlines.

7) The shear zones on the northwest limbs of the anticlines were produced by southeast-dipping reverse faults. This finding is probably the most significant because the movements indicated by the analyses of these outcrops are probably the most reflective of the large-scale movements that produced the major folds and faults in the study area.

8) Several exposures have slip planes oriented transverse to the regional strike or slip lines that are not oriented NW-SE. All but one of these outcrops are located in the junction or recess between the central and southern segments of the Appalachian Valley and Ridge Province. The results of the analyses for these exposures indicate movement of material out of the junction area toward the

northeast and southwest (Fig. 8).

9) The discfolds, which were produced by reverse faulting on northwest limbs of anticlines, were formed coevally with the later stages of major large-scale folding and faulting. The discfolds on the southeast limbs of the anticlines could have developed during any stage of growth of the anticlines after Middle Devonian, although if conclusion "2" is correct, then several thousand feet of younger rock was deposited on the Millboro shales before they were deformed. The orientations and overall vergences of the shear zones in relation to the time of their formation indicate that the shear zones reflect northwestern translation of material and not shearing evolved by layer-parallel extension on the steepened limbs of the major folds.

10) The study of the discfolds in the Millboro Formation detected no differences in the style or intensity of the discfolds or in the sizes of the shear zones between the southern and central segments of the Appalachian Valley and Ridge Province; however, contrasts were detected in the orientations of the tectonic movements that produced the shear zones.

11) The majority of the strikes of the slip planes for both segments are roughly parallel to the regional strike of the appropriate segment (Figs. 8,9, Table 3), and the slip lines are oriented approximately normal to the strike of the slip planes. Therefore the slip planes of the southern segment strike more to the east than those of the central and the slip lines of the southern segment

trend more to the north than those of the central (Table 3). These results indicate that at least for the portions of the central and southern segments of the Appalachian Valley and Ridge Province that were studied, the two segments were converging to the northwest. This type of movement would have created a space problem in the recess. The apparent movement of material out of the recess is suggested by the analyses of the outcrops in the junction zone (refer to conclusion 8; Fig. 8). Another indication of this type of movement would be presence of cross-folds in the junction zone, but these would probably be of low amplitude and hard to detect.

12) Because the discfolds were formed late in the period of major folding and faulting (at least those produced by reverse faulting on the northwest limbs of anticlines), and because the kinematic analyses of them indicate transport directions from the southeast that are consistent with those that must have occurred earlier in the development of the large-scale structures, the writer concludes that there has been little northwestern rotation of the southern segment in relation to the central segment. The sharp differences in structural and topographic trends between the central and southern segments of the Appalachian Valley and Ridge Province are due to a difference in the original orientation of the greatest shortening. Of course, to test whether this difference is truly regional in extent for the two segments, discfolds should be analyzed through a greater extent of the two segments than this study permits.

Several major ideas concerning the production of the different shortening and movement directions that produced the converging central and southern segments are: 1) an early-developed, irregular continental margin, perhaps produced by transform faults along a Precambrian rift as suggested by Thomas (1976), 2) that the recess could be the result of a "failed arm" of a Precambrian triple junction that was carried away as suggested by Rankin (1975), and/or 3) a difference in the timing of the movement of the two segments as has been suggested by several workers. The apparent interaction of the two segments as suggested by this study and the lack of major overlapping and juxtaposition of the large-scale structures in the recess indicate that the timing was probably not significantly different, although there is some evidence (Rodgers, 1970; Dean, Kulander, and Williams, 1977) that the deformation of the southern segment may have occurred a little sooner or that the rocks in the segment may have been able to transmit the stresses at a greater rate due to factors such as the lack of the Silurian Salina Group as a major detachment zone in the southern segment (W. D. Lowry, personal communication, June, 1977; Wheeler, 1977b).

13) Kinematic analyses of the discfolds in the Millboro Formation have detected shear movements that could not have been otherwise detected because of the lack of lithologic markers in the shales and/or because the movement occurred parallel to the regional strike of the beds.

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APPENDIX A

DETAILED METHODOLOGY AND FOLD CRITERIA

(Modified after Hansen, 1967, 1971; Scott and Hansen, 1969; Wheeler, 1977a,b)

Location of and Measurement of Data

1) locate outcrop(s) with exposure of mesoscopic discfolds that are disharmonic, of 1C geometry (Fig. A1), asymmetric, and of diverse orientations (see discussion of discfolds in text under "DISCFOLDS").

2) determine from published geologic maps and/or field checks the general structural position of the outcrop(s).

3) record the nature and size of the shear zone(s) and the average attitude (strike and dip) of the nearby uncontorted beds.

4) observe the general fold geometries (Fig. A1) of the discfolds (see discussion of fold geometries of discfolds in text under "DISCFOLDS" and in Hansen, 1971, p. 157-162), i.e., be sure the mesoscopic folds are discfolds.

5) measure the following properties for as many discfolds (approximately 15-25) as feasible in one general shear zone (do not measure chevron folds, kinkbands, or other folds than discfolds):

a) trend (of horizontal projection of hinge line, AB, Fig. A2) and plunge(P) of the hinge line (BC, Fig. A2).

b) attitude (strike and dip) of the axial surfaces (AS,

Figure A1. Geometrical classification of folds (modified from Ramsay, 1967, Fig. 7-24). Refer to Ramsay (1967, p. 365-377) for discussion of the fold classes.

FOLD CLASSES

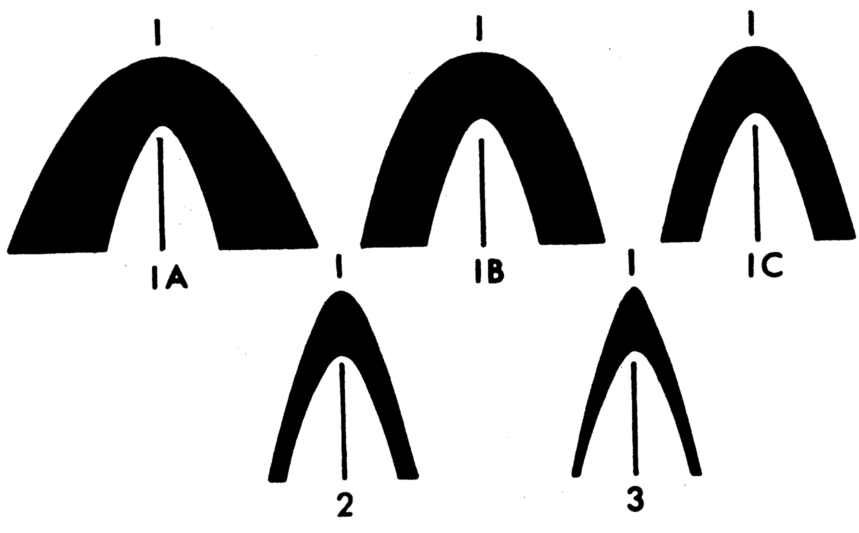


Figure A2. Fold terminology used in this study (modified from Ramsay, 1967, Fig. 7-13). The trend of the fold was determined by measuring the trend of the horizontal projection (AB) of the hinge line (BC). The plunge (P) of the hinge line was measured as the angle ABC. The attitude (strike and dip) of the axial surface (AS) was measured. The large arrow indicates the direction of the plunge of the hinge line.

FOLD TERMINOLOGY

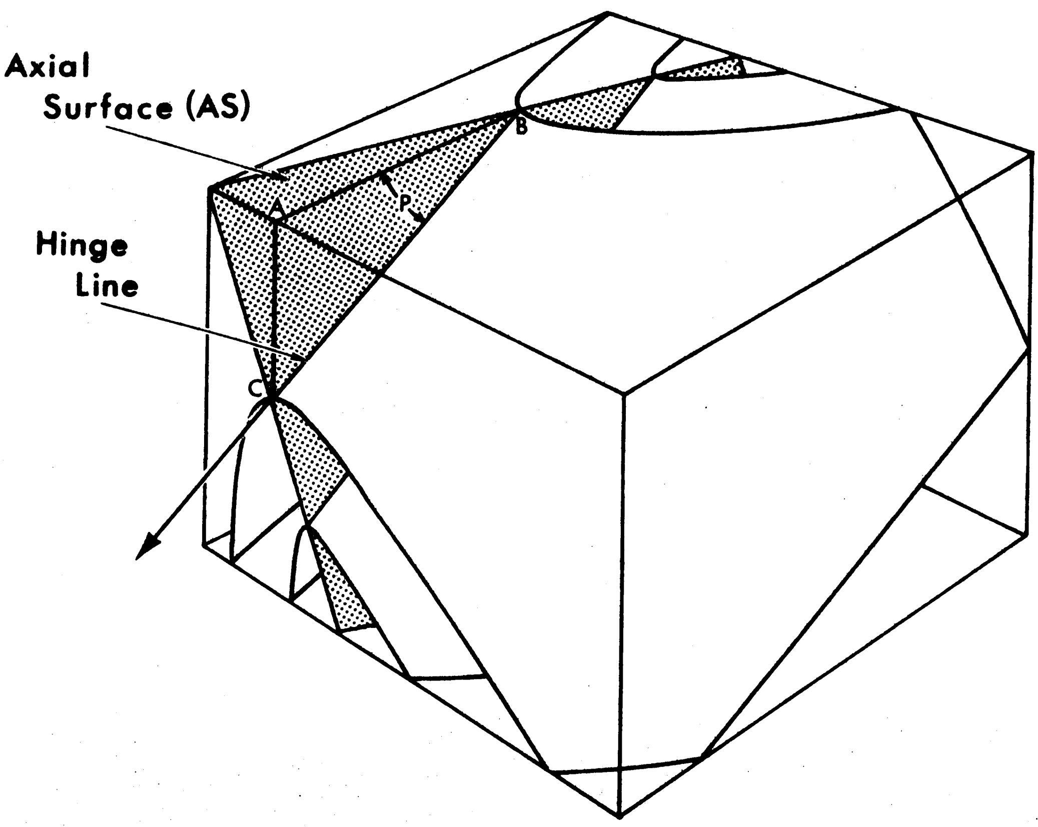


Fig. A2).

c) asymmetry (clockwise (cw) or counterclockwise (ccw) while looking down the plunge of the fold, Fig. A3). For an example, see photo A. of Plate 3. The pair of folds are an example of ccw asymmetry if viewed looking down the plunges of the folds.

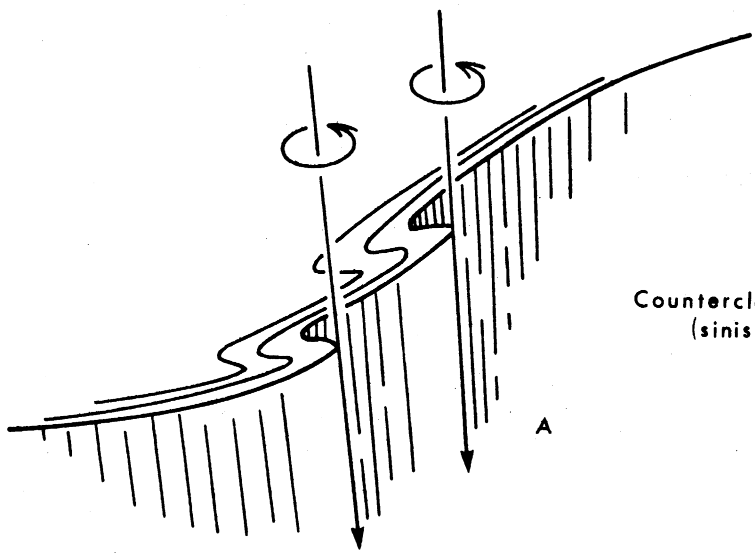
d) after 10-15 folds have been measured, make, while at the outcrop, a lower hemisphere, equal area, spherical projection of the hinge lines of the folds. The general pattern of the commonly oriented folds can then be observed, and one should try to measure some folds of more diverse orientation in order to narrow the separation arc.

e) in this study measurements were seldom made on both folds of a given pair (paired anticline and syncline), but if the investigator does wish to measure both, he or she should record which folds are pairs (see discussion of paired folds and how to treat them in Wheeler, 1977b).

f) the operator error of the investigator should be checked at the start of the study by comparing his measurements to those of a partner for the same set of folds.

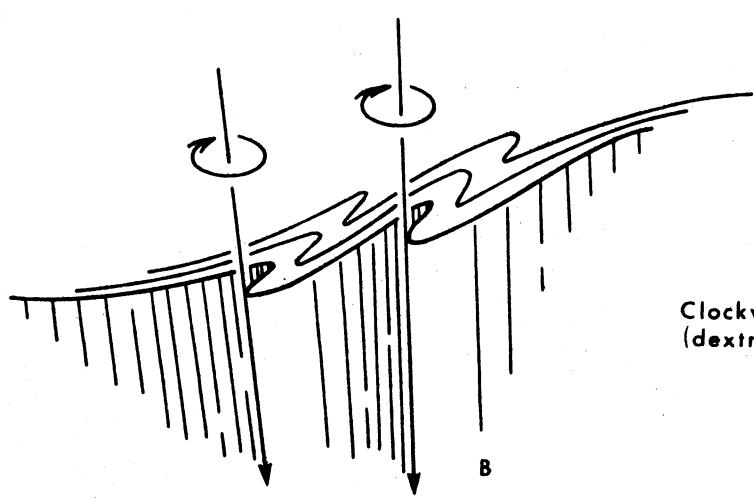
Figure A3. Fold asymmetries (modified from Hansen, 1971, Fig. 9). The down-plunge directions for the folds in both A and B are indicated by the straight arrows.

FOLD ASYMMETRIES



Counterclockwise
(sinistral)

A



Clockwise
(dextral)

B

Kinematic Analysis of Data

For each outcrop or general shear zone follow the steps outlined below to construct a lower hemisphere spherical projection of the data on an equal area net (Fig. A4):

1) plot the hinge lines of all the discfolds as points on the projection, show the asymmetry of each fold by a cw or ccw curved arrow, and fit a great circle (slip plane) to the resulting girdle of points. This plane can be fit visually or by a computer program such as the one used in this study that was based on the least-squares method of Ramsay (1967, p. 18-19).

2) plot the pole (piSP) to the slip plane (SP).

3) visually determine the dominantly cw and ccw asymmetry domains.

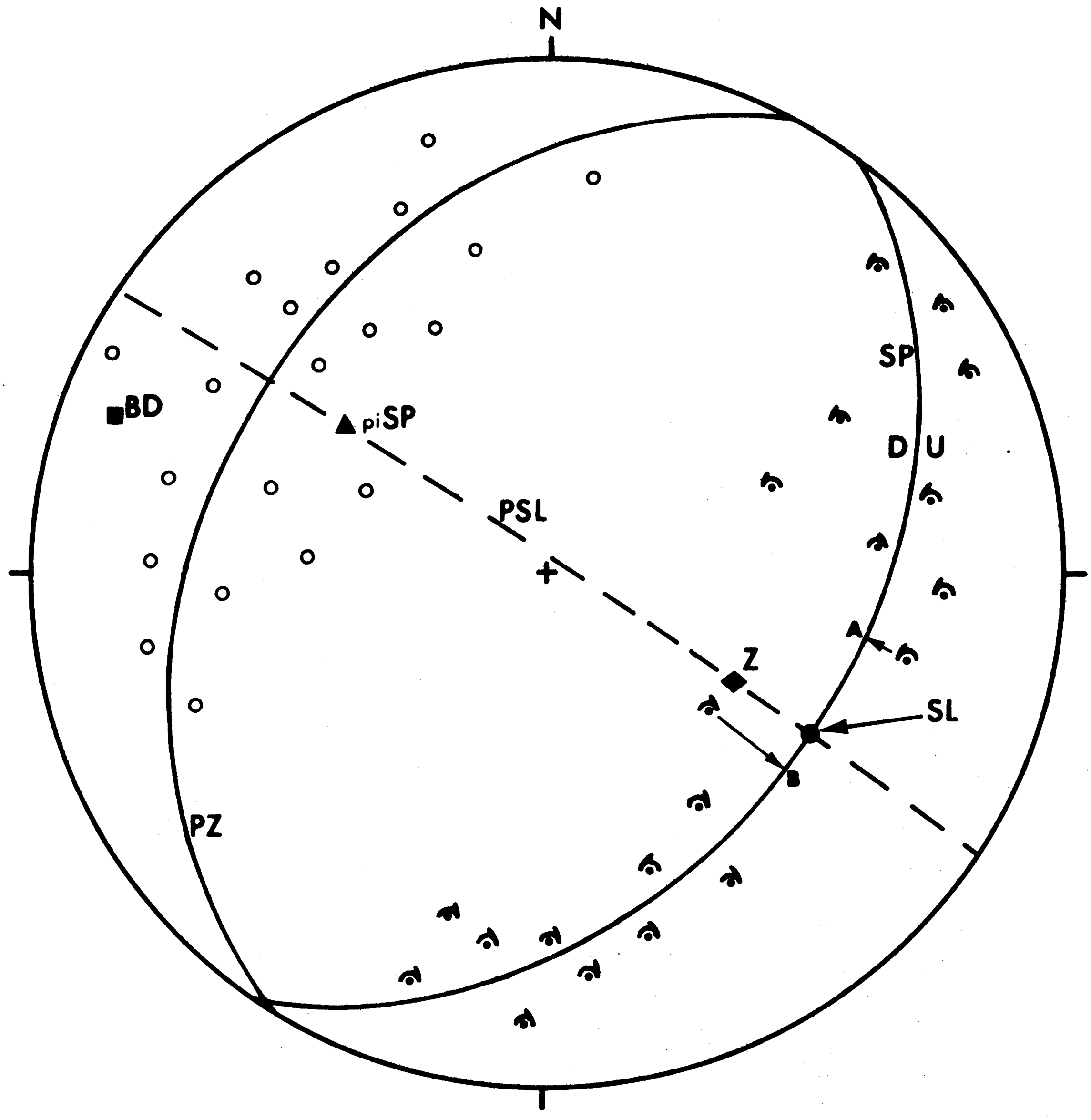
4) choose one cw and one ccw fold (A and B of Fig. A4), which are closest to one another but still each within their respective asymmetry fields.

5) project each of the two folds into the SP along a plane that contains the piSP and the fold.

6) the resultant segment of the SP between the 2 projected hinge lines (between A and B of Fig. A4) is the separation arc (SA); measure its width in degrees.

7) the sense of movement or vergence along the SP can be determined by observing the relative position of the 2 domains of asymmetry. Label the SP to show the movement (U for the side that

Figure A4. Hypothetical lower-hemisphere spherical projection of hinge line (solid dots represent the horizontal projections of the trends of the hinge lines and their plunges) and axial surface (poles of which are shown as open circles) data of discfolds on an equal area (Schmidt) net, constructed using the SA and ASF methods. Terminology and symbols: asymmetry of each fold (as determined looking down the plunge of the fold) is indicated by the short, curved counterclockwise (ccw) or clockwise (cw) arrows: slip plane (SP, great circle fit to the plot of the hinge lines); slip line (SL); pole to SP (piSP); pole to the great circle (PZ) that was fit to the poles of the axial surfaces, i.e., the pi-axis (Z) of axial surfaces; plane that contains piSP and Z and used to determine SL (PSL); pole to attitude of the uncontorted bedding (BD). The movement along SP is indicated by the U, D (U for upthrown and D for downthrown block). A and B are the points that were constructed by the projection of the two folds (shown by arrows; refer to steps 3-6 under "Kinematic Analysis" in APPENDIX A for methodology) onto SP in order to determine the separation arc. Thus, the projection shows a NE-SW striking, SE-dipping slip plane with a vergence indicated by the slip line and the asymmetries of the folds toward the northwest.


N
BD
piSP
PSL
SP
D
U
A
Z
SL
B
PZ

moved up, D for the downthrown side).

8) plot the pole to the average attitude of the bedding for the outcrop, and measure the angle between that point and the piSP along a great circle that contains both points.

9) the slip line (SL) or direction of relative movement along the SP should be contained within the SA. The use of the ASF method (Scott and Hansen, 1969; Wheeler, 1977b), as outlined below, will determine the exact orientation of the SL (Fig. A4).

10) plot the poles to the axial surfaces of each of the disc-folds on the same spherical projection made in steps 1-8. Fit a great circle (PZ of Fig. A4) to the resulting girdle of points and plot the pole (Z) to this plane. The point Z is thus a pi-axis fit to the axial surfaces, i.e., it is an estimate of a line that is the most common to the axial surfaces.

11) when fitting planes to the girdles of hinge lines the data may cluster near the poles of the net when the projection is turned to fit a great circle (examples in this study, outcrops 20,26). This results in an inability to accurately choose a great circle that best fits the points. In order to fit the plane, rotate the data 90° about a horizontal axis roughly perpendicular to the cluster of points, in order to get the points plotting toward the center of the projection. Fit a great circle to the girdle of points and rotate the pole to that plane 90° in the opposite direction about the same given axis. Draw in the plane to the pole and the result is the SP. If the poles to axial surfaces cluster, use a

similar technique to fit PZ.

12) plot a plane (PSL of Fig. A4) that contains Z and piSP. The point of intersection of that plane and the SP is the SL. Determine the orientation of that line.

13) for each projection, measure the angular deviation of each hinge line from the slip plane (example, e(SP) for SP in Fig. 6 is 9^{o}). The average of all these deviations (e) is a measure of the uncertainty of the slip plane for that projection. Use the same method to determine e for Z, i.e., measure the angular deviations between each pole to the axial surfaces and the plane (PZ of Fig. A4) that was fit to them, and average the deviations (example, e(Z) for PZ in Fig. 6 is 14^{o}). For this study, the result of the method (i.e., visual versus computer fit) that provided a plane with the lowest e was used for each case. As discussed in the text under "Kinematic Analysis", the computer fits usually but not always gave a smaller e than the visual fits.

Factors that Indicate the ASF Method has Broken Down

1) are all or the majority of the hinge lines sub-parallel?
2) is the separation arc large (greater than $110\text{-}120^{o}$)?
3) is the slip line subparallel to the major cluster of hinge lines?

If these factors are true for any given spherical projection, the slip line for that projection is probably invalid and should not be used. However, the results of the SA method (slip plane, separation arc, and overall vergence) may still be valid.

Consistency Tests

All of the data should be checked for consistency by nonparametric statistical methods described and outlined by Wheeler (1977a,b; see discussion in text under "Consistency Tests of Disc-folds Vergences"). For this study, the results of the kinematic analysis for a given outcrop were not used if a p-value or significance level greater than 0.085 was obtained for the consistency of the asymmetries and (or) the axial surfaces. Although a p-value of 0.085 may seem high in light of the chance of getting a low p-value purely by chance when testing 29 outcrops (actually with 29 outcrops, there are 2-3 chances), there is a break above 0.085 on histograms of the p-values, and the majority of the p-values are much lower than 0.085 (Table 2). No outcrops were accepted with mean p-value over 0.042.

Results of Kinematic Analyses

(see discussions in text under "INTERPRETATION OF DATA" and "RESULTS").

APPENDIX B

SUMMARY OF DATA AND KINEMATIC ANALYSES

Key (see "APPENDIX A" for the complete definitions of the terms)

Unit - formation from which the discfolds were measured.

Bedding - average attitude of the uncontorted strata.

SP - slip plane.

SA - separation arc.

SL - slip line.

Angle - angle (in degrees) between the attitude of the uncontorted bedding and SP.

B - hinge line.

AS - axial surface.

SS - shear sense or asymmetry.

Outcrop 1

Location: (Radford South 7.5 Minute Quadrangle)

Roadcut along a broad curve in State Route 787, 0.15 mile (0.24 km) south of junction of State Routes 787 and 611.

Unit: Millboro Formation

Bedding: N58E/75SE (? overturned)

SP: N68E/26SE

SA: 110

SL: N46W/25SE

Angle: 49

Data:

Fold #	B	AS	SS
1	N65E/05NE	N67E/69NW	--
2	N68E/16NE	N78E/68NW	ccw
3	N84W/32SE	N81E/67SE	ccw
4	N66E/12NE	N66E/80SE	ccw
5	N79E/07NE	N74E/48SE	ccw
6	N51E/29SW	N50E/83SE	--
7	N50E/12SW	N45E/83SE	cw
8	N80E/15SW	N74E/75NW	cw
9	N73E/10SW	N65E/79SE	--
10	N66E/15NE	N48E/51SE	ccw
11	N64E/03NE	N62E/86SE	--
12	N46E/30SW	N86E/43SE	cw

Fold #	B	AS	SS
13	N44E/03SW	N46E/86SE	-
14	N81E/17SW	N76E/87SE	-
15	N65E/14SW	---	-
16	N41E/14SW	N42E/90SE	-
17	N39E/10SW	N36E/73NW	-
18	N48E/08NE	N45E/74SE	-
19	N49E/05SW	---	-
20	N29E/36SW	---	-
21	N40E/05NE	N12E/25SE	ccw
22	N52E/12SW	N40E/26SE	cw

Outcrop 2

Location: (McDonalds Mill 7.5 Minute Quadrangle)

Roadcut along State Route 622, 0.6 mile (0.99 km) east of junction of State Routes 622 and 629.

Unit: Millboro Formation

Bedding: N75E/45SE

SP: N70W/27SW

SA: 108

SL: N26E/27SW

Angle: 27

Data:

Fold #	B	AS	SS
1	N86E/23SW	N74W/66SW	cw

Fold#	B	AS	SS
2	N73E/19SW	N70E/49SE	cw
3	N84E/44SW	N80W/78SW	cw
4	N79E/32SW	N80W/60SW	cw
5	N77W/28SE	N83E/58SE	ccw
6	N72W/25SE	---	ccw
7	N83E/13SW	N62W/32SW	cw
8	N81E/06SW	N82E/66SE	cw
9	N50W/18SE	N76W/27SW	ccw
10	N43W/15SE	N54W/44SW	ccw
11	N86E/06NE	N76E/44SE	ccw
12	N61W/31SE	N83W/36SW	ccw
13	N51W/07NW	N45W/50SW	cw
14	N75W/08NW	N78W/60SW	cw
15	N62W/10NW	N62W/59SW	-
16	N84W/12NW	N85E/56SE	cw
17	N56E/22SW	N66E/59SE	-
18	N89E/09SW	N87E/60SE	cw
19	N67W/03NW	---	-
20	N41W/02NW	N31W/51SW	cw

<u>Outcrop 3</u>

Location: (McDonalds Mill 7.5 Minute Quadrangle)

Roadcut located along a National Forest gravel road 0.65 mile (1.05 km) from junction, which is 10.85 miles (17.50 km) southeast of the junction of State Routes 621 and 311, of the road with State Route 621. The outcrop is located almost directly below a powerline.

Unit: Millboro Formation

Bedding: N39E/42SE

Data:

Fold #	B	AS	SS
1	N14E/55NE	N04E/78SE	ccw
2	N18E/45NE	N43E/61NW	ccw
3	N85E/21NE	N88E/22NW	ccw
4	N25E/21SW	N21E/71NW	cw
5	N37E/31NE	N51E/63NW	ccw
6	N28E/55NE	N51E/71NW	ccw
7	N37E/51NE	N57E/78NW	ccw
8	N10W/31NW	N25W/55NE	ccw
9	N86E/54NE	N77E/73SE	ccw
10	N78W/46SE	N58E/54SE	ccw
11	N60E/38NE	N57E/88SE	ccw
12	N22W/68SE	N05W/88SW	cw
13	N50E/53NE	N51E/88SE	-
14	N10W/90NW	N08W/88SW	-
15	N28E/53NE	N43E/74NW	ccw
16	N45E/15SW	N37E/66NW	cw
17	N70W/32SE	N72W/73SW	ccw
18	N89W/14SE	N85E/72SE	ccw

Outcrop 4

Location: (Interior 7.5 Minute Quadrangle)

Roadcut along State Route 635, 1.1 miles (1.77 km) west of the junction of State Routes 635 and 613.

Unit: Millboro Formation

Bedding: N50E/68SE

SP: N74E/80SE

SA: 50

SL: N24W/80SE

Angle: 26

Data:

Fold #	B	AS	SS
1	N68E/30NE	N16E/34SE	cw
2	N76E/57NE	N59E/74SE	ccw
3	N56E/36NE	N58E/85NW	ccw
4	N53E/54NE	N30E/63SE	ccw
5	N88E/20NE	N89E/85SE	ccw
6	N85E/47NE	N44E/58SE	ccw
7	N81E/41NE	N80E/90SE	ccw
8	N42E/13SW	N39E/73SE	ccw
9	N43E/53NE	N53E/90SE	-
10	N80E/65NE	N67E/88SE	ccw
11	N82E/10SW	N82E/90SE	cw
12	N82W/57SE	N75W/90NE	ccw
13	N83E/35NE	N80E/85SE	ccw

Fold #	B	AS	SS
14	N70W/56SE	N88E/75SE	ccw
15	N57E/83NE	N52W/80NE	ccw
16	N80E/35NE	N84E/90SE	ccw
17	N75E/03SW	N75E/83SE	cw
18	N67E/40SW	N75E/85SE	cw
19	N85W/62SE	N83W/90NE	ccw
20	N89E/38NE	N89W/85NE	ccw
21	N82E/03SW	N80E/81NW	cw
22	N75W/52SE	---	cw
23	N68E/20SW	N71E/75SE	cw
24	N62E/45SW	N85W/60SW	cw
25	N78E/08SW	N79E/87SE	-

Outcrop 5

Location: (Waiteville 7.5 Minute Quadrangle)

Roadcut along State Route 635, 2.8 miles (4.52 km) west of Waiteville.

Unit: Millboro Formation

Bedding: N25E/76SE

Data:

Fold #	B	AS	SS
1	N40E/51NE	N26E/78SE	ccw
2	N27E/44NE	N28E/85SE	cw
3	N22E/46NE	N26E/90SE	ccw

Fold #	B	AS	SS
4	N30E/49NE	N27E/89SE	ccw
5	N30E/50NE	N47E/77NW	-
6	N47E/27NE	N48E/88SE	ccw
7	N37E/04SW	N42E/67NW	cw
8	N63E/20NE	N60E/90NW	ccw
9	N47E/30NE	N69E/55NW	ccw
10	N47E/07SW	N46E/70NW	cw
11	N50E/05SW	N60E/85NW	cw

Outcrop 6

Location: (Looney 7.5 Minute Quadrangle)

Small quarry along dirt road located just off State Route 621, 0.6 mile (0.97 km) northeast of Webbs Mill.

Unit: Millboro Formation

Bedding: N32E/51SE

SP: N42E/68SE

SA: 59

SL: N59W/68SE

Angle: 17

Data:

Fold #	B	AS	SS
1	N30E/32NE	N33E/73NW	ccw
2	N16E/49NE	N20E/82NW	ccw
3	N10E/17NE	N30E/48NW	ccw

Fold #	B	AS	SS
4	N43E/25NE	N46E/80NW	ccw
5	N30E/34SW	N29E/89NW	cw
6	N71E/04SW	N65E/58NW	cw
7	N48E/26NE	N70E/61NW	ccw
8	N37E/05SW	N35E/74NW	cw
9	N42E/02SW	N46E/80NW	cw
10	N81E/05SW	N72E/69NW	cw
11	N56E/42NE	N61E/76NW	ccw
12	N50E/13NE	N75E/54NW	ccw
13	N62E/35NE	N78E/69NW	ccw
14	N50E/24NE	N73E/64NW	ccw
15	N56E/09NE	N57E/84NW	ccw
16	N80E/22SW	N51E/88NW	cw
17	N65E/04SW	N66E/90NW	-
18	N63E/15NE	N54E/83NW	ccw
19	N70E/41NE	N75E/90NW	ccw
20	N89E/39NE	N82E/90NW	ccw
21	N28E/44SW	N32E/88NW	cw
22	N27E/20SW	N30E/78SE	cw
23	N82W/64SE	N83W/84SW	ccw
24	N87E/55NE	N83E/86SE	ccw

Outcrop 7

Location: (Craig Springs 7.5 Minute Quadrangle)

Roadcut and small quarry located along State Route 632, 4.0 miles (6.45 km) northeast of Maggie.

Unit: Millboro Formation

Bedding: N59E/37SE

SP: N68E/25SE

SA: 108

SL: N24W/26SE

Angle: 13

Data:

Fold #	B	AS	SS
1	N10E/63SW	N05W/78SW	cw
2	N41E/02SW	N42E/84SE	cw
3	N44E/24SW	N43E/85SE	cw
4	N20E/12SW	N22E/88NW	cw
5	N41E/17SW	N51E/90NW	cw
6	N30E/29SW	---	cw
7	N12E/04SW	N18E/74SE	cw
8	N35E/01NE	N44E/62SE	ccw
9	N53E/10SW	N56E/90NW	cw
10	N45E/14SW	N50E/72SE	cw
11	N32E/16SW	--	cw
12	N65E/06NE	N65E/90NW	ccw
13	N53E/10SW	N54E/46NW	ccw

Outcrop 8

Location: (Craig Springs 7.5 Minute Quadrangle)

Stream-cut along Johns Creek, 20 feet (6.10 m) northwest of State Route 632, 3.45 miles (5.57 km) northeast of Maggie.

Unit: Millboro Formation

Bedding: N50E/45SE

SP: N59E/25SE

SA: 107

SL: N05W/23SE

Angle: 20

Data:

Fold #	B	AS	SS
1	N34E/19SW	N25E/78NW	cw
2	N35E/08SW	N35E/79SE	cw
3	N25E/13SW	N23E/90SE	cw
4	N52E/03SW	N55E/57SE	cw
5	N30E/06NE	N31E/73SE	ccw
6	N40E/02SW	N40E/83SE	cw
7	N48E/08NE	N51E/66SE	ccw
8	N54E/15SW	N39E/53NW	cw
9	N53E/07SW	N60E/87SE	cw
10	N46E/10SW	N39E/90SE	cw
11	N74E/04NE	N78E/83SE	ccw
12	N53E/18SW	---	cw
13	N52E/23NE	N56E/89SE	ccw

Fold #	B	AS	SS
14	N35E/15SW	N29E/82NW	cw
15	N47E/22SW	---	cw
16	N52E/02NE	N52E/90SE	ccw
17	N18E/27SW	---	cw
18	N31E/26SW	N47E/68SE	cw
19	N32E/16SW	N40E/86SE	cw
20	N26E/03SW	N22E/83SE	cw
21	N54E/12NE	---	ccw
22	N46E/12SW	N50E/64SE	cw
23	N40E/08SW	N45E/84SE	cw

Outcrop 9

Location: (Catawba 7.5 Minute Quadrangle)

Very steep stream-cut along Craig Creek, 850 feet (259.1 m) from where the creek passes under State Route 311, at a point which is 3.3 miles (5.32 km) southwest of New Castle.

Unit: Millboro Formation

Bedding: N44E/39SE

Data:

Fold #	B	AS	SS
1	N85E/22SW	N85W/72NE	ccw
2	N86E/42SW	N73E/90NW	ccw
3	N73W/30SE	N76W/83SW	ccw
4	N46W/11SE	N54W/63SW	ccw

Fold #	B	AS	SS
5	N42W/04NW	N39W/75SW	cw
6	N60W/14NW	N63W/83SW	-
7	N74W/24NW	N81W/90NE	ccw
8	N80W/29SE	N83W/81SW	ccw
9	N72W/55SE	N87E/66SE	ccw
10	N31W/54SE	N50W/78SW	cw
11	N77W/26SE	N79W/86SW	-
12	N80E/13SW	N81E/76SE	cw
13	N79E/26SW	N78E/90NW	cw

Outcrop 10

Location: (Catawba 7.5 Minute Quadrangle)

Roadcut located along State Route 42, 1.6 miles (2.58 km) southwest of junction of State Routes 42 and 311.

Unit: Millboro Formation

Bedding: N49E/36SE

SP: N08E/24SE

SA: 2

SL: N89W/24SE

Angle: 24

Data:

Fold #	B	AS	SS
1	N81E/20NE	N74E/76SE	ccw
2	N88E/41NE	N82E/90NW	ccw

Fold #	B	AS	SS
3	N84E/22NE	N86E/83SE	ccw
4	N68W/27SE	N58W/78NE	cw
5	N86E/33NE	N86E/82SE	ccw
6	N86W/14SE	N73W/75NE	-
7	N69E/25NE	N62E/76SE	cw
8	N76E/20NE	N76E/81SE	ccw
9	N84E/24NE	N73E/73SE	-
10	N62E/18NE	N89E/64NW	cw
11	N73E/18NE	N75E/85SE	ccw
12	N81W/31SE	N66W/72NE	cw
13	N79W/20SE	N67W/70NE	cw
14	N88W/13SE	N74W/67NE	cw
15	N73W/20SE	N74W/88SW	cw

Outcrop 11

Location: (Catawba 7.5 Minute Quadrangle)

Small pit located across a larger exposure along State Route 42, 1.35 miles (2.18 km) southwest of junction of State Routes 42 and 311.

Unit: Millboro Formation

Bedding: N20E/45SE

Data:

Fold #	B	AS	SS
1	N46W/13SE	N50W/77SW	cw

Fold #	B	AS	SS
2	N58W/31SE	N72W/77SW	ccw
3	N16W/28SE	N37W/48SW	ccw
4	N46W/12SE	N58W/34SW	-
5	N29W/20SE	N66W/32SW	ccw
6	N06W/54SE	---	-
7	N10W/36SE	N05W/85NE	-
8	N02E/18SW	---	-
9	N45W/22SE	N60W/53SW	ccw
10	N69W/12SE	N71W/61SW	ccw
11	N65W/22SE	N77W/44SW	ccw
12	N72W/39SE	N85W/79SW	ccw
13	N82E/05NW	N80E/48SE	ccw
14	N34W/03SE	N34W/81SW	cw

Outcrop 12

Location: (Catawba 7.5 Minute Quadrangle)

Part of a long roadcut along State Route 616, 0.7 mile (1.13 km) east of where the road passes over Craig Creek.

Unit: Millboro Formation

Bedding: N45E/48SE

SP: N27E/39SE

SA: 100

SL: N71W/39SE

Angle: 15

Data:

Fold #	B	AS	SS
1	N57E/14NE	N62E/78NW	ccw
2	N62E/11NE	N65E/84SE	ccw
3	N41E/14NE	N41E/89SE	ccw
4	N66E/15NE	N63E/54SE	ccw
5	N36E/19NE	---	ccw
6	N46E/14NE	N47E/90NW	ccw
7	N25E/26SW	N14E/72NW	cw
8	N50E/24NE	N49E/81SE	ccw
9	N43E/18NE	N45E/85SE	ccw
10	N52E/40NE	N89E/56NW	ccw
11	N45E/35NE	N52E/79NW	ccw
12	N63E/30NE	N65E/90NW	ccw
13	N76E/48NE	N82E/88NW	ccw
14	N50E/04NE	N50E/54SE	ccw
15	N19E/11SW	N29E/79SE	cw
16	N11E/04SW	N14E/85NW	cw
17	N45E/05NE	N38E/65SE	ccw
18	N19E/06SW	---	cw

Outcrop 13

Location: (Catawba 7.5 Minute Quadrangle)

Part of a long roadcut along State Route 616, 0.65 mile (1.05 km) east of where the road passes over Craig Creek.

Unit: Millboro Formation

Bedding: N60E/90SE

SP: N39E/52SE

SA: 2

SL: N77W/49SE

Angle: 43

Data:

Fold #	B	AS	SS
1	N75W/25SE	N37E/30SE	ccw
2	N57E/41NE	N62E/90NW	cw
3	N40E/14NE	N31E/53SE	ccw
4	N83W/66SE	N48W/73NE	cw
5	N83E/40NE	N35E/50SE	ccw
6	N73E/36NE	N60E/73SE	ccw
7	N76E/54NE	N52E/75SE	ccw
8	N75E/43NE	N66E/78SE	ccw
9	N70E/47NE	N70E/90NW	ccw
10	N74E/52NE	N67E/85SE	ccw
11	N74E/40NE	N44E/61SE	ccw
12	N66E/13SW	N75E/65SE	cw
13	N32E/36SW	N79E/55SE	cw
14	N72E/75NE	N54W/76NE	ccw
15	N44E/29NE	N30E/73SE	ccw
16	N40E/31SW	N52E/85SE	cw

Outcrop 14

Location: (Potts Creek 7.5 Minute Quadrangle)

Part of a large roadcut along State Route 611, 2.25 miles (3.63 km) northeast of junction of State Routes 611 and 311.

Unit: Millboro Formation

Bedding: N70E/72SE (? overturned)

SP: N71E/51SE

SA: 78

SL: N28W/51SE

Angle: 21

Data:

Fold #	B	AS	SS
1	N81W/47SE	N86W/83SW	ccw
2	N88W/25SE	N81E/67SE	ccw
3	N86W/33SE	N78W/68NE	ccw
4	N80E/64NE	N67E/90NW	ccw
5	N61E/25SW	N63E/86SE	cw
6	N64E/39SW	N72E/86NW	cw
7	N60E/16SW	N65E/77SE	cw
8	N61E/18SW	N55E/85SE	cw
9	N50W/40SE	N50W/90NE	ccw
10	N71E/18NE	N73E/78NW	ccw
11	N62W/27SE	N53W/88SW	ccw

Outcrop 15

Location: (Potts Creek 7.5 Minute Quadrangle)

Part of a large roadcut along State Route 611, 2.25 miles (3.63 km) northeast of junction of State Routes 611 and 311.

Unit: Millboro Formation

Bedding: N80E/55NW

SP: N46E/27SE

SA: 82

SL: N69W/25SE

Angle: 68

Data:

Fold #	B	AS	SS
1	N63E/09SW	---	ccw
2	N69E/36NE	N69E/90NW	ccw
3	N70E/48NE	N74E/84NW	ccw
4	N60E/34NE	N68E/73NW	ccw
5	N58E/18NE	N65E/79NW	cw
6	N67E/32NE	N75E/75NW	ccw
7	N65E/42NE	N70E/82NW	-
8	N71E/26NE	N65E/86SE	ccw
9	N45E/02NE	N41E/85SE	ccw
10	N80E/15NE	N80E/80NW	ccw
11	N60E/14SW	N64E/72SE	cw
12	N38E/29SW	N57E/65SE	cw
13	N58E/20NE	N44E/74SE	ccw

Fold #	B	AS	SS
14	N72E/26NE	N73E/70NW	ccw
15	N45E/12SW	N45E/90NW	cw
16	N58W/12SE	N63W/88NE	ccw
17	N72W/34SE	N64W/71NE	ccw
18	N66W/31SE	N65W/90NE	ccw
19	N74W/07SE	N78W/86NE	ccw
20	N54E/25SW	N52E/78SE	cw
21	N59E/19SW	N69E/80SE	cw
22	N82E/12SW	N81E/79SE	cw

Outcrop 16

Location: (New Castle 7.5 Minute Quadrangle)

Small stream exposure at junction of Barbours Creek and South Prong Creek. The junction is just off State Route 617, 0.6 mile (0.97 km) northeast of the Pines Campground.

Unit: Millboro Formation

Bedding: N66E/65SE

Data:

Fold #	B	AS	SS
1	N44W/52SE	N27W/80NE	ccw
2	N57W/58SE	N78W/81SW	ccw
3	N69W/66SE	N70W/87SW	ccw
4	N55W/50SE	N34W/63NE	ccw
5	N67W/75SE	N33W/78NE	cw

Fold #	B	AS	SS
6	N73W/60SE	N64W/74NE	ccw
7	N74E/45NE	N70E/90NW	cw
8	N74E/43NE	N62E/70SE	-
9	N84E/35NE	N57E/61SE	cw
10	N55E/65SW	N50E/82NW	cw
11	N44E/65SW	N42E/84NW	cw

Outcrop 17

Location: (Paint Bank 7.5 Minute Quadrangle)

Roadcut along State Route 602, 1.5 miles (2.42 km) southeast of the junction of State Routes 602 and 600.

Unit: Millboro Formation

Bedding: N71E/83SE

Data:

Fold #	B	AS	SS
1	N56E/10NE	N55E/90NW	-
2	N80E/02SW	N72E/80NW	ccw
3	N55E/13NE	N59E/56NW	cw
4	N75E/09NE	N76E/81SE	-
5	N50E/04SW	N47E/78NW	-
6	N56E/05SW	N55E/71NW	cw
7	N54E/03NE	N50E/78NW	ccw
8	N75E/08SW	N70E/78NW	-
9	N71E/24SW	N76E/74SE	cw

Fold #	B	AS	SS
10	N76E/10SW	N77E/80SE	cw
11	N77E/16SW	N70E/75NW	cw
12	N68E/28SW	N72E/69SE	cw
13	N60E/15SW	N63E/83SE	cw
14	N64E/29NE	N57E/80SE	ccw

Outcrop 18

Location: (Paint Bank 7.5 Minute Quadrangle)

Roadcut along State Route 602, 1.35 miles (2.18 km) southeast of the junction of State Routes 602 and 600.

Unit: Millboro Formation

Bedding: N80E/79NW

Data:

Fold #	B	AS	SS
1	N79E/16SW	N80E/86SE	ccw
2	N75E/26SW	N86W/64SW	ccw
3	N72E/18SW	N70E/60SE	ccw
4	N79E/05SW	N71E/77SE	ccw
5	N80E/26SW	N69E/71NW	ccw
6	N70E/25SW	N68E/78NW	ccw
7	N81E/30SW	N81W/64SW	ccw
8	N85E/46SW	N80E/82NW	ccw
9	N46E/21SW	N55E/82SE	ccw
10	N68E/14NE	N68E/44SE	cw

Fold #	B	AS	SS
11	N78E/31SW	N68E/62SW	ccw
12	N87E/35SW	N68E/64NW	ccw
13	N71E/20NE	---	cw
14	N54E/39NE	N70E/90NW	cw
15	N86E/20NE	---	-
16	N67E/50SW	N69E/89NW	ccw
17	N82E/44SW	N76E/84SE	cw
18	N61E/16SW	N62E/88NW	ccw
19	N61E/41SW	N71E/64SE	ccw
20	N62E/43SW	N79E/75SE	ccw
21	N44E/38SW	N50E/84SE	ccw
22	N45E/24SW	N59E/75SE	ccw
23	N75E/01SW	N71E/90NW	ccw

Outcrop 19

Location: (Ronceverte 7.5 Minute Quadrangle)

Small exposure along a dirt road that runs alongside State Route 3, 0.5 mile (0.81 km) northwest of Gap Mills. The exposure is a few hundred feet to the southeast of a white frame house.

Unit: Millboro Formation

Bedding: N75E/85SE (? overturned)

SP: N40E/54SE

SA: 119

SL: N83E/44NE

Angle: 45

Data:

Fold #	B	AS	SS
1	N53E/39NE	N59E/85NW	ccw
2	N65E/37NE	N68E/85SE	ccw
3	N59E/34NE	N88W/54NE	ccw
4	N48E/16NE	N50E/66NW	ccw
5	N52E/25NE	N64E/66NW	ccw
6	N42E/26NE	N52E/56NW	ccw
7	N77E/45NE	N72E/86SE	ccw
8	N89W/30SE	N72W/61NE	ccw
9	N77E/42NE	N78E/78NW	-
10	N12E/62NE	N50E/65NW	-
11	N45E/45NE	N45E/90SE	ccw
12	N58E/22NE	N46E/87SE	ccw
13	N55E/31NE	N39E/68SE	ccw
14	N45E/31NE	N50E/73NW	ccw
15	N58E/28NE	N82E/59NW	ccw
16	N60E/13SW	N55E/65NW	cw
17	N54E/14SW	N50E/47NW	cw
18	N67E/37NE	N81E/75NW	ccw
19	N39E/03SW	N41E/78NW	cw
20	N65E/09SW	N62E/62NW	cw

Outcrop 20

Location: (Paint Bank 7.5 Minute Quadrangle)

Small quarry located on a farm just off State Route 311, 0.8 mile (1.29 km) southeast of junction of State Routes 311 and 600. The exposure is across Paint Bank Creek and directly behind a small stone house.

Unit: Millboro Formation

Bedding: N48E/78SE

SP: N50E/78SE

SA: 58

SL: N51W/78SE

Angle: 2

Data:

Fold #	B	AS	SS
1	N24E/63SW	N38E/87NW	cw
2	N34E/59SW	N36E/88NW	cw
3	N38E/45SW	N51E/87SE	cw
4	N51E/29SW	N61E/83SE	-
5	N48E/34SW	N46E/85SE	cw
6	N47E/42SW	N52E/90NW	cw
7	N56E/28NE	N65E/73NW	ccw
8	N39E/60SW	N40E/87NW	cw
9	N30E/03NE	N34E/84NW	ccw
10	N29E/39SW	---	ccw
11	N20E/55SW	N27E/80SE	cw

Fold #	B	AS	SS
12	N07W/20SE	N04E/60SE	cw
13	N20E/33SW	N60E/45SE	cw
14	N32E/45SW	N71E/60SE	cw
15	N16E/43SW	N62E/56SE	cw
16	N70E/33SW	N86W/62SW	cw
17	N50E/39SW	N79E/61SE	cw
18	N59E/47SW	N61E/84SE	cw
19	N61E/24SW	---	cw
20	N34E/54SW	N29E/83NW	cw
21	N47E/12SW	N45E/90SE	cw
22	N32E/57NE	N21E/44SE	ccw
23	N25E/29NE	N17E/84SE	ccw
24	N44E/13NE	N37E/78SE	ccw
25	N60E/45NE	N46E/76SE	ccw
26	N18E/40NE	N16E/83SE	ccw
27	N86E/33NE	N59E/58SE	ccw
28	N60E/04NE	N56E/80SE	ccw

Outcrop 21

Location: (Alleghany 7.5 Minute Quadrangle)

Roadcut along a National Forest gravel road, 0.45 mile (0.73 km) from junction, which is 0.55 mile northeast of the town of Potts Creek, of the gravel road and State Route 18. The exposure is located along a sharp curve in the road.

Unit: Millboro Formation

Bedding: N50E/54SE

SP: N71W/23SW

SA: 87

SL: N21E/24SW

Angle: 44

Data:

Fold #	B	AS	SS
1	N58W/01NW	N54W/84SW	cw
2	N68W/02NW	N59W/67SW	cw
3	N65E/11SW	N58E/37NW	-
4	N43E/16SW	N70E/38SE	-
5	N55E/11SW	N58E/76SE	cw
6	N48E/09SW	---	cw
7	N60W/18SE	N70W/59SW	ccw
8	N70W/08SE	N75W/75SW	ccw
9	N85E/17SW	---	cw
10	N61E/24SW	N78E/72SE	cw
11	N34E/26SW	N74E/37SE	cw
12	N70E/50SW	N73E/85SE	cw
13	N82E/74SW	N84W/82SW	ccw
14	N86E/05NE	N82E/70SE	ccw

Outcrop 22

Location: (Alleghany 7.5 Minute Quadrangle)

Part of a large stream-cut just before a sharp bend in Potts Creek. State Route 609 is along the opposite side of the creek, and the road joins State Route 18 at a junction that is 1.9 miles (3.06 km) west of Jorden Mines.

Unit: Millboro Formation

Bedding: N40E/54SE

SP: N41E/36SE

SA: 32

SL: N64W/36SE

Angle: 18

Data:

Fold #	B	AS	SS
1	N55E/56NE	N85E/75NW	ccw
2	N44E/33NE	N79E/66NW	ccw
3	N63E/13SW	N64E/80NW	cw
4	N60E/14NE	N53E/82SE	ccw
5	N56E/12NE	N55E/90SE	ccw
6	N54E/03SW	N53E/90SE	cw
7	N54E/15SW	N55E/90SE	cw
8	N71E/34NE	N79E/85SE	ccw
9	N66E/18NE	N61E/77SE	ccw
10	N82W/21SE	N85W/67NE	ccw
11	N68E/01NE	N74E/86SE	-

Fold #	B	AS	SS
12	N82E/30NE	N73E/81SE	cw
13	N68E/08NE	N72E/88SE	ccw
14	N56E/26NE	N69E/74NW	ccw
15	N59E/11NE	N65E/70NW	ccw
16	N87E/40NE	N76W/87NE	ccw
17	N74W/35SE	N88W/77SW	ccw
18	N29E/76SW	N38E/90NW	cw
19	N80W/15SE	N74W/80NE	ccw
20	N68W/49SE	N50W/78SW	ccw
21	N89E/56NE	N58W/70NE	ccw
22	N57E/58NE	N69E/70SE	ccw

Outcrop 23

Location: (Alleghany 7.5 Minute Quadrangle)

Part of a large stream-cut along Potts Creek. The exposure is directly across from State Route 609, 0.1 mile (0.16 km) from junction, which is 1.9 miles (3.06 km) west of Jordan Mines, of State Routes 609 and 18.

Unit: Millboro Formation

Bedding: N31E/57SE

SP: N25E/34SE

SA: 94

SL: N69W/34SE

Angle: 23

Data:

Fold #	B	AS	SS
1	N48E/18NE	N56E/72NW	ccw
2	N65E/39NE	N58E/81SE	ccw
3	N43E/51NE	N39E/82SE	ccw
4	N60E/22NE	N59E/90NW	ccw
5	N55E/16NE	N59E/67NW	ccw
6	N46E/13NE	N43E/86SE	ccw
7	N54E/07NE	N50E/86SE	ccw
8	N47E/16NE	N33E/49SE	ccw
9	N30E/08NE	N34E/78NW	ccw
10	N35E/20NE	N89E/22NW	cw
11	N35E/13NE	N35E/81NW	ccw
12	N66E/24NE	N73E/63NW	ccw
13	N41E/12NE	N43E/66NW	ccw
14	N57E/14NE	N58E/82NW	ccw
15	N44E/25SW	N30E/63NW	cw
16	N52E/13SW	N48E/73NW	cw
17	N44E/16NE	N40E/90NW	ccw
18	N79E/38NE	N62W/47NE	cw
19	N39E/10NE	N30E/72SE	ccw
20	N69E/20NE	N82W/28NE	ccw
21	N80W/35SE	N79W/76SW	ccw
22	N24E/10SW	N24E/84NW	cw
23	N33E/20NE	N68E/89SE	ccw

Fold #	B	AS	SS
24	N80W/33SE	N45W/54NE	cw

Outcrop 24

Location: (Eagle Rock 7.5 Minute Quadrangle)

Part of a large roadcut along U.S. Route 220, 1.4 miles (2.26 km) north of point where route 220 crosses the James River. The measurements were taken at the northern end of the outcrop.

Unit: Millboro Formation

Bedding: N47E/78SE

SP: N51E/33SE

SA: 43

SL: N68W/30SE

Angle: 44

Data:

Fold #	B	AS	SS
1	N18W/44SE	N10E/75SE	cw
2	N59E/40NE	N82E/69NW	ccw
3	N65E/25NE	N74E/76NW	-
4	N64E/25NE	N85W/54NE	ccw
5	N70E/03NE	N69E/62SE	ccw
6	N66E/18NE	N64E/70SE	ccw
7	N40E/00NE	N40E/60SE	-
8	N74W/23SE	N83E/51SE	ccw
9	N70W/27SE	N80W/68SW	ccw

Fold #	B	AS	SS
10	N88E/24NE	N71E/51SE	ccw
11	N70E/25NE	---	ccw
12	N66E/07NE	N44E/27SE	ccw
13	N81E/33NE	N74E/80SE	ccw
14	N69E/16NE	N61E/69SE	ccw
15	N02W/37SE	N42E/45SE	cw
16	N78E/02SW	N75E/76SE	-
17	N70E/07NE	N60E/79SE	-
18	N33E/08SW	N36E/68SE	cw
19	N56E/07SW	N58E/55SE	cw
20	N59E/16SW	N65E/60SE	cw
21	N62E/03NE	N62E/80SE	-
22	N88W/05SE	---	ccw

Outcrop 25

Location: (Strom 7.5 Minute Quadrangle)

Roadcut along sharp curve in State Route 621, 2.85 miles (4.60 km) southeast of junction of State Routes 621 and 616 at Rich Patch.

Unit: Millboro Formation

Bedding: N42E/65SE

SP: N17E/51SE

SA: 54

SL: N74W/51SE

Angle: 25

Data:

Fold #	B	AS	SS
1	N11W/26SE	N06W/85NE	cw
2	N21W/34SE	N22W/89SW	cw
3	N15E/18SW	N20E/75SE	cw
4	N21E/16NE	N25E/75NW	ccw
5	N35E/07SW	N39E/81NW	cw
6	N27E/15NE	---	ccw
7	N11E/08NE	N13E/75NW	-
8	N17E/20SW	N15E/75SE	cw
9	N31E/39NE	N24E/80SE	ccw
10	N83E/56NE	N23E/68SE	ccw
11	N44E/34NE	N41E/84SE	ccw

Outcrop 26

Location: (Strom 7.5 Minute Quadrangle)

Roadcut along sharp curve in State Route 657, 0.75 mile (1.21 km) east of the junction of State Routes 657 and 619.

Unit: Millboro Formation

Bedding: N31E/67SE (? overturned)

SP: N34E/84SE

SA: 92

SL: N54W/84SE

Angle 17

Data:

Fold #	B	AS	SS
1	N22E/65SW	N53E/75SE	cw
2	N34E/66SW	N28E/77NW	cw
3	N35E/39SW	N34E/84NW	-
4	N60E/39SW	N21E/90NW	cw
5	N05E/30SW	N18E/90NW	cw
6	N29E/53SW	N42E/85NW	cw
7	N35E/24SW	N41E/80NW	cw
8	N19E/23NE	N15E/84NW	ccw
9	N31E/27SW	N30E/73NW	cw
10	N33E/02NE	N37E/51NW	ccw
11	N07W/55SE	N30E/76SE	cw
12	N30E/04SW	N16E/12NW	ccw
13	N37E/06SW	N39E/57SE	cw
14	N13E/58SW	N02E/74NW	-

Outcrop 27

Location: (Callaghan 7.5 Minute Quadrangle)

Small quarry along State Route 600, 0.5 mile (0.81 km) southwest of junction of route 600 and U.S. Route 60. The quarry is located very close to where Interstate Route 64 passes over route 600.

Unit: Millboro Formation

Bedding: N41E/58SE

Data:

Fold #	B	AS	SS
1	N65E/02SW	N63E/75SE	cw
2	N62E/06SW	N69E/55SE	cw
3	N65E/10SW	N68E/68SE	cw
4	N61E/11NE	N65E/76SE	ccw
5	N54E/11NE	N46E/80SE	ccw
6	N50E/01NE	N52E/86SE	-
7	N45E/00NE	N47E/42NW	-
8	N46E/03NE	N59E/59NW	ccw
9	N51E/16NE	N50E/88NW	ccw
10	N74E/13NE	N67E/62SE	ccw
11	N68E/04SW	N65E/75SE	cw
12	N74E/13NE	N75E/83NW	ccw
13	N50E/06SW	N50E/84NW	cw

Outcrop 28

Location: (Clifton Forge 7.5 Minute Quadrangle)

Roadcut along State Route 696, 1.4 miles (2.26 km) west of junction of route 696 and Interstate Route 64. There is a large pond south of the exposure.

Unit: Millboro Formation

Bedding: N50E/44SE

SP: N38E/17SE

SA: 121

SL: N35W/17SE

Angle: 27

Data:

Fold #	B	AS	SS
1	N54E/18NE	N60E/73SE	-
2	N50E/54NE	N30E/68SE	ccw
3	N55E/20NE	N56E/89SE	ccw
4	N60E/24NE	N53E/51SE	ccw
5	N72E/12NE	N73E/66SE	-
6	N50E/31NE	N24E/49SE	-
7	N61E/06SW	N58E/51SE	cw
8	N70E/23NE	---	-
9	N85W/13SE	N87W/62SW	ccw
10	N88E/17NE	N85E/63SE	ccw
11	N64E/13NE	N65E/76SE	ccw
12	N74E/23NE	N74E/80SE	ccw
13	N62E/03SW	N61E/72SE	cw
14	N64E/13SW	N74E/59SE	cw
15	N68E/26NE	N62E/54SE	ccw
16	N48E/03SW	N49E/70SE	cw
17	N62E/10SW	---	-
18	N48E/28SW	N50E/76SE	cw
19	N64E/09NE	N64E/50SE	ccw
20	N80E/02SW	N81E/63SE	cw
21	N79E/02NE	N79E/43SE	ccw
22	N47E/28SW	N63E/66SE	cw

Outcrop 29

Location: (Clifton Forge 7.5 Minute Quadrangle)

Roadcut along dirt road that passes alongside U.S. Route 60, 0.4 mile (0.65 km) east of junction of route 60 and State Route 629. The exposure is 0.1 mile (0.16 km) east of where a set of C. and O. railroad tracks pass over route 60.

Unit: Millboro Formation

Bedding: N35E/35SE

Data:

Fold #	B	AS	SS
1	N44W/59SE	N32E/60SE	cw
2	N22E/30SW	N43E/42SE	cw
3	N07E/40SW	N03E/84NW	-
4	N02E/34SW	N44W/48SW	ccw
5	N20W/40SE	---	-
6	N25W/43SE	N49E/50SE	cw
7	N04E/29SW	N06E/82SE	cw
8	N25W/47SE	N15E/71SE	cw
9	N37E/10NE	N33E/51SE	ccw

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KINEMATIC ANALYSES OF DISCFOLDS IN DEVONIAN MILLBORO
FORMATION IN THE CENTRAL-SOUTHERN
APPALACHIAN JUNCTION ZONE

by

John L. Stubbs, Jr.

(ABSTRACT)

A method of kinematic analysis has been applied to discfolds in the Devonian Millboro Formation in the junction zone and adjacent, differently trending segments of the Central and Southern Appalachian Valley and Ridge Province. Types and kinematic signatures of shearing movements that produced discfolds at twenty localities have been recognized. Discfolds are a type of flexural fold produced by planar shearing movements during northwestern translation and deformation of the Paleozoic cover, and their analyses reflect the orientations of the large-scale movements that produced the major folds and faults. Most analyses indicate northeast-striking, southeast-dipping slip planes, northwest-trending slip lines, and overall vergence of the shear zones to the northwest. Discfolds on northwest limbs of major anticlines were produced by shearing along late-stage, southeast-dipping reverse faults, and those on the southeast limbs by shearing along southeast-dipping, bedding-parallel reverse faults and/or by large-scale flexural flow.

Analyses of discfolds in the junction zone indicate movement of material out of the zone toward both the northeast and southwest.

Visual and statistical comparisons between analyses of the central and southern segments show contrasts in the orientations of the slip planes and slip lines. Thus, the transport directions of the two segments converged toward the northwest, and are consistent with those that must have operated earlier in the formation of the major folds and faults. This conclusion coupled with the apparently similar timing of the discfolds indicates that there was, at most, only slight northwestern rotation of the southern segment in relation to the central.