BROKEN-FORMATIONS OF THE PULASKI THRUST SHEET NEAR PULASKI, VIRGINIA

by

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DEDICATION

This dissertation is dedicated to Dr. C. G. Tillman whose untimely death was a great loss to those who loved and respected him. He was dedicated to the science of geology and concerned for the welfare of his numerous students throughout the years. He is greatly missed.

ACKNOWLEDGMENTS

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INTRODUCTION

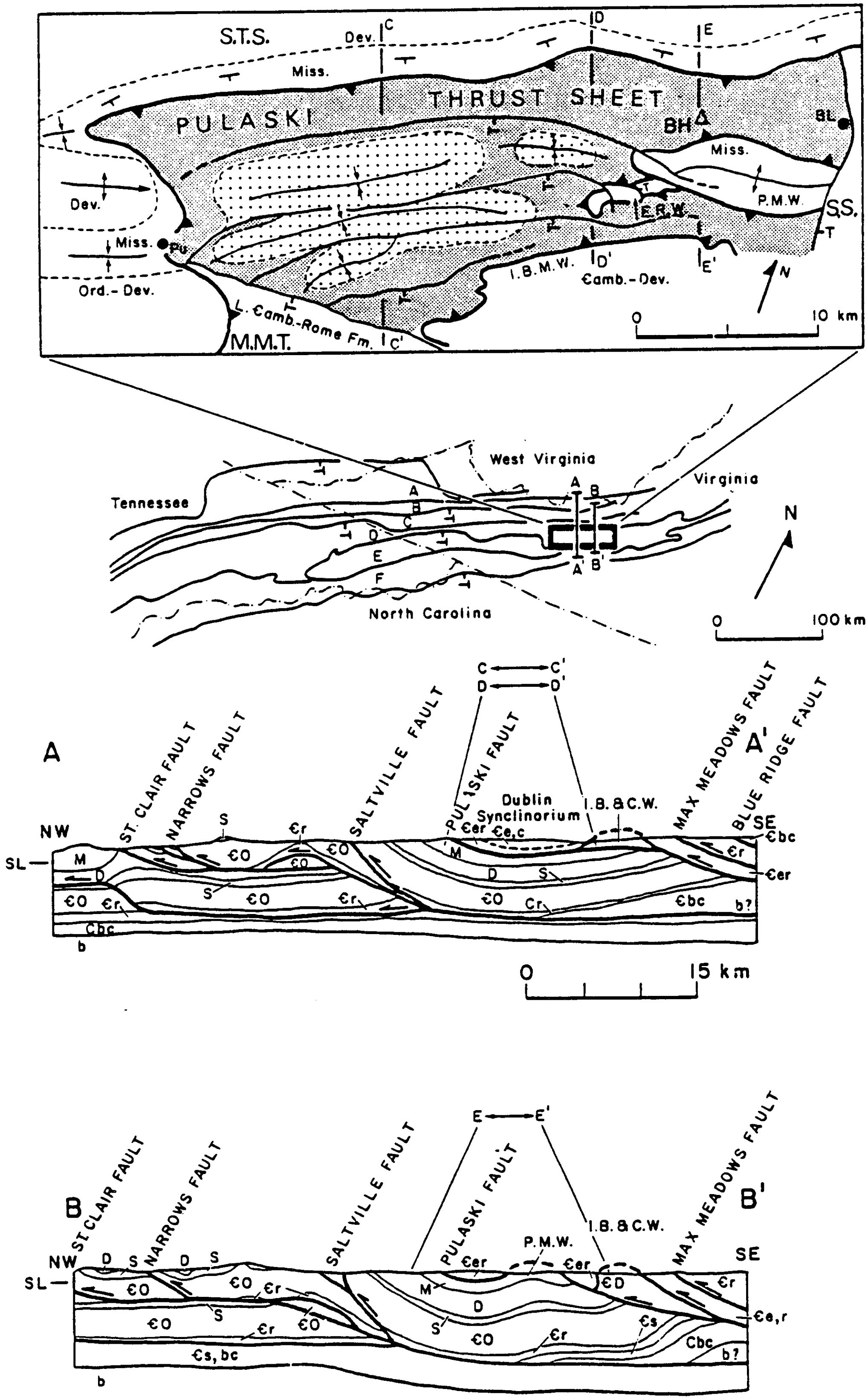
Broken-formations (Hsu, 1974; Harris and Milici, 1977) are mappable (1:24,000 scale) rock-stratigraphic units in which formation boundaries and/or bedding planes within a single formation are disrupted by intense faulting, brecciation and folding.

Broken-formations in the lower portions of the Pulaski thrust sheet, near its type area of Pulaski, Virginia (Fig. 1) contain some of the most strongly deformed sedimentary rocks in the foreland fold-and-thrust belt of the Appalachians. Deformation in this zone ranges from grain-scale cataclasis to pervasive macroscopic faulting. Although somewhat similar deformed zones have been described above thrusts in northeast Tennessee (Harris and Milici, 1977), the broken-formations of the Pulaski thrust sheet are unique in their thickness (300-500 meters), degree of rock disruption, and their association with the extensive and spectacular Max Meadows tectonic breccias (Cooper and Haff, 1940; Cooper, 1946, 1970; Rodgers, 1970). The tectonic breccias are anomalous when compared with fault rocks of other thrusts in the Appalachian Valley and Ridge Province (Rodgers, 1970), and in other thrust-belts of the world (Gretner, 1977).

The deformed rocks above the Pulaski fault have been characterized as (1) a broken limestone of inconceivable structure (Campbell, 1894; Campbell and others, 1925), (2) a chaotically dismembered formation (Cooper, 1970) and a broken-formation (Henika, 1981), and (3) a polydeformed terrain (Bartholomew and Lowry, 1979; Bartholomew and Schultz, 1980). Anomalous trending structures (folds and faults at high angles

Figure 1. Regional index map, generalized geologic map of the study area and regional cross sections A-A' and B-B'. Thrust sheets on regional map are (A) Cumberland, (B) St. Clair, (C) Narrows-Copper Creek, (D) Saltville, (E) Pulaski, (F) Blue Ridge.

Abbreviations are: BL, Blacksburg; Pu, Pulaski; BH, bore hole; I.B. & C.W., Ingles-Barringer and Christiansburg windows; P.M.W., Price Mountain window; E.R.W., East Radford window; I.B.M.W., Ingles-Barringer Mountain window; S.T.S., Saltville thrust sheet; M.M.T., Max Meadows thrust sheet; S.S., Salem Synclinorium; Miss., Mississippian; Dev., Devonian; S, Silurian; Ord., Ordovician; C.O., Cambro-Ordovician; Ce,c, Cambrian Elbrook and Conococheague Formations; Ce,r, Cambrian Elbrook and Rome Formations; Cs, Cambrian Shady Formation, Cbc, Cambrian basal clastics; b, basement; gray shade on Pulaski thrust sheet is Cambrian Elbrook and Rome and Max Meadows breccia, stiple is Cambrian Conococheague Formation.



S.T.S.
Dev.
Miss.
PULASKI THRUST SHEET
BH
BL
Miss.
P.M.W.
S.S.
T
E.R.W.
Dev.
Miss.
Pu
Ord.-Dev.
I.B.M.W.
Camb.-Dev.
L. Camb.-Rome Fm.
M.M.T.
C
C'
D
D'
E
E'
N
0
10 km
West Virginia
Virginia
Tennessee
North Carolina
A
B
C
D
E
F
A'
B'
N
0
100 km
C ⟷ C'
D ⟷ D'
A
A'
ST. CLAIR FAULT
NARROWS FAULT
SALTVILLE FAULT
PULASKI FAULT
MAX MEADOWS FAULT
BLUE RIDGE FAULT
Dublin Synclinorium
I.B. & C.W.
NW
SE
SL
M
D
S
ЄO
Єr
Єer
Єe,c
Єbc
Cbc
Cr
b
b?
0
15 km
E ⟷ E'
B
B'
ST CLAIR FAULT
NARROWS FAULT
SALTVILLE FAULT
PULASKI FAULT
MAX MEADOWS FAULT
P.M.W.
I.B. & C.W.
NW
SE
SL
D
S
ЄO
Єr
Єer
ЄD
M
Єs
Єe,r
Cbc
Єs, bc
b
b?

to "typical" Appalachian Valley and Ridge structures), complex fold styles such as recumbent isoclines, abundant tectonic breccia and the high degree of stratal disruption, have led to speculation about the genesis of the broken-formations. Attention has centered on the timing of the deformation, i.e., Alleghanian and/or possible pre-Alleghanian orogenesis (Campbell and others, 1925; Bartholomew and Lowry, 1979; Bartholomew and Schultz, 1980), regional stress-strain history (Bartholomew and others, 1980) and the mechanisms of regional thrust emplacement (Cooper, 1970; Rodgers, 1970; Schultz, 1979A, 1979B).

Recent detailed geologic mapping (Figs. 2,3), macroscopic and mesoscopic structural analysis, mesoscopic fold analysis after Fleuty (1964), and outcrop mapping have made it possible to define in a semi-quantitative way deformation in the broken-formations. The analyses document the deformational processes accompanying Pulaski thrust emplacement. The data are used to compare deformational features in the broken-formations with rocks traditionally placed in an Alleghanian structural setting and to model the progressive development of these deformed rocks. The relationship of thrust faulting to cataclasis and elevated fluid pressures is discussed with reference to specific unique characteristics found in the lower portions of the Pulaski thrust sheet. Finally, comparisons are made between rocks of the broken-formations of the Pulaski thrust sheet and rocks in the lower parts of thrust sheets outside the study area.

Figure 2. Credit map; (A) Bartholomew and Lowry (1979); (B) Bartholomew <u>in</u> Schultz and Bartholomew, in press; (C) Schultz <u>in</u> Schultz and Bartholomew, in press, and Schultz <u>in</u> Bartholomew and Schultz, in preparation; (D) Bartholomew and Schultz, in preparation; (E) Brown and Ingram <u>in</u> Bartholomew, in preparation.

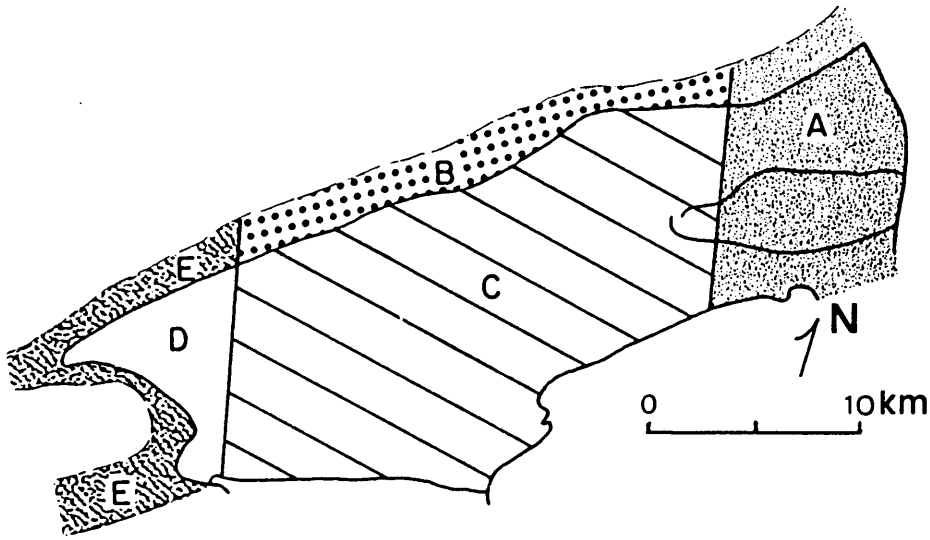
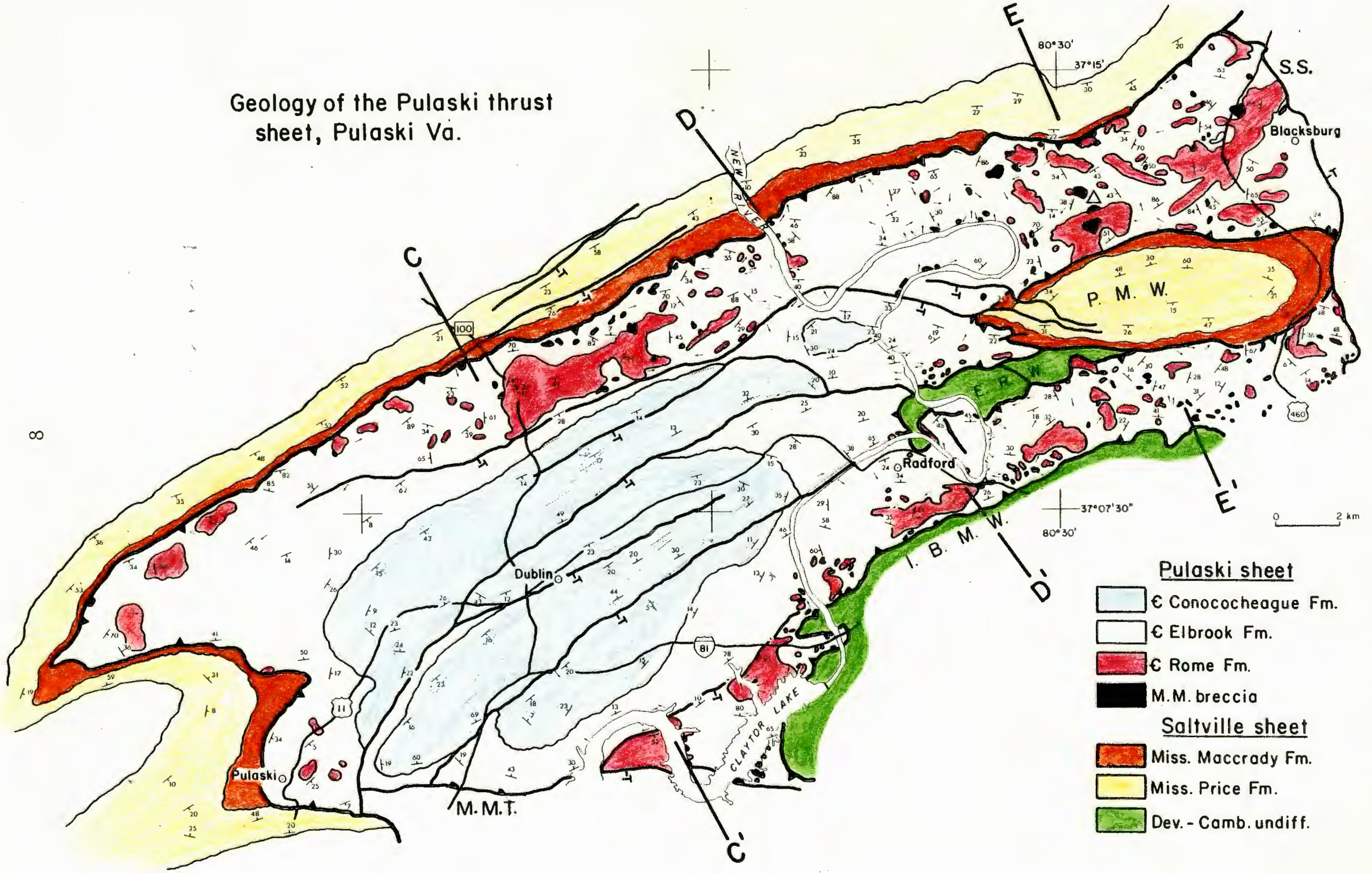

A
B
C
D
E
E
E
N
0
10km

Figure 3. Geologic map of the study area showing location of cross sections C-C', D-D', and E-E'. M.M., Max Meadows; P.M.W., Price Mountain window; I.B.M.W., Ingles-Barringer Mountain window; M.M.T., Max Meadows thrust sheet, S.S., Salem Synclinorium. Note position of bore hole (open triangle) on section line E-E'.

Geology of the Pulaski thrust sheet, Pulaski Va.



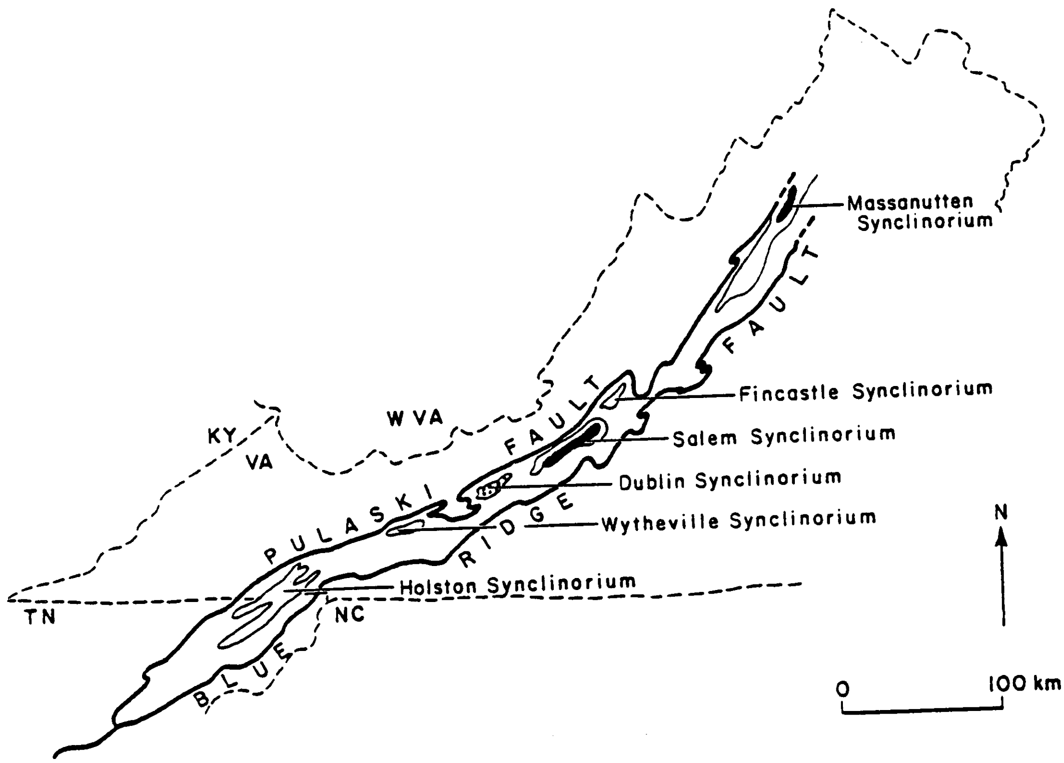
GEOLOGIC SETTING

The Pulaski thrust is one of several major southeast dipping Alleghanian thrusts of the southern Appalachians (Fig. 1). It has been traced along strike approximately 500 kms (Cooper, 1970; Rodgers, 1970) from near Staunton, Virginia, southwest into Tennessee where it is overridden by rocks of the Blue Ridge thrust sheet. Estimates of the displacement of the thrust, near the study area, range from 15 km (Cooper, 1970; Lowry, 1971) to 50 km (Bartholomew, 1979). Near Pulaski (Figs. 1, 3), Cambrian rocks are thrust over rocks of Mississippian age; thus, the oldest age of thrust emplacement is Mississippian. The preserved thickness of the Pulaski sheet ranges from approximately 1500 meters in the study area (Fig. 1) to 4000 meters in adjacent areas where rocks ranging from Cambrian to Mississippian are found (Tillman and Lowry, 1971). Regional scale synclinoria are the dominant first-order structures of the Pulaski thrust sheet (Fig. 4), and adjacent southeasterly anticlinoria are in general overridden by the Blue Ridge thrust sheet.

Conodont color alteration indexes (Epstein and others, 1977) indicate that rocks of the Pulaski sheet were subjected to temperatures in the range of 300-400°C as the result of either initial burial or tectonic burial. Chlorite and muscovite occur in carbonates near the base of the sheet (Appendix I) and probably were derived from clay minerals during this period of metamorphism.

The Pulaski sheet has undergone a four-fold deformation sequence (Bartholomew and others, 1982). From relatively oldest to youngest these are (1) decollement thrusting along a footwall of Cambrian rocks,

Figure 4. Large-scale synclinoria of the Pulaski thrust sheet. Rocks within the synclinoria are: heavy shading, Mississippian through Devonian; white, Silurian through Ordovician; stipple pattern, Upper Cambrian of Dublin synclinorium. Pulaski fault dies out in a fold at its northern terminus and in Tennessee is overridden by the Blue Ridge thrust sheet.



Massanutten Synclinorium
Fincastle Synclinorium
Salem Synclinorium
Dublin Synclinorium
Wytheville Synclinorium
Holston Synclinorium
PULASKI FAULT
BLUE RIDGE FAULT
KY
VA
W VA
TN
NC
N
0
100 km

(2) thrusting over a ramp that formed in folded and faulted rocks ranging in age from Cambrian to Mississippian, (3) decollement thrusting along a footwall of Mississippian rocks, and (4) folding and faulting of the emplaced Pulaski sheet and of rocks of the footwall of the Pulaski sheet (Saltville sheet).

Rocks of the Pulaski sheet (Fig. 3 and Appendix II) consist of two distinctively different litho-tectonic units (Fig. 5). Rocks of the lower part of the sheet have high anisotropy, alternating high and low competency, and high rheologic contrasts. These rocks are chiefly laminated and thinly bedded dolomites, argillaceous dolomites and calcareous phyllites, alternating with massive dolomites and limestones of the Lower Cambrian Rome Formation and the lower part of the Middle Cambrian Elbrook Formation (Butts, 1933, 1940; Hergenroder, 1958; Cooper, 1961). The upper part of the Pulaski sheet has rocks of low anisotropy, dominantly high competency, and low rheologic contrasts. These rocks are massive dolomites and thin- to thick-bedded limestones of the upper part of the Middle Cambrian Elbrook Formation and the Upper Cambrian Conococheague Formation (Butts, 1933, 1940; Hergenroder, 1958; Cooper, 1961).

Rocks overridden by the Pulaski thrust sheet and those north of its present leading edge are bounded on the northwest by the southeast-dipping Saltville fault (Fig. 1). Saltville thrust sheet rocks exposed in windows of the Pulaski sheet range in age from Cambrian through Mississipppian (Figs. 1, 3, 6). CAI indexes for rocks of the Saltville sheet indicate that temperatures of metamorphism ranged from 200-300°C (Epstein and others, 1977).

Figure 5. Stratigraphic and litho-tectonic sections for the Pulaski and Saltville thrust sheets.

Lithologic symbols: 1. sandstone, 2. siltstone, 3. mudstone (phyllites on Pulaski sheet), 4. coal, 5. limestone, 6. dolomite, 7. limy dolomite, 8. argillaceous dolomite, 9. "ribbon" dolomitic limestones, 10. flat pebble conglomeratic limestones, 11. oolitic limestones.

Litho-tectonic designation:

A. moderately incompetent, moderate anisotropy;

B. moderately competent, low anisotropy;

C. moderately to very incompetent, high anisotropy;

D. highly competent, low anisotropy;

E. moderately incompetent, high anisotropy;

F. very competent, low anisotropy;

G. moderately incompetent, high anisotropy.

Abbreviations are: Hunt., Huntersville Formation; R.G., Rocky Gap Formation; Egg., Eggleston Formation; Mocc., Moccasin Formation; Nol., Nolichucky Formation; M, Mississippian; D, Devonian; S, Silurian; O, Ordovician; C, Cambrian.

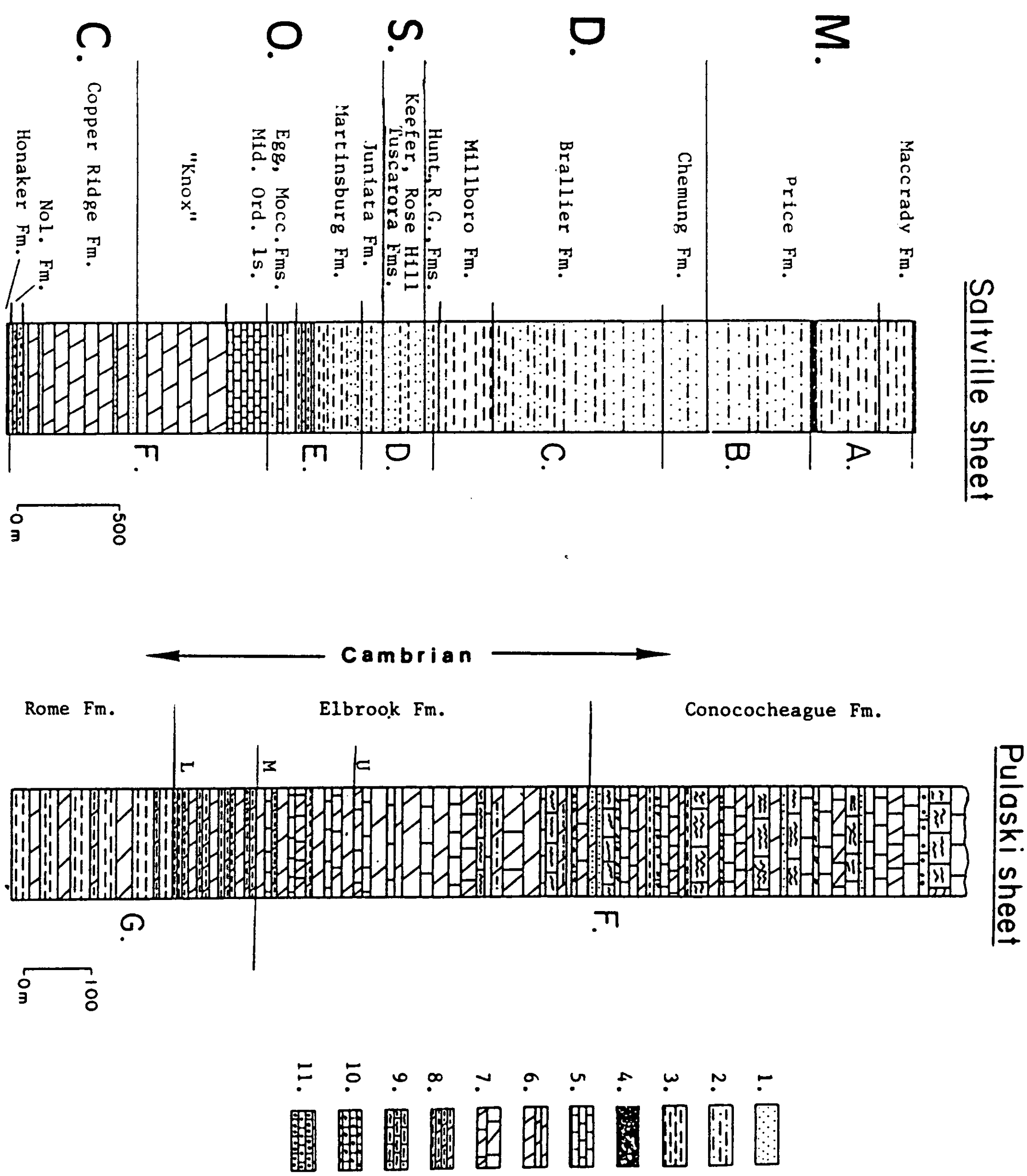
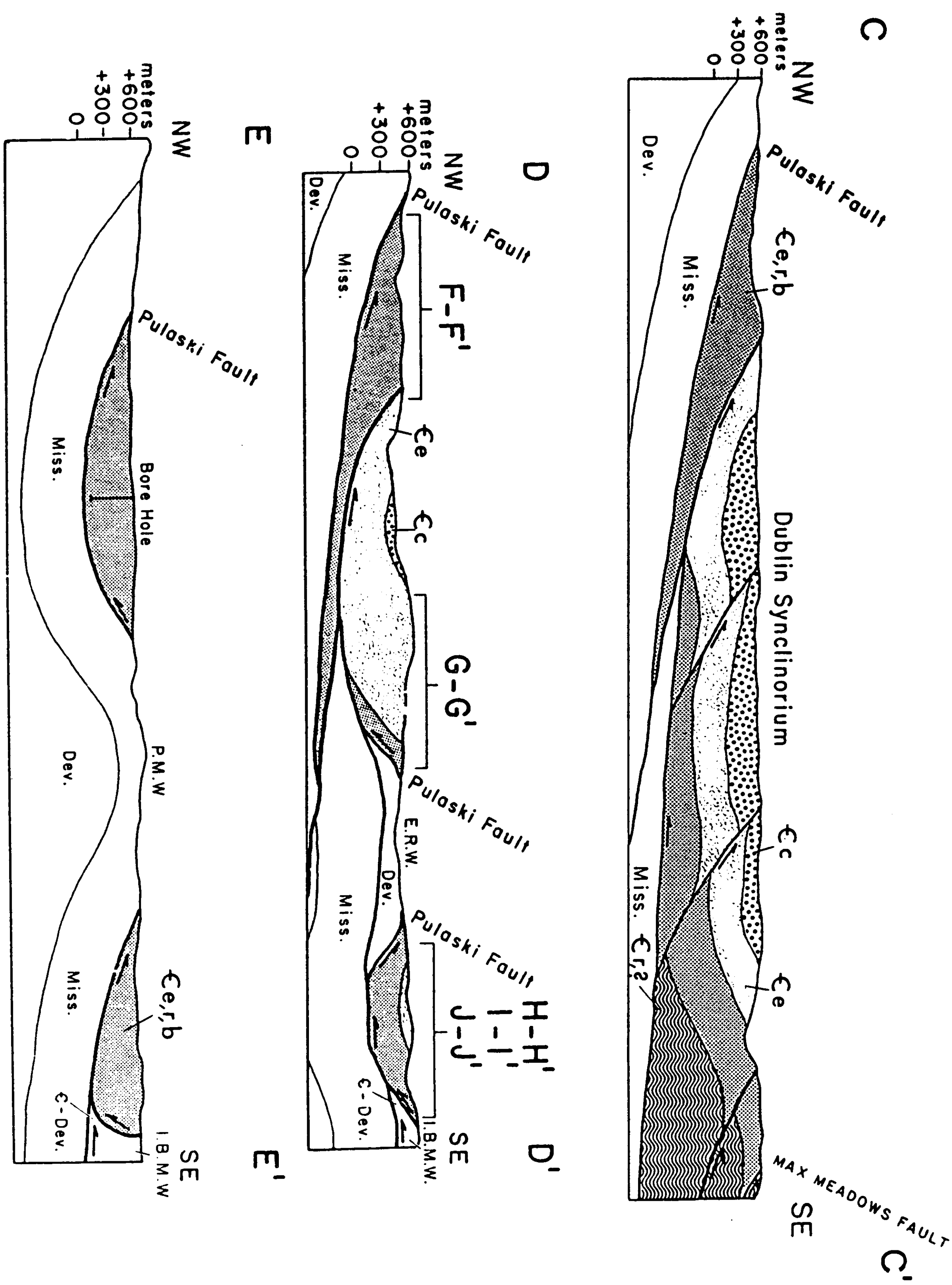

Saltville sheet
M.
D.
S.
O.
C.
Maccrady Fm.
Price Fm.
Chemung Fm.
Brallier Fm.
Millboro Fm.
Hunt., R.G., Fms.
Keefer, Rose Hill
Tuscarora Fms.
Juniata Fm.
Martinsburg Fm.
Egg, Mocc. Fms.
Mid. Ord. ls.
"Knox"
Copper Ridge Fm.
Nol. Fm.
Honaker Fm.
A.
B.
C.
D.
E.
F.
500
0m
Pulaski sheet
Cambrian
Conococheague Fm.
Elbrook Fm.
Rome Fm.
U
M
L
F.
G.
100
0m
1.
2.
3.
4.
5.
6.
7.
8.
9.
10.
11.

Figure 6. Structure sections of the Pulaski sheet within the study area. See Figures 1 and 3 for location.

Section C-C' shows regional synclinal nature of the Pulaski thrust sheet and the distribution of structural divisions. Section D-D' shows folded and faulted Saltville and Pulaski thrust sheets and tectonic slices in East Radford (E.R.W.) and Ingles-Barringer Mountain (I.B.M.W.) windows. Section E-E' shows folded Pulaski and Saltville thrust sheets. Note position of bore hole (see Figures 3 and 8), north of the Price Mountain window (P.M.W.).

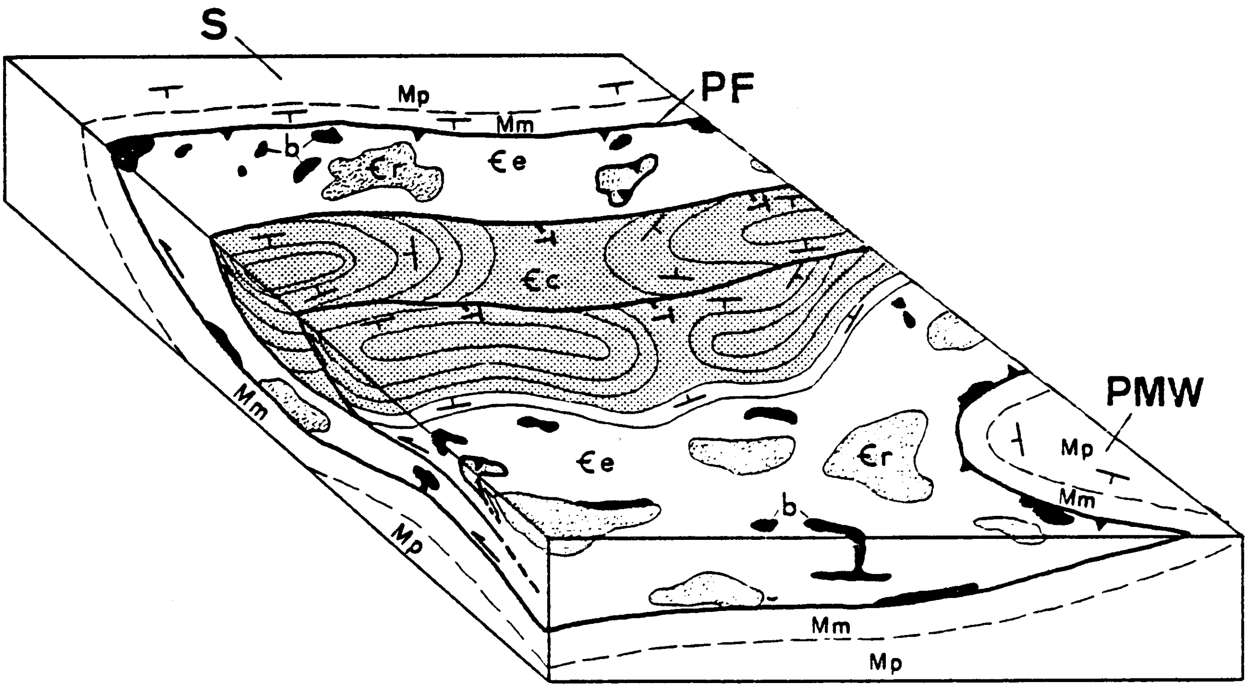
Broken-formations consist of Cambrian Elbrook, Rome and breccia (Ce,r,b); fold-and-thrust division consists of Cambrian Elbrook (Ce) and Cambrian Conococheague (Cc). Cr,? includes Rome and possibly older units.


C
NW
meters
+600
+300
0
Dev.
Pulaski Fault
Ꞓe,r,b
Miss.
Dublin Synclinorium
Ꞓc
Ꞓe
Miss.
Ꞓr,?
MAX MEADOWS FAULT
SE
C'
D
NW
meters
+600
+300
0
Dev.
Pulaski Fault
Miss.
F-F'
Ꞓe
Ꞓc
G-G'
Pulaski Fault
E.R.W.
Dev.
Miss.
Pulaski Fault
H-H'
I-I'
J-J'
Ꞓ-Dev.
I.B.M.W.
SE
D'
E
NW
meters
+600
+300
0
Pulaski Fault
Miss.
Bore Hole
P.M.W
Dev.
Ꞓe,r,b
Miss.
Ꞓ-Dev.
I.B.M.W
SE
E'

Saltville thrust sheet rocks included in this study are the upper part of a 4500-meter sequence of clastic and carbonate rocks comprising several contrasting litho-tectonic units (Fig. 5). Mississippian rocks analyzed in this study consist of sandstones, siltstones, mudstones and coal of the Price and Maccrady Formations (Butts, 1933, 1940; Cooper, 1961; Kreisa and Bambach, 1973).

The study area consists of three distinct structural divisions (Figs. 6, 7) based on formation map patterns, surface structural trends, macro- and mesoscopic fold styles, orientation of structures, and the presence or absence of Max Meadows tectonic breccia. The divisions are the (1) "broken-formations," (2) "fold-and-thrust" divisions of the Pulaski sheet, and (3) "footwall" division of the underlying Saltville thrust sheet.

Figure 7. Schematic block diagram (not to scale) showing general distribution of the three structural divisions in study area; the "footwall" division includes folded Mississippian rocks of the Maccrady (Mm) and Price (Mp) Formations of the Saltville thrust sheet(s); the "broken-formations" consisting of the Elbrook Formation (Ce) with lesser amounts of Rome (Cr) and Max Meadows breccia (b) and the "fold-and-thrust" division consisting of the Elbrook and Conococheague (Cc) Formations of the Pulaski thrust sheet. P.F., Pulaski fault; P.M.W., Price Mountain window.


S
PF
Mp
Mm
b
€r
€e
€c
PMW
Mp
Mm
€e
€r
b
Mm
Mp
Mm
Mp

THE FAULT SURFACE AND MAX MEADOWS BRECCIA

The fault surface of the Pulaski thrust is rarely exposed in the study area but where seen it is one of three types. The first type consists of fractured, veined and folded Cambrian dolomites, argillaceous dolomites and phyllites of the broken-formations lying on macerated, fractured and foliated Mississippian mudstones. In places, a foliated, slickensided, black clay gouge up to 20 cm thick is present (Stanley and Schultz, 1983). Foliated, macerated, and brecciated Mississippian mudstones are limited to within three meters or less of the contact although mesoscopic folding and faulting related to Pulaski thrust emplacement may be present up to 100 meters below the Pulaski sheet.

The second type of thrust contact consists of Max Meadows tectonic breccia, ranging from less than a meter to greater than three meters thick, resting on macerated, foliated and brecciated Mississippian mudstones (Plate 1; A, B, C). At one locality (Plate 1; A, C) small dikes of Max Meadows breccia project downward into the footwall rocks.

The breccias are one of two types or a mixture of both depending on parent material. The most common type of breccia was derived from thinly bedded to thinly laminated argillaceous dolomites of the Elbrook Formation. This type consists of poorly sorted, angular to subrounded clasts of dolomite in a fine- to very fine-grained matrix of crushed dolomite (Plate 1: D). Clasts range from less than one centimeter to greater than one meter with rare blocks up to several meters long. These breccias are massive to crudely layered and are well to poorly

Plate 1. A, B and C are at the same location, on County Route 696, just south of Wake Forest, Montgomery County, Virginia, along the leading edge of Pulaski fault near section line D-D'.

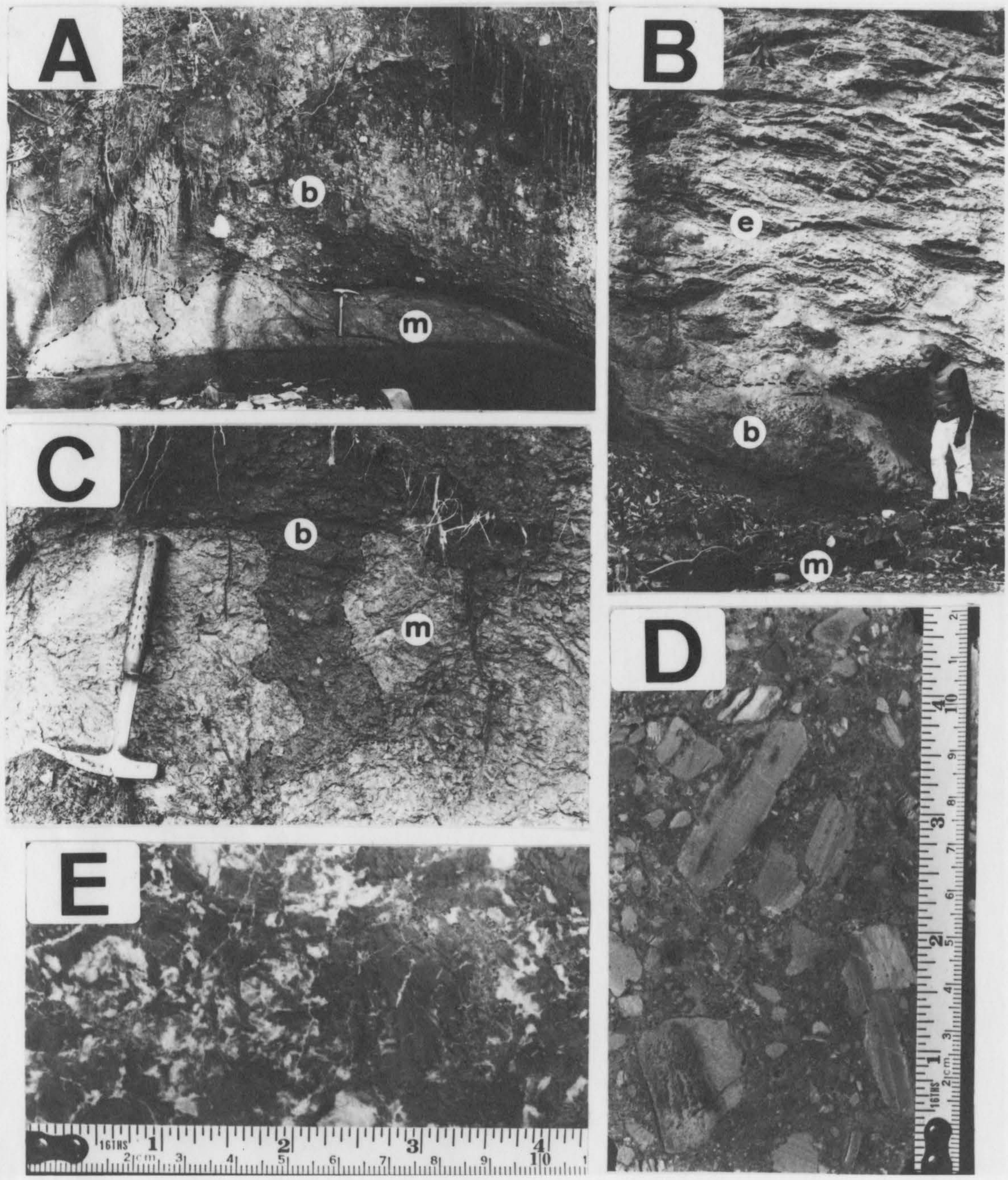
A. Pulaski fault (dashed line) along leading edge of Pulaski thrust sheet where Max Meadows breccia (b) is in contact with southeast dipping, macerated Mississippian Maccrady mudstones.

B. Pulaski fault (in stream) along leading edge of Pulaski thrust sheet. Deformed Elbrook dolomites of the broken-formations (e) overlie Max Meadows breccia (b) which is in fault contact with Mississippian Maccrady mudstones (m).

C. Details of small Max Meadows breccia (b) dike into Mississippian Maccrady mudstones along Pulaski fault contact.

D. Dolomite type of Max Meadows breccia with angular dolomite clasts in fine-grained dolomite matrix.

E. Phyllite type of Max Meadows breccia containing "shreddy" clasts of laminated phyllite in macerated phyllite and minor dolomite matrix.


A
b
m
B
e
b
m
C
b
m
D
E

indurated depending on the degree of matrix recrystallization and subsequent weathering. Well indurated blocks of breccia may be surrounded by poorly consolidated breccia. Breccia is finest grained along the thrust contact where it may grade into a dolomite gouge at the contact surface. A rude foliation is commonly present nearest the fault surface. Away from the thrust contact the breccias grade into highly fractured, veined and folded rocks (Plate 1; B).

A second type of breccia was derived from calcareous phyllite and phyllitic mudstones of the lower part of the Elbrook Formation and the upper part of the Rome Formation. These breccias consist of phyllitic clasts in a macerated phyllite and minor crushed dolomite matrix (Plate 1; E). Phyllite breccias are well to poorly indurated and foliate to non-foliate.

Analytical results (Appendix I) of a phyllitic breccia and a dolomite breccia show that the clay fractions are dominated by chlorite and muscovite with minor interstratified-intergraded mica-montmorillonite or mica-vermiculite. In both types, x-ray diffractograms (Appendix I) show that micas are well crystallized and probably were derived from reordering of detrital clay minerals during regional metamorphism at temperatures in the range of 300-400°C. This result is in agreement with conodont color alteration indexes for rocks in the study area (Epstein and others, 1977).

The third type of contact of the Pulaski thrust surface is a 1 to 30 meter thick zone of deformed Cambrian through Devonian tectonic slices in between deformed Mississippian mudstones below and Max Meadows breccias or Cambrian dolomites and phyllites above (Schultz, 1979B, Fig. 9). The tectonic slices were derived from the footwall of the Pulaski sheet during the ramp stage of sheet emplacement. Within the stacked tectonic slices, massive dolomites and sandstones are cataclastically deformed with original sedimentary fabrics obliterated by grain-scale fracturing and subsequent comminution to form suites of cataclasites (Schultz, 1979A). In sharp contrast, interbedded sequences of thin limestones, sandstones and shales have a distinctive "melange-like" deformational fabric which consists of chocolate-tablet boudinage of competent rocks in a foliated shale matrix (Schultz,1979A). Extension fractures, shear fractures, tectonic stylolites and intracrystalline deformational fabrics (deformation bands and böhm lamellae, subgrain and new grain growth textures) occur throughout these fault rocks (Schultz,1979A, 1979B).

BROKEN-FORMATIONS

Above the fault surface, the broken-formations consist of lesser amounts of folded and faulted phyllitic mudstones and carbonates of the Rome Formation and Max Meadows type breccia in a complexly folded and faulted terrain of carbonates of the Elbrook Formation. The broken-formations range from 300 to 500 meters thick and are readily distinguished from rocks structurally above (fold-and-thrust) and below (footwall rocks of the Saltville sheet) by (1) a sharp increase in the variability of fold and fault morphology, (2) an increase in the variability of fold style as defined by Fleuty (1964) graphs (greater range in fold plunges and dips of axial surfaces), (3) a low degree of preferred orientation to macro- and mesoscopic structures, (4) a sharp increase in fold and fault frequency, and (5) the presence of Max Meadows type breccia.

Max Meadows type breccias in the broken-formations are similar to those found along the base of the Pulaski sheet. Both phyllite and dolomite types are present in areas of both Rome and Elbrook but only dolomite breccias occur in the structurally higher parts of the broken-formations. Breccia occurs well above the basal fault surface but decreases in abundance away from this contact with both less frequent breccia zones and thinner zones (Fig. 8). Breccias in the broken-formations are either sill-like bodies (bedding-parallel) that are folded about macro- and mesoscopic structures (Figs. 9, 10, 11, 12) or dike-like bodies that truncate bedding in macro- and mesoscopic structures (Figs. 9, 10, 11, 12 and Plate 2A,C,D).

Figure 8. Generalized lithologic section of a core through the broken-formations. Note the repeated Elbrook section, the faults (F), mesoscopic fold zones (f), dip variability and increase in breccia downhole.

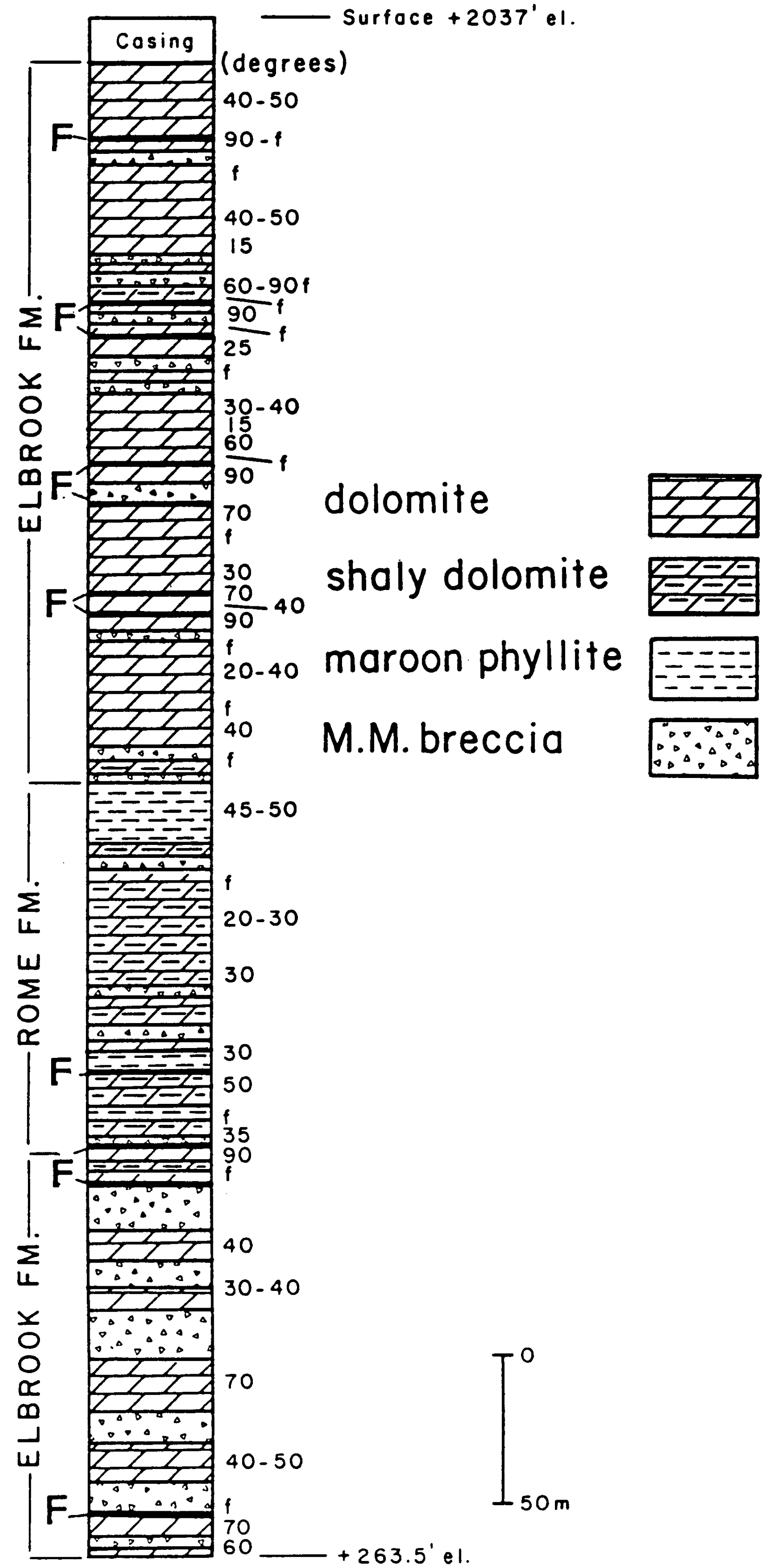

Surface +2037' el.
Casing
(degrees)
40-50
90-f
f
40-50
15
60-90f
90 f
f
25
f
30-40
15
60
f
90
70
f
30
70
40
90
f
20-40
f
40
f
45-50
f
20-30
30
30
50
f
35
90
f
40
30-40
70
40-50
f
70
60
+263.5' el.
ELBROOK FM.
ROME FM.
ELBROOK FM.
F
dolomite
shaly dolomite
maroon phyllite
M.M. breccia
0
50m

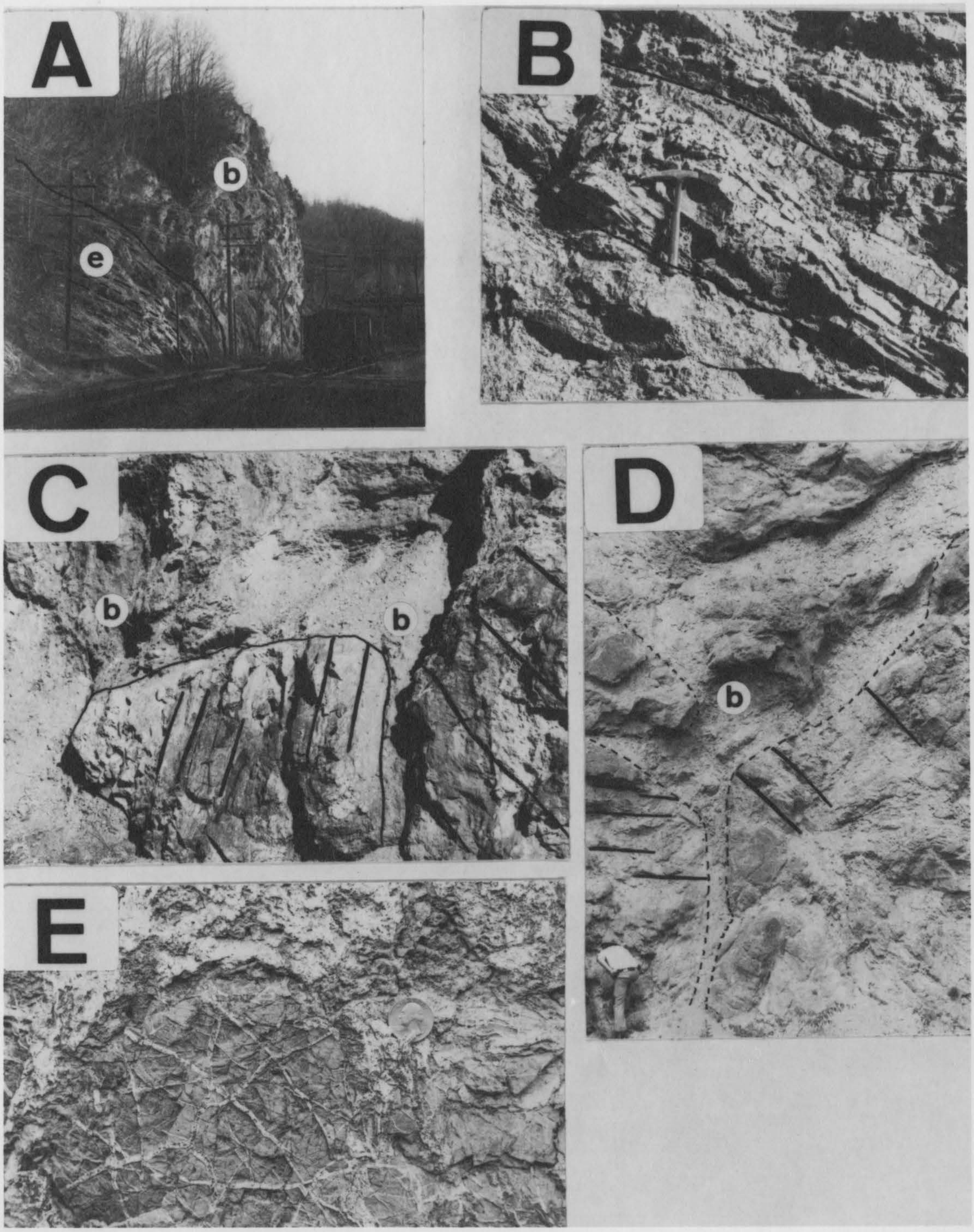
Plate 2. A. Large intrusive mass of Max Meadows tectonic breccia (b) in contact with folded Cambrian Elbrook dolomite (e). Outcrop is near southeast end of section G-G', just north of Virginia Route 114 bridge over New River.

B. Block of argillaceous Elbrook dolomite in the broken-formations bounded both above and below by small-scale shear thrusts. Outcrop is in section L-L'.

C. Elbrook dolomite (bedding shown by heavy lines) surrounded by Max Meadows breccia (b). This block was probably derived from steeply dipping dolomites along the breccia dike margin. Outcrop is in section M-M'.

D. Max Meadows breccia dike (b) in folded and faulted Elbrook dolomites in the broken-formations. Outcrop is in section L-L'.

E. Fretwork intersection of carbonate veins in argillaceous Elbrook dolomite in broken-formations. Outcrop is in section L-L'.


A
b
e
B
C
b
b
D
b
E

Breccia sills range from less than 3 cm to over 30 meters thick and usually thicken and thin both along strike and up and down the dip of enclosing beds. Sill margins are either irregular surfaces grading into highly fractured, folded and veined rocks, or sharp surfaces bounded by relatively undeformed rocks.

Rare fold hinges occur in large breccia masses and are most common where breccia grades into folded and fractured rocks.

Breccia dikes range in size from a few centimeters to 30 meters in thickness and vertical exposures of dikes more than 30 meters high are common. Wall-rock deformation consists of dragged bedding and slickensided and grooved surfaces (Cooper and Haff, 1940). Deformation of the wall rocks is usually limited to within 1-2 meters of the contact where breccia truncates bedding at a high angle. The long dimension of clasts in dikes shows no preferred orientation; however, often there is grading of larger to smaller clasts toward dike margins. Clasts in the breccia dikes may or may not be of the same lithology as the enclosing rocks. Commonly breccia dikes can be traced into breccia sills and are continuous with them (Fig. 10, G-G').

Rocks of the Elbrook and Rome Formations associated with the breccias are complexly deformed but each can be recognized and mapped as separate parts of the broken-formations. Typical map patterns (Figs. 3, 13) are in irregularly-shaped masses of Rome surrounded by rocks of the Elbrook Formation. The Rome-Elbrook contact is both folded and faulted (Figs. 10-13A,B). Some Rome masses are thrust slices structurally above the Elbrook (Figs. 10-13). Elsewhere the Rome is in

Figure 9. Index map of outcrop sections F-F' to R-R'. Note position of regional section D-D'. Symbols: Mm, Mississippian Maccrady Formation; Mp, Mississippian Price Formation; C-D, Cambrian through Devonian; Cc, Cambrian Conococheague Formation; Ce,r,b, Cambrian Elbrook, Rome and Max Meadows breccia.

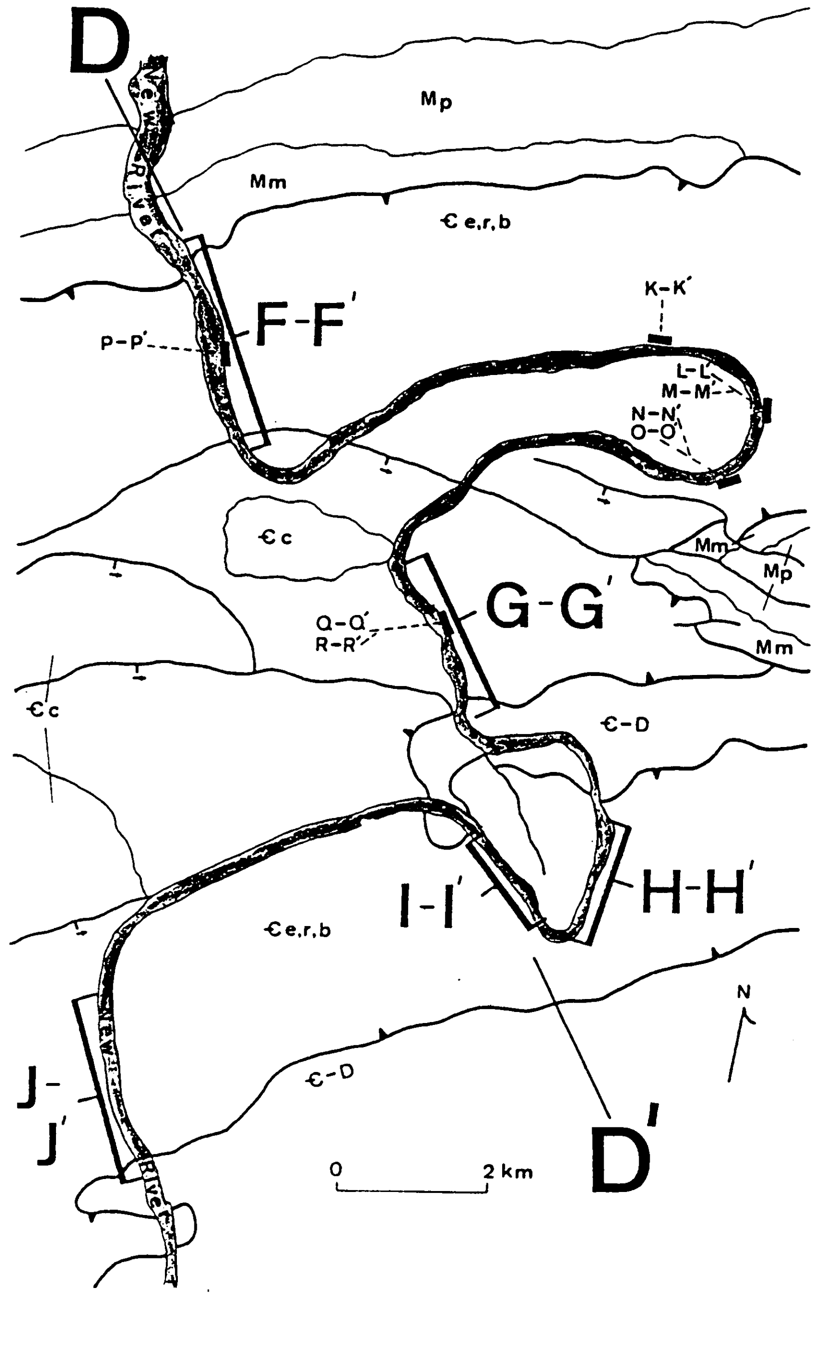

D
Mp
Mm
Є e,r,b
F-F'
p-p'
K-K'
L-L'
M-M'
N-N'
O-O'
Єc
Mm
Mp
G-G'
Q-Q'
R-R'
Mm
Єc
Є-D
I-I'
H-H'
Єe,r,b
N
Є-D
J-
J'
0
2 km
D'

Figure 10. Outcrop sections along New River (Figure 9 shows location of sections) showing structures typical of both the broken-formations and the fold-and-thrust division of the Pulaski thrust sheet (symbols as in Figure 1).

Section F-F'. Outcrop section showing the leading edge of the Pulaski thrust sheet and field relations of the Rome and Elbrook Formations and Max Meadows breccia. Breccia occurs as sills and dikes. The Rome-Elbrook contact is both folded and faulted. The southeast-dipping thrust at SE end of the cut separates rocks of the broken-formations (on NW) from less deformed rocks of the fold-and-thrust division.

Section G-G'. Outcrop section of fold-and-thrust division and broken-formations. Decollements occur in lower portion of fold-and-thrust division. The transitional zone between the fold-and-thrust division and structurally lower broken-formations consists of thin breccia zones between intensely folded shaly dolomites of lower part of Elbrook Formation. Northwest-dipping Pulaski fault and northwest-dipping decollements show that the large-scale fold (axis on NW end of section) post-dates Pulaski emplacement and a period of mesoscopic deformation.

Section H-H'. Outcrop section of lower portion of fold-and-thrust division and structurally lower rocks of the broken-formations. Although Rome occurs near its correct stratigraphic position, the Elbrook-Rome contact is faulted. The northwest-dipping fault at the SE end of the cut places breccia derived from Rome phyllites (rb) over blocks of Elbrook and dolomite-type of Max Meadows breccia. The relative timing of deformation is similar to that seen in G-G'.

Section I-I'. Outcrop section of rocks in the broken-formations. The Rome at this locality occurs along the Pulaski fault surface. Note Rome-derived breccia (rb) and the folded sill of breccia.

Section J-J'. Outcrop section of rocks in the Rome and Elbrook Formations and dikes ans sills of Max Meadows breccia in the broken-formations passing upward into gently-folded rocks of the Elbrook Formation in the fold-and-thrust division (on the NW).

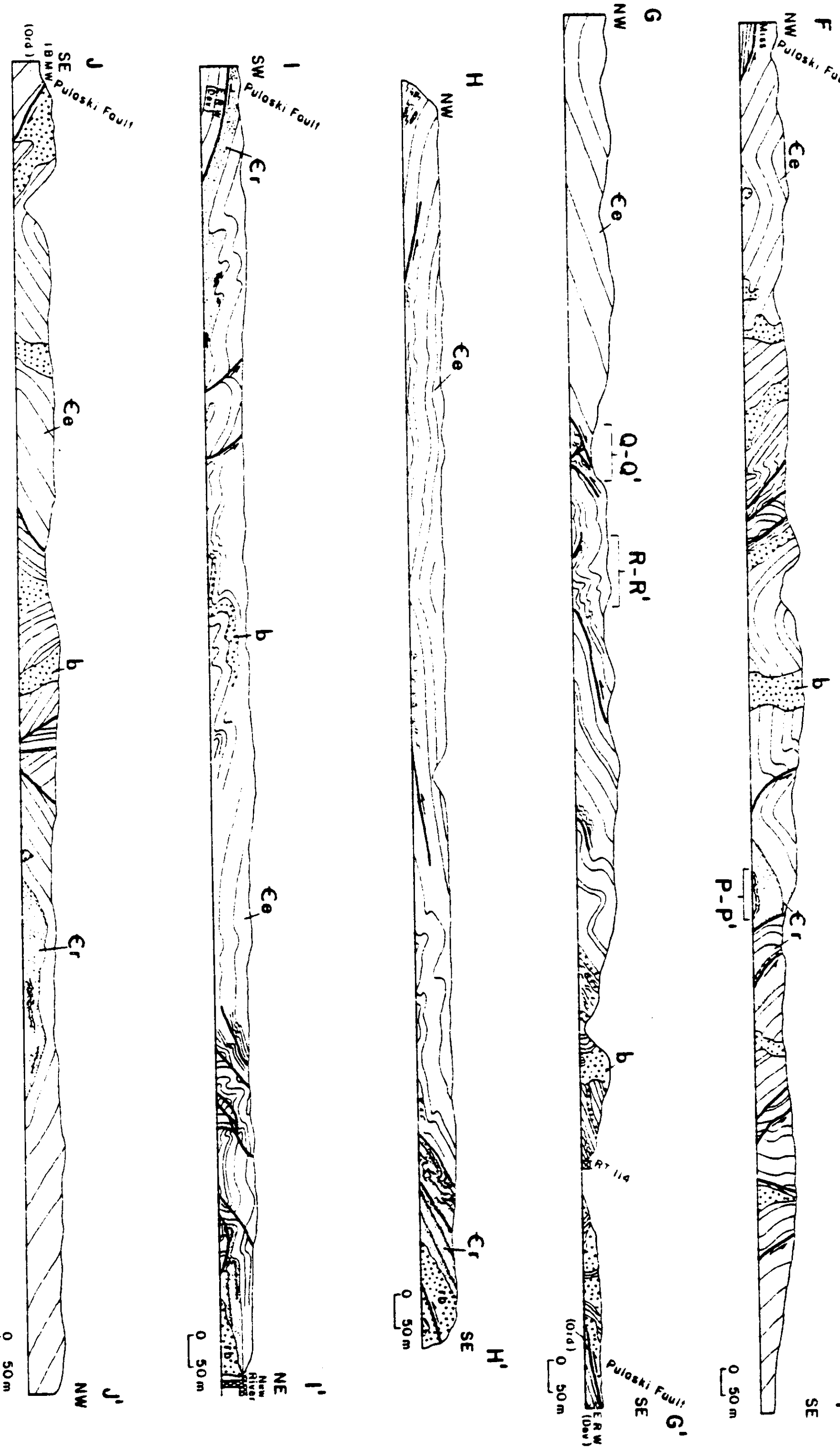

F
NW
Puloski Fault
Ɛe
b
P-P'
Ɛr
SE
F'
0 50m
G
NW
Ɛe
Q-Q'
R-R'
b
RT 114
(Ord)
Puloski Fault
SE
G'
H
NW
Ɛe
Ɛr
SE
H'
0 50m
I
SW
Puloski Fault
Ɛr
b
Ɛe
NE
New River
I'
J
SE
(Ord)
Puloski Fault
Ɛe
b
Ɛr
NW
J'

Figure 11. Typical outcrops in the broken-formations. See Figure 9 for section locations (symbols as in Figure 1).

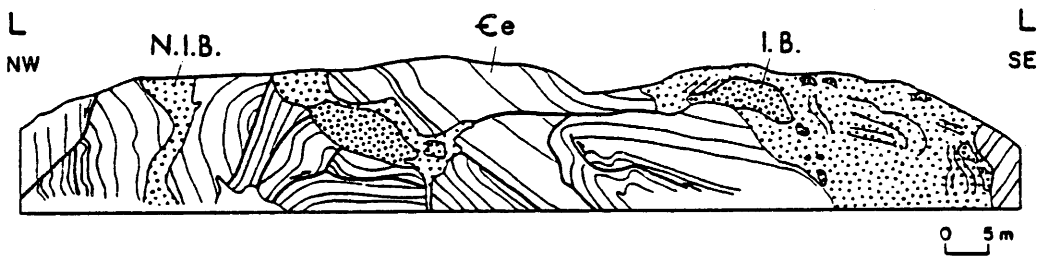
Section K-K'. Folded and faulted Elbrook dolomite in the broken-formations. Note folded faults, disharmonic folding, southeast asymmetry of folds and folded axial surfaces.

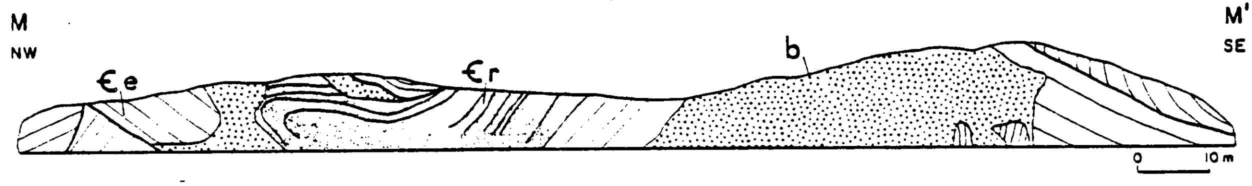
Section L-L'. Folded, faulted and brecciated Elbrook dolomite of the broken-formations. Note broken recumbent fold, folded faults, and breccia dikes. Blocks of well indurated breccia (dense breccia pattern; IB) are surrounded by poorly indurated breccia (open breccia pattern; NIB).

Section M-M'. Folded and faulted rocks of the Rome and Elbrook Formations and Max Meadows breccia in the broken-formations. The Rome-Elbrook contact is both folded and faulted.

Section N-N'. Folded and faulted rocks of the Rome and Elbrook Formations of the broken-formations. Rome is surrounded by faults, which have been folded. Breccia has both dike and sill aspects.


K
NW
€e
K'
SE
0
5m


L
NW
N.I.B.
€e
I.B.
L'
SE
0
5m


M
NW
€e
€r
b
M'
SE
0
10m

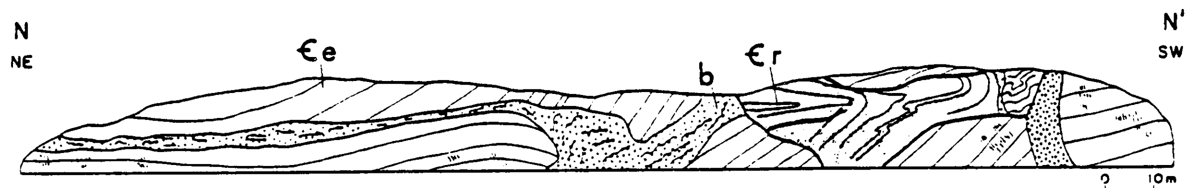

N
NE
€e
b
€r
N'
SW
0
10m

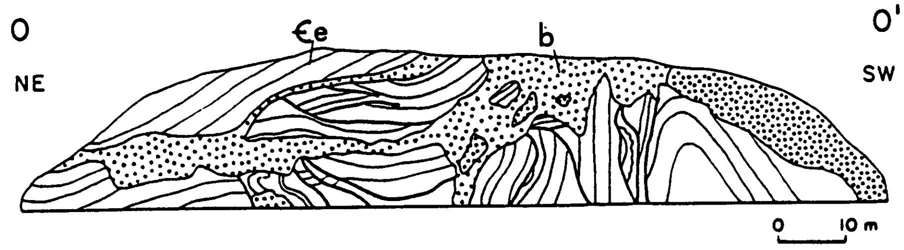
Figure 12. Typical outcrops in the broken-formations (O-O', P-P') and fold-and-thrust division (Q-Q', R-R'). See Figure 9 for section locations (symbols as in Figure 1).

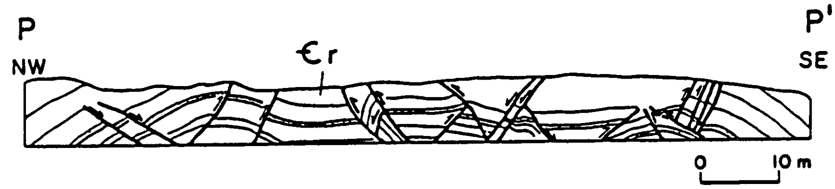
Section O-O'. Folded, faulted and brecciated Elbrook dolomite of the broken-formations.

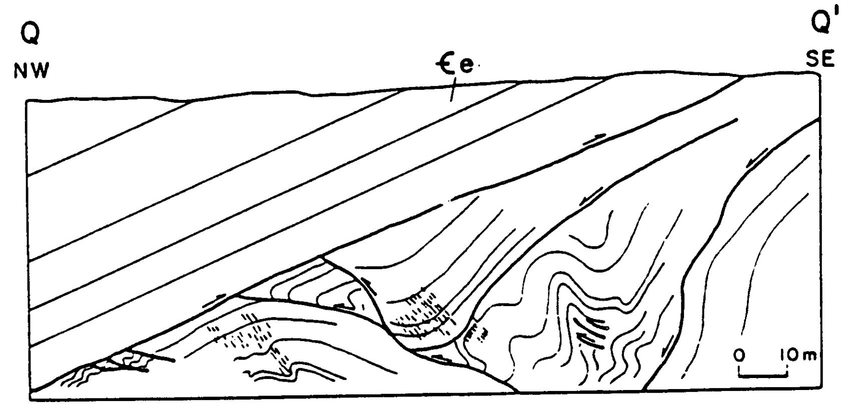
Section P-P'. Extensional and contractional faults in phyllites and dolomite (marker bed shaded) of the Rome Formation in the broken-formations.

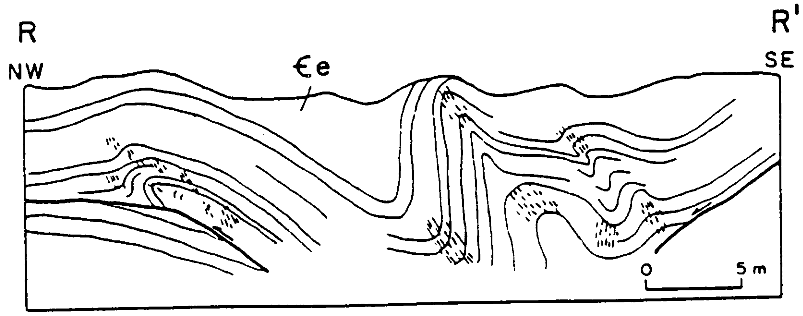
Section Q-Q'. Mesoscopic folds and faults in dolomite of the upper Elbrook fold-and-thrust division of Pulaski thrust sheet. Short dashes are cleavage traces.

Section R-R'. Mesoscopic folds above a bedding-parallel decollement. Cleavage (short dashes) is axial planar to folds and best developed in shaly dolomite beds in middle part of Elbrook Formation.


O
NE
€e
b
O'
SW
0
10 m


P
NW
€r
P'
SE
0
10 m


Q
NW
€e
Q'
SE
0
10m


R
NW
€e
R'
SE
0
5 m

normal stratigraphic contact and may be above or below the Elbrook (Figs. 10-13A,B) depending on fold geometry.

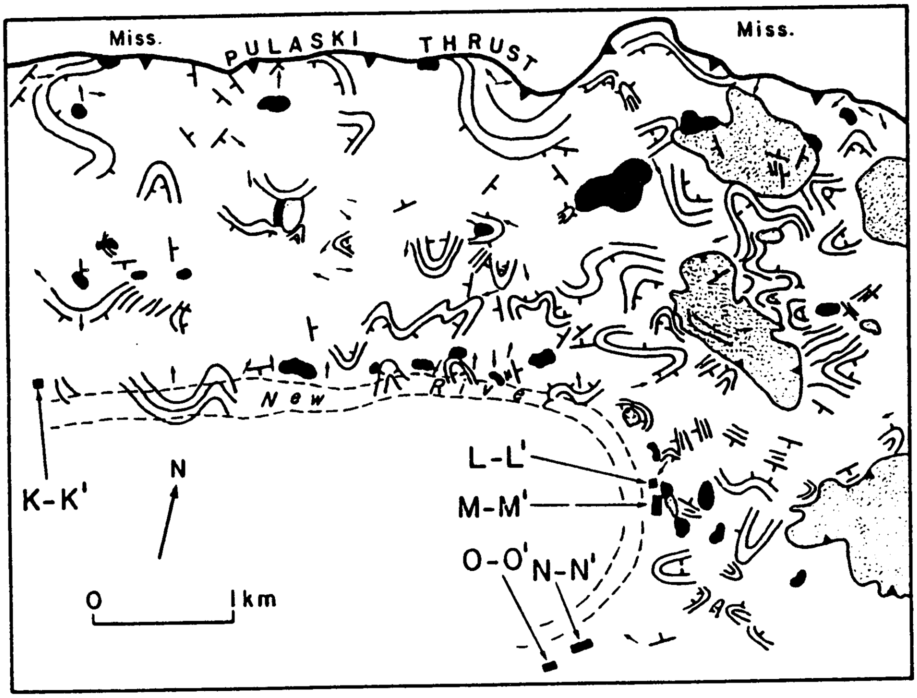
Surface structural trends in the broken-formations (Fig. 13A,B) comprise discontinuous patterns that reflect the first-order magnitude macroscopic folds which have variable orientations (Fig. 14A). Strikes, dips and lithologies are commonly so variable that outcrops less than five meters apart could not be correlated across the covered interval. Bedding trends (Fig. 15A) across the entire zone of broken-formations have a low degree of preferred orientation (Fig. 16A and Table 1). Similar variability in bed orientation is also present vertically which was determined from core drilling through the broken-formations (Fig. 8).

Mesoscopic deformation is highly variable from outcrop to outcrop. Relatively undeformed blocks of dolomite are in fault contact with folded, faulted and brecciated blocks of dolomite (Figs. 10-12). In the strongly deformed blocks (Figs. 10-12) macro- and mesoscopic faults are abundant (Plate 2B). Faults are both planar and folded (Figs. 10-12) and the lack of marker beds and the degree of stratal disruption preclude determination of relative movements on most faults. Faults have variable orientations (Fig. 15A) and range from parallel to bedding to high angles to bedding. Several relative generations of faults are present in most outcrops (Figs. 10-12), and vertically repeated stratigraphic sections are common (Figs. 8-12).

Calcite-filled extension fractures are abundant in dolomites of the broken-formations (Plate 2E; Cooper, 1970). Single outcrops have upwards of thousands of veins. In strongly deformed and brecciated

Figure 13. A. Geologic map and surface structural trend map of portion of the broken-formations. Dip direction of bedding in linear outcrop belts and on fold noses is shown. Rome Formation is shaded gray; Max Meadows breccia is black; Elbrook Formation is unshaded; small arrows are axis trends of mesoscopic folds. Note position of sections K-K' to O-O'.

B. Geologic map and surface structural trend map of a portion of the broken-formations showing the transition to the structurally higher fold-and-thrust division (large syncline, center of map). Symbols and shading same as A. Note position of section H-H'. See Figure 21A for location of A and B.


Miss.
PULASKI THRUST
Miss.
New River
K-K'
N
L-L'
M-M'
O-O'
N-N'
0
1 km

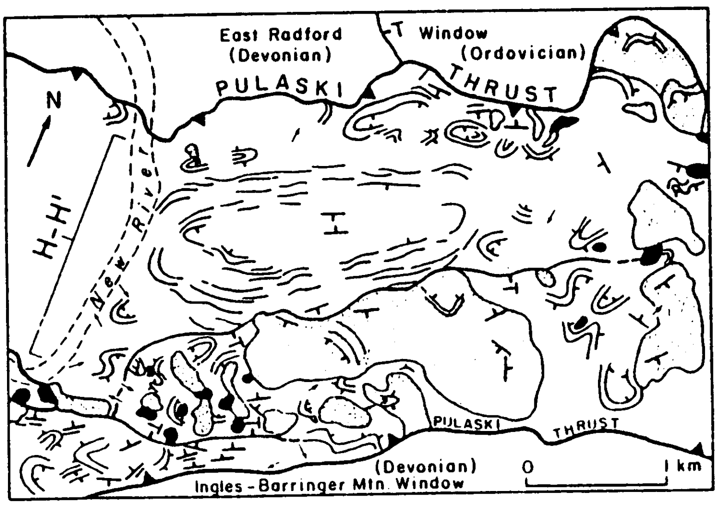

East Radford
(Devonian)
T Window
(Ordovician)
PULASKI THRUST
N
H-H'
New River
PULASKI THRUST
(Devonian)
Ingles-Barringer Mtn. Window
0
1 km

Figure 14. A. Rose diagram of macroscopic fold crestal traces in the broken-formations of Pulaski thrust sheet.

B. Rose diagram of macroscopic fold crestal traces in the fold-and-thrust division of the Pulaski thrust sheet. Arrows are crestal traces of macroscopic folds in Mississippian rocks of the Saltville thrust sheet. P.M.A., Price Mountain anticline.

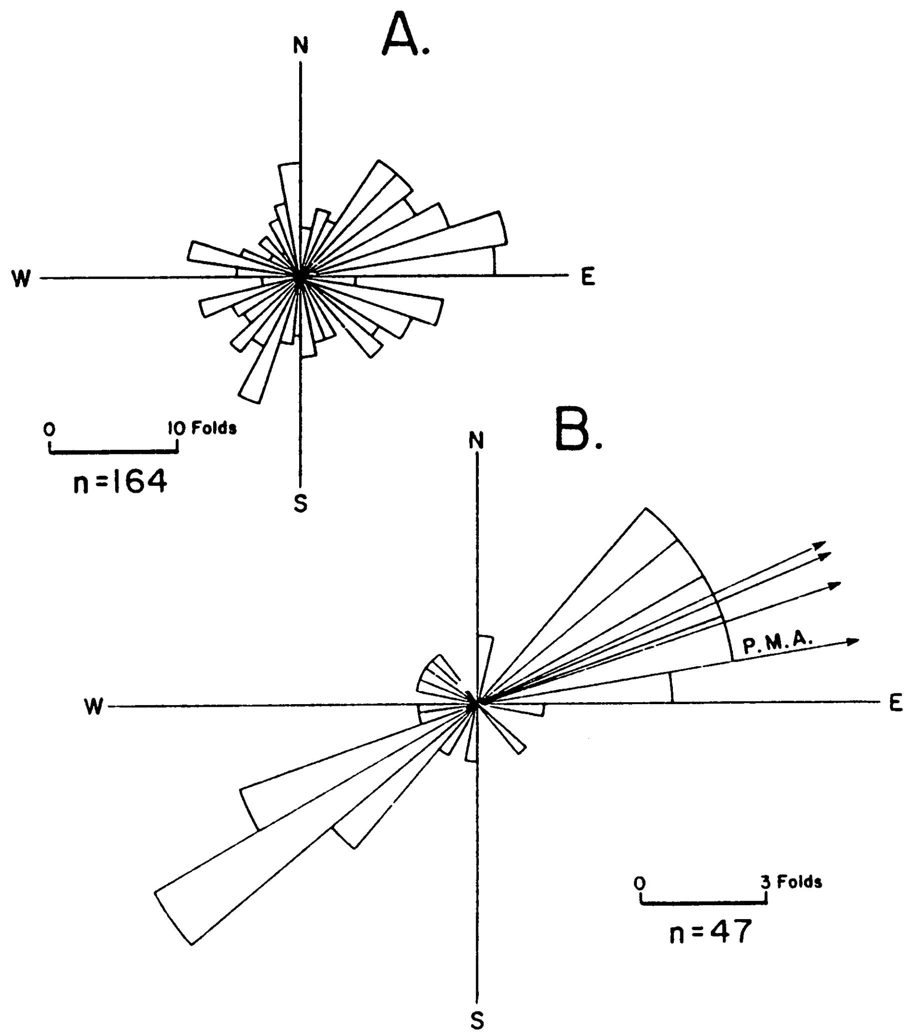

A.
N
W
E
S
0
10 Folds
n=164
B.
N
W
E
S
P.M.A.
0
3 Folds
n=47

Figure 15. Comparative structural data for broken-formations (A) and fold-and-thrust (B) division of the Pulaski thrust sheet and of the footwall division (C) of the Saltville thrust sheet. S_o, contoured poles to bedding; AS, contoured poles to axial surfaces of mesoscopic folds; AX, contoured axes of mesoscopic folds; F, poles to faults in outcrops K-K' through O-O' of the broken-formations; S_1, poles to cleavage; N, number of observations; C, contour intervals; dashed line, border of area of no data points.

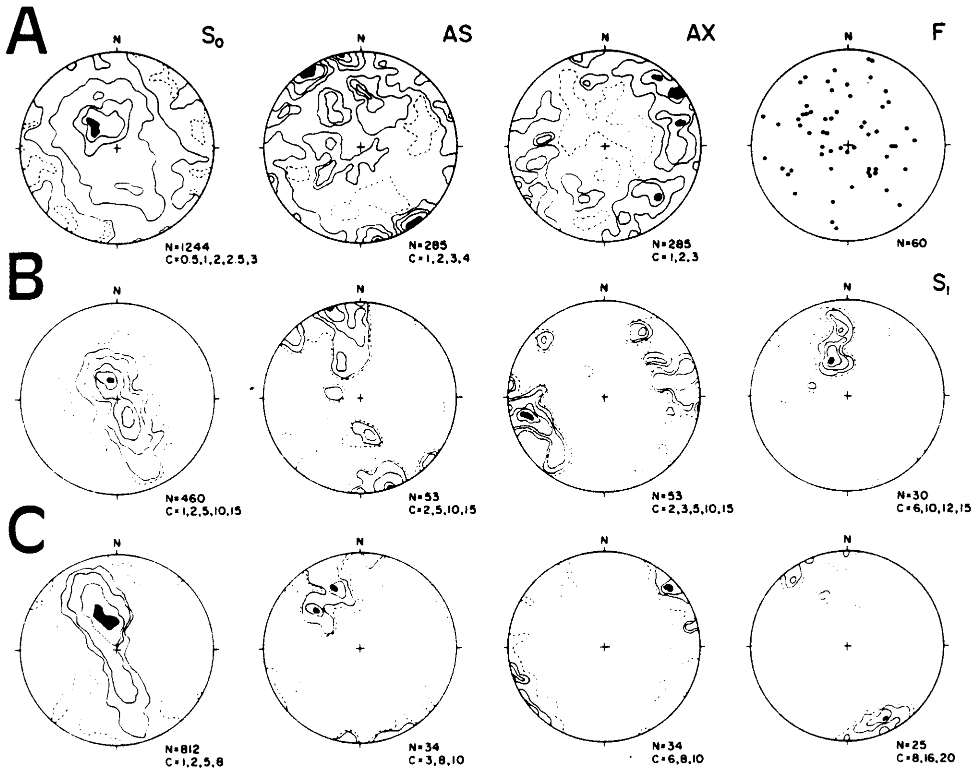

A
S0
AS
AX
F
N
N=1244
C=0.5,1,2,2.5,3
N=285
C=1,2,3,4
N=285
C=1,2,3
N=60
B
S1
N=460
C=1,2,5,10,15
N=53
C=2,5,10,15
N=53
C=2,3,5,10,15
N=30
C=6,10,12,15
C
N=812
C=1,2,5,8
N=34
C=3,8,10
N=34
C=6,8,10
N=25
C=8,16,20

Figure 16. Comparative preferred orientation curves based on structural data for broken-formations (black triangles) and fold-and-thrust division (circle with cross) of the Pulaski thrust sheet and the footwall division (x's) of the Saltville thrust sheet. Note that the slope of a curve is a function of the area (and radii of that area) enclosed within any given contour on the stereonet. The slope of curves for data in the fold-and-thrust and footwall divisions is always greater than curves in the broken-formations because the higher contour intervals have correspondingly smaller areas (radii), i.e., have a greater degree of preferred orientation (Appendix III). A, poles to bedding; B, poles to mesoscopic fold axial surfaces; C, mesoscopic fold axes; D, poles to cleavage.

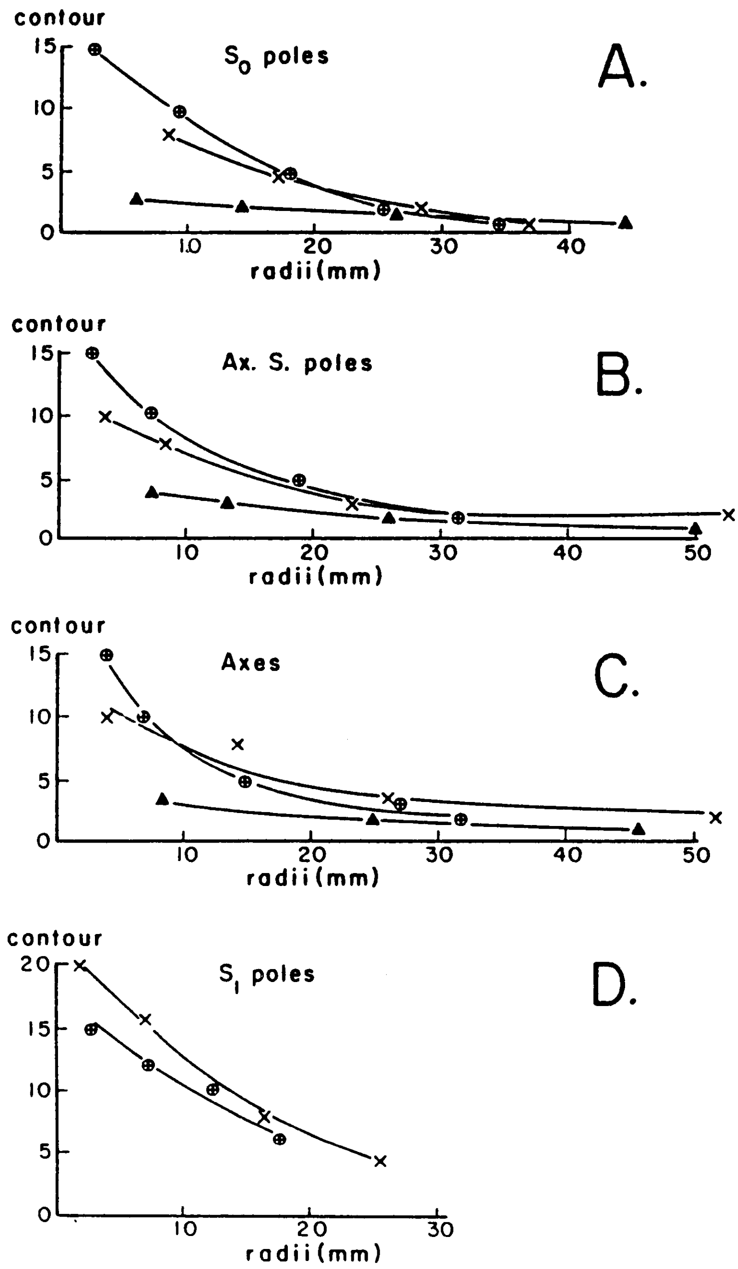

contour
S0 poles
A.
radii(mm)
contour
Ax. S. poles
B.
radii(mm)
contour
Axes
C.
radii(mm)
contour
S1 poles
D.
radii(mm)

Table 1. Comparative fold data.

	Footwall		Fold and thrust		Broken-formation	
	Macro	Meso	Macro	Meso	Macro	Meso
wavelength	4-6 km	1 cm-100 m	3-5 km	1 cm-100 m	0.25-0.5 km	1 cm-100 m
amplitude	0.5-1.5 km	1 cm-10 m	50- 70 m	1 cm-15 m	25-50 m	1cm-15 m
plunge	15° - 25°	0° - 30°	10° - 20°	0°-40°	10°-50°	0°-85°
axial surface dip	70°- 90°	35°- 90°	70°- 90°	25° - 90°	65°- 90°	0° - 90°
interlimb angle	130° - 150°	150° - 50°	150° - 170°	150° - 40°	150° - 25°	140° - 0°

Table 2. Comparative preferred orientation data.

S_0 footwall:y= 9.6, sl.=-.2, θ=10.4°,n=812 R= 1.2, cc.= -.98, O area= 48.7% fold & thrust: y= 14.6, sl.=-.4, θ= 20.7°,n=460 R= 7.4, cc.=-.96, O area= 64.0% broken-formation: y= 3.3, sl.= -.4, θ= 2.6°,n=1244 R= .47, cc.=-.99, O area= 0%	S_1 footwall: y= 20.1, sl.=-.6, θ= 31.1°,n=25 R= 13.6, cc.=-.99, O area= 89.7% fold & thrust: y= 15.4, sl.=-.46, θ=24°,n=30 R= 8.1, cc.=-.99, O area= 89.1% broken-formation: insufficient data
AxS footwall: y= 9.1, sl.=-.16, θ=8.3°,n=34 R= 2.3, cc.=-.89, O area=80.7% fold & thrust: y= 14.4, sl.=-.43, θ=22.3°,n=53 R= 3.5, cc.=-.91, O area=74.3% broken-formation: y=4.1, sl.=-.05, θ=3.6°,n=285 R=.48, cc.=-.96, O area=10.3%	Ax footwall: y= 9.8, sl.=-.17, θ=8.8°,n=34 R= 2.4, cc.=-.91, O area=84.1% fold & thrust: y= 13.9, sl.=-.42, θ=21.7°,n=53 R= 5.2, cc.=-.92, O area= 70.1% broken-formation: Y= 3.4, sl.=-.05, θ= 2.6°,n=285 R= .31, cc.=-.99, O area= 17.2%

zones, veins are so prevalent that they form complex fretwork intersections (Plate 2E). Veins are more abundant nearest breccia, in fold cores, and above faults.

Mesoscopic folds in the broken-formations are highly variable in orientation and style (Figs. 15A, 17A and Plate 3A-D). They range from open to isoclinal (interlimb angles from greater than 180° to less than 20°) (Table 1) and from upright to recumbent (Fig. 18A). Reclined folds (Figs. 18A) are present across the domain. Folds are disharmonic and fold hinges range from angular to rounded, and axes and axial surfaces are planar to strongly folded. Conjugate folds (box folds) (Fig. 17A and Plate 3A) and folds with broken limbs and hinges (Fig. 19A,B) are common in the lower parts of the broken-formations.

Axial surface and axis trends (Fig. 15A) range through 360° and have a low degree of preferred orientation (Fig. 16A). No consistent relationship is discernible between fold style (Fleuty graphs) and orientation (Fig. 20).

Cleavage is relatively rare in rocks of the broken-formations but where present, it is well developed and is a spaced, stylolitic type. Cleavage surfaces are planar and gently warped and cleavage occurs in folds of variable orientations.

Plate 3. A. Mesoscopic box fold in argillaceous Elbrook dolomite. Note folded breccia (b). Outcrop is located near southeast end of section G-G'.

B. Mesoscopic fold in argillaceous Elbrook dolomite in the broken-formations with northwest dipping axial surface. This open fold has probably undergone rigid body rotation (after its initial formation) by larger scale folding and/or faulting. Outcrop is located at northern end of section L-L'.

C. Upright, open folds in typical very argillaceous Elbrook dolomite in transition of fold-and-thrust division to broken-formations. Outcrop is located on the southeast end of section H-H'.

D. Broken, recumbent, tight to isoclinal mesoscopic folds in the Elbrook Formation of broken-formations. Outcrop is located on the southeast end of section H-H'.

E. A fold-fault modified mesoscopic fold in the Elbrook Formation of broken-formations. This fold has a folded axial surface, collapsed hinge and faces southeast. Outcrop is located in the northwest end of section K-K'.

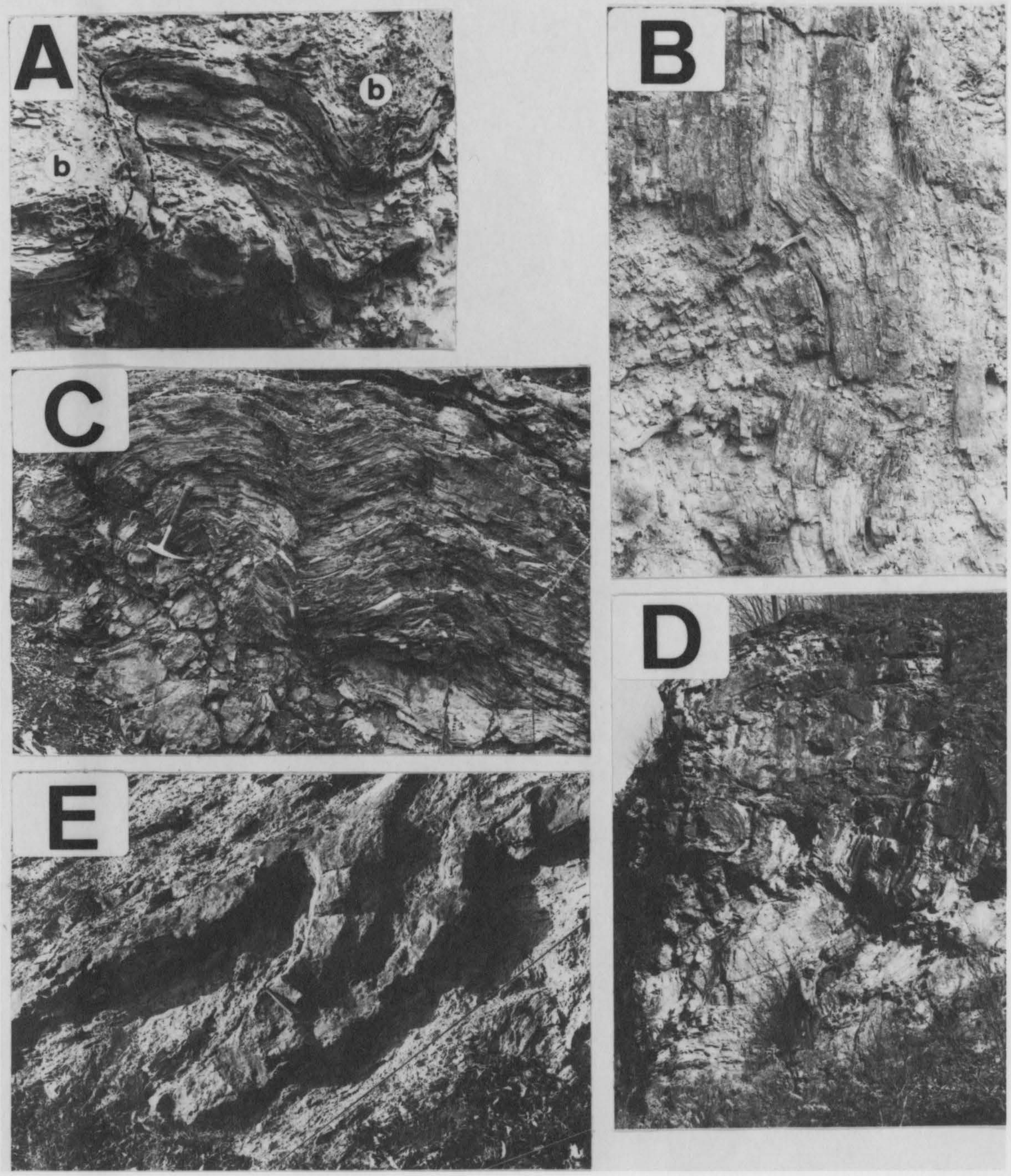
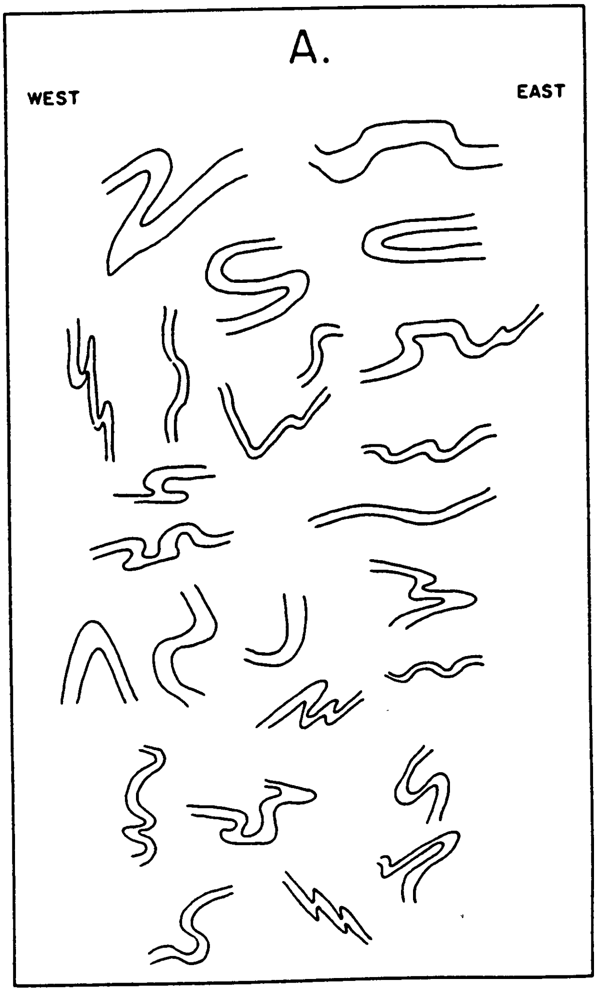

A
b
b
B
C
D
E

Figure 17. Typical mesoscopic folds of the Pulaski thrust sheet. Folds range in size from about 10 cm to approximately 10 m.

A. Profiles of selected mesoscopic folds in the broken-formations of Pulaski thrust sheet (Elbrook Formation).

B. Profiles of selected mesoscopic folds in the fold-and-thrust division of the Pulaski thrust sheet (Elbrook and Conococheague Formations).


A.
WEST
EAST

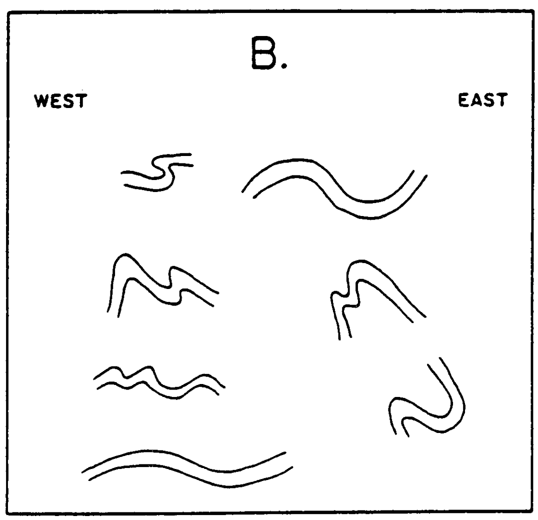

B.
WEST
EAST

Figure 18. Comparative Fleuty (1964) graphs of mesoscopic folds in the broken-formations (A) and fold-and-thrust division (B) of Pulaski thrust sheet and the footwall division (C) of the Saltville thrust sheet. Folds in the broken-formations (A) have a greater variability in both their axial surface dip and hinge plunge than folds in either B or C. Reclined folds, i.e., folds that plunge directly down the dip of their axial surface, are common in the broken-formations.

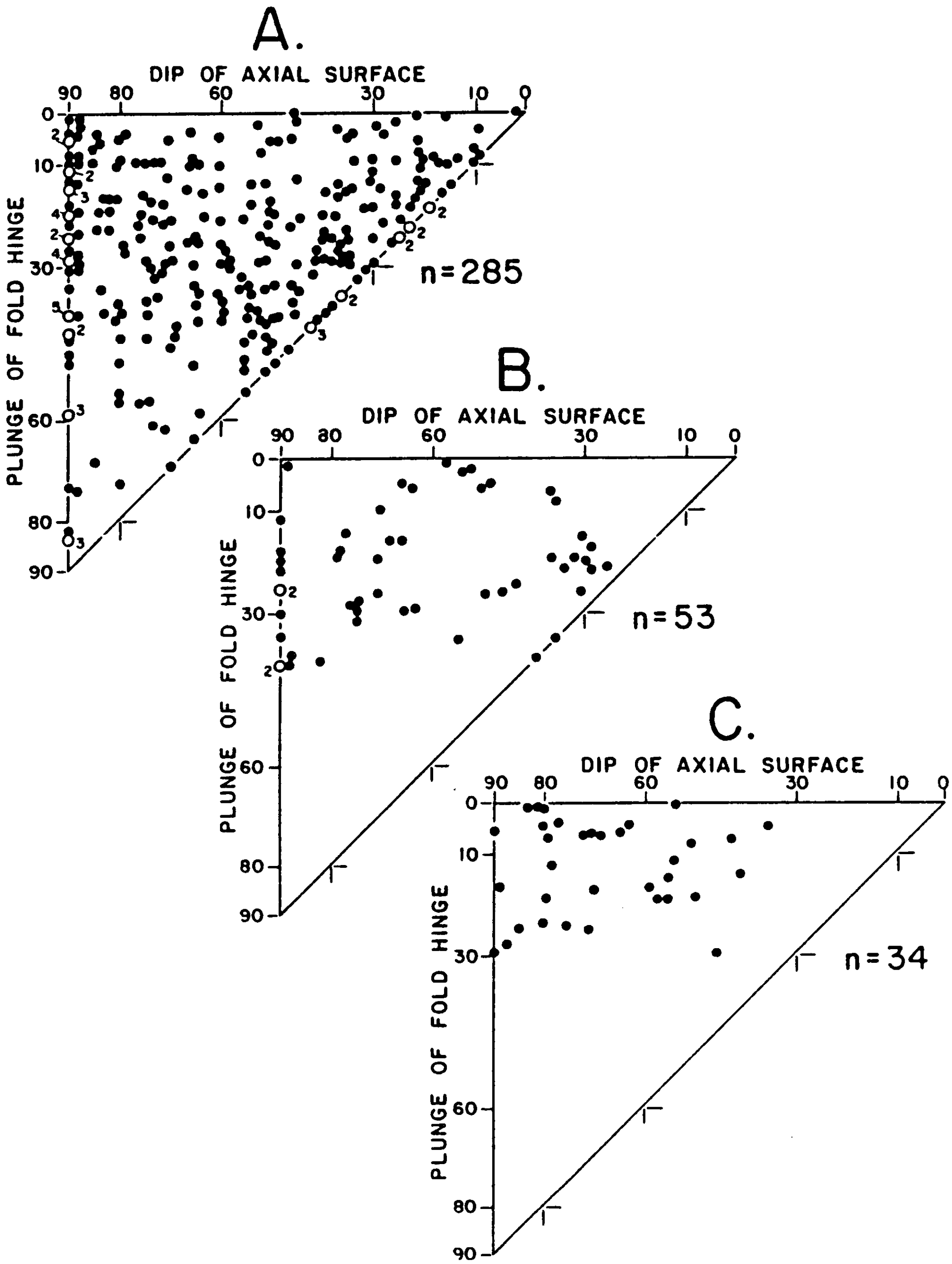

A.
DIP OF AXIAL SURFACE
PLUNGE OF FOLD HINGE
n=285
B.
DIP OF AXIAL SURFACE
PLUNGE OF FOLD HINGE
n=53
C.
DIP OF AXIAL SURFACE
PLUNGE OF FOLD HINGE
n=34

Figure 19. A. Faulted mesoscopic fold in thin-bedded argillaceous dolomite of the Elbrook Formation in the broken-formations. Gouge-filled faults (wavy lines) bound the fold both above and below and modify the fold hinge. Fold is in outcrop section O-O'.

B. Faulted (heavy lines) and brecciated recumbent folds in thin-bedded dolomite and calcareous phyllite of the Rome Formation in the broken-formations in a road cut on Virginia Route 624, 0.5 mile north-west of U.S. Route 460 bypass, Montgomery County, Virginia (b, breccia).

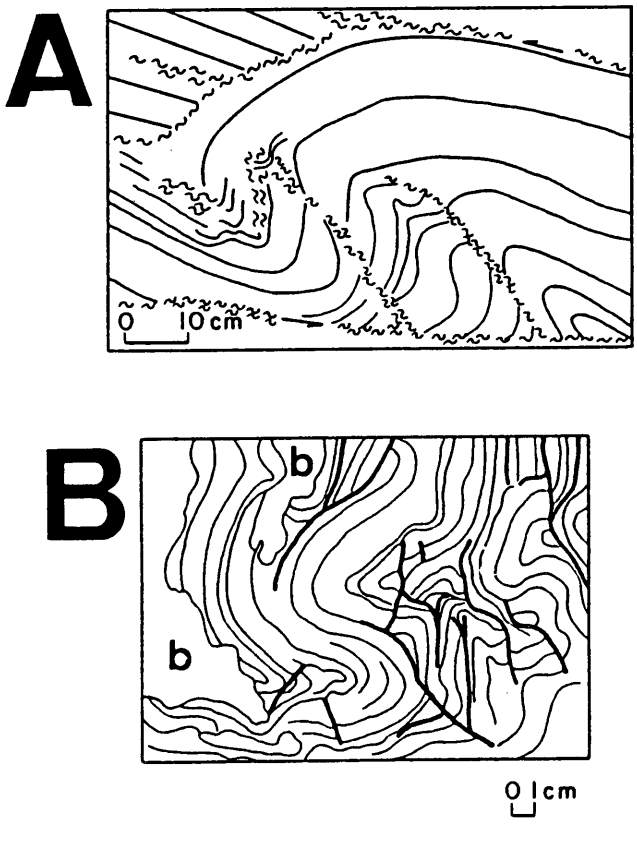
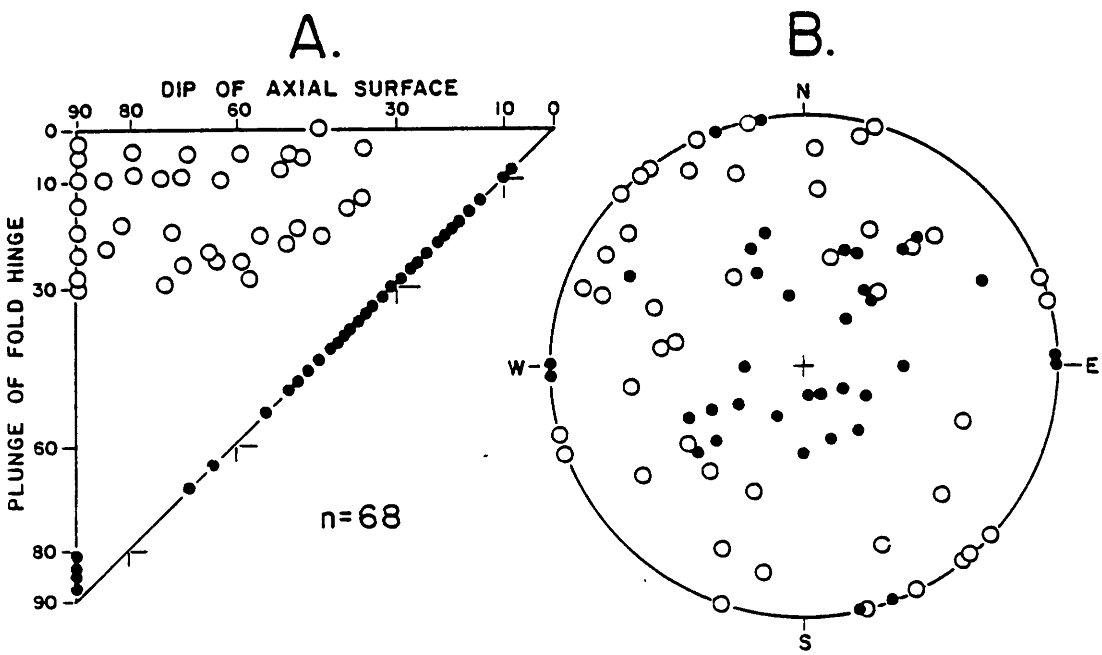

A
0 10 cm
B
b
b
0 1 cm

Figure 20. Fleuty plot (A) of selected mesoscopic folds in the broken-formations and the corresponding poles to axial surfaces (B) of the same folds. Open and closed circles are the same folds in both A and B. No consistent relationship is apparent between fold "style" (in A) and fold orientation (in B).


A.
DIP OF AXIAL SURFACE
90
80
60
30
10
0
PLUNGE OF FOLD HINGE
0
10
30
60
80
90
n=68
B.
N
W
E
S

ROCKS ABOVE THE BROKEN-FORMATIONS

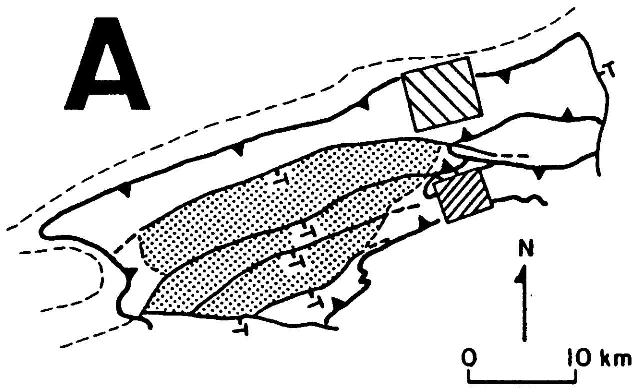
The fold-and-thrust division of the Pulaski sheet occurs above the broken-formations and ranges up to 800 meters thick. The boundary between the fold-and-thrust division and the broken-formations is either a fault (Figs. 6, 7) or a thin transitional zone (Fig. 10, G-G'). Structures more characteristic of the broken-formations occur with greater frequency in this transitional zone. Max Meadows breccia and stratal disruption are not characteristic of the fold-and-thrust division, although thin (0.5 meter) zones of breccia are found along some bedding-plane faults.

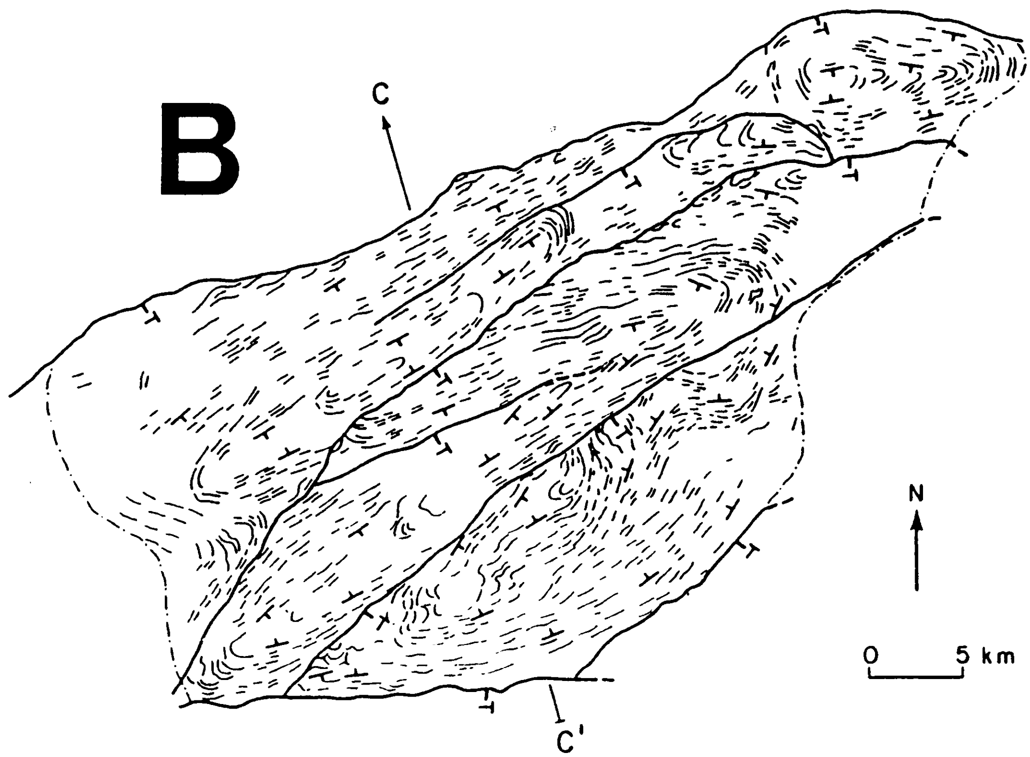
In the study area, the fold-and-thrust division is regionally synclinal (Figs. 3, 6, 7 and 21) and consists of four relatively large fault-modified synclines and several smaller structures. The majority of the faults in the fold-and-thrust division were inferred from the trend surface map (Fig. 21) because surface exposures of the faults are rare except along New River (Fig. 10, F-F'). The first-order folds (Fig. 21) are ten orders of magnitude greater than the first-order folds of the broken-formations and are consistently NE-SW trending (Fig. 14B). Regional-scale faults die out in the cores of these folds or truncate a major portion of the fold limb (Fig. 21). These southeast-dipping thrusts have juxtaposed the regional-scale synclines, truncating the intervening anticlines (Figs. 6, 21).

Across the entire fold-and-thrust division mesoscopic deformation is limited and the majority of mesoscopic folds, faults and cleavage are localized in three or four zones in shaly dolomites less than 30

Figure 21. A. Index map for Figure 21B (stipple pattern) and for trend maps, Figure 13A (top ruled rectangle) and Figure 13B (bottom ruled rectangle).

B. Surface structural trend map of the fold-and-thrust division of the Pulaski thrust sheet. Heavy lines are thrust faults, lighter lines are bedding traces, heavy strike and dip symbol shows general bedding trends and dip direction, dash-dot line is approximate boundary of this structural division. The trends show four, fault-modified synclines. Cross section C-C' (Figure 6) shows the overall synclinal nature of the fold-and-thrust division.


A
N
0
10 km


B
C
C'
N
0
5 km

meters thick. These zones (Fig. 12, Q-Q', R-R' and Plate 4B-D) occur in the lower 200 meters of the division, and structurally above them only regional-scale folding is present in the Pulaski sheet. Bedding (Fig. 15B) and mesoscopic folds (Fig. 15B) in the fold-and-thrust division are consistent in trends and have a high degree of preferred orientation (Fig. 16B) in sharp contrast to rocks of the underlying broken-formations.

Bedding-plane decollements and low angle shear thrusts dominate in the lowest parts of the division, and smaller scale faults are found in the thin deformation zones between the larger faults (Fig. 12, Q-Q', R-R'). In these thin deformed zones incompetent rocks have undergone folding, cleavage development, faulting and minor brecciation. In places (Fig. 12, Q-Q') an upper boundary decollement separates all mesoscopic deformation from rocks of the structurally higher parts of the Pulaski sheet.

Within the zones of mesoscopic deformation, folds (Fig. 17B and Plate 4B-D) have rounded to angular hinges, straight to gently folded axes and axial surfaces, and locally are disharmonic and of conjugate form (Fig. 12, Q-Q' and Plate 4E). The majority of mesoscopic folds are open to tight (Table 1) and upright to moderately inclined (Fig. 18).

A spaced, stylolitic cleavage is well developed in rocks within the zones of mesoscopic deformation (Plate 4B,C,E). Cleavage is exceptionally well developed in the shaly, thin-bedded to thinly laminated dolomites in the axial portions of folds (Plate 4B,C,E). Cleavage trends (Fig. 15B) are consistent with trends of bedding and folds.

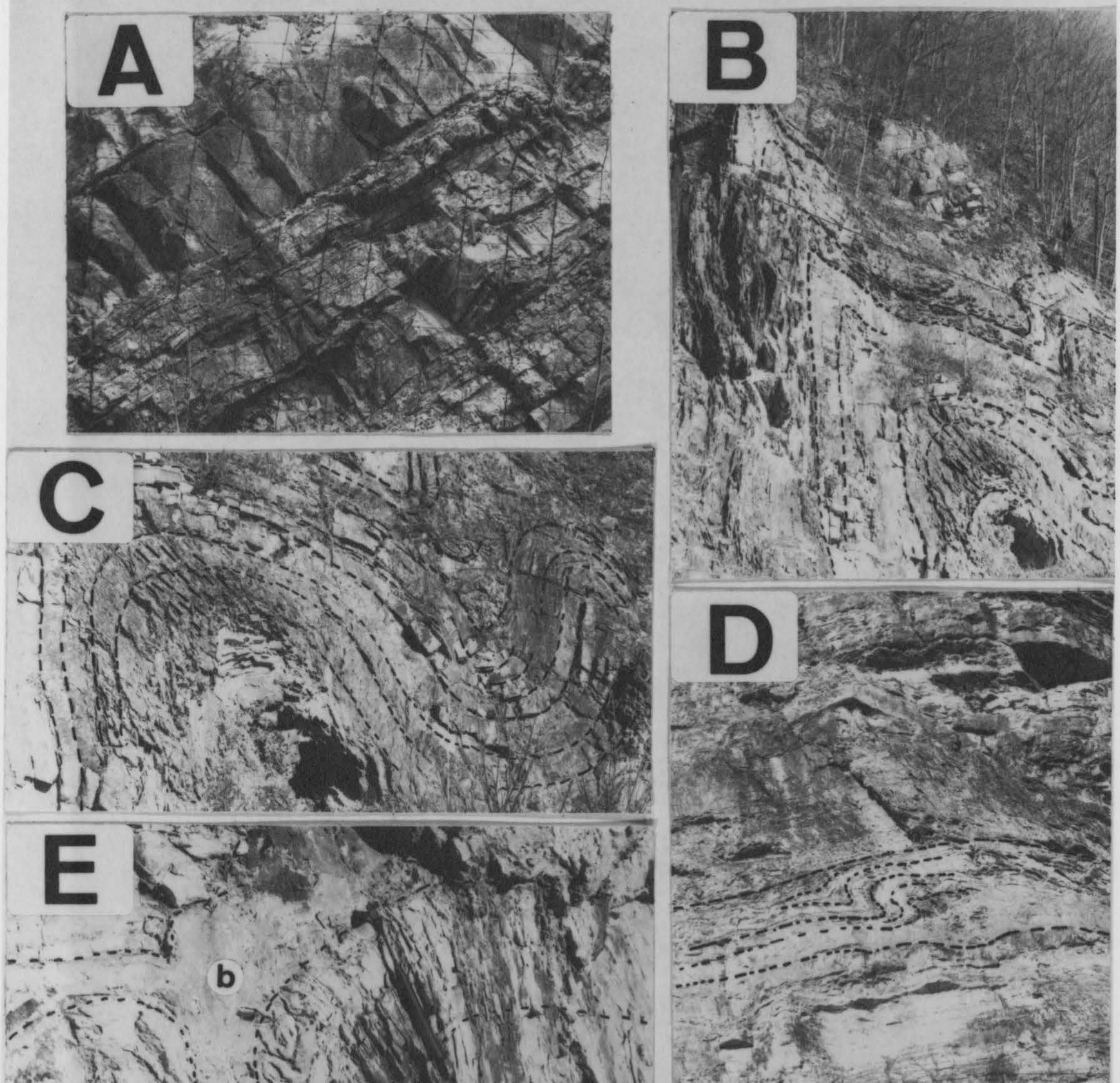
Plate 4. A. Typical outcrop of relatively undeformed dolomite, limy dolomite and limestone of middle part of Elbrook Formation in lower part of fold-and-thrust division. These northwest dipping beds are on southeast limb of a large syncline seen in section G-G'. Hammer is in center-right of photograph.

B. Disharmonic, northwest facing mesoscopic folds in the fold-and-thrust division. Cleavage is well developed in the axial portion of the fold (just above cave) in shaly dolomite. These folds (R-R' and on G-G') have been rotated by large-scale folding so that they have the "wrong" sense of asymmetry for their position on the large-scale fold limb. Cave is two meters high.

C. Detail of anticline-syncline pair and cleavage seen in B.

D. Isolated mesoscopic fold in dolomites and limestones in upper part of Elbrook Formation in the fold-and-thrust division. Fold is bounded above and below by bedding-parallel decollements and is northwest facing on a northwest dipping limb of a large-scale fold (on section G-G' between location of Q-Q' and R-R'). Rod in lower right corner is three meters long.

E. Detail of mesoscopic box fold with well developed axial plane cleavage (parallel to handle of hammer). Thin breccia zone (b) fills the tight fold core. Outcrop is in section Q-Q'.


A
B
C
D
E
b

FOOTWALL DEFORMATION

Macroscopic folds in Mississippian rocks of the Saltville thrust sheet in the study area (Figs. 1, 3) include the anticlines and synclines along the western edge of the Pulaski thrust sheet, the Price Mountain anticline exposed in the Price Mountain window, and the northwest limb of the Dublin synclinorium (southeast limb of the Poplar Hill anticline) (Lowry, 1979). These folds are similar in size, style and orientation (Figs. 1, 3, 14B and Table 1) to those folds of the fold-and-thrust division of the Pulaski thrust sheet. Bedding trends (Fig. 15C) of all Mississippian rocks in the study area have a high degree of preferred orientation (Fig. 16A).

Mesoscopic folds in overridden Mississippian strata related to the emplacement of the Pulaski thrust sheet are rare in this structural division and are localized in shales and siltstones near the thrust contact, along the leading edge of the Pulaski thrust sheet and in the Price Mountain window. These mesoscopic folds have rounded hinges and straight to very gently warped axial surfaces and axes. Fold hinges are sub-horizontal to gently plunging and axial surfaces are upright to moderately inclined (Fig. 18C). Interlimb angles range from 50 to 150 degrees (Table 1). Trends of mesoscopic folds (Fig. 15C) have a high degree of preferred orientation (Fig. 16B,C). Axial plane cleavage (Bartholomew and Lowry, 1979) is found in most of these folds and is oriented similar to bedding (Fig. 15C).

Other mesoscopic deformation is associated with thrust faults which occur in coal beds of the Price Formation and locally offset the Pulaski thrust and overturn bedding (Schultz, 1979A, 1979B). The deformation includes folding and contractional and extensional faulting (Schultz, 1979A, 1979B).

Cambrian through Devonian age rocks of the Saltville thrust sheet exposed along the western edge of the Price Mountain window and in the East Radford and Ingles-Barringer and Christiansburg windows (Figs. 1, 3) consist of folded and faulted, stratigraphically attenuated and inverted tectonic slices (Schultz, 1979B). The slices were derived from folded and faulted rocks on the southeast limb of the Dublin synclinorium (Christiansburg anticline) (Lowry, 1979). Deformation of this southeasterly portion of the Saltville block predates emplacement of Cambrian rocks of the Pulaski thrust sheet against them. Although deformation of rocks in the southeasterly windows is complex (Schultz, 1979A, 1979B), structural trends (Schultz, in preparation) are similar to those of Mississippian rocks described above.

DISCUSSION

The foregoing comparative structural analyses contrast the style of deformation of the Pulaski broken-formations and the rocks structurally above and below. Post-Middle Mississippian macro- and mesoscopic structures in the footwall block of the Pulaski sheet have similar styles and trends and share the same high degree of preferred orientation as Middle Cambrian rocks in the upper part (fold-and-thrust division) of the Pulaski sheet. These structures have traditionally been associated with the Alleghanian orogeny and are related in a straightforward way to the direction of regional tectonic transport, i.e., northwest-directed shortening.

In sharp contrast, the orientations and styles of structures in the broken-formations of the Pulaski sheet are not related in a similar simple way to "Alleghanian" stresses and must reflect some unique set of conditions occurring in this zone during Pulaski thrust emplacement.

Important interdependent factors which may bear on the genesis of the broken-formations are (1) the physical conditions current with thrust emplacement including sliding mechanisms and the role of fluid pressures, (2) the unique lithologic characteristics of rocks in the broken-formations, and (3) the possible variation in stress because of the proximity to the sole fault.

A dominant deformation process in and near the Pulaski thrust surface and in the broken-formations above this surface was cataclasis (Cooper and Haff, 1940; Cooper, 1970; Schultz, 1979A, 1979B). Max Meadows breccias and other cataclastic rocks were generated by pervasive fracturing and subsequent frictional wear along the fault surface and along numerous faults in the broken-formations during the major thrusting episode. Sliding on pervasively sheared cataclasites and breccias facilitated sheet emplacement. In those areas where breccias and cataclasites are absent, slip was along a dolomite to shale contact with sliding of upper plate dolomites on lower plate shales and/or on thin clay gouges derived from the shales. Because exposures of the thrust contact are rare, the relative amount of slip by cataclastic flow or by shale sliding can not be estimated; however, the presence of abundant breccia and other cataclastic rocks suggests emplacement of the Pulaski sheet in a regime dominated by brittle deformation. Cataclastic fault rocks form under elastico-frictional conditions (Sibson, 1977) in which temperatures and pressures range from lowest greenschist to sub-greenschist facies. Phyllite clasts in the tectonic breccias of the Pulaski sheet indicate that breccia probably formed after regional greenschist metamorphism.

The role of elevated fluid pressures in reducing effective normal stresses along a fault surface to facilitate thrust movement has been extensively reviewed (Gretner, 1969). Several features in the lower portions of the Pulaski thrust sheet suggest that elevated fluid pressures were present sometime during thrust emplacement. The abundance of carbonate-filled fractures along the thrust surface and in the broken-formations attest to hydro-fracturing as an important mechanism associated with Pulaski thrusting. Veining is most intense in rocks in contact with breccia and clasts in breccia contain veins but veins are absent in well-indurated breccia matrix, thus hydro-fracturing is probably an integral part of breccia genesis and may be the initial stage of breccia formation (Cooper and Haff, 1940; Cooper, 1970). Hydro-fracturing occurs when fluid pressures are greater than lithostatic load (Sibson, 1981); thus elevated fluid pressures may have been present during the early phases of thrusting, perhaps reducing effective normal stresses and aiding in initial detachment.

The presence of the numerous syntectonic veins suggests active solution-transfer in the lowest parts of the Pulaski thrust during deformation. The conspicuous lack of similar veins above the broken-formations indicates confinement of fluids to rocks in the lowest parts of the sheet. Confinement of these fluids may have been by the relatively thick intervals of argillaceous dolomites and shales of the lower part of the Elbrook Formation and the upper part of the Rome Formation in the broken-formations.

Dikes of fault gouge and breccia occur on the Heart Mountain thrust (Pierce, 1979) and on the Muddy Mountain thrust (Brock and Engelder, 1977). However, their presence has not been used to substantiate high fluid pressures that would have facilitated thrust emplacement. Dikes of breccia into the upper plate of the Heart Mountain sheet have been attributed to post-emplacement loading (Pierce, 1979), and those occurring along the base of the Muddy Mountain thrust are thought to have formed from passive flowage into pre-existing cracks (Brock and Engelder, 1977).

The breccia dikes of the Pulaski sheet are much larger than those of the Heart Mountain or Muddy Mountain sheets (tens of meters versus several meters). If injection was into pre-existing fractures, these fractures were greatly widened during breccia emplacement. Dragged bedding at dike margins, blocks peeled from dike walls, and slickensided and grooved wall contacts suggest forceful injection of breccia rather than passive flowage. Since dikes post-date initial breccia formation, it is probable that elevated fluid pressures persisted in the lower portions of the sheet after the major phase of hydro-fracturing occurred.

Lithology exerted an important influence on (1) sliding mechanisms during thrust emplacement, (2) the styles of macroscopic and mesoscopic folds, (3) the relative frequency and magnitude of macroscopic and mesoscopic structures, (4) the relative timing of fold development, and (5) breccia formation.

Lithologic contrasts along the sole fault controlled sliding mechanisms during emplacement, i.e., sliding on pervasively sheared cataclasites versus sliding on a sheared shale. Mesoscopic deformation of footwall-derived tectonic slices is highly variable and lithologically dependent.

In a similar way, the lithologic characteristics of the Rome, Elbrook and Conococheague Formations (Fig. 5) probably had a major influence on the vertical change in style of deformation of the Pulaski sheet.

Rocks of the broken-formations (Fig. 5) consist of approximately equal parts of thick (30-70 meters) incompetent rocks (mm-laminated to cm-bedded argillaceous dolomites and calcareous phyllites) alternating with thick (50-100 meters) competent rocks (massive dolomites and limestones). In sharp contrast, rocks above the broken-formations, in the fold-and-thrust division (Fig. 6) consist of less than 10 percent thin (5-30 meters) incompetent intervals (shaly dolomites)and thick (100-200 meters) competent intervals (massive dolomites and limestones). In a relative sense, rocks in the lower part of the Pulaski sheet have higher viscosity and rheologic contrasts and a higher degree of anisotropy than rocks structurally higher.

Additionally, there is an increase in shale and phyllite in the lower part of the Elbrook and upper part of the Rome Formations nearer the base of the sheet. This increase reflects both thicker shale and phyllite beds and more frequent shale and phyllite partings, laminations and thin (1-3 cm) beds in dolomitic intervals. Consequently, from higher to lower levels of the thrust sheet there is not only a greater proportion of incompetent rocks but also a significant increase in the number of bedding planes, which are potential slip surfaces, and a decrease in the thickness of single beds.

Polyclinal conjugate folds (box folds) form in rocks that have well-developed layering, i.e., in thinly laminated to thin-bedded sedimentary rocks (Ramsay, 1967) and in rocks of relatively high anisotropy (Cobbold and others, 1971). These rock characteristics and the multiple detachment surfaces in rocks of the broken-formations led to the development of numerous stacked zones of mesoscopic conjugate folds. Importantly, these folds had an initial variability in their asymmetries (Fig. 22A) so that axial surfaces were at high angles to one another early in the folding sequence.

Additionally, in layered sedimentary rocks, wavelengths of folds are directly proportional to the thickness of competent units (Currie and others, 1962). Wavelengths of macroscopic folds in the upper part of the Pulaski sheet are large (kms) and mesoscopic folds are relatively rare because the competent rocks are in thick intervals and they dominate the litho-tectonic unit. The wavelengths of macroscopic folds in the broken-formations are much smaller (tens of meters) because the competent units are thinner. Mesoscopic folds are more abundant in the broken-formations because of the greater proportion of incompetent, thin-bedded lithologies which are susceptible to differential bedding-plane movement and subsequent mesoscopic folding.

With equal compressive stresses across a multilayer, the greater the competency difference, the more rapidly folds develop in the competent layers (Ramberg, 1964). The presence of more "mature" folds in the broken-formations, i.e., folds with lower wavelengths and interlimb angles and greater amplitudes, may reflect relatively more rapid cycling through folding stages because of higher rheologic contrasts. Also, elevated fluid pressures may have enhanced ductility and accelerated fold development. If this was so, folds in the broken-formations were subject to subsequent modification such as rigid body rotation and/or refolding early in the deformation cycle, and while rocks higher in the sheet were undergoing gentle folding. This is important because folds which may appear to have formed from an earlier period of deformation (poly-deformed in a metamorphic sense) may simply have undergone more rapid development during one orogenic event.

Although many rock types are present as clasts in the Max Meadows tectonic breccia, the dominant clasts were derived from laminated to thinly bedded argillaceous dolomites, phyllitic dolomites and calcareous phyllites. These rocks types were most susceptible to brecciation (Cooper, 1970) because numerous faults were localized in these weaker parts of the stratigraphic section. Also, these incompetent lithologies were more prone to rapid development of complex folding and fracturing, with subsequent brecciation, during the folding and differential movement of the more competent units.

Recent models (Wiltschko, 1979) of stresses within thrust sheets have shown that when thrust sheets move over ramps, the stresses are greatest in rocks near the base of the sheet. Also, during the sequential stages of decollement to ramp phases of thrusting, rocks in the lower portion of the thrust sheet experience both contraction and extension (Wiltschko, 1979).

Because rocks in the broken-formations, along the base of the Pulaski sheet, have been cycled through decollement and ramp stages of thrusting, it is possible that they experienced relatively greater stress and both contractional and extensional stresses during sheet emplacement. In this way, faults which formed during one stage of thrusting may have been folded or cut by faults in very different orientations and/or with different senses of movement during slightly later stages of movement. The combination of greater stresses and variable stress types, may have been important in the development of the characteristic style of deformation in the broken-formations.

SYNTHESIS AND MODEL FOR GENERATING BROKEN-FORMATIONS

In the study area, macroscopic and mesoscopic folding and faulting were dominant deformational processes in footwall and hanging wall rocks away from the Pulaski thrust surface. Both macro- and mesoscopic fold-fault relationships are complex because of superposition of repeated episodes of folding and faulting of different scales throughout the orogenic cycle. Deformation of both the Pulaski and Saltville sheets can be placed within a relative time sequence (Fig. 22A,B) using cross-cutting and overprinting relations inferred from the geologic map of the study area (Fig. 3) and from outcrops along New River (Figs. 10-12).

Regional scale folding and faulting of Saltville thrust sheet rocks predated initiation of Pulaski thrusting. Veining (hydro-fracturing) predated earliest mesoscopic folding and faulting in rocks of the broken-formations while formation of Max Meadows breccia slightly post-dated this earliest mesoscopic fold stage. Additionally, regional scale folding and faulting postdated emplacement of the Pulaski thrust sheet and modified all earlier structures. Modification included rotation of cleavage and axial surfaces of earliest mesoscopic folds in both the Mississippian rocks of the footwall and in Cambrian rocks of the fold-and-thrust division of the Pulaski thrust sheet so that folds are northwest facing regardless of their position on regional scale folds (Fig. 10, G-G', H-H'). Latest stage regional stresses were accommodated by thrust faulting, which modified regional folds (offset the axis of the Price Mountain anticline) and locally cut the Pulaski fault (Fig. 3).

Figure 22. Map and graph of relative timing of deformation in the study area.

1. Emplacement of Cambrian rocks of Pulaski thrust sheet against deformed Cambrian through Devonian rocks of the Saltville thrust sheet.

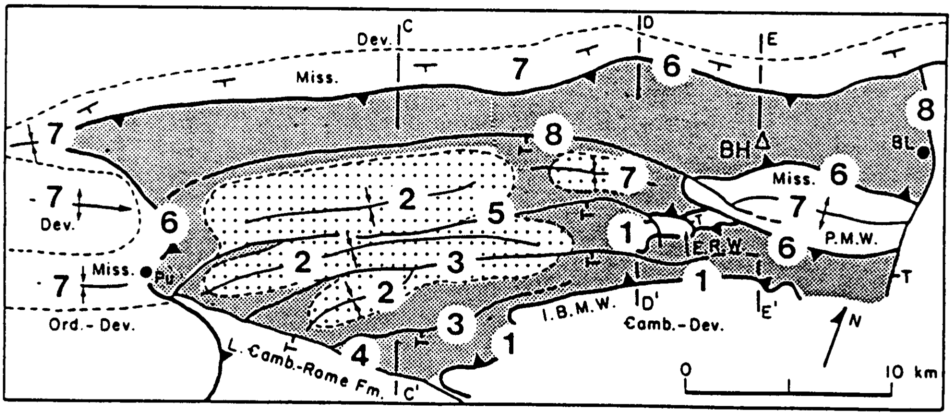
2-5. Folding and faulting of Pulaski thrust sheet prior to its final emplacement. (4 is emplacement of Max Meadows thrust sheet.)

6. Emplacement of Cambrian rock of Pulaski thrust sheet against Mississippian rocks of Saltville thrust sheet.

7. Regional-scale folding of Pulaski and Saltville thrust sheets.

8. Faulting which modifies late-stage folds (7) and offsets Pulaski fault.

White diamond is initiation of Pulaski thrusting; black diamond is final emplacement of Pulaski sheet.


Dev.
Miss.
Ord.- Dev.
Camb.-Dev.
L. Camb.-Rome Fm.
I.B.M.W.
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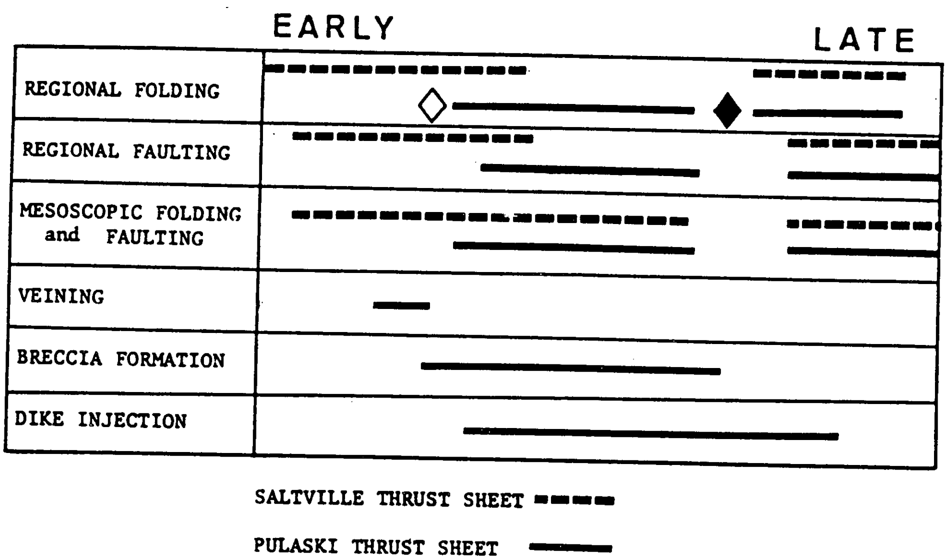

EARLY
LATE
REGIONAL FOLDING
REGIONAL FAULTING
MESOSCOPIC FOLDING and FAULTING
VEINING
BRECCIA FORMATION
DIKE INJECTION
SALTVILLE THRUST SHEET
PULASKI THRUST SHEET

Although rocks in the study area have undergone these repeated episodes of faulting and folding, structures in the Mississippian footwall division and in the fold-and-thrust division of the Pulaski thrust sheet have a high degree of preferred orientation and they can be correlated to the direction of regional tectonic transport during Alleghanian thrusting in the southern Appalachians.

Because of lithology, possible elevated fluid pressures, and stress variability, the response of rocks in the broken-formations to deformation accompanying thrust emplacement was considerably different than that of structurally higher rocks of the Pulaski sheet. Earliest folds and faults underwent a significantly greater degree of subsequent modification. Initial fold variability and relatively more rapid development of folds and associated faults enhanced the effects of later modification processes so that locally there were many more cycles of folding and faulting during the single deformation period.

The enveloping surfaces of second- and third-order mesoscopic folds, which formed above early faults, underwent rigid body rotation during slightly later first-order faulting and/or during rotation of the enclosing rocks by subsequent faulting (Fig. 23B). During rigid body rotation, the orientations of fold axes and axial surfaces were altered but fold shapes, i.e., interlimb angles, wavelengths, amplitudes, and curvature of axial surfaces and axes, remained constant. In a like manner, faults related to the earliest folding were rotated and/or folded by slightly later stages of faulting (Fig. 23B).

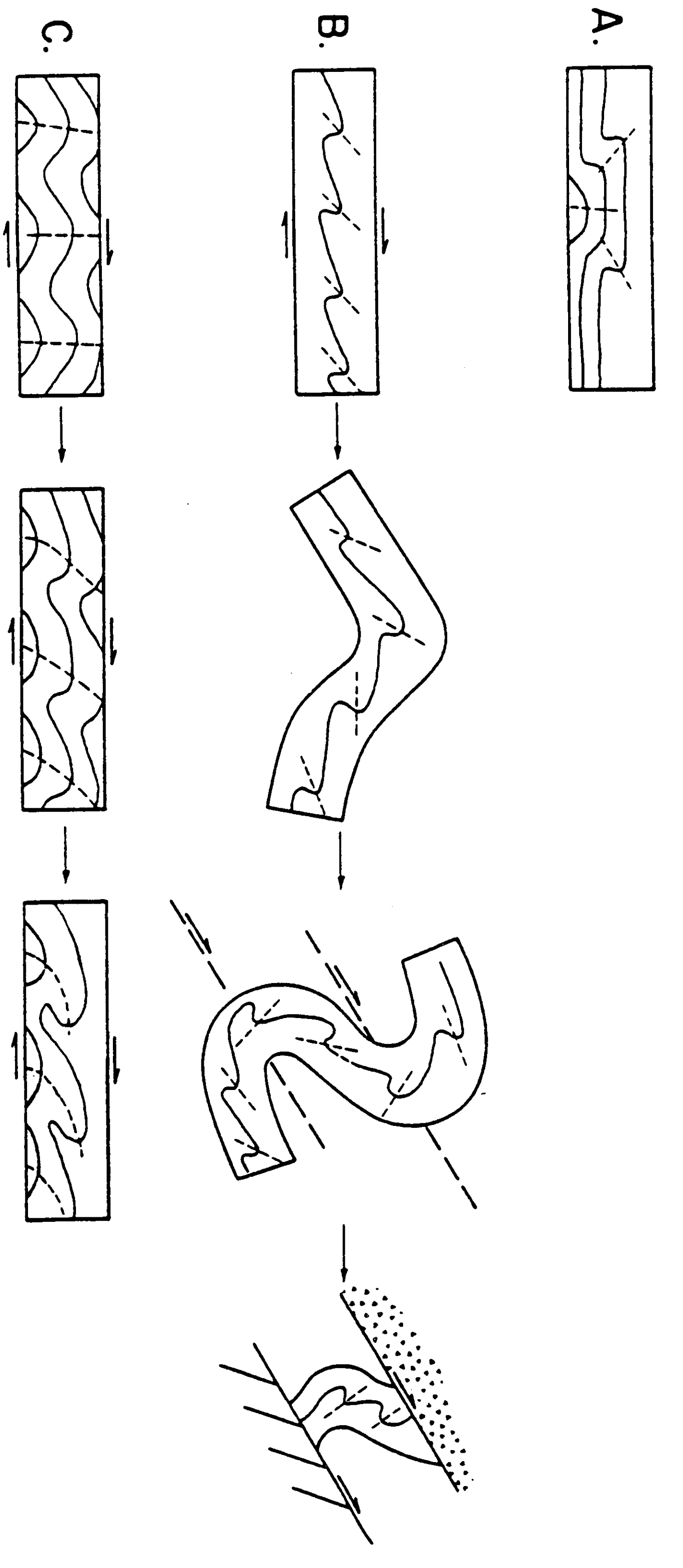
Elsewhere in the broken-formations, continuous stress modified fold shape in blocks that are bounded by sub-parallel faults

Figure 23. Models of folding and faulting in the broken-formations (axial surfaces are dashed).

A. Polyclinal box-fold formed between two decollements.

B. Superposition of repeated folding and faulting.

C. Folding of mesoscopic fold axial surfaces by continuously applied stress to a block between two decollements.


A.
B.
C.

(Fig. 23C). In this case folds underwent a complete folding cycle of initial formation, hinge tightening, hinge migration, refolding, and in some cases eventual core brecciation and limb faulting. These folds (Fig. 23C) are typically upright nearest the basal fault and recumbent nearest the upper fault boundary (Fig. 23C). The orientations of fold axes remained constant throughout the fold modification but axial surfaces underwent refolding.

The two modifying processes are end-member cases of fold-fault interaction which varied both spatially and temporally in the broken-formations throughout deformation of the entire Pulaski sheet. This variability led to a fold-and-fault population in which little consistent correlation exists between styles of structures and their orientations.

During the earliest stages of deformation, folding and faulting may have occurred only in a relatively narrow zone near the thrust surface and may have been concentrated in the very weakest layers. As rocks in these intervals became complexly folded, faulted and brecciated, continued shortening within them may have become restricted ("strain hardened," Sanderson, 1979; "developed obstructions to further movement," Harris and Milici, 1977), and the deformed zones were then temporarily or permanently abandoned for more suitable incompetent intervals. In this way, the zone of broken-formations widened above the basal fault as thrusting progressed.

Although breccias and cataclasites occur on the Saltville (Cooper, 1939; 1970; House and Gray, 1982), the Narrows (Cooper and Haff, 1940; Cooper, 1970) and St. Clair thrusts (Cooper, 1970; Olson, 1979) northwest of the present study area (Fig. 1), they are thin, and broken-formations similar to those of the Pulaski thrust sheet are noticeably absent. This may be due to (1) the abandonment of the broken-formations in the subsurface during ramp stages of thrust emplacement (Harris and Milici, 1977), (2) differences in regional tectonic setting, and (3) differences in hanging wall lithologies (Cooper, 1970).

Recognition of abandoned broken-formations in the subsurface northwest of the study area must await future drilling and exploration. Although rocks of the Pulaski sheet have undergone a higher grade of metamorphism than the Saltville, Narrows or St. Clair thrust sheets (Epstein and others, 1977), greenschist facies conditions probably predate the major phase of Pulaski thrusting and thus may not have had a significant effect on development of the broken-formations.

Exposures of thrust contacts are numerous northwest of the present study area, and comparisons of hanging wall lithologies are possible. Immediately above the thrust surface of the Saltville, Narrows and St. Clair thrusts just northwest of the study area are thick sequences of Cambro-Ordovician carbonates of high competency and very low anisotropy (unit G, Fig. 5) in contrast to rocks of the broken-formations of the Pulaski sheet (unit H, Fig. 5).

South of the study area, rocks of the Max Meadows thrust sheet are dominantly of the Rome Formation. Mesoscopic folds and faults in the Rome Formation on the Max Meadows sheet have considerable variability in styles and orientations (Bartholomew and others, 1981). The Rome Formation south of the study area consists of alternating thick zones of thinly laminated phyllitic mudstones and minor massive bedded dolomites. These rocks are of moderate anisotropy and low competency. Although further study of these rocks and the rocks above thrusts northwest of the study area is needed, it is possible that lithology is one of the most important factors responsible for the style of deformation above thrust faults in this part of the southern Appalachians (Hayes, 1891; Cooper, 1970).

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Appendix I

BRECCIA ANALYSIS

Two samples of Max Meadows breccia were collected and x-ray diffractograms were made to identify the phyllosilicates present.

Sample one was collected approximately 100 m east of the junction of the Norfolk and Southern Railway tracks and County Route 643, Yellow Sulphur Springs Road, Montgomery County, Virginia. The sample consisted of 2 kg of light green, poorly consolidated material taken from a non-layered mass of the Max Meadows breccia.

Sample two was collected from outcrops along the access loop of Interstate Route 81, south side, at the Radford, Virginia exit for Route 624. The sample consisted of poorly consolidated white to gray carbonate-clast breccia in a fine-grained dolomite matrix.

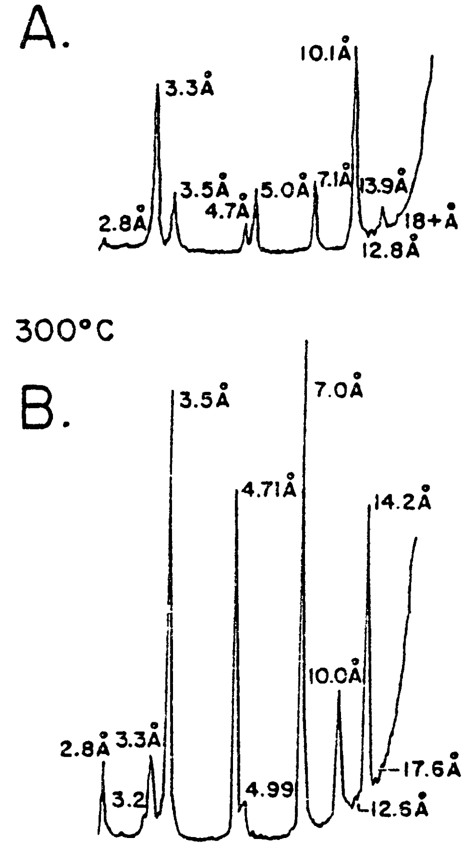
To facilitate x-ray analysis, the clay fraction was removed from cementing agents (dolomite and calcite) by repeated HCl washes; however, pH was not allowed to drop below 4 to prevent clay mineral destruction. The clay fraction was concentrated by flocculation and centrifugation.

X-ray runs were made on samples at room temperature, and following heat treatments of 110, 300 and 550°C. X-ray patterns derived form copper K-alpha radiation reflections of d spacings of the phyllosilicates present. Figure 24 summarizes the results.

Figure 24. X-ray diffractograms of Max Meadows breccia. Angstrom (Å) spacings for micas in green phyllitic breccia (A) and in white dolomite breccia (B) are shown. Percents are of total mica content.

A. Green phyllitic breccia: chlorite--3.5,4.7,7.1,13.9 Å, 30%; muscovite--3.3,5.0,10.1 Å, 60%; interstratified/intergraded mica-montmorillonite, mica-vermiculite--12.8,18+ Å, 10%.

B. White dolomite breccia: chlorite--3.5,4.71,7.0,14.2 Å, 55%; muscovite--3.3,4.99,10.0 Å, 30%; interstratified/intergraded mica-montmorillonite, mica-vermiculite--12.6,17.6 Å, 12-13%.

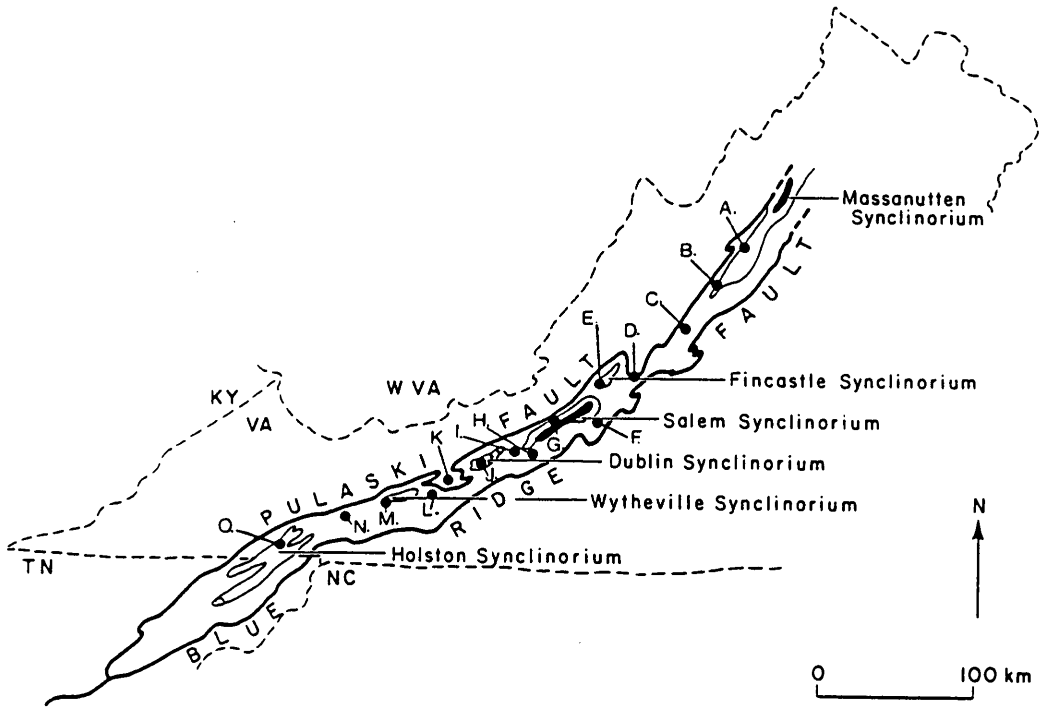

A.
10.1Å
3.3Å
3.5Å
4.7Å
5.0Å
7.1Å
13.9Å
2.8Å
18+Å
12.8Å
300°C
B.
3.5Å
7.0Å
4.71Å
14.2Å
10.0Å
2.8Å
3.3Å
3.2
4.99
17.6Å
12.6Å

Appendix II

CAMBRIAN STRATIGRAPHY OF THE PULASKI THRUST SHEET

Location of Lower to Upper Cambrian sections and their characteristics. Sections are on the Pulaski sheet unless otherwise specified. Descriptions use the original author's terminology.

Figure 25. Location map of Lower to Upper Cambrian sections of the Pulaski thrust sheet.


Massanutten Synclinorium
A.
B.
C.
D.
E.
F.
G.
H.
I.
J.
K.
L.
M.
N.
O.
Fincastle Synclinorium
Salem Synclinorium
Dublin Synclinorium
Wytheville Synclinorium
Holston Synclinorium
PULASKI FAULT
BLUE RIDGE FAULT
KY
VA
W VA
TN
NC
N
0
100 km

Location	Formation	Thickness (feet)	Characteristics
A. Gathright and others (1977)	Conococheague	1600-3000	ss. 1-10 feet, discontinuous, algal ls., flat pebble cgs., ls/sandy partings, linear topography
	Elbrook	2800-3000	massive and laminated dol., algal ls., shaly dol., phyllite at base
	Rome	1100	maroon and green phyllite and sh., minor ls., dol., and ss.
B. Rader (1967)	Conococheague	2200-2500	ss. 0-10 feet, discontinuous, linear topog., flat pebble cgs., sandy dol., black oolitic cherts
	Elbrook	2000+	shaly dol., algal ls., massive dol.
	Rome	1000+	red and green sh., olive dol., slst.
C. Bick (1960)	Conococheague	2000	dol. in west*, ls. in east*, blue ls./sandy laminations
	Elbrook	2300	dol., minor ls., shaly dol.
	Rome	1500-2000	red-green sh., ls. dol.
D. Spencer (1968)	Conococheague	2000	ss. 10-20 feet, discontinuous, flat pebble cgs., ls./sandy laminations, oolitic ls.
	Elbrook	1000-2000	shaly dol., green phyllitic sh. near base
	Rome	1000-1500	maroon and green sh., massive ls.
E. McGuire (1970)	Conococheague-Copper Ridge	800-1100	*east facies--ls., crinkled laminations, oolitic cherts, flat pebble cgs.; *west facies--sandy dol., 4" ss. stringers, dol.
	Elbrook	1200-2500	gray-green sh., shaly dol., algal ls., ss. stringers
	Rome	300-2000	maroon and green sh., minor dol., and ls.
F. Bartholomew (1981)	Conococheague	700	*upper--algal ls., siliceous oolite, qtz. ss.; *lower dol., sandy dol., thin ss., discontinuous lenses
	Elbrook	--	dol., algal ls., shaly dol.
	Rome	--	gray-green and maroon phyllitic mdst.
G. Aronson (1966); Tillman	Copper Ridge	1000+	*Salem Syncl.-upper--ribbon ls., oolitic chert, ss. dol., ss. 1-5 feet. *Conococheague-like facies as tongues, ribbon ls., flat pebble cgs., silty ls., algal ls.
	Elbrook	1000+	dolomitic sh., shaly dol., algal ls.
H. Broughton (1971)	Copper Ridge	1000+	*Christ. window, Saltville sheet--ss. 1-30 feet, dol. oolitic chert, crinkled silty laminations *Conococheague facies in middle--edgewise cgs., ribbon ls., oolitic ls.
	Elbrook	1000+	shaly dol. and ls., green sh. at base
	Rome	2000	tan, red, green sh., silty dol.

I. Bartholomew and Lowry (1979)	Copper Ridge	1200	*Salem syncl.--ss. 10-20 feet, discontinuous, sandy dol., siliceous oolite, massive dol.
	Elbrook	1500	ss. 1-10 cm, dol., green-gray phyllites, ribbon ls.
	Rome	--	*Pulaski sheet--maroon and green phyllitic mdst., dol., ss.
J. Butts (1933, 1940); Hergenroder (1958); Schultz (this study)	Conococheague	1400-1800	ribbon l s., flat pebble cgs., ss. 2-8 in. (6 feet by Hergenroder) discontinuous ss., linear topog.
	Elbrook	1500-1800	shaly dol., green dol. shales, phyllites at base, massive dol., algal ls.
	Rome	1500-2000	green and maroon phyllitic mdst., massive dol.
K. Cooper (1939)	Conococheague	1500-1800	*Draper Mtn.--ss. 1-25 feet, flat pebble cg
	Elbrook	1800	Pulaski sheet--shaly dol., dolomitic ls., ls.
	Rome	2000	green and red sh., massive dol.
L. Marshall (1959)	Conococheague	1200+	Pulaski sheet?--ss. stringers and thin lenses, linear topog., edgewise cgs., oolitic ls., black chert, ls.
	Elbrook	1800+	dol. and ls., shaly dol.
	Rome	2000	red, green and yellow sh., dol. and ls.
M. Cashion (1968)	Conococheague	2000	ss. lenses to 12", sandy dol. and ls., ribbon ls.
	Elbrook	2000	thin shaly dol./ls.
N. French (1967)	Conococheague	1500-1800	ss. minor up to 12", 50% ribbon ls., dol.
	Elbrook	2000	shaly dol., massive dol., ls., oolites and flat pebble cgs. in upper part
O. Tyler (1960); Bartlett and Biggs (1980)	Conococheague	1600+	ss. 0-3 feet, lenticular and discontinuous, ribbon ls.
	Elbrook	2000	shaly dol. and ls., dol.
	Rome	1000-1400	maroon and green micaceous sh.

Appendix III

DEGREE OF PREFERRED ORIENTATION

Following Hopwood (1968) the total area enclosed by successive contours was planimetrically determined. The radii (r) of each area was calculated using area = πr^2, and plots of the radii against the percent of the contour were made for each structural element (Fig. 16).

R, the coefficient of preferred orientation (Hopwood, 1968), was calculated using $R = \frac{\theta \cos \theta}{r}$ where r is the radii of the area of greatest concentration and θ is the angle of the plotted line and the abscissa of the graph (Fig. 16). θ was derived statistically by applying a linear regression analysis to the data to find a best fit line. The y intercept of the line was determined from

$$y = \frac{\Sigma y \Sigma x^2 - \Sigma x \Sigma xy}{n \Sigma x^2 - (\Sigma x)^2}$$

and the slope was derived from

$$sl = \frac{n \Sigma xy}{n \Sigma x^2} - \frac{\Sigma x \Sigma y}{(\Sigma x)^2} .$$

In the analysis (Table 2), the greater the degree of preferred orientation, the greater the slope, the higher the value of the y-intercept and the larger the angle θ. Results (Table 2) agree well with the calculated area of zero concentration (no data points) which will be higher if more points occur in a smaller area of the net.

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BROKEN-FORMATIONS OF THE

PULASKI THRUST SHEET

NEAR PULASKI, VIRGINIA

by

Arthur Philip Schultz

(ABSTRACT)

Broken-formations (Hsu, 1974; Harris and Milici, 1977) occur in the lower part of the Pulaski thrust sheet and contain some of the most strongly deformed sedimentary rocks in the Valley and Ridge province of the southern Appalachians. Deformation in this zone ranges from grain-scale cataclasis to regional-scale faulting. The broken-formations are distinguished from rocks structurally higher on the sheet and from rocks of the underlying Saltville sheet by (1) a sharp increase in the variability of fold and fault styles, (2) greater ranges in fold plunges and dips of axial surfaces, (3) a low degree of preferred orientation of folds and faults, (4) an increase in the frequency of mesoscopic structures, and (5) the presence of Max Meadows tectonic breccia. Structural analyses indicate that deformation in the broken-formations is Alleghanian in age and that the deformed zone formed under elastico-frictional conditions, possibly under elevated fluid pressures with temporally variant stresses and that lithology may have played an important role in localizing the broken-formations along the base of the Pulaski sheet.