Structural Analysis of the Valley and Ridge Extension of the Parsons Lineament

by

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STRUCTURAL ANALYSIS
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(ABSTRACT)

The Parsons Lineament (a major Appalachian Cross-strike Structural Discontinuity, CSD) extends from the Plateau of West Virginia into the Valley and Ridge Province in northern Rockingham County, Virginia. Regional and second-order folds change in strike from typical Central Appalachian trends (N30-35°E) to near due north within the CSD, regional anticlines plunge out, and major thrusts terminate within this zone. In the Rockingham County portion of the Broadtop Synclinorium, the CSD is marked by an increase in intensity (ratio of surface area to volume) of systematic joints and second-order, sinistral strike-slip faults. Two sets of regional joints occur : J_1, a pervasive east-west-trending, near vertical joint set, and J_2 which varies with structural position. Peaks in J_1 intensity coincide with known strike-slip faults and pronounced photolineaments. J_2 is associated with closure on the Bergton anticline. Drilled depths to the Oriskany horizon, age relations and intensity of systematic joints suggest deformation associated with a northeast-facing lateral ramp is responsible for both the Parsons lineament and closure on the Bergton natural gas field.

Within the North Mountain thrust sheet, the Parsons CSD consists of a linear zone of anomalously-trending, second-order folds and shears near the nose of the Linville anticline. Blind thrusts responsible for second-order folding are exposed in a quarry face and strain values (from pressure fringes adjacent to pyrite framboids in Martinsburg shales) suggest that the second-order folds adjacent to the Linville anticline are the result of movement on the Saumsville fault in the subsurface. Age relations of S_1 and S_2 cleavages and V_2 calcite veins indicate an east-to-west order of thrusting for the Pulaski-Staunton and Saumsville faults. The linear disturbed zone results from displacement transfer at the termination of the Saumsville fault and, together with the structural anomalies in the Broadtop Synclinorium, constitutes the Valley and Ridge extension of the Parsons CSD.

ACKNOWLEDGEMENTS

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I am forever in debt to my parents for their financial and emotional support throughout my education.

In addition, thanks go to Adam, George, Rik, and Todd of my favorite band, , for keeping me on the guest list.

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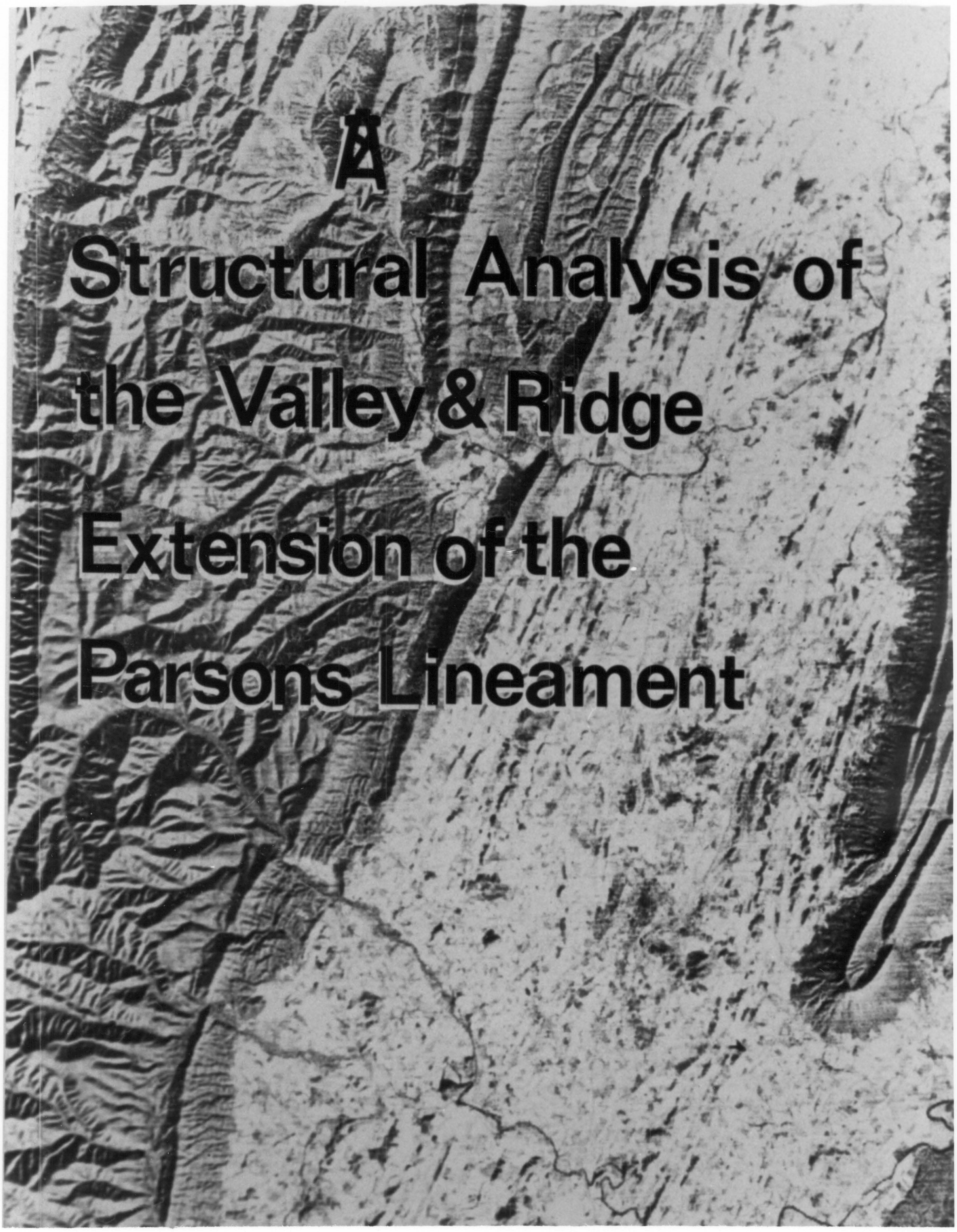
A
Structural Analysis of
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Parsons Lineament

GENERAL INTRODUCTION

A salient structural feature of the Central Appalachians is the Cross-strike Structural Discontinuity (CSD) of Wheeler (1978,1980). Originally recognized by Gwinn (1964), a CSD is a linear disruption of regional, strike-parallel structural trends typified by tear faults, abrupt changes in strike and dip, fold terminations, and an increase in the intensity of systematic jointing (Wilson, 1980). While all CSDs appear to be photolineaments, all photolineaments are not necessarily CSDs (Wise,1982). This study examines the CSD responsible for the Parsons Lineament in order to characterize the deformation and delineate the deformational sequence which resulted in the Valley and Ridge extension of this lineament.

CSDs are regional zones of increased fracturing (Wheeler,1980); the underlying structure which forms the lineament both influences thrust mechanics and is responsible for closure on the Bergton natural gas field. Fracturing associated with this CSD links porous horizons in the Oriskany sandstone and increases its permeability.

Regional analysis of penetrative strain in the North Mountain thrust sheet and non-penetrative strain (fracture intensity) in the Broadtop Synclinorium were used in this study. Each structural province is treated separately in individual papers.

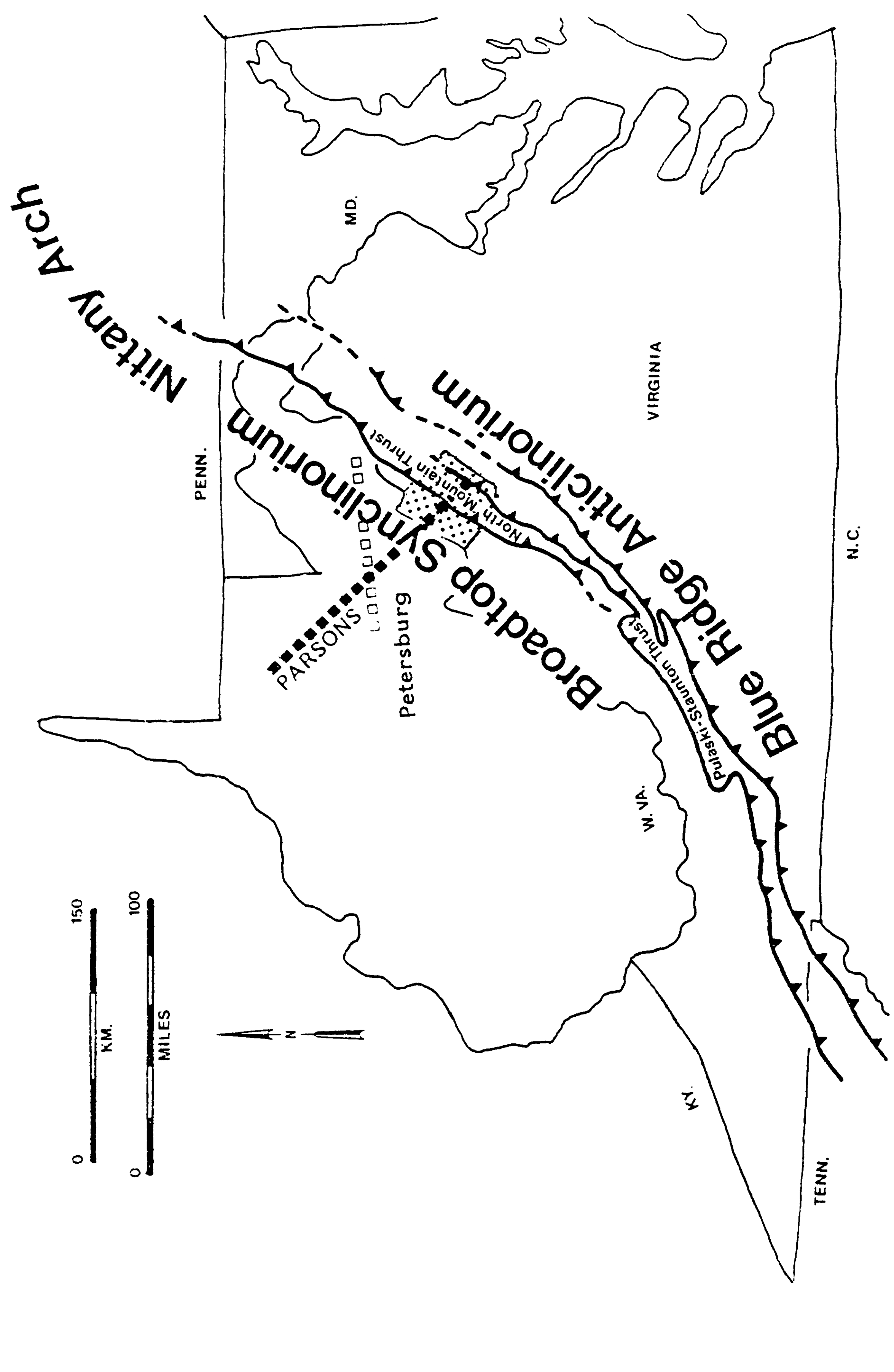
REGIONAL GEOLOGIC SETTING

Northern Rockingham County, Virginia, is in the Central Appalachians approximately equidistant from the Central-Southern juncture and the Nittany Arch (Fig.1). The Central Appalachian structural style consists of expansive synclinoria with subordinate intervening anticlines (Butts,1933,1940). These anticlines are produced by movement along thrusts which do not reach the surface (blind thrusts) but have the same listric, stair-like geometries envisioned by Rich (1934) for the Southern Appalachians (Gwinn,1964; Harris and Milici,1977; Perry,1978; Harris,1979; Harris et. al.,1982).

The Pulaski-Staunton thrust and the North Mountain thrust are the two principal overthrusts in the region of this study; both are among the most persistent structural features within the Appalachian Orogen (Fig.1). The Pulaski-Staunton thrust, which terminates in Rockingham County (Brent,1960) and separates the Massanutten Synclinorium from the North Mountain sheet, forms the southeastern border of the study.

The Pulaski-Staunton thrust has a minimum displacement of approximately 6.5 kilometers (4 miles) and a maximum stratigraphic throw of 1350 meters (4000 feet) in Rockingham County. The North Mountain thrust has a maximum stratigraphic throw of 5500 meters (16,500 feet) (Brent,1960) but the horizontal displacement is unknown. Mitra (1982) described the footwall of this thrust as the North Mountain ramp with the displacement less than 20 kilometers (12 miles).

Fig. 1. Regional location map showing locations of major thrusts, geologic provinces, and the Petersburg and Parsons Lineaments.


Nittany Arch
PENN.
MD.
VIRGINIA
Broadtop Synclinorium
Blue Ridge Anticlinorium
North Mountain Thrust
Pulaski-Staunton Thrust
PARSONS
Petersburg
W. VA.
N.C.
KY.
TENN.
N
0
150
KM.
0
100
MILES

The North Mountain thrust separates the strongly folded carbonates and calcareous shales of its hanging wall from the open folds of the Broadtop synclinorium's middle to upper Paleozoic clastic sequence (Jacobeen and Kanes,1974,1975). This study concerns deformation within the North Mountain sheet and the Broadtop synclinorium as far as the West Virginia line, which coincides with the trough of the Bergton anticline's complimentary syncline.

GENERAL STRATIGRAPHY

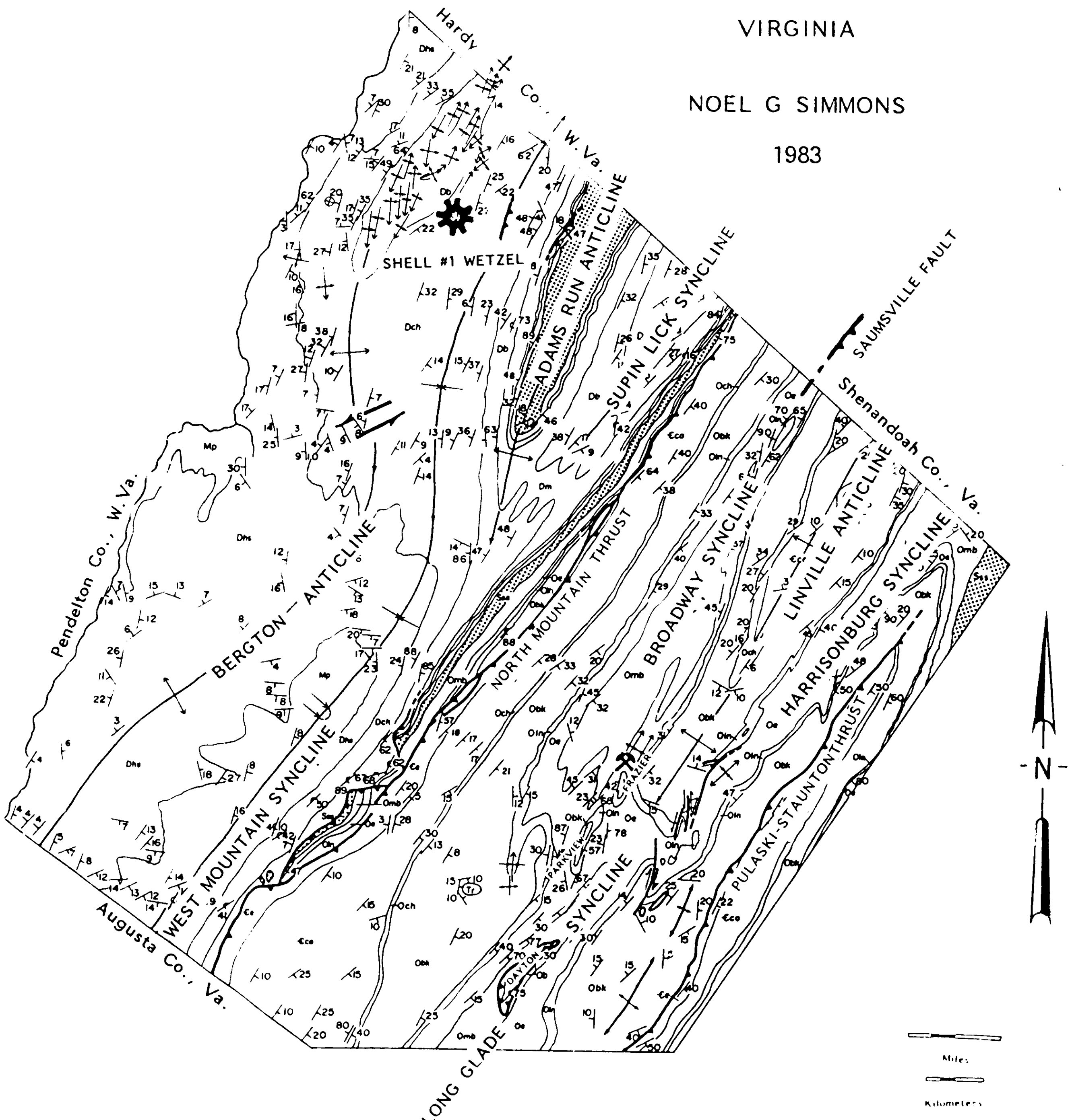
The sedimentary rocks exposed in the northern portion of Rockingham County, Virginia, belong to two major thrust sheets : the North Mountain thrust sheet and the Appalachian Plateau Structural Province which contains the Broadtop Synclinorium (Fig.1). Within the study area, the Cambrian Elbrook dolomites through Ordovician Martinsburg shales (total thickness = 6500^+ meters) are exposed in the North Mountain sheet, while Martinsburg through Mississippian Pocono sandstones (total thickness = 4900^+ meters) crop out in this portion of the Appalachian Plateau Structural Province (Fig.2). Drilled thicknesses for the Silurian sandstones to the Cambrian Conococheaque limestones (total thickness = 2350^+ meters) at the basal detachment are available from the Shell #1 Wetzel deep test (Virginia Division of Mineral Resources well files). The thickness of the individual units varies due to structural complications (Brent,1960) and facies relations (Lowry,1971; Read, 1980; Mussman,1982).

Fig. 2. Geologic map of study area showing names of regional folds and thrusts, klippe and second-order folds. Modified from Brent (1960), Fara (1960, cited in Cooper,1960, Gathright (personal communation, 1983).

GEOLOGIC MAP OF NORTHERN ROCKINGHAM COUNTY, VIRGINIA

NOEL G SIMMONS

1983



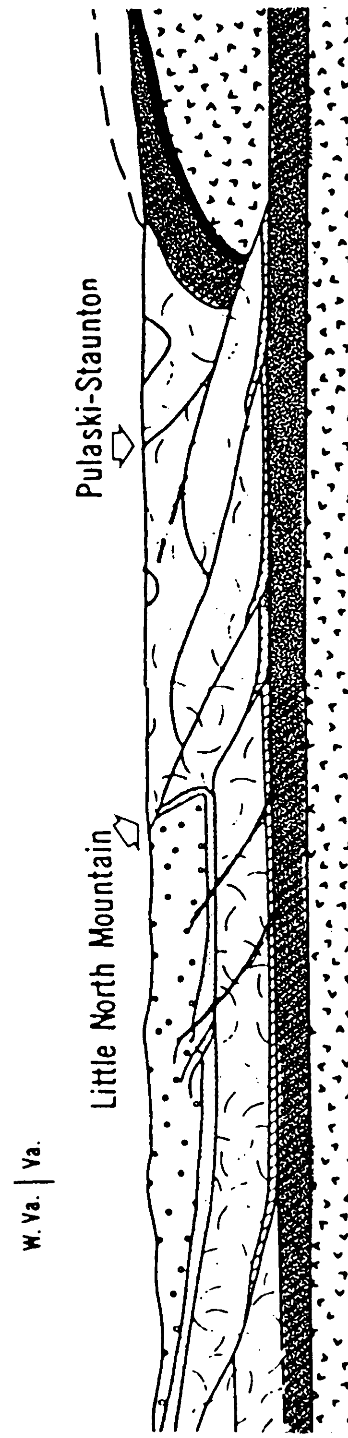
Modified from Brent (1960)

LEGEND

Tr	Triassic Intrusives
Mp	Mississippian Pocono Formation
Dhs	Devonian Hampshire Shales
Dch	Devonian Chemung Sandstones
Db	Devonian Brallier Shales
Dm	Devonian Millboro-Onondoga Shales
Do	Devonian Oriskany Sandstones
Dh	Devonian Helderburg Formation
Sss	Silurian Sandstones (undifferentiated)
Omb	Ordovician Martinsburg Shale
Oe	Ordovician Edinburg Formation
Oln	Ordovician Lincolnshire Formation
Obk	Ordovician Beekmantown Formation
Och	Ordovician Chepultapec Formation
Ɛco	Cambrian Conococheaque Formation
Ɛe	Cambrian Elbrook Formation

SYMBOLS

- Contact (exposed or approximate)
- 20 Attitude of Bedding
- 88 Overturned Bedding
- Thrust Fault (teeth on hanging wall)
- Strike-slip Fault
- Anticline
- Syncline
- Overturned Syncline



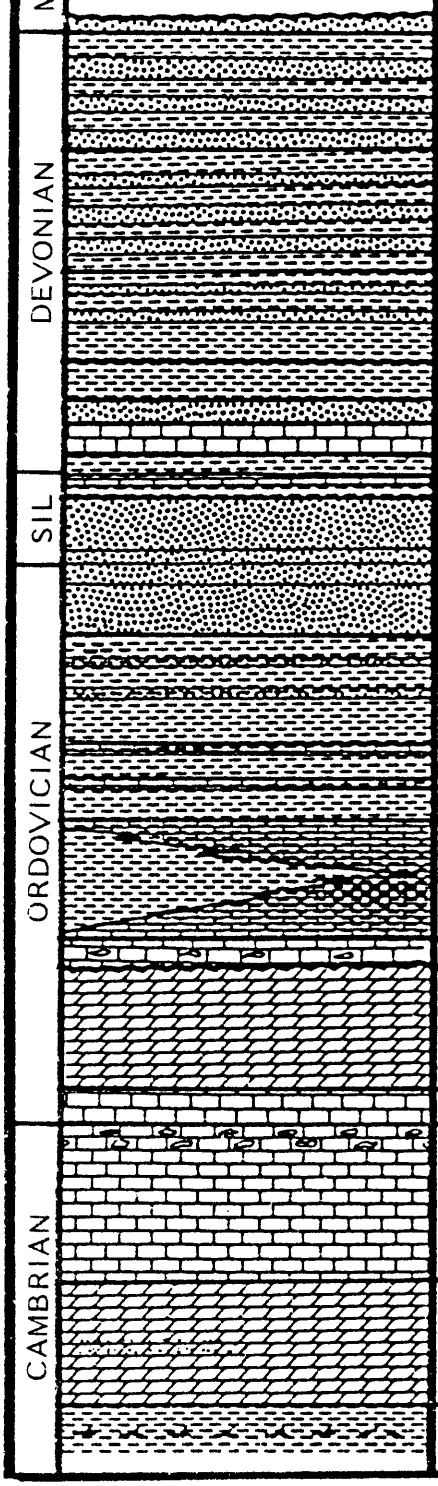
Detailed descriptions of each unit are available in Brent (1960) and Fara (1971). Minor changes in formation names for the Silurian rocks were introduced by Rader and Perry (1976). These papers summarize the general characteristics of each formation and incorporate the works of Butts (1933,1940), Oder (1927), Harnesberger (1950), Flewellen (1950), Cooper (1955), and Edmundson and Young (1955).

The stratigraphic column may be divided into separate litho-tectonic units based on each formation's response to deformation (Fig.3). Litho-tectonic groups are divided into either of two groups : "ductile" incompetent units where decollements occur, and relatively less ductile, competent units which are the sheets above and below the decollement.

PREVIOUS WORK

The Central Appalachian structural style of open anticlines created by duplication of thick Cambro-Ordovician carbonates above blind thrusts at ramps has been previously discussed by Gwinn (1964,1970), Jacobeen and Kanes (1974), and Perry (1978). Butts' (1933,1940) regional mapping was updated by Brent (1960) in a relatively detailed county map that served as base map for Figure 2 (this study contributes another 531 outcrops to his data base). The pioneering work of Cloos (1971) also overlaps this study, but his work is regional in scope.

Fig. 3. Generalized stratigraphic column for Rockingham County, Virginia from Brent(1960). "D" and "R" under lithotectonic unit indicate ductile and rigid units, respectively.



FORMATION	LITHOTECTONIC UNIT THICKNESS	D	R
POCONO FORMATION Massive white to gray sandstone with some dark shale	300 ft. 92 m		■
HAMPSHIPE FORMATION Chiefly red sandstone, some flagstones, shales, and mudrock	2000 ft. 612 m		■
CHEMUNG FORMATION Gray to greenish silty sandstone and brown to gray shale fossiliferous	2000 ft. 612 m		■
BRALLIER SHALE Greenish to brown stiff micaceous shale and fine-grained, thin-bedded, greenish sandstone, sparsely fossiliferous.	1200 ft. 367 m	■	
MILLBORO AND ONONDAGA SHALES Fissile black shale, weathers light gray or pinkish; Needmore shale in Massanutten Mountain.	400-500 ft. 122-153 m	■	
ORISKANY SANDSTONE Coarse-grained to white quartz sandsandstone with some calcareous cement; fossiferous	50-150 ft. 15 45 m		■
HELDERBERG LIMESTONE Gray limestone, crinoial limestone, cherty limestone, and some shale; fossiliferous	320-1000 ft. 98-306 m	■	
"SILURIAN SANDSTONES" S CLINTON TUSCARORA O OSWEGO JUANITA	600-1050 ft. 184-321 m		■
MARTINSBURG SHALE Chiefly shale and silty shale; greenish sandstone commonly at top	1500-3000 ft. 459-918 m	■	
EDINBURG SHALE Dark graptolite bearing shale, dense black limestone, and nodular weathering limestone.	1500 ft. 459 m	■	
NEW MARKET AND LINCOLNSHIRE LIMESTONE Dense light gray limestone and dark, mediumcoarse cherty limestone	100-350 ft. 31-107 m		■
BEEKMANTOWN FORMATION Thick-bedded, gray, medium grained dolomite and some blue limestone, much chert	2000 ft. 612 m		■
CHEPULTEPEC LIMESTONE Gray and blue dense limestone some dolomite	500 ft. 153 m		■
CONOCOCHEAGUE LIMESTONE Thick-bedded bluish limestone, gray dolomite, some sandstone	2500 ft. 765 m		■
ELBROOK DOLOMITE Thick-bedded dolomite limestone some shale	2000 ft. 612 m		■
ROME (WAYNESBORO) FORMATION Red and brown shale some sandstone and limestone	1700 ft. 520 m	■	

The Petersburg and Parsons lineaments (Fig.1) are the best documented of the CSDs as a result of the detailed field studies by Wheeler (1980) and his students at West Virginia University (Mullenax,1975; McColloch,1976; Trumbo,1976; Lacaze,1978; Sites,1978; Dixon,1979; Wilson,1980). The Parsons lineament has been projected from the Appalachian Plateau into the Valley and Ridge Province (Wheeler,1978; Wilson,1980; Pilant and Likiak,1982).

THE PARSONS CROSS-STRIKE STRUCTURAL DISCONTINUITY : IMPLICATIONS FOR STRUCTURAL RELATIONS AND STRAIN IN THE NORTH MOUNTAIN THRUST SHEET, CENTRAL APPALACHIANS

Abstract - Ordovician Martinsburg shales in regional synclines of the North Mountain thrust sheet, near the termination of the Pulaski-Staunton and Saumsville fault of the Appalachian fold and thrust belt, have strains that are relatively low ($1.53 \leq X/Z \leq 5.05$). Chlorite pressure fringes adjacent to pyrite framboids indicate coaxial deformation during the development of second-order folds within regional synclines, and non-coaxial deformation in the footwall just below klippen of the Pulaski-Staunton thrust. Anomalously-trending, second-order folds near the nose of the Linville anticline, are the result of movement over ramps along blind thrusts. Farther northeast, second-order folds parallel the regional trends in the Broadway syncline, and show an increase in asymmetry and strain values toward the surface terminus of the Saumsville fault, suggesting that second-order, ramp-generated folds are the expression of the Saumsville fault in the subsurface. Post-cleavage calcite veination during second-order flexural fold development crosscuts a local S_2 crenulation cleavage formed during emplacement of the Pulaski-Staunton thrust. The linear zone of the anomalously-trending, second-order folds and strike-slip faults result from displacement transfer at the termination of the Saumsville fault and constitutes the Valley and Ridge extension of the Parsons lineament.

INTRODUCTION

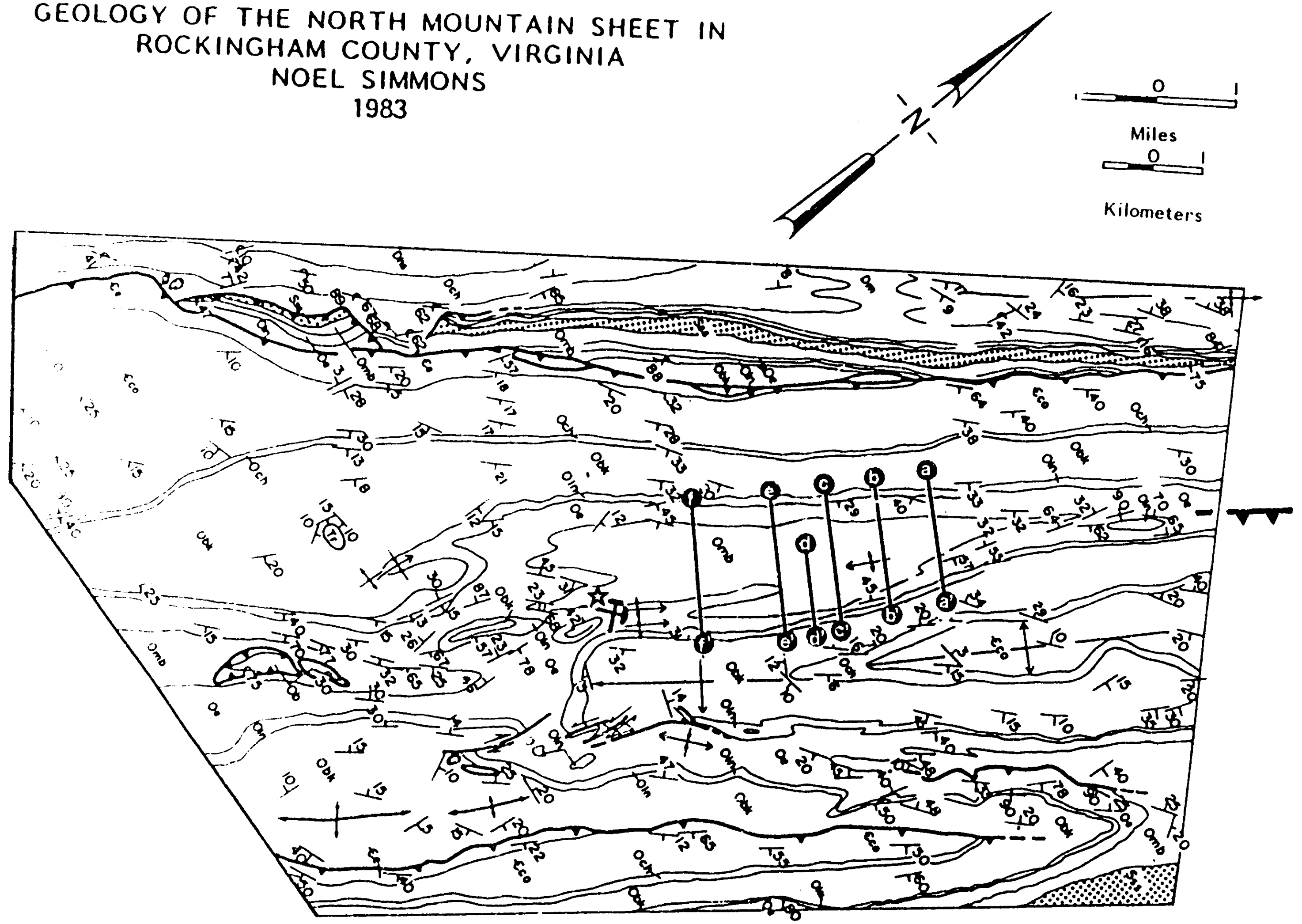
The Parsons Lineament is perhaps the best known of the Cross-strike Structural Discontinuities (CSDs) of the Appalachian Plateau Province (Wheeler et. al.,1974; Mullenax,1975; Trumbo,1976; McColloch,1976; Holland and Wheeler,1977; Wheeler and Sites,1977; Sites,1978; Wheeler,1978; Lacaze,1978; Wilson,1980), yet no detailed field work had been done on CSDs in the Valley and Ridge Province. Previous research in the Plateau primarily concerned fracture intensity (ratio of surface area to volume of joints). Studies of the geologic history of a major CSD through penetrative strain analysis are necessary to clarify the role CSDs play in thin-skinned tectonics.

The sequential development of regional folds and thrusts in North Mountain thrust sheet has been determined through detailed analysis of cleavage formation, second-order fold development, and calcite veination. Pressure fringes of chlorite surrounding pyrite framboids reflect both total strain and incremental strain histories of the rock during penetrative deformation. Incremental strain analysis provides information on the deformation path experienced by the rock (Durney and Ramsay,1973), style of folding both on a local and regional scale and the order of thrusting.

This study describes : 1) individual structural elements and their cross-cutting relations ; 2) variation in total and incremental strain on local and regional scales ; 3) a sequence of deformational events that may explain the

Fig. 4. Geologic map of the North Mountain thrust sheet with locations of cross-sections for figure 5. Quarry symbol is figure 7 and star is figure 9.

GEOLOGY OF THE NORTH MOUNTAIN SHEET IN ROCKINGHAM COUNTY, VIRGINIA
NOEL SIMMONS
1983



nature and origin of the Parsons Lineament in this portion of the North Mountain thrust sheet.

GEOLOGIC SETTING WITHIN THE NORTH MOUNTAIN SHEET

The trends of regional folds and major thrusts strongly conform to typical Central Appalachian trends of N30 - 35°E (Figs. 1,2 and 4). A major exception occurs near the nose of the Linville anticline. Here, arcuate and northward trending second-order folds (the Parkview anticline (Brent,1960) and Frazier anticline, respectively) and dextral strike-slip faults (Butts,1933; Brent,1960) disrupt regional trends.

Both the Pulaski-Staunton and North Mountain thrusts extend beyond the study area for hundreds of kilometers (Edmundson,1958; Bick,1960; Gwinn,1964; Perry,1978). The Linville anticline is bound on the northwest by the Saumsville fault from north of Timberville where this fault reaches the surface to where the Saumsville fault is truncated at its juncture with the North Mountain and Alonzaville faults (Young and Rader,1974). Second-order folds, roughly parallel to the regional trends, characterize its complimentary syncline (Broadway syncline) on the northwest.

The Dayton klippen (Figs.2,4) are the other major structures within the study area. Brent (1960) originally mapped an overturned section of Beekmantown dolomite and Lincolnshire limestones as a single klippe. However, the structure is breached, exposing the underlying Martinsburg shale (Fara cited in Cooper,1960; Fara,1971).

The Edinburg through Martinsburg package consists of interbedded calcareous shales and argillaceous lime mudstones. Ordovician Martinsburg shales are the youngest rocks exposed in the troughs of the three major synclines. The Lincolnshire and Martinsburg Formations develop a moderate to weak cleavage in calcareous shales and stylolitic cleavage in argillaceous lime mudstones. These rocks have Conodont Alteration Index (CAI) values of 4.0-4.5 (Epstein et. al., 1977) which indicates a peak temperature of 200-250°C for incipient metamorphism. Assuming a geothermal gradient of 25°C/km., the CAI value implies a maximum burial depth of 10 kilometers for rocks of the North Mountain sheet.

Considerable confusion exists within the literature over the appropriate names of regional-scale folds within the North Mountain thrust sheet in the Central Appalachians in general and Rockingham County in particular (Table 1). In a manner analogous to the stratigraphic code governing formation names, the first usage (either explicitly or implicitly) of a name for a structure takes precedence over later names.

Northern Rockingham County is also the locus of considerable Post-Paleozoic igneous activity. Both the North Mountain sheet and the Broadtop Synclinorium are cut by numerous dikes of olivine diabase (Brent, 1960). Brent (1960) mapped several northward-trending dikes (not shown) in the North Mountain sheet, one of which was injected sub-parallel to the dominant strike-slip fault in the disturbed zone.

Butts (1933,1940) implicent names	Edmundson (1945) implicent names	Brent (1960)	Lowry (1971)
Long Glade Syncline	Long Glade Syncline	Long Glade Syncline	Long Glade Syncline
Broadway Syncline	---------	Linville Creek Syncline	Broadway Syncline
--------	Linville Anticline	Mayland Anticline	Linville Anticline
--------	---------	"finger-like projection of the Massanutten Syncline"	Harrisonburg Syncline

Fara (1971)	Young and Rader (1974)	Rader and Perry (1976)	This Paper
Long Glade Syncline	--------	--------	Long Glade Syncline
---------	Harmony Syncline	Linville Creek Syncline	Broadway Syncline
---------	Rinkerton Anticline	Mayland Anticline	Linville Anticline
---------	---------	---------	Harrisonburg Syncline

Table 1. Names for formations used by other authors and this study.

Additionally, a large plug of olivine basalt occupies a structural depression in the northwestern limb of the Long Glade syncline (Butts,1933,1940; Brent, 1960).

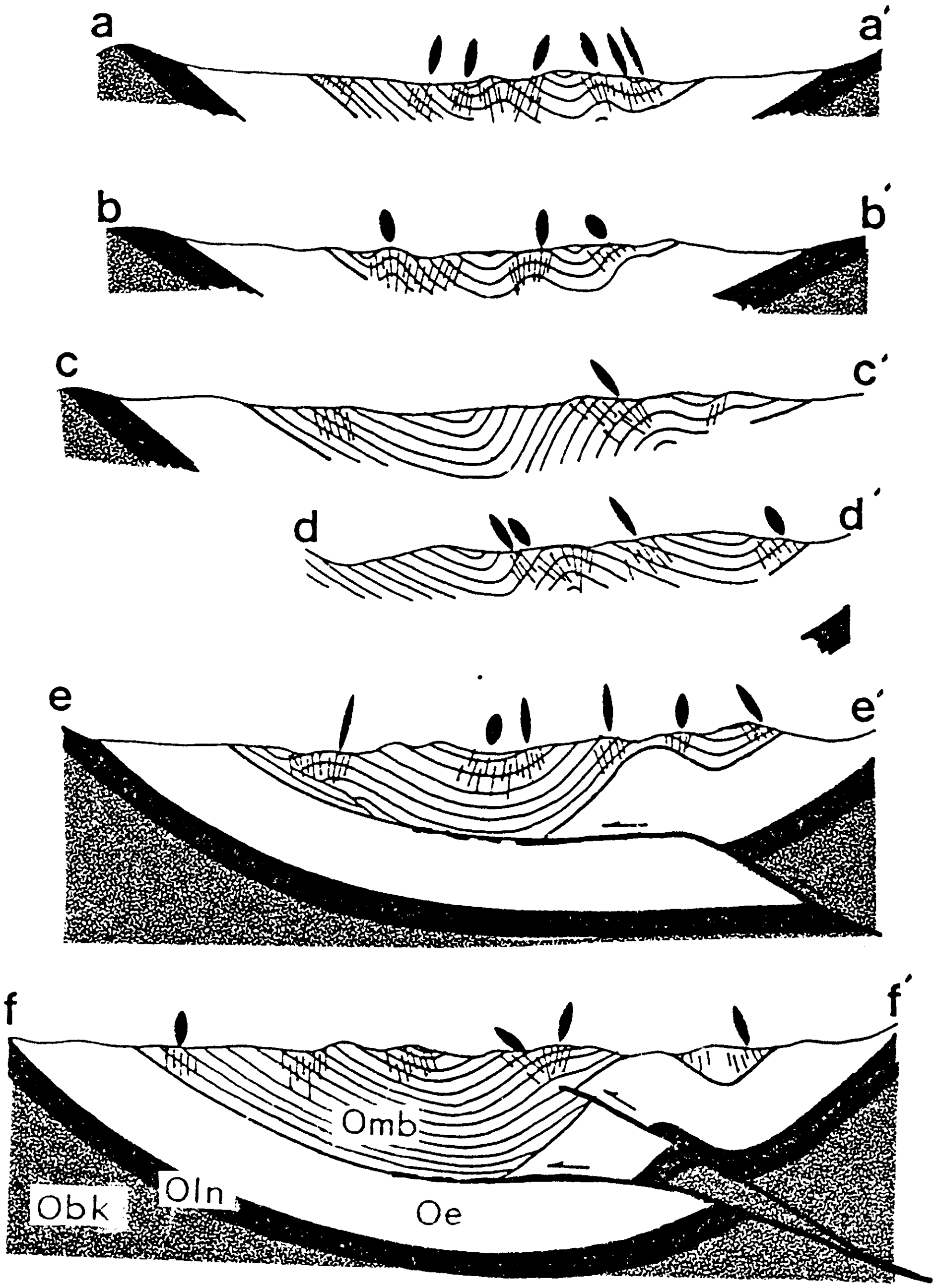
STRUCTURAL ELEMENTS

Second-order Folds

Most of the second-order folds occur within the Broadway and Long Glade synclines. These folds involve rocks as old as Ordovician Beekmantown and are particularly well developed in the Lincolnshire, Edinburg and Martinsburg Formations. Broad open folds with half-wavelengths of 0.5km. to 1.0 km. occur in the Lincolnshire and Edinburg Formations, whereas folds within the Martinsburg are somewhat tighter, with half-wavelengths estimated at 0.25 km. to 0.5 km. Folds generally are asymmetric with southeastward-dipping axial planes and become progressively more asymmetric northeastward along strike (Fig.5,f-f' to a-a').

Second-order folds generally have gentle plunges except near the nose of the Linville anticline where the doubly-plunging Parkview and Frazier anticlines plunge more steeply. Additionally, the Frazier anticline's northerly trend deviates significantly (30°) from regional trends (Brent,1960).

Fig. 5. Cross-sections through the Broadway syncline showing cleavage and X/Z strain in the Martinsburg Formation.


a
a'
b
b'
c
c'
d
d'
e
e'
f
f'
Omb
Oln
Obk
Oe

Second-order folds in the Edinburg Formation exposed in the Frazier North Quarry (Fig.4), have distinctive ramp-induced geometries (Fig.6). The quarry face exposes the minor blind thrusts responsible for this folding.

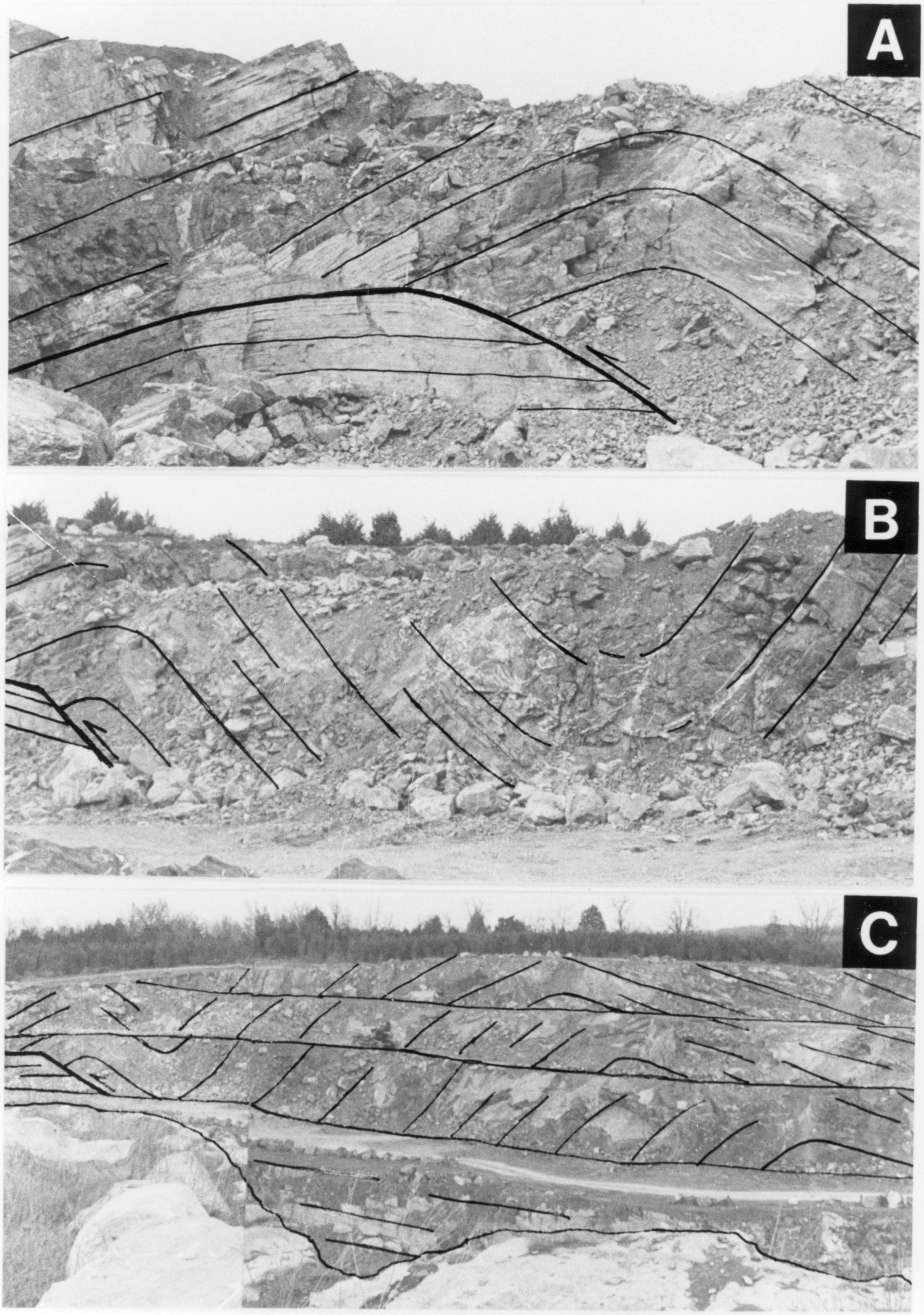
Faults

The small thrusts exposed within the Frazier North Quarry have demonstrable offset of only about 10-20 meters, based on the buckle shortening of the hanging wall. However, in several cases the faults are sub-parallel to bedding and displacement is unknown (Fig.6). Their presence is marked only by a low-angle truncation of the bedding planes accompanied by slickenslides.

Butts (1933,1940) mapped a north trending, dextral strike-slip fault which displaces the Lincolnshire limestone contact by roughly 2 kilometers (Fig.4). Further work by Brent (1960) revealed several smaller shears and a reverse fault in the same area (Fig.4). The small folds within the Harrisonburg syncline adjacent to these shears are believed to be geometrically related movement on these faults (Brent,1960).

A small thrust near the termination of the Pulaski-Staunton thrust (Fig.4) is marked only by topographic expression and a small outcrop of tightly folded Edinburg limestone. Movement along this fault appears to be insignificant.

Fig. 6. Second-order folds in the Edinburg Formation caused by movement over ramps along blind thrusts in the Frazier North Quarry.


A
B
C

Cleavage

Cleavage within the rocks of the Martinsburg Formation varies from a strong, spaced cleavage in the highly deformed rocks adjacent to the Dayton klippe to an anastomozing cleavage in the calcareous shales of the Broadway syncline. Thick-bedded argillaceous lime mudstones interbedded with calcareous shale have a weak anastomozing cleavage that is commonly refracted as it passes into the shale layer. Cleavage is generally stronger on the southeastern limb of the Broadway syncline than on the northwestern limb.

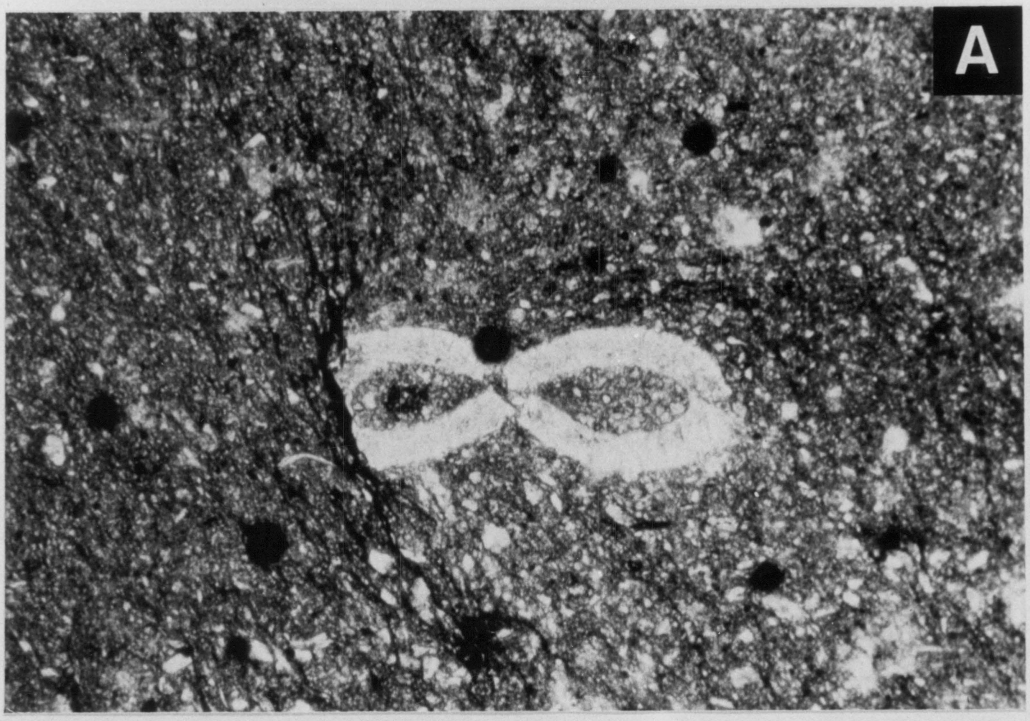
Cleavages produced under low pressure/temperature regimes appear to be the result of an interplay between recrystallization and dissolution caused by pressure solution coupled with solution-dependent grain boundary sliding of favorably oriented mica grains (White and Knipe,1978; Gray,1981; Morris,1981). Dissolved fossils in the Martinsburg shale support this hypothesis for the rocks within Rockingham County (Fig.7).

Cleavage fans in a convergent manner (Ramsay,1967) across second-order folds (Fig.5) with fan angles up to 35°. Cleavage dips consistently southeastward on the southeastern limb to vertical or slightly northwestward dipping across the major syncline (Fig.5). In general, the strike of the cleavage parallels the major structures except near the southeasternmost second-order fold and in the

Fig. 7. Dissolved fossils in Martinsburg shale

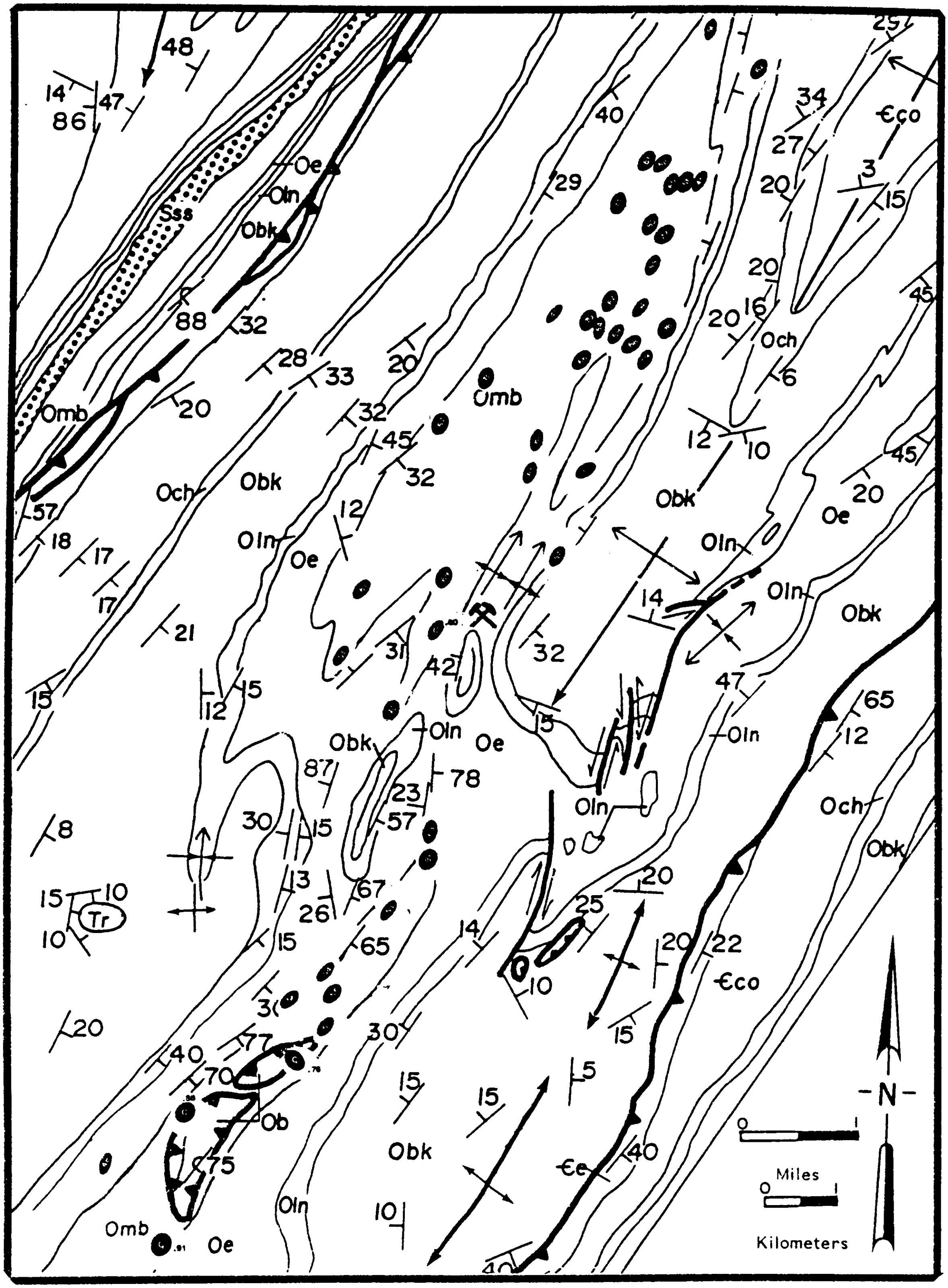
a. Dissolved trilobite fragment

b. Dissolved brachiopod spine


A


B

Fig. 8. Y/Z strain and cleavage traces in the North Mountain sheet; long axes of ellipses indicate strike of cleavage.


Sss
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N

Martinsburg immediately beneath the Dayton klippe (Fig.8). A second cleavage which slightly crenulates the first is developed locally along state route 701 at the present leading edge of the Dayton klippe (Figs.8,9a,9b). Cleavage in the Martinsburg Formation is asymptotic to the sole thrust of the klippen in the transport direction (T.Gathright, personal communication,1983) and the shales are considerably veined by white calcite (Brent,1960).

Calcite Veins

Bedding-parallel veins of blocky calcite occur frequently in the Edinburg and Martinsburg formations in the Broadway syncline. These veins are clearly younger than the regional cleavage (S_1) because the blocky calcite traps fragments of cleaved shale within the vein (Fig.9c). These veins are 1-3 cm. thick and often show slickensides along their boundaries. Additionally, en echelon tension gashes of blocky calcite occur in folds of the Edinburg formation in the Frazier North Quarry and in the Martinsburg shales along U.S. route 421 (Figs.6 and 10).

The Martinsburg shales at the leading edge of the Dayton klippe contain two generations of calcite veins. One set (V_1) is crenulated by both sets of cleavage, whereas the other set (V_2) cuts both cleavages and bedding (Fig.9). These relationships require the following sequence of events:

(1) locally developed veination (V_1)

Fig. 9. Age relations of the structural elements

a. Folded S_0 and S_1, cut by S_2 and then V_2 extension fractures (from Martinsburg shale at leading edge of the Dayton klippen).

b. Slightly crenulated S_0, S_1, and V_1; S_2 at low angle to S_1 (from Martinsburg shale at the leading edge of the Dayton klippen).

c. S_0, S_1, and V_2 in Martinsburg shales of the Broadway syncline; note cleaved shale trapped in V_2.

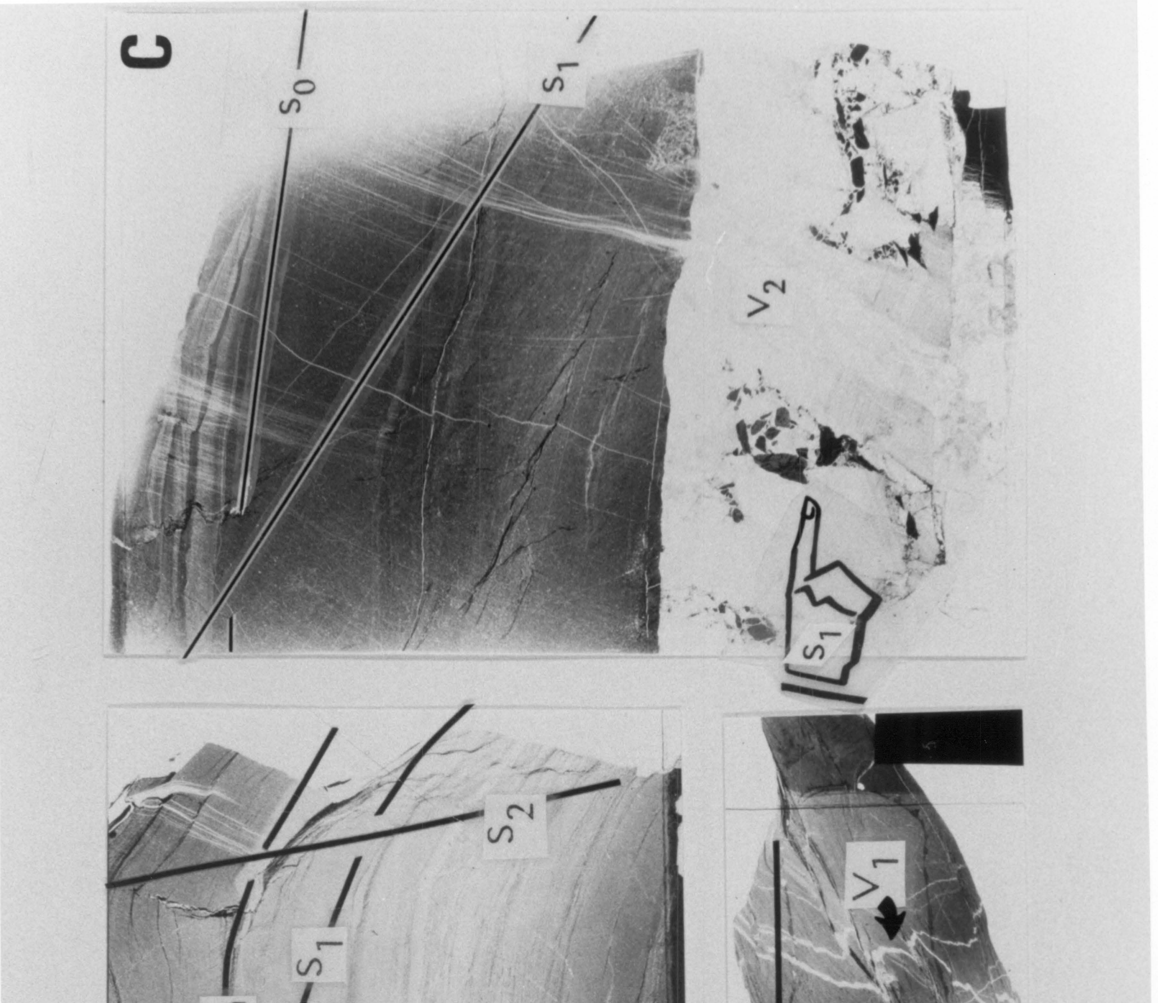

A
B
C
S_0
S_1
S_2
V_1
V_2

Fig. 10. En echelon V_2 tension gashes (filled with blocky calcite) along state highway 42 south of Broadway, Virginia.

(2) regional cleavage (S_1)

(3) local crenulation cleavage (S_2)

(4) regional calcite veination (V_2) - bedding-parallel in regional folds (i.e., Broadway syncline) and irregularly adjacent to the Dayton klippe.

STRAIN

Pressure fringes, developed from syntectonic fiber growth at pyrite framboids during deformation, record the penetrative strain experienced by the host rock. Incremental and total strains determined from fringes were used to delineate the regional strain patterns and variations in strain across second-order folds.

Pressure Fringes

Pressure fringes have been used to document incremental strain histories (Elliot,1972; Durney and Ramsay,1973; Wickam,1973; Gray and Durney,1979; Mullenax,1981; Reks,1981; Beutner and Diegel, in prep.; Spears,1983). Syntectonic fibers tend to grow parallel to the principal extension direction (Durney and Ramsay,1973).

Straight fibers imply uniform extension (coaxial deformation),where elongation (e_1) is given by :

$$e_1 = l_n/l_o = \text{fiber length/pyrite radius},$$

whereas a change in the orientation of the principal extension direction (non-coaxial deformation) produces curved fibers (Durney and Ramsay,1973). Total elongation is related to the fiber length (Fig.11) through the trigonometric function :

$$e_{1n} = l_n / (\Sigma \, l_i \cos\theta_i + l_o)$$

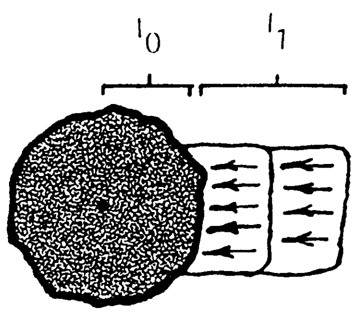
These methods assume that no body rotation has occurred and therefore record only the internal deformation of the rock. Both straight (Fig.12) and curved (Fig.13) fibers of chlorite were observed in the Martinsburg shales.

The syntectonic chlorite fibers observed in this study appear to have developed through antitaxial growth (nucleation at the pyrite framboid) because in disaggregated pyrite framboids, fibers record the extension of the pyrite in an area where no clay minerals were present (Fig.12). Antitaxial growth is favored by other workers in the Appalachians in rocks of similar composition (Mullenax,1981; Reks,1981; Beutner and Diegel, in prep.; Spears,1983). Under antitaxial growth, the last increment of extension recorded by the fiber is immediately adjacent to the pyrite framboid.

Thin sections of the Martinsburg shales (and some Edinburg and Lincolnshire) were examined in XZ section, where X,Y, and Z represent

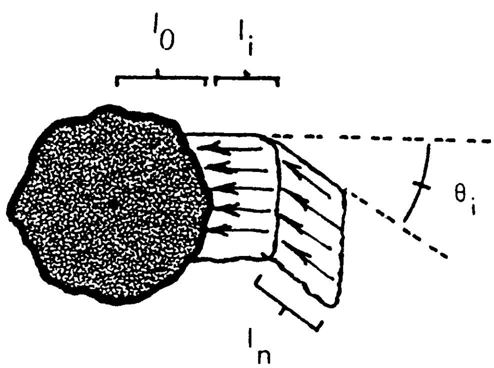
Fig. 11. Durney and Ramsay (1973) Method for calculating elongation using antitaxial fiber growth in pressure fringes adjacent to pyrite framboids.

COAXIAL DEFORMATION



$$e_1 = \frac{(l_1 + l_0) - l_0}{l_0} = \frac{l_1}{l_0} = \frac{\text{fiber length}}{\text{pyrite radii}}$$

NON-COAXIAL DEFORMATION



$$e_{1n} = \frac{l_n}{\Sigma\, l_i \cos\theta_i + l_0}$$

θ_i = angle between "i^{th}" chord and "n^{th}" chord.

e_{1n} = "n^{th}" incremental elongation.

DURNEY AND RAMSAY METHOD (1973)

Fig. 12. Straight fibers indicating coaxial deformation

a. in intact framboid

b. in disagreggated pyrite framboids.

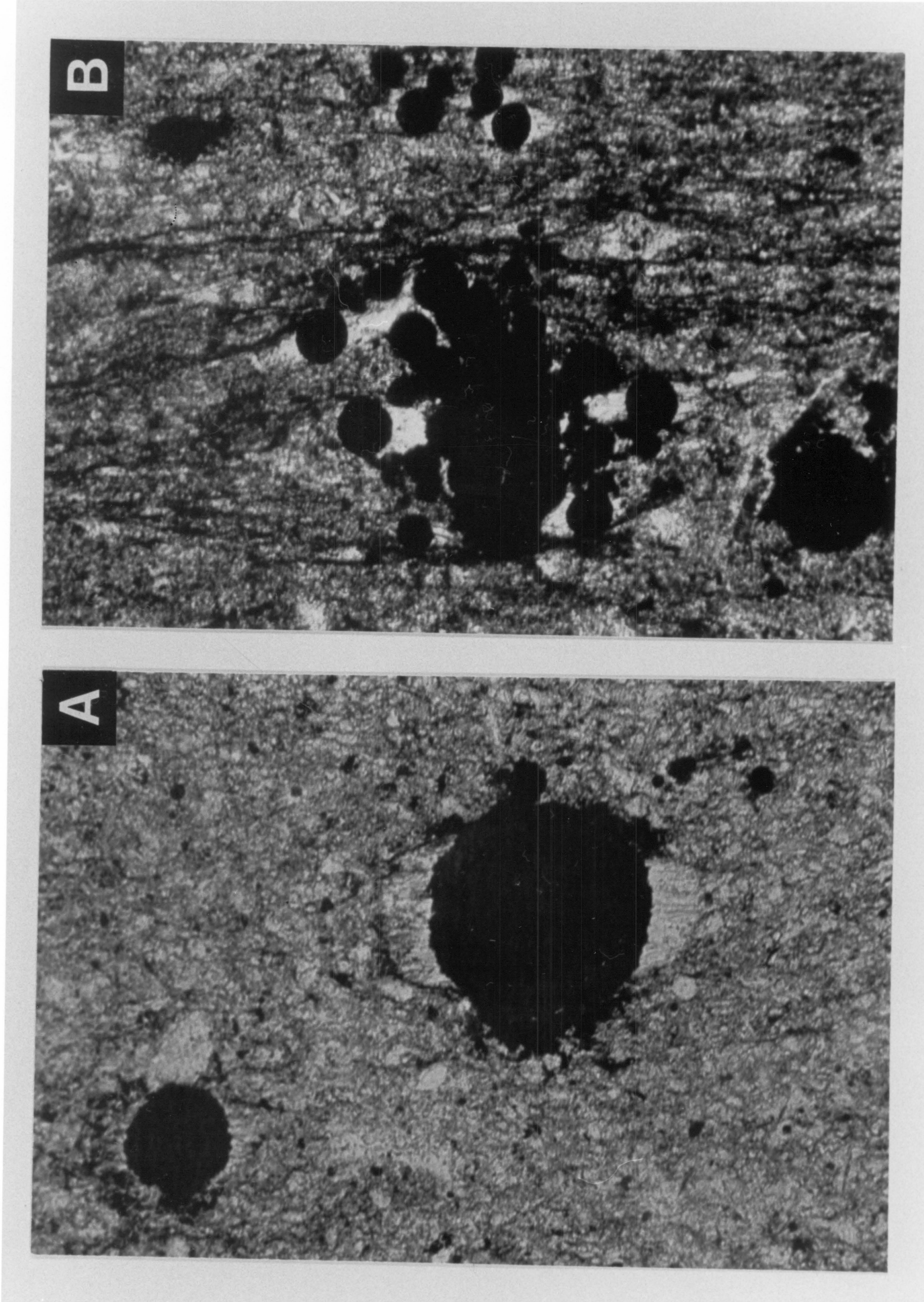
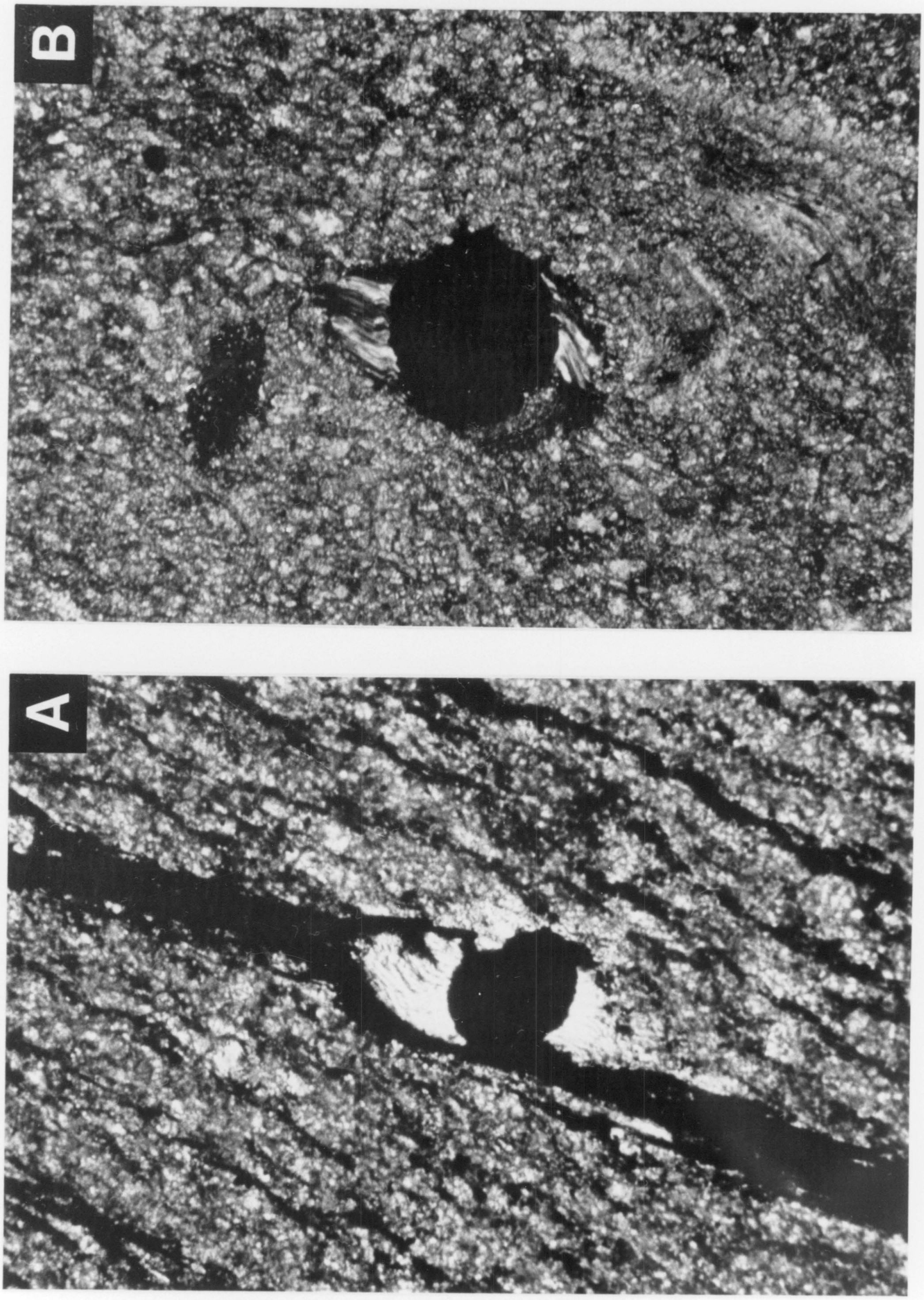

B
A

Fig. 13. Curved fiber growth indicating non-coaxial deformation in Martinsburg shales adjacent to the Dayton klippen.


B
A

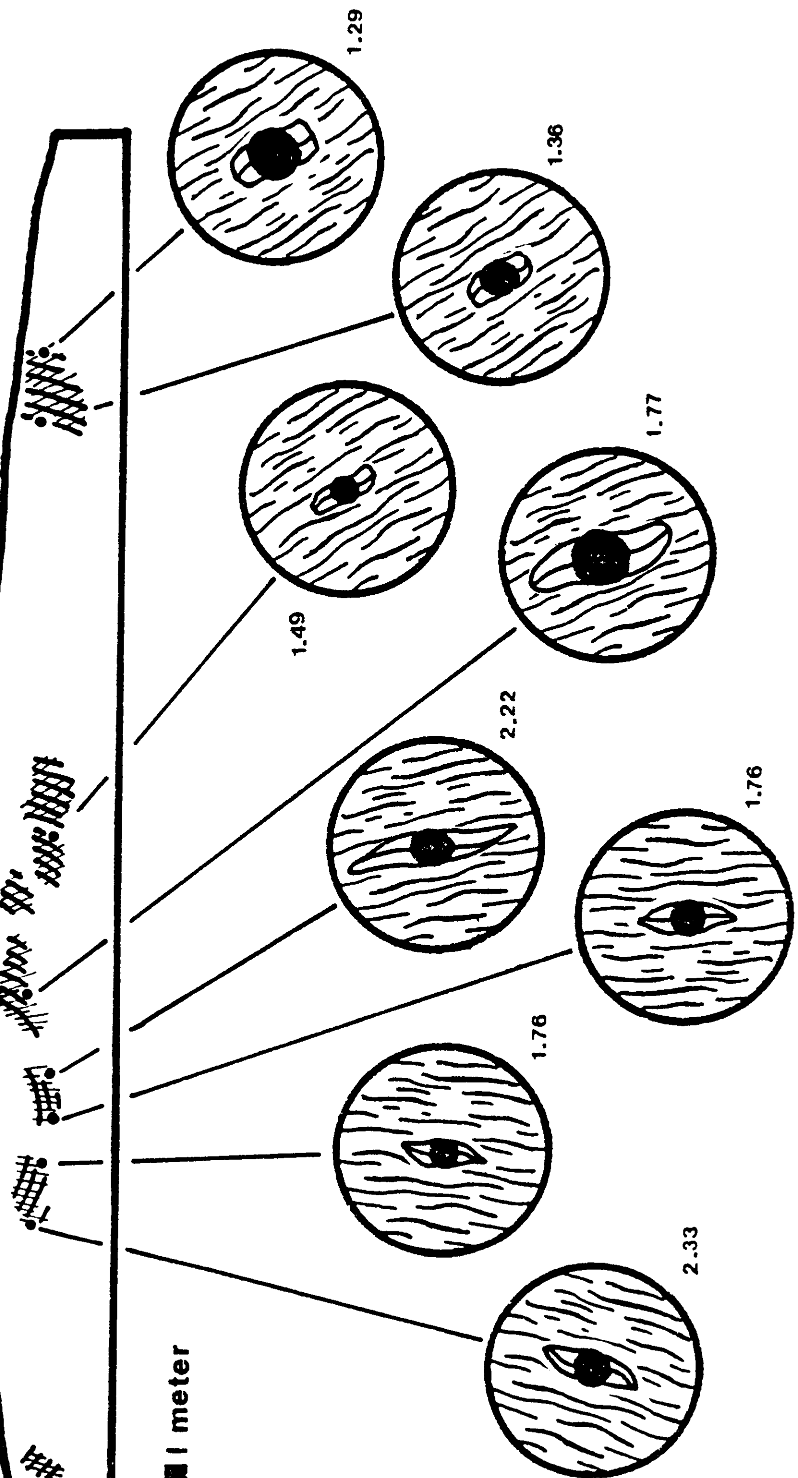
the principal, intermediate and minimum extension directions. Cleavage approximately defines the XY plane, and fiber growth parallels the principal extension direction (X). Previous workers in the Appalachians have consistently reported that pyrite framboids in YZ sections show no fringes (Reks,1981; Beutner and Diegel, in prep.; Spears,1983). Assuming plane strain and constant volume, the Y and Z directions are equal to 1 and $(1/1+e_1)$, respectively. The dissolved fossils (Fig.7) indicate that some volume loss or redistribution has occurred, but there is no evidence with which to quantify this for the area as a whole. The assumption of constant volume and plane strain may not be strictly true, but does allow comparison with the research of other workers in the Appalachians. These assumptions allow the total strain ellipsoid to be calculated.

Strain Patterns

Measurement of pressure fringes adjacent to pyrite framboids allows strain analysis of second-order folds and regional folds.

Variations in strain across a second-order fold. The values of total strain vary with structural setting within second-order folds. XZ strains within the hinge areas are generally higher (1.75 - 2.33) than in the limbs (1.29 - 1.49) (Fig.14). Fiber growth reflects non-coaxial deformation in the only fold exposed well enough for detailed study. Fibers in the southeastern limb have an opposite sense of rotation to those in the northwestern limb (Fig.14); near the hinge the fibers are

Fig. 14. Distribution of curved fibers and convergent cleavage indicating flexural-slip folding in second-order fold of the Broadway syncline. Starred locality in figure 4.


1.29
1.36
1.49
1.77
2.22
1.76
1.76
2.33
1 meter

very nearly straight and the curvature increases away from the hinge area (Fig.14).

In contrast to this second-order fold, other samples within the Broadway syncline have straight fibers. Curved fibers were observed only in three other localities in the vicinity of the Dayton klippe (ellipses labelled C in Fig.8); fringes in these localities show great curvature and irregular growth habits (Fig.13) which reflect changes up to 90° in the orientation of the principal elongation direction. Rotation of the principal strain axes results in strain superposition, and therefore, anomalously low total strains are preserved in rocks at these localities.

Regional variations in strain. Strain values vary with structural position in the regional folds in addition to the variations within the second-order folds. YZ strains in this portion of the North Mountain thrust sheet have relatively low strains (0.45 - 0.81) (Fig.8). Strain ellipsoid orientations indicate that the trends of major folds and faults developed perpendicular to the direction of minimum elongation except where rigid body rotation associated with faulting is suspected.

Major folds appear to have a different distribution of strain values from those found in the second-order fold. Strain values are consistently higher on the southeastern limb of the Broadway syncline than on the northwestern limb. Strain also increases northeastward along strike toward the terminus of the Saumsville fault (Fig.8) because the depth of erosion exposes structurally lower levels near to the fault where strains are higher. Because cleavage fans across the Broadway syncline, ellipses in X/Z sections also vary from southeastward-dipping on the southeastern limb to sub-vertical on the northwestern limbs of the major synclines.

Strains measured in rocks within the Edinburg formation or at the Edinburg-Martinsburg contact are generally lower than those measured within the Martinsburg shales proper. The lower strains reflect the higher rigidity of the Edinburg limestones, and near the Martinsburg-Edinburg contact some strain shadow effects are to be expected.

DISCUSSION

Second-order fold development in the Broadway syncline, cleavage formation, and calcite veination document the relations between emplacement of the Pulaski-Staunton thrust and regional fold development. The opposite sense of rotation of gently curved fibers in the second-order fold (Fig.14) indicates that flexural slip was the dominant fold mechanism operating during regional penetrative deformation. In contrast, the three other localities with curved fibers adjacent to the Dayton klippen (ellipses labelled C in Fig.8) all have the same clockwise sense of rotation and record very large (Fig.13a) and abrupt (Fig.13b) changes in curvature consistent with the cleavage rotations and high shear strain in the Martinsburg shales immediately adjacent to the Pulaski-Staunton thrust. Anomalous strikes and asymptotic form of cleavage in this area further substantiate high shear strains related to emplacement.

The post-cleavage calcite veination ties these two very different structural settings in space and time. Calcite veins in the Broadway syncline are dominantly bedding-parallel or en echelon, and suggest continued flexural-slip fold development after cleavage formation. The increase in strain and asymmetry of these folds toward the northeast, coupled with the known blind thrusting which typifies these folds (Fig.6), suggests that these folds are an expression of increased displacement along blind thrusts and proximity to the Saumsville fault which is exposed at the surface just north of the area.

Local S_2 crenulation cleavage (Fig.9), curved fibers of pressure fringes adjacent to the Dayton klippe, and the cleavages in the Long Glade syncline document strains accompanying emplacement of the Pulaski-Staunton thrust. The cross-cutting relations of V_2 calcite veins and cleavage suggest that the veins are not directly caused by the initial phases of Pulaski-Staunton thrusting, but rather are part of the same deformational episode as the bedding-parallel veins associated with structures caused by Saumsville Faulting.

Both regional and second-order folds synformally preserve klippe of the Pulaski-Staunton thrust (Brent,1960; Fara,1971). This relation requires the Pulaski-Staunton thrusting to predate (at least the final stages of) folding in the North Mountain thrust sheet. Furthermore, if the second-order folding is caused by movement on the Saumsville Fault, then the relationship of the synformally preserved Madison and Harrisonburg klippen to their footwalls requires an east-to-west order of thrusting, in accordance with Perry (1978), for this portion of the Central Appalachians.

This ordering places constraints on the mechanical behavior of the North Mountain thrust sheet. The Pulaski-Staunton thrust stepped up from the Rome horizon across the Cambro-Ordovician carbonates and ramped into the Martinsburg horizon (Fig.15a), forming a doubly-plunging anticline (Fara,1971). This anticline subsequently faulted again (Fig.15b) out of the core (Fara,1971), and isolated the overturned, northwestern limb as a horse block (Fig.15c).

The Saumsville fault probably developed in response to continued shortening north of the terminus of the Pulaski-Staunton thrust (Fig.15d). The Pulaski-Staunton and Saumsville faults may overlap in the subsurface to accommodate displacement transfer as suggested elsewhere by Dahlstrom (1969,1970). The Linville anticline is a ramp anticline associated with movement across the ramp along the Saumsville fault (Fig.15e). However, because the major horse block derived from previous Pulaski-Staunton thrusting was already in place, the additional thicknesses of rigid carbonates in both the horse block and the Pulaski-Staunton sheet prevented any southwestern development of the Linville anticline.

Fig. 15. Schematic diagram of deformation in the North Mountain thrust sheet.

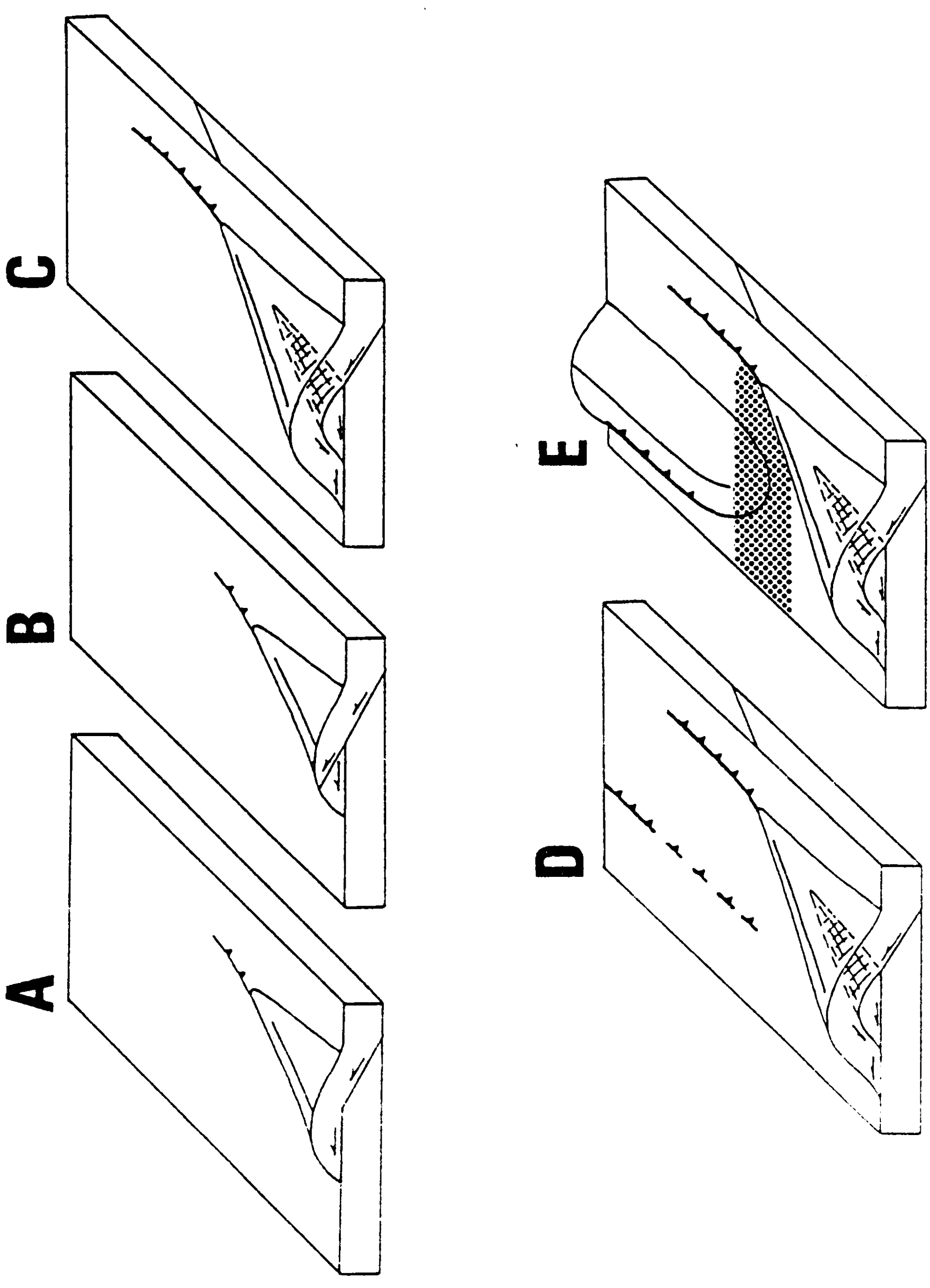
a. Initial ramping of first stage of Pulaski-Staunton faulting.

b. Pulaski-Staunton thrust develops as out-of-the-core thrust.

c. Pulaski-Staunton thrust overrides faulted northwestern limb, isolating it as a horse block (Dayton and Burketown klippe) (Fara,1971).

d. Development of Saumsville fault in response to displacement transfer.

e. Development of the Linville anticline by movement over ramp; stippled area represents the linear tear and transfer zone of anomalously-trending second-order folds and shears.


A
B
C
D
E

Model analogs of thrust fault terminations (Gardner and Spang, 1973) indicate a fanning of principal strain trajectories around thrust terminations in response to rotation from the scissors-like motion of the thrust. The model suggests that the small-scale shears and anomalous trends of second-order folds within the disturbed zone are the results of similar rotational movements along the Saumsville Fault. The blunted nose of the Linville anticline and second-order folds and faults are the result of a linear tear and transfer zone (Fig. 15e). The Beekmantown-cored Parkview and Frazier anticlines result from imbrication in this zone during lateral and forward movement on the blind thrust. The arcuate outcrop pattern of the Parkview anticline may result from this oblique movement as well.

Perturbations in stress fields near basement faults cause thrusts to cut up-section in the direction of tectonic transport (Jacobeen and Kanes, 1974, 1975) and similar processes transverse to strike are postulated for the Parsons and Petersburg Lineaments (Gwinn, 1964). The Parsons lineament has a magnetic signature (Zietz et. al., 1977, 1980) which may represent a cross-fault in the basement (Pilant and Likiak, 1982). Increased fracture intensities within a north-northwest-trending structural anomaly which disrupts regional trends in the next thrust sheet to the northwest (Simmons, 1983) are also associated with this magnetic anomaly. Additionally, paleozoic trends appear to have localized igneous intrusion during the Post-Paleozoic (Brent, 1960), suggesting that the basement cross-fault responsible for this CSD acted as a conduit for magma into the overlying structural complexities. The regional fault terminations, magnetic signature, Post-Paleozoic igneous activity, major fold-plunge depressions, and the linear disturbed zone described in this paper suggest a genetic relationship between basement and deformation in the cover rocks. The Parsons CSD appears to have affected regional geologic history persistently throughout its existence, establishing this CSD as one of the major tectonic elements in the Appalachians.

FRACTURE INTENSITIES OF SYSTEMATIC JOINTS ASSOCIATED WITH THE PARSONS LINEAMENT IN THE BROADTOP SYNCLINORIUM, ROCKINGHAM COUNTY, VIRGINIA

Abstract - Age relations and intensity (ratio of surface area to volume) of systematic joints, together with as the drilled depths to the Oriskany horizon in the Bergton anticline, suggest deformation associated with a northeast-facing lateral ramp is responsible for the Parsons Lineament, a major Cross-strike Structural Discontinuity (CSD). CSDs typically show increased fracture intensities in traverses perpendicular to the Parsons Lineament. In this area, there are two sets of regional joints which display such increased intensities: J_1, a pervasive east-west-trending near-vertical joint set, and another set, J_2, that varies with structural position. Additionally, other sets occur in the overturned limbs of the North Mountain thrust's footwall and associated with minor thrusts and second-order shear zones within the lineament. The axes of the West Mountain syncline and the Bergton anticline depart from regional trends (N30-35°E), swing due north for 16km (10 miles) around the nose of the Adams Run anticline and return to normal Central Appalachian trends over a distance of 19 km (12 miles). At the northern curvature, closure exists on the anticline, resulting in the Bergton gas field, a small borderline commercial field. The older joint set is related to the second-order shears in the lineament. J_2 is associated with closure on the Bergton anticline, suggesting that movement over a lateral ramp is directly responsible for closure.

INTRODUCTION

The Parsons Lineament (Fig.1) represents the major cross-strike structural discontinuity (CSD) disrupting regional trends in central Rockingham County, Virginia. The style of folding, faulting and intensity of systematic joints are the surficial expressions of the Parsons CSD. Fracture intensities can be used to identify the second-order shears which characterize the lineament and help to explain the nature of the deformation responsible for the development of closure in the Bergton natural gas field.

The Bergton gas field is the easternmost gas field in the Central Appalachians and appears to be intimately related to the proposed Valley and Ridge extension of the Parsons Lineament (Wheeler,1978; Wilson,1980). A study of the major CSD associated with this gas field can serve as an analog for future exploration in similar structural settings within the Central Appalachians, but no work has yet been done on CSDs within the Valley and Ridge Province.

Mesoscopic folds, faults, and joints are the principal structural elements of the Broadtop Synclinorium. The fracture intensity for the joints can be used to identify and characterize both local and regional fracture zones. Relations between these elements, combined with an analysis of joints in Chemung sandstones, can be used to determine the nature and origin of the Parsons Lineament in the Broadtop Synclinorium.

GEOLOGIC SETTING IN THE BROADTOP SYNCLINORIUM

Regional folds and faults in the Central Appalachians normally trend N30-35°E. Regional folds are strongly disrupted by a north-northwest trending linear zone of fold plunge depression that coincides with the nose of the Adam's Run anticline and the rapid change in the strike of the Bergton anticline (Fig.16). Within this zone, at least one sinistral strike-slip fault offsets the Bergton anticline.

The only major thrust exposed in this portion of the study is the North Mountain thrust which forms the eastern boundary of the Broadtop Synclinorium for hundreds of kilometers (Jacobeen and Kanes,1974,1975). The overturned footwall of the North Mountain thrust is a pervasive synclinal structure. A local culmination, which exposes second-order folds in the Devonian Millboro shales, divides this structure into two regional synclines (Fig.16): the West Mountain syncline and the Supin Lick syncline (Harnesberger,1950; Young and Harnesberger, 1955; Brent,1960).

The Supin Lick syncline plunges northward into Shenandoah County and continues for approximately 22 kilometers (14 miles), and exposes rocks as young as Devonian Hampshire shales in its trough. The southeastern limb of the West Mountain syncline adjacent to the North Mountain thrust is extensively thrust faulted (Giles,1927; Brent,1960). This structure as well as the Bergton anticline extends 40 km (25 miles) southwestward into Augusta and Rockbridge Counties (Butts,1933,1940;

Fig. 16. Geologic map of the Rockingham County portion of the Broadtop synclinorium. Rectangular grid is the outline of figure 31, the oil derrick marks the location of the Bergton natural gas field.

GEOLOGY OF THE BROADTOP SYNCLINORIUM IN ROCKINGHAM COUNTY, VIRGINIA

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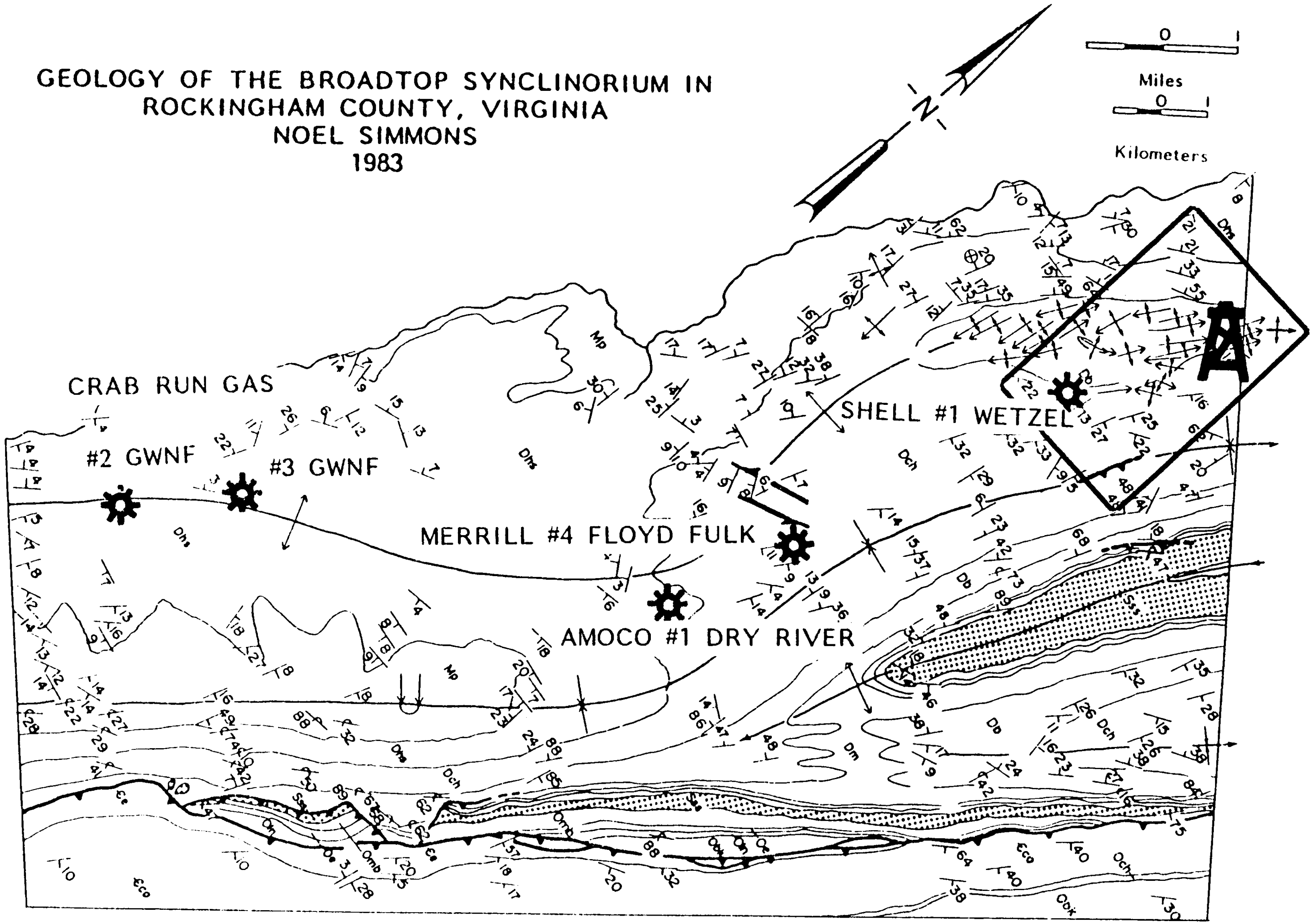


Young and Harnesberger, 1955; Brent, 1960). Southwest of the lineament, the West Mountain syncline contains rocks as young as the Mississippian Pocono sandstones and coal measures (Butts, 1933, 1940). The oldest rocks cropping out in the Bergton anticline are the Devonian Millboro shales. The Adam's Run anticline exposes Martinsburg shales in its core (Rabchevesky, 1963) and continues 27 kilometers (17 miles) into Hardy County, West Virginia before terminating in a complex zone of en echelon anticlines (Cardwell et. al., 1968).

No Post-Paleozoic intrusions have yet been mapped in this section of the Broadtop Synclinorium. However, Virginia Division of Mineral Resources well files indicate occurrences of igneous rock at depths of 1330, 1695, and 1745 feet in the Crab Run Gas #2 George Washington National Forest test well.

STRUCTURAL ELEMENTS

The relations of mesoscopic folds, faults, and joints to the regional structure were examined to establish the structural style and effects of Parsons Lineament through this portion of the Broadtop Synclinorium.

Mesoscopic Folds

Numerous mesoscopic folds occur in the Brallier shales of the Bergton anticline. They typically have half-wavelengths of 300-400 m, and are broad open folds with straight limbs, angular hinges and interlimb angles of 121-158° (mean = 128°) on the northwestern limb of the regional fold and 85-110° (mean = 95°) on the southeastern limb. These folds plunge gently in the direction of the regional plunges of the Bergton anticline except on the southeastern limb near the culmination of the regional structure where several folds have plunges opposite to the regional trend (Fig.16).

This zone of plunge reversals corresponds to the area of embayed contacts that Young and Harnesberger (1955) attributed to regional cross-folds. Within this zone, at the Brallier-Chemung contact (Fig.16) is a fold with distinctive kink-fold morphology (Fig.17). The other embayed contact on the southeastern limb appears to be the result of a tendency for mesoscopic folds in the Brallier shales to have a more northerly strike than the regional structure.

Chevron folds occur in the lower Brallier shales of the overturned southeastern limbs of the West Mountain and Supin Lick synclines. They have sharp hinges and variably-dipping axial planes (Figs.18a,b) as a result of the overturning of this limb of the regional structure during thrusting. The series of second-order folds along the local culmination that separates the West Mountain and Supin Lick synclines are developed within approximately the same stratigraphic horizon: the lower Brallier and Millboro shales (Young and Harnesberger,1955). These asymmetric folds have rounded anticlinal and angular synclinal hinges (Fig.18c).

Fig. 17. Kinked-fold in Chemung sandstones on the southeastern limb of the Bergton anticline.

a. View looking N80°E, oblique to axes of both folds.

b. View looking S30°W, down the axis of fold 2.

c. Stereographic projection of normals to bedding and fold axes.

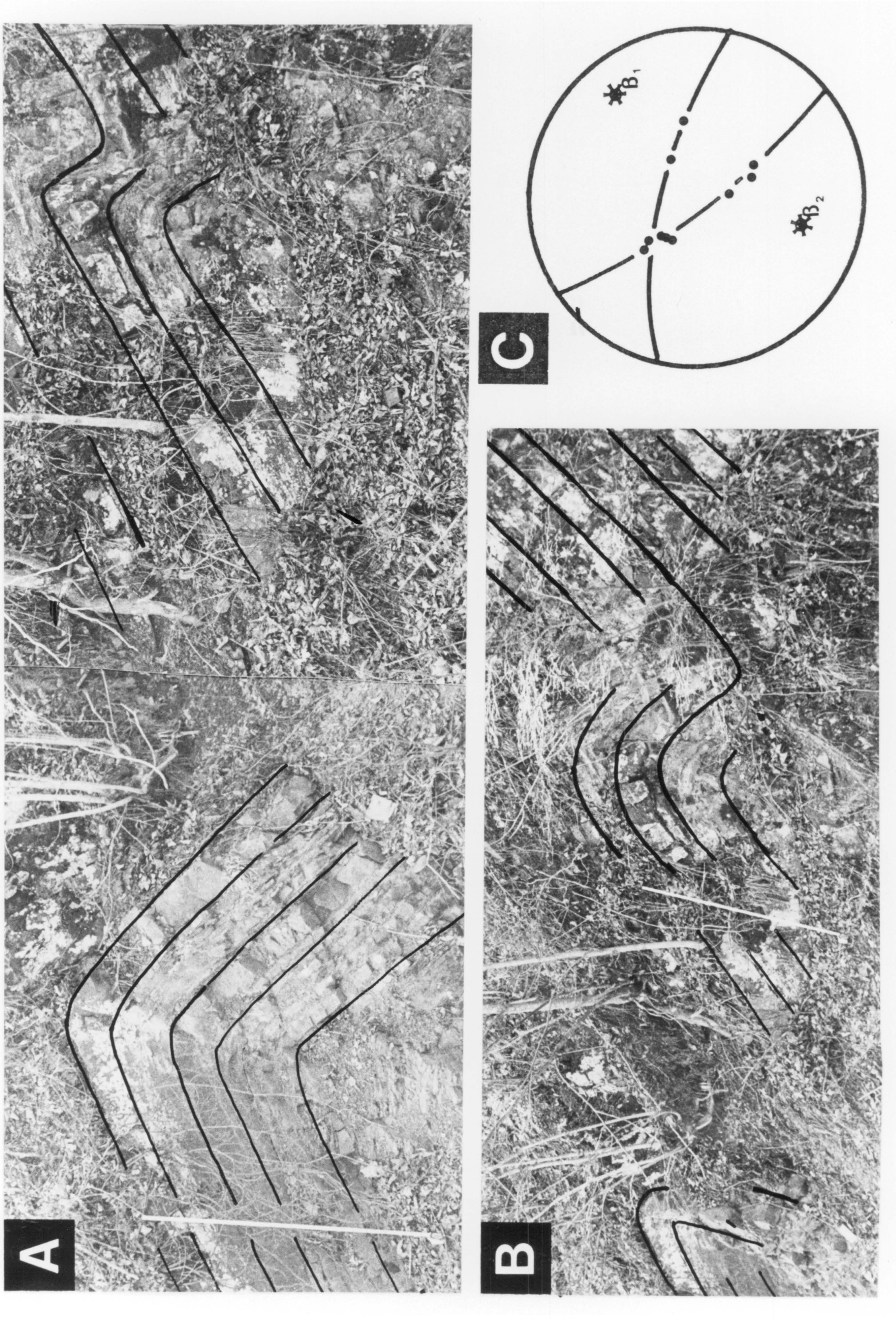
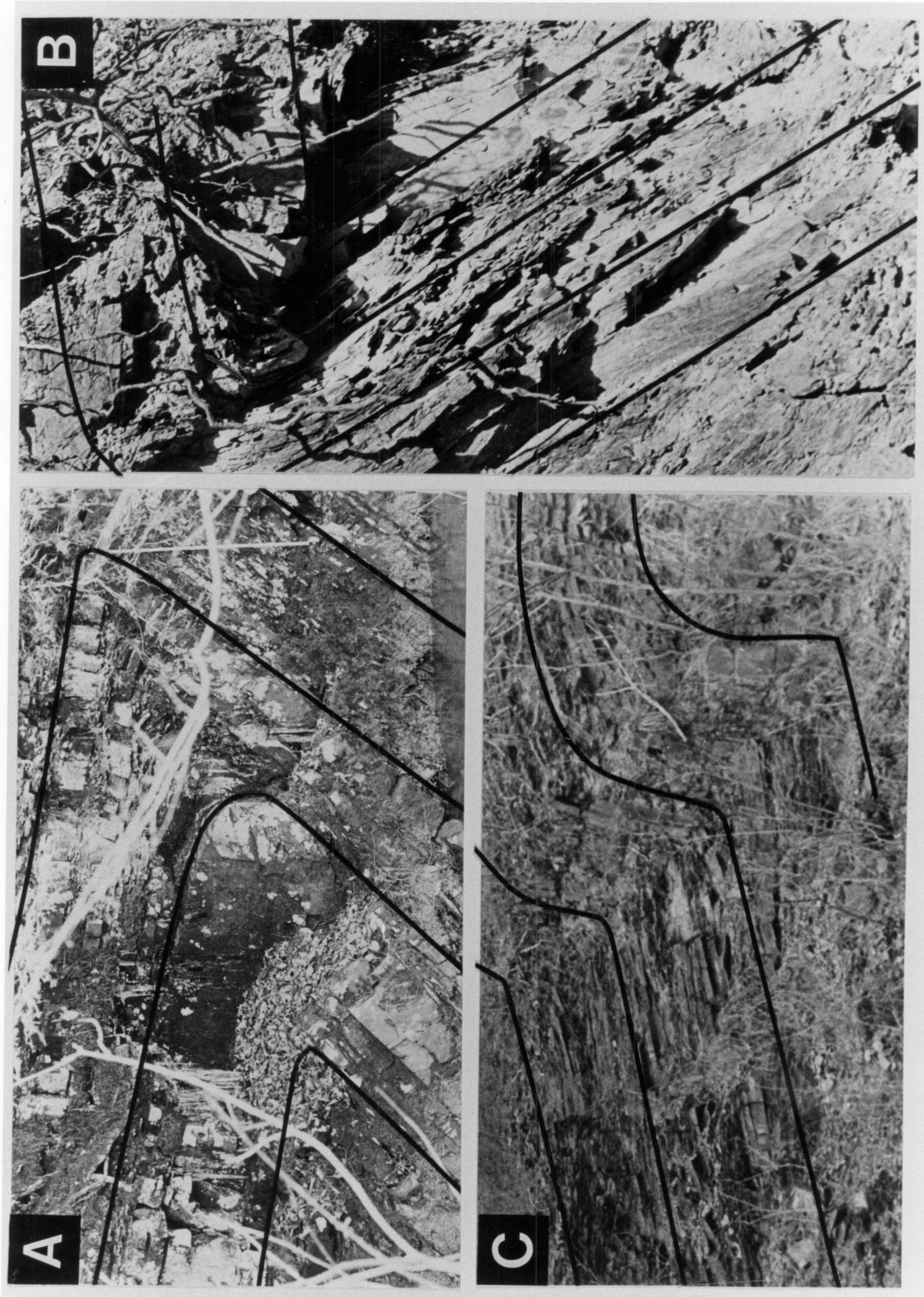

A
B
C

Fig. 18. Folds in the lower Brallier and Millboro shales.

a. Chevron folds in the overturned limb of the Supin Lick syncline.

b. Chevron folds in the overturned limb of the Supin Lick syncline.

c. Asymmetrical fold in the local culmination along state highway 259.


B
A
C

Second-order folds are also found in the Chemung and Hampshire formations on the northwestern limb of the Bergton anticline (Fig.19). Typically, these folds follow the trend of the major structure. However, a fold at the Hampshire-Chemung contact (just northwest of the fold shown in Fig.19) has an anomalous east-northeast trend (Fig.16).

Movement on mesoscopic thrusts located in the axis of the West Mountain syncline folds the thick-bedded Chemung sandstones into open upright anticlines and closely folded, overturned synclines (Fig.20). These cylindrical folds trend N05°E to due north, subparallel to the strikes of the three thrusts. In the footwall of the leading (westernmost) thrust, silty shales are folded into close chevron folds as a result of small-scale ramping brought about by drag on the thrust.

Faults

The three thrusts in the axis of the West Mountain syncline have an average attitude of N06°E/28°E and minimum displacements of 22, 25, and 20 meters for the leading, middle, and trailing thrusts, respectively. Their stratigraphic throw is a minimum of 31.5 meters (using the cumulative displacement of 67 meters and 28° dip on the thrusts to calculate the vertical component). The thick sandstone bed in the hanging wall of the leading thrust is unusually thick and coarse-grained; 400 meters to the west is an identical bed which dips 26° to the east. Assuming a constant dip over the 400 meters, this implies that the maximum stratigraphic throw could be as great as 195 meters.

Fig. 19. Second-order fold in the Chemung sandstones on the northwestern limb of the Bergton anticline.

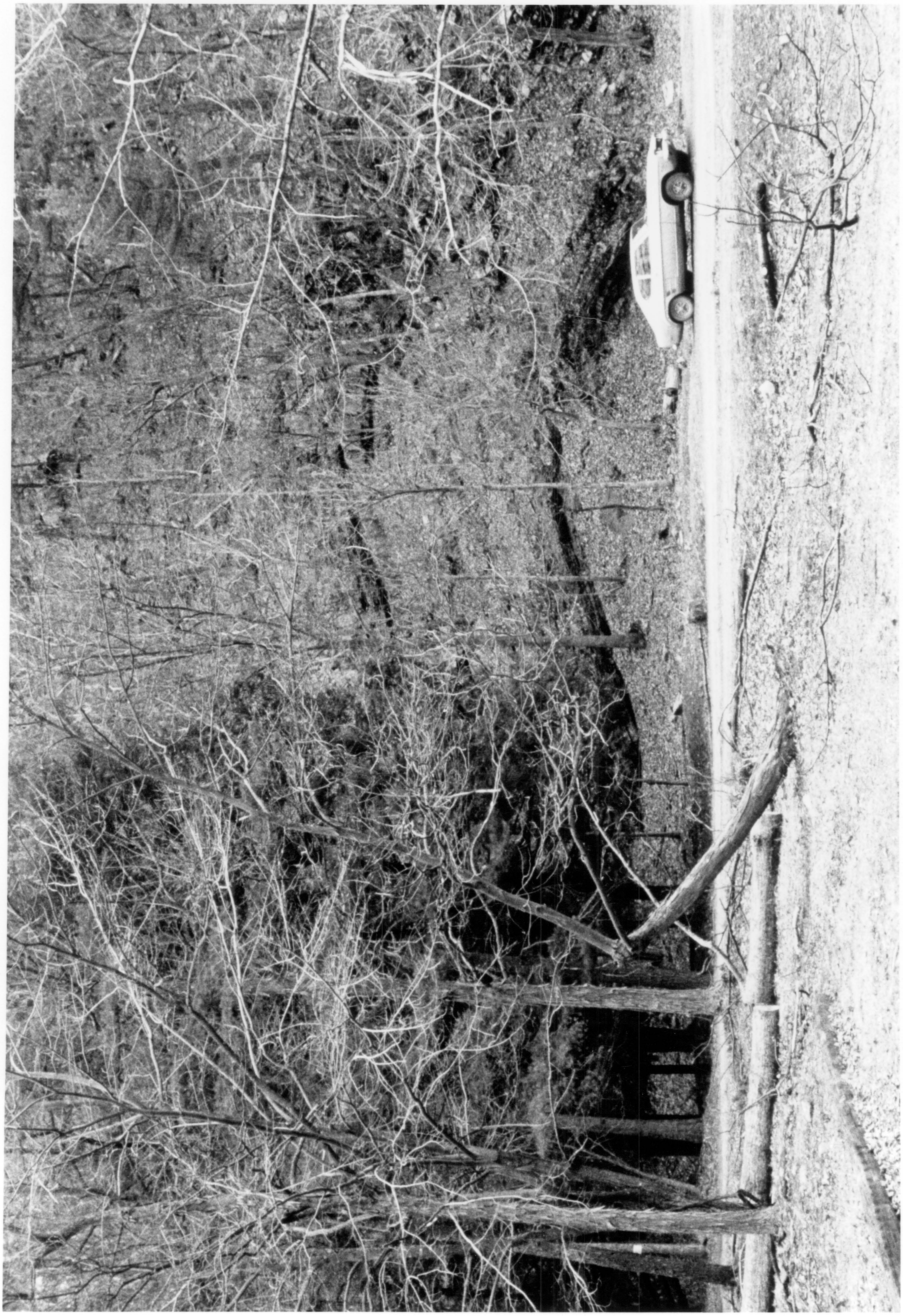
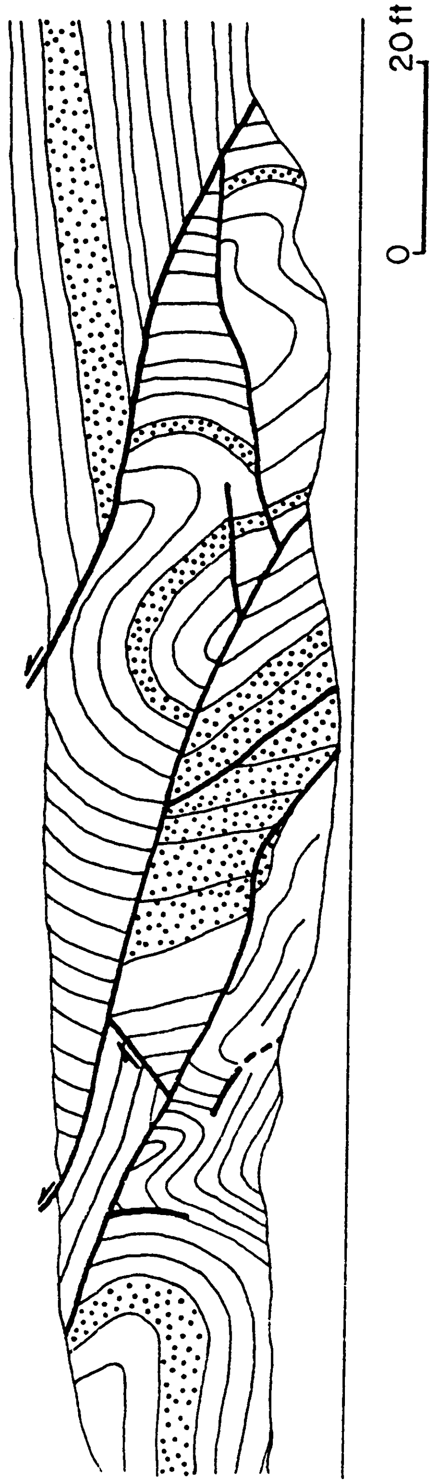


Fig. 20. Mesoscopic folds and thrusts in the Chemung formation (along state route 820) in the trough of the West Mountain syncline. Stippled beds are sandstones.


0
20 ft

Immediately to the southeast, another small thrust is responsible for a strongly overturned section of Oriskany sandstone on the northwest limb of the Adams Run anticline (Fig.21).

Near the center of the north-trending portion of the Bergton anticline, horizontal slickensides on east-west trending joint sets exhibit sinistral strike-slip motion (Fig.22). Additionally, the axis of the Bergton anticline is offset with the same relative sense of movement. These relationships occur along an east-west trending photolineament associated with the Little Dry River valley (Fig.23) and suggest that this photolineament is the geomorphic expression of a sinistral, strike-slip fault. Two other zones of northwest trending photolineaments coincide with the points of maximum curvature where the axes of the West Mountain syncline and the Bergton anticline enter and exit the Parsons Lineament.

Joints

The joints within the Bergton anticline belong to two principal sets: a pervasive east-west trending set and a set whose orientation varies with structural position (Fig.24). Both sets are near vertical regardless of the dip of bedding, implying that these fractures are late-stage features. The gouge-like horizontal slickensides found along the Little Dry River lineament (Figs.22,23) imply the east-west trending sets are Alleghenian features because they accommodate movement on second-order shears in the CSD. East-west trending joint sets in the Appalachian

Fig. 21. Overturned section of Oriskany sandstone on the northwestern limb of the Adams Run anticline.

Fig.22. Horizontal slickensides on east-west trending joint faces indicating left-lateral slip along the Little Dry River valley photolineament.

Fig. 23. Landsat image with geologic overlay.

GEOLOGY OF THE BROADTOP SYNCLINORIUM IN ROCKINGHAM COUNTY, VIRGINIA

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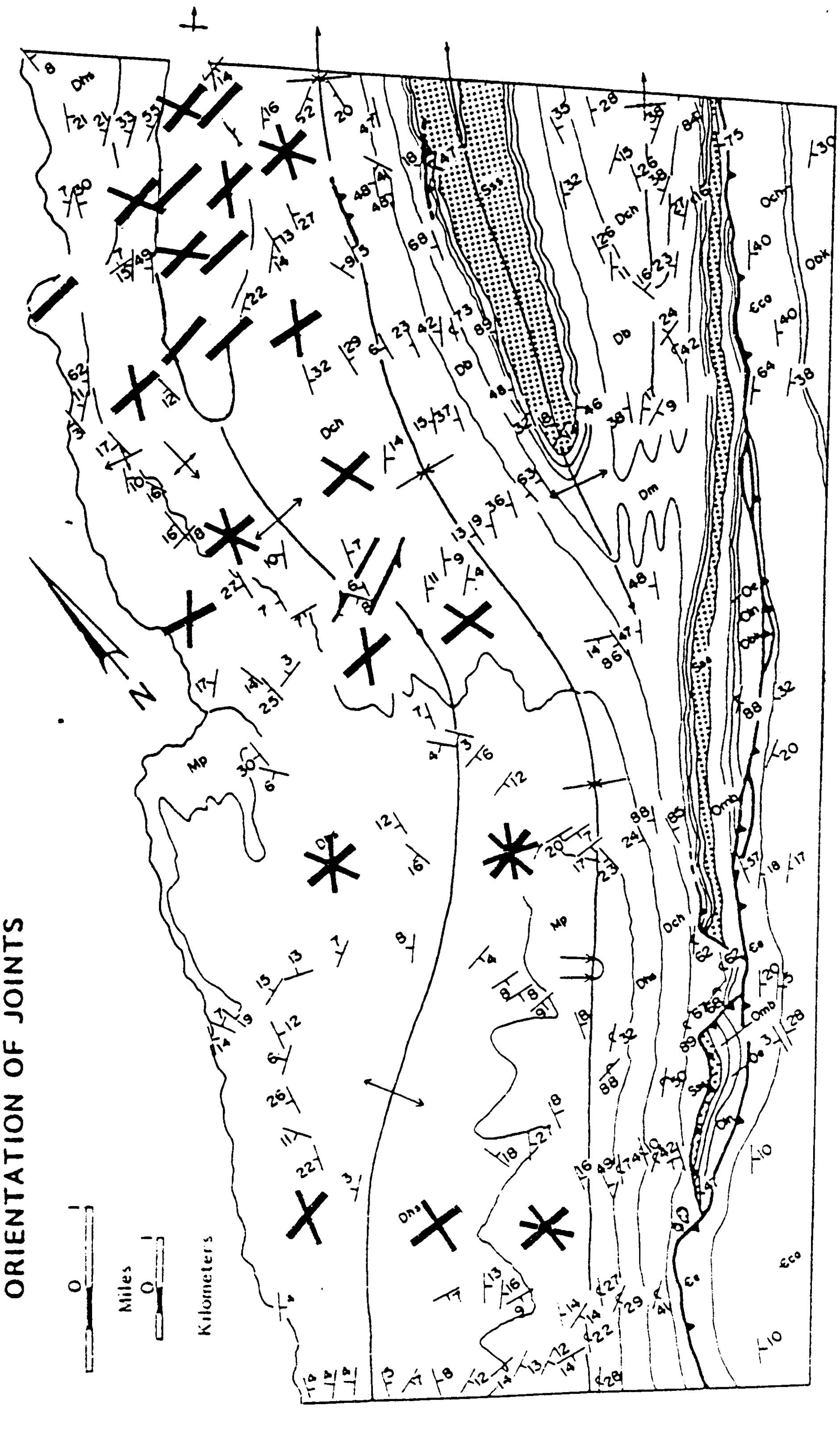
Fig. 24. Orientation of near vertical, systematic joint sets in the Bergton anticline.



ORIENTATION OF JOINTS

Plateau "formed late in the folding history, possibly as shear joints where structures were effectively locked (Dean et. al.,1982)".

Age relations can be determined from several field criteria: a younger joint will change orientation immediately adjacent to an older joint set so that the fracture may intersect the free surface of the older joint at a right angle (Wheeler and Holland,1978). Such behavior requires the joint with the hooked surface to be younger. If the walls of the older joint are cemented together, then a younger joint will cross-cut the plumose structure or other fine details found on the face of the older joint (Wheeler, personal communication,1981).

Age relations for joints in the Bergton anticline are somewhat unclear. In 70% of the outcrops within the Chemung Formation where age relations were observable, these criteria indicate that the east-west joint set predates the other set. The relatively ambiguous age relations suggest that both sets occurred very nearly at the same time during the Alleghenian orogeny.

FRACTURE INTENSITY

The spacing of systematic joint sets records the non-penetrative strain experienced by the rock during deformation. The fracture intensity is easily calculated from the perpendicular spacing between joint faces of a single set and bedding thickness (Dixon,1979; Wheeler and Dixon,1980). Three spacing measurements per set were recorded at each outcrop. Fracture intensity for a single set of joints is calculated using the cylindrical algorithm developed by Wheeler and Dixon (1980):

$$I = \frac{(n)(2\pi)(\text{thickness}/2)}{2\pi(\text{thickness}/2)(\text{spacing1}+\text{spacing2}+\ldots\ldots.)} = \frac{n}{(\text{spacing1}+\text{spacing2}+..)}$$

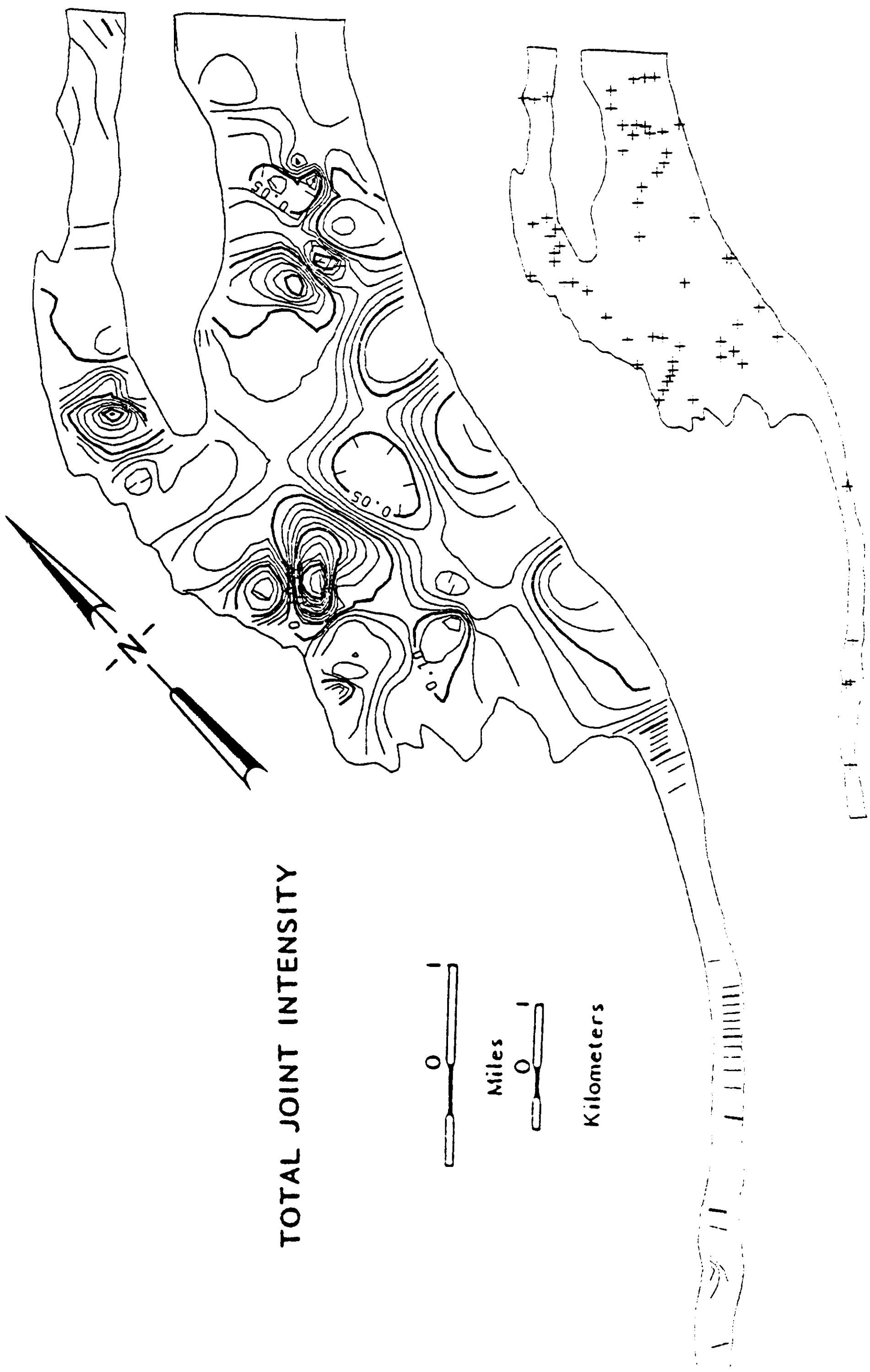
where n is the number of joints used in the analysis. The total intensity for each outcrop is simply the sum of the individual intensities for all the sets at that outcrop. The units of intensity are cm^2/cm^3.

Distributions of Fracture Intensities

Joint intensities, measured within the Chemung Formation of the Bergton anticline, document the fracture history of the Parsons Lineament and its relation to the development of closure on the Bergton anticline.

Variations in Total Intensity. Total intensities for all joint sets show a significant increase near the center of the Chemung outcrop pattern (Figs.25,26a). A view perpendicular to strike and parallel to the Parsons Lineament (Figs.25,26b) shows a significant increase in fracture intensity across the CSD. Lastly, in a view parallel with the second order shear fault observed in the Little Dry River valley, the peaks in intensity coincide not only with the known strike-slip fault, but also with the photolineaments parallel to it (Figs.25,26c). The peaks in joint intensity parallel to these other lineaments and the anomalous west-northwest trending fold at the Chemung-Hampshire contact (Fig.25)

Fig. 25. Contour map of total intensity for all joint sets in the Chemung Formation (smaller outline shows location of data points).



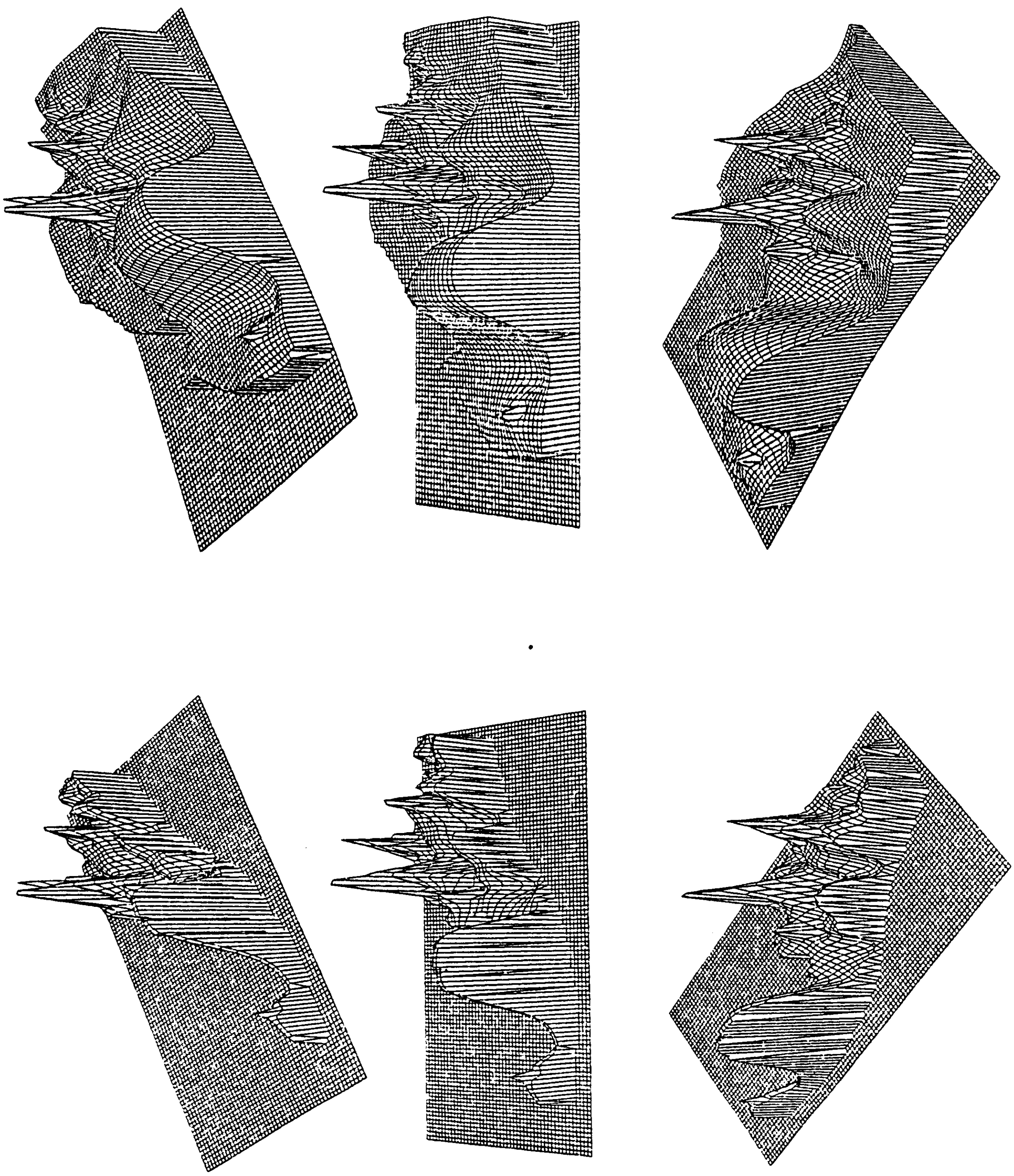
TOTAL JOINT INTENSITY

Fig. 26. Transect plots of total intensity for all joint sets in the Chemung Formation.

a. Looking north, with contacts and without, showing mathematically-generated trends.

b. Looking perpendicular to strike and parallel to the Parsons lineament - note increase within lineament.

c. Looking parallel to second-order shears, note alignment of peaks with known strike-slip faults and photolineaments.



a b c

suggests that these lineaments are also second-order shears associated with the Parsons Lineament.

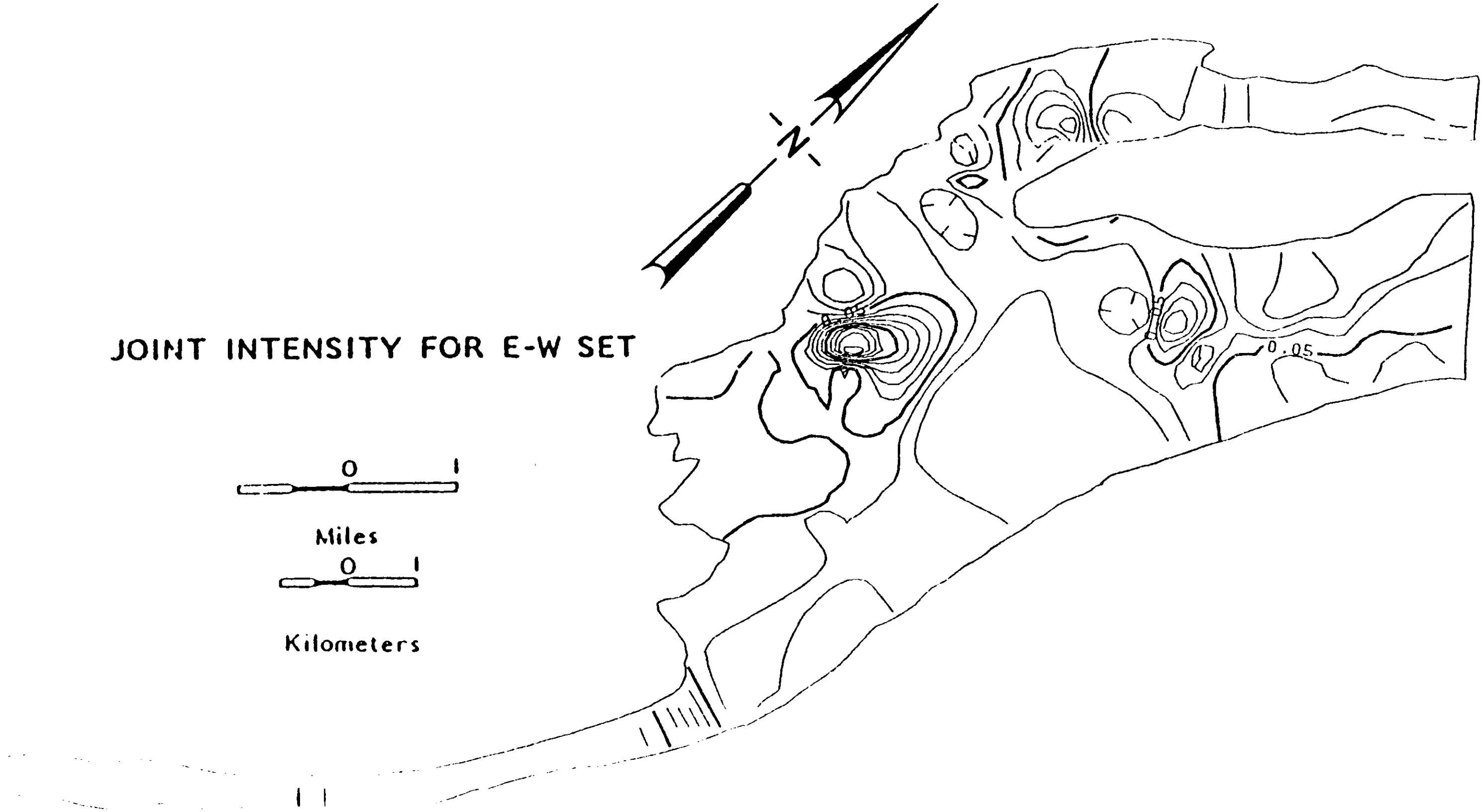
Variations in East-West Trending Joint Intensities. East-West trending joints define the increase in total intensity associated with the Parsons Lineament (Figs.27,28a). These east-west trending joint sets are responsible for the alignment of peaks associated with the second-order shears in the Parsons Lineament (Figs.27,28b, and 28c).

Variations in Intensity of Regionally Variable Joint Sets. The latest stage joints measured in this study have a more irregular distribution of peaks than the east-west trending set (Figs.29,30a). Nevertheless, the peaks in intensity of these joints are largely centered over the nose of the Bergton anticline (Figs.29,30b, and 30c).

DISCUSSION

The age relations of joints and their distribution of fracture intensities establish the Parsons CSD as the dominant structural feature controlling the development of closure on the Bergton anticline. A positive magnetic anomaly through this portion of Rockingham County (Zietz et. al.,1977,1980) may represent a basement fracture transverse to the structural grain of the Appalachians (Pilant and Likiak,1982). Additionally, the Oriskany horizon in the Crabb Run Gas #2 and #3 George Washington Forest exploratory wells are at -4435 and -4599 feet, respectively, as opposed to -1129 and -2039 for the shallowest and

Fig.27. Contour map of the intensity for the east-west trending joint sets in the Chemung Formation.



JOINT INTENSITY FOR E-W SET

Fig. 28. Transect plots of intensity for east-west trending joint sets.

a. Looking north, with contacts and without, showing mathematically-generated trends.

b. Looking perpendicular to strike and parallel to the Parsons lineament - note increase within lineament.

c. Looking parallel to second-order shears, note alignment of peaks with known strike-slip faults and photolineaments.

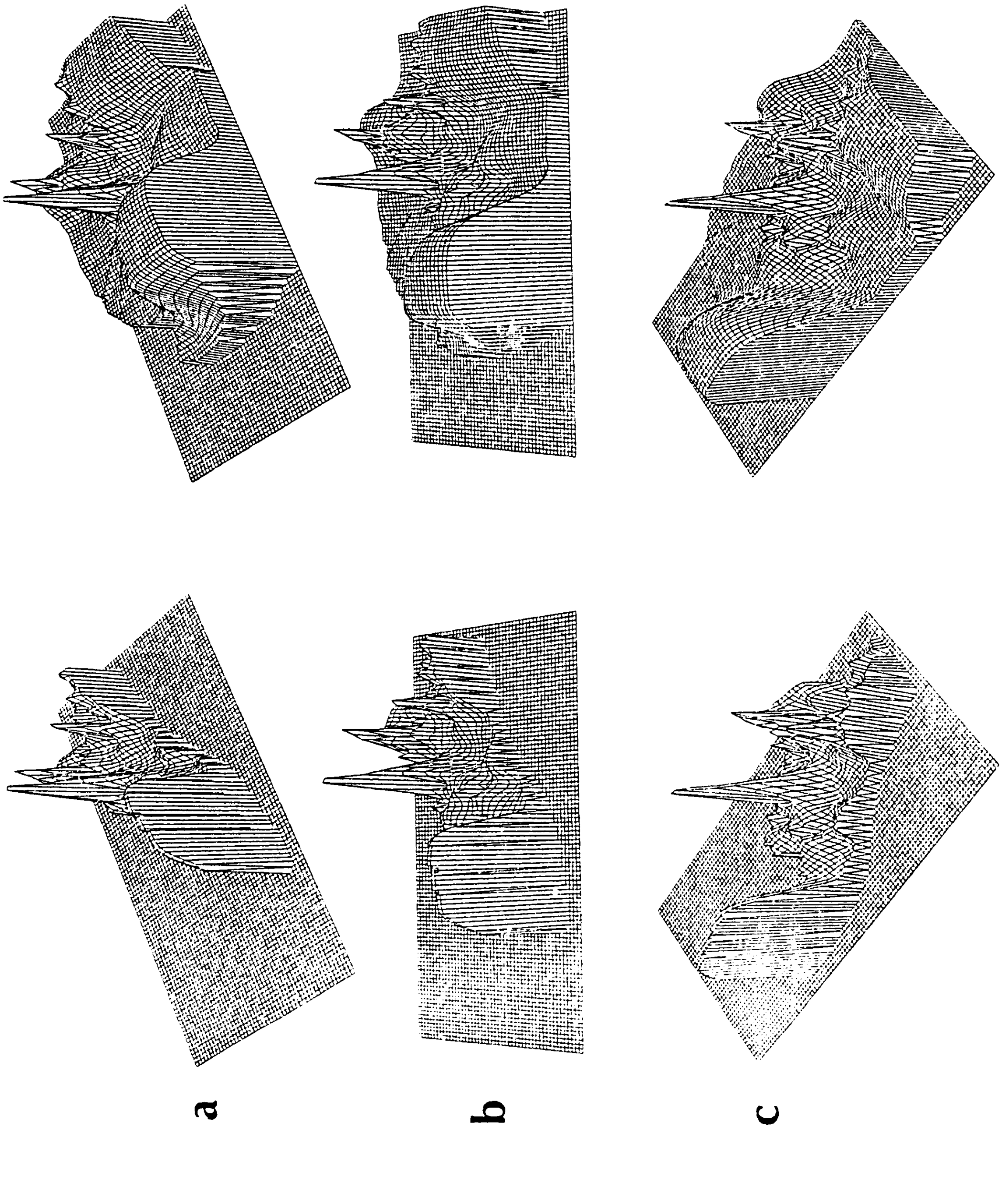
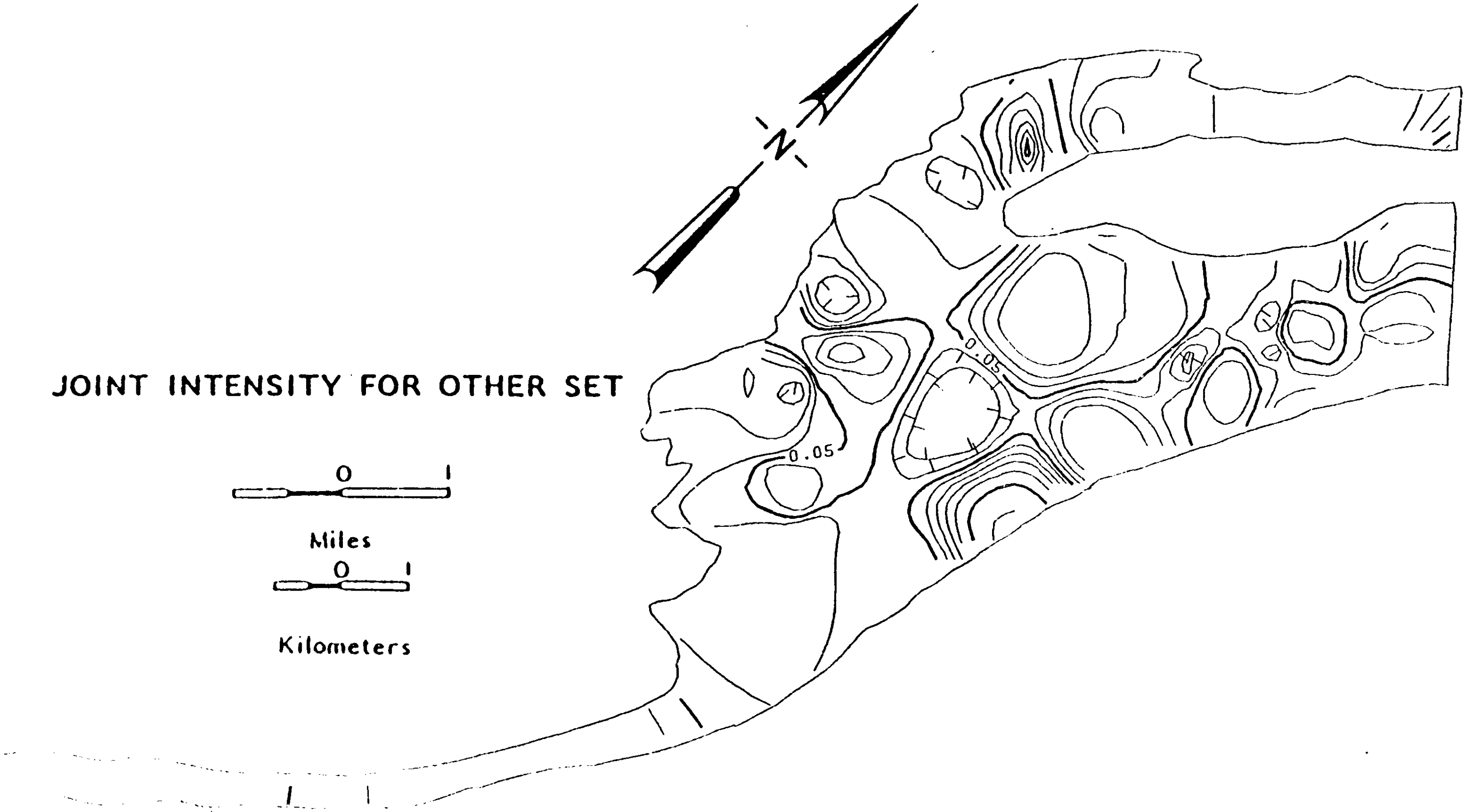

a
b
c

Fig. 29. Contour map of intensities for regionally variable joint sets in the Chemung Formation.



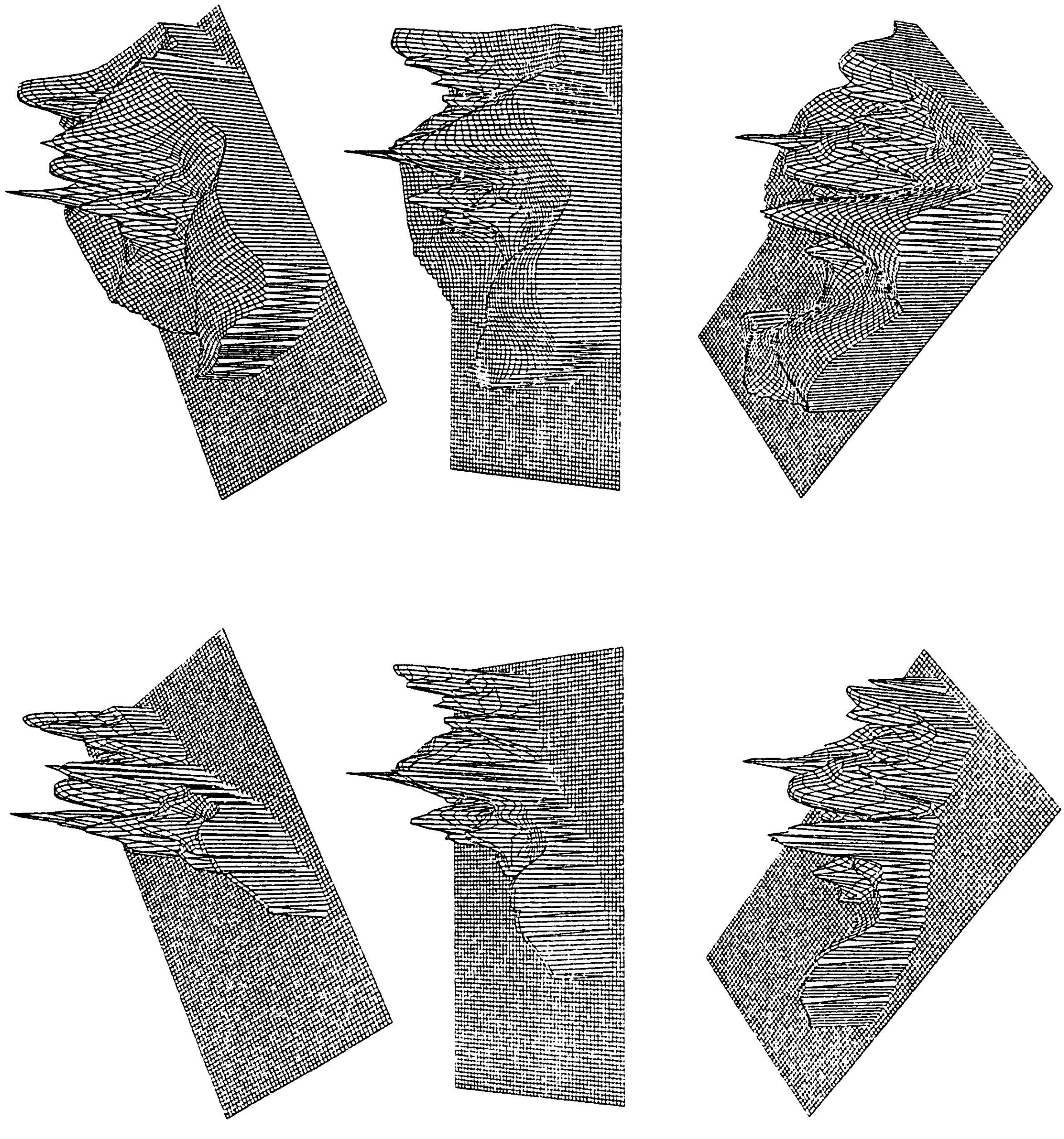
JOINT INTENSITY FOR OTHER SET

Fig. 30. Transect plots of intensity for regionally variable joint sets in the Chemung Formation.

a. Looking north, with contacts and without, showing mathematically-generated trends.

b. Looking perpendicular to strike and parallel to the Parsons lineament - note increase within lineament, and over culmination of Bergton anticline.

c. Looking parallel to second-order shears, note weak alignment.

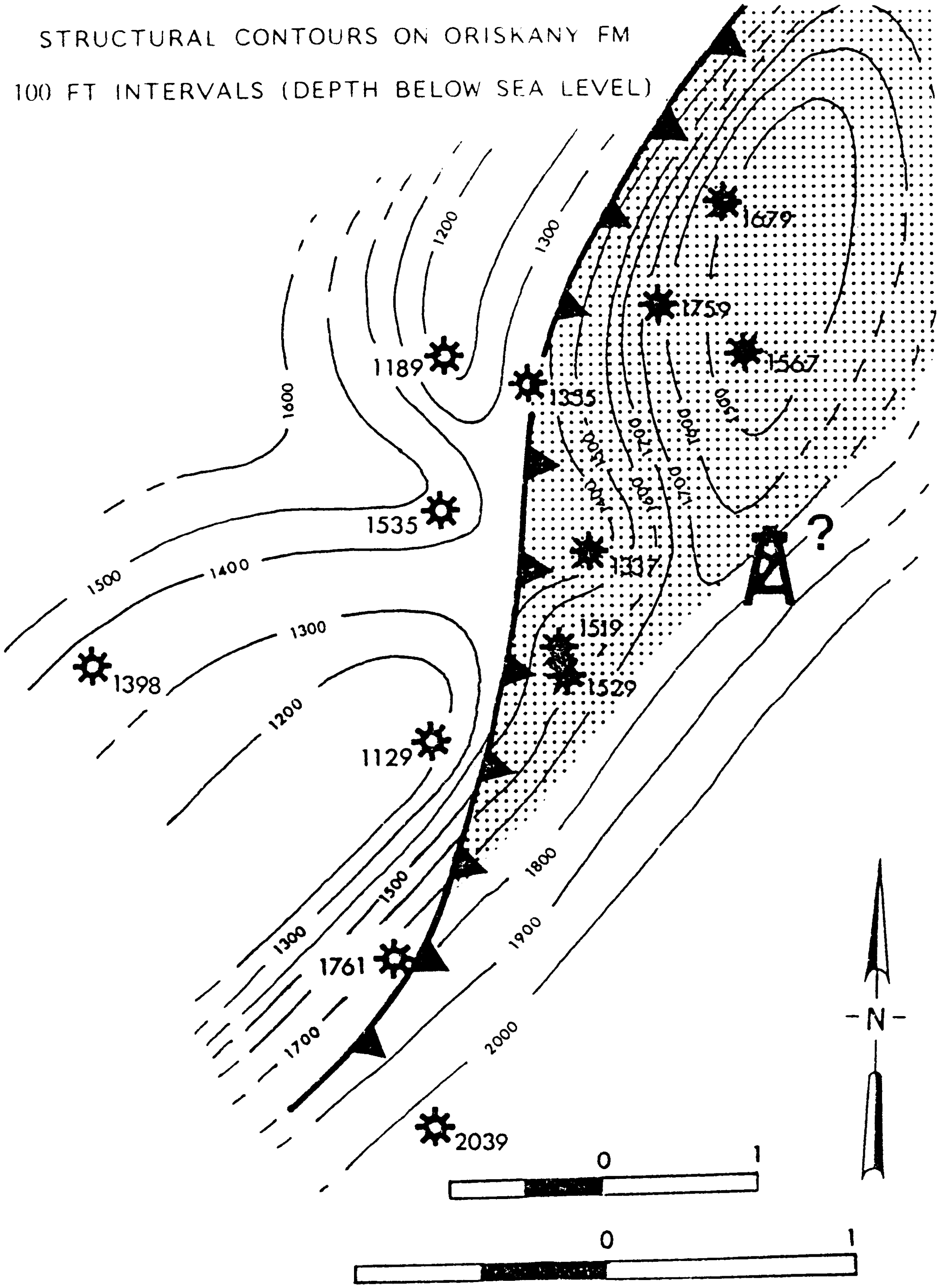


a b c

deepest Oriskany horizons in the Bergton Gas field (Fig.31). All available information from this study indicates that a northeast-facing lateral ramp in the Cambrian carbonates exists beneath the linear zone of fold plunge depression that constitutes the Parsons Lineament within the Valley and Ridge Province.

The northerly-trending folds within the Brallier shales and thrust-generated folds more closely parallel the CSD than do regional folds, suggesting some lateral movement on the ramp. From data collected in the Shell #1 Wetzel deep test, the Bergton anticline is known to have a basal decollement which places Cambrian Conococheaque over Middle Ordovician Stones River limestones (Virginia Division of Mineral Resources well files). The lateral ramp allowed the differential movement necessary to accommodate the rise of the Adam's Run anticline, resulting in the profound left-lateral offset of structural trends across the Parsons Lineament and its second-order shears. Structural contours on the Oriskany horizon confirm Young and Harnesberger's (1955) contention that regional cross-folds are, in part, responsible for productivity in the Bergton field. The depression in the contours (Fig.31), the zone of fold plunge reversal in the mesoscopic folds of the Brallier shales (Fig.16), and the unique kinked folds within the Chemung formation (Fig.17) indicate lateral compression. These relations suggest that closure on the Bergton anticline results from movement across the lateral ramp whose surficial expression is the Parsons Lineament.

Fig. 31. Structural Contours on the Oriskany sandstone horizon. Contour interval is 100 feet (depth below sea level). Stippling shows known extent of gas field. Blackened well symbols are producers, oil derrick shows approximate location of New Frontier Energy's recent (Jan.'83) exploratory well (reportedly dry-reliable information presently unavailable).


STRUCTURAL CONTOURS ON ORISKANY FM
100 FT INTERVALS (DEPTH BELOW SEA LEVEL)
1200
1300
1600
1500
1400
1300
1200
1500
1300
1700
1800
1900
2000
1189
1355
1535
1398
1129
1761
2039
1679
1759
1567
1337
1519
1529
?
N
0
1
0
1

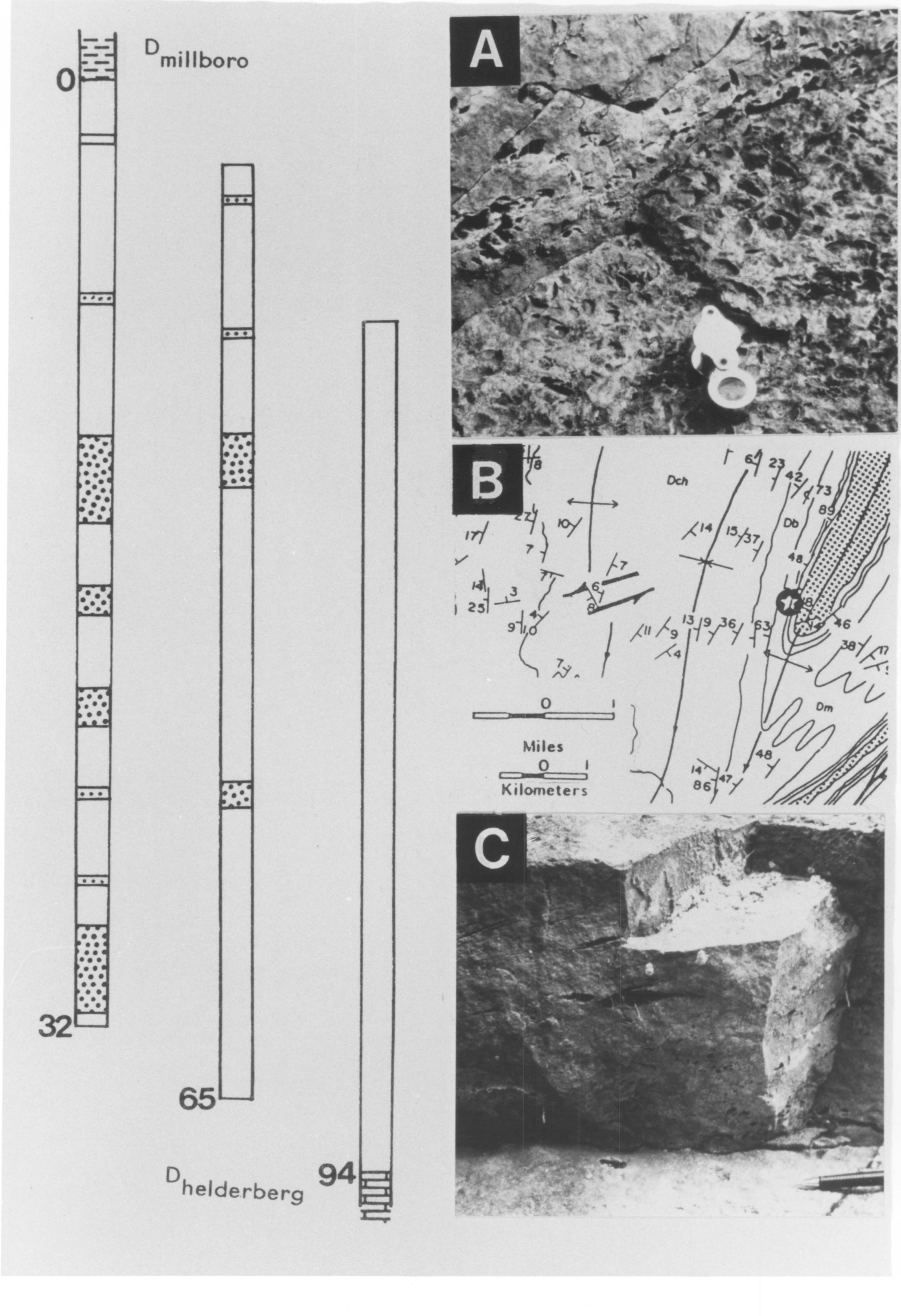
Porosity in the reservoir rock of the Bergton field (Oriskany sandstone) is distributed in isolated layers of relatively coarse-grained, fossiliferous layers (Fig.32) which have matrix porosities of 10.9-12.2° and an air permeability of 14.7 md. Porosity is intergranular and moldic (Fig.32) formed through leaching of the brachiopods. Fracturing can link these porous horizons and greatly increase the effective permeability of the field. CSDs are a powerful exploration tool because they can create closure and impose an additional episode of intense fracturing on an area. Such fracturing not only affects the reservoir rock but also may serve to establish migration pathways in adjacent source rocks.

Fig. 32. Distribution of porous horizons (stippled) in the Devonian Oriskany sandstone of the Fulks Run section.

a. Moldic porosity after spiriferid brachiopods.

b. Location of section.

c. Cross-beds and moldic porosity in Oriskany sandstone.


D millboro
0
32
65
94
D helderberg
A
B
Dch
Db
Dm
Miles
Kilometers
C

REFERENCES CITED

Bick, Kenneth F., 1960, Geology of the Lexington Quadrangle, Virginia : Va. Division of Mineral Resources, Rept. of Invest. 1, 40 pp.

Brent, William B., 1960, Geology and Mineral Resources of Rockingham County : Va. Division of Mineral Resources, Bull. 76, 174 p.

Beutner, E.C., and Diegel, F.A., 1983, Determination of Fold Kinematics from Syntectonic Fibers in Pressure Shadows, Martinsburg Slate, New Jersey : pre-print.

Butts, Charles, 1933, Geologic map of the Appalachian Valley in Virginia: Va. Geol. Survey, Bull. 42, 56 p.

Butts, Charles, 1940, Geology of the Appalachian Valley in Virginia : Va. Geol. Survey, Bull. 52, pt. 1, 568 p.

Cardwell, D.H., Erwin, R.B., and Woodward, H.P., 1968, Geologic Map of West Virginia, W. Va. Geologic Survey.

Cloos, Ernst, 1971. Microtectonics along the western edge of the Blue Ridge, Maryland and Virginia, Johns Hopkins Press, 234 p.

Cooper, B.N., 1955, Middle Ordovician rocks between Staunton and Strasburg, Virginia : Guidebook for Joint Field Conference, Harrisonburg, Virginia, Va. Division of Mineral Resources, pp. 22-33.

Cooper, B.N., 1960, Geology of the region between Roanoke and Winchester in the Appalachian Valley of western Virginia : Johns Hopkins Press, 84 p.

Dahlstrom, C.D.A., 1969, Balanced cross sections : Canadian Jour. Earth Sci., v. 6, pp. 743-757.

Dahlstrom, C.D.A., 1970, Structural geology in the eastern margin of the Canadian Rocky Mountains : Bull. Canad. Petrol. Geol., v.18, pp. 332-406.

Dean, S.L., Baranski, M., Bertoli, L., Kribbs, G., and Stephens, T., 1982, Regional fracture analysis in western Valley and Ridge and adjoining Plateau, West Virginia and Maryland (abs.) : Bull. Am. Assoc. Pet. Geol., v. 67, no. 3, p. 448.

Dixon, J.M., 1979, Techniques and Tests for measuring joint intensity: Ph.D. dissertation, West Virginia Univ., 144 pp.

Durney, D.W. and Ramsay, J.G.,1973. Incremental strains measured by syntectonic crystal growths: in Gravity and Tectonics (DeJong,D.A., and Scholten,R.,eds.), Wiley, New York : 67-96.

Edmundson,R.S.,1958, Industrial limestones and dolomites in Virginia, James River district west of the Blue Ridge : Va. Division of Mineral Resources Bull. 73, 137 pp.

Edmundson,R.S., and Young,R.S.1955, The Antietam-Beekmantown section in Shenandoah Valley, Virginia : Guidebook for Joint Field Conference, Harrisonburg area, Virginia, Va. Division of Mineral Resources,pp. 17-21.

Elliot, D.,1972, Deformation paths in structural geology: Geol. Soc. Amer. Bull., v. 83 , pp. 2621-2638.

Epstein, A.G., Epstein, J.B., and Harris, L.D.,1977, Conodont color alteration - an index to organic metamorphism: U.S.G.S. Prof. paper no.995.

Fara,M.,1971, The Burketown and associated klippen of the Staunton thrust, Augusta and Rockingham Counties, Virginia : in Lowry, W.D. (ed.), Contrast in style of deformation of the Southern and Central Appalachians of Virginia, VPI&SU Guidebook no.6, pp. 97-124.

Flewellen,B.N.,1950, Geology of Burketown Klippe and Vicinity, Harrisonburg Quadrangle, Augusta and Rockingham County, Virginia : M.S. thesis, Univ. Va., 83 p.

Gardner,D.A.C., and Spang,1973, Model studies of the displacement transfer associated with overthrust faulting : Bull. Can. Pet. Geol., v.21,no.4,pp.534-552.

Giles,A.W.,1927, The geology of Little North Mountain in northern Virginia and West Virginia : Jour. Geol., v.35,no.1,pp.32-57.

Gray,D.R.,1981, Compound tectonic fabrics in singly folded rocks from southwest Virginia, U.S.A. : Tectonophysics, v.78, pp.229-248.

Gray, D.R. and Durney, D.W.,1979, Investigation on the mechanical significance of crenulation cleavage : Tectonophysics, v.58 ,p. 35-79.

Gwinn, V.E.,1964, Thin-skinned tectonics in the plateau and northwestern Valley and Ridge provinces of the Central Appalachians: Geol. Soc. Amer. Bull., v.75 ,pp. 863-900.

Gwinn, V.E.,1970, Kinematic patterns and estimates of lateral shortening, Valley and Ridge and Great Valley provinces, central Appalachians, south-central Pennsylvania: in Fisher, G.W.(ed.), Studies of Appalachian geology; Central and Southern, Wiley - Interscience, New York : 127-146.

Harnesberger,W.T.,1950, Geology of the Bergton Area, Northwest Rockingham County, Virginia : M.S. Thesis, Univ. Va., 108 p.

Harris, L.D.,1979, Similarities between the thin-skinned Blue Ridge anticlinorium and the thin-skinned Powell Valley anticline : Geol. Soc. Amer. Bull., v.90, Part 1 ,pp. 525-539.

Harris, L.D., Dewitt, W., Jr., and Bayer, K.C.,1982, Interpretive seismic profile along I-64 from the Valley and Ridge to the Coastal Plain in Central Virginia : U.S. Geol. Surv. Oil and Gas Investigations chart OC-123.

Harris, L.D. and Milici, R.C.,1977, Characteristics of thin-skinned style of deformation in the Southern Appalachians, and potential hydrocarbon traps : U.S. Geol. Survey Prof. Paper, 1018,p. 1-40.

Holland,S., and Wheeler,R.L.,1977, Parsons structural lineaments, a cross-strike zone of more intense jointing in West Virginia (abs.) : Geol. Soc. America Abs. with Programs, v.9, pp. 147-148.

Jacobeen,F.,Jr., and Kanes,W.H.,1974, Structure of the Broadtop synclinorium and its implications for Appalachian structural style : Bull. Am. Assoc. Pet. Geol., v.58, pp. 362-375.

Jacobeen,F.,Jr., and Kanes,W.H.,1975, Structure of the Broadtop synclinorium, Wills Mountain anticlinorium and Alleghany Frontal zone : Bull. Am. Assoc. Pet. Geol., v.59, pp. 1136-1150.

LaCaze,J.A.,sm,1978, Structural analysis of the Petersburg structural lineament in the eastern Appalachian Plateau province, Tucker Co., West Virginia : M.S. Thesis, West Virginia Univ., 69 pp.

Lowry,W.D.,1971, Syntectonic sedimentation in the Shenandoah Valley : in Lowry,W.D.(ed.), Contrast in style of deformation of the southern and central Appalachians of Virginia, VPI&SU Guidebook no.6, pp. 125-140.

McColloch,G.H.,Jr.,1976, Structural analysis in the central Appalachian Valley and Ridge, Grant and Hardy Counties, M.S. Thesis, West Virginia Univ., 62 pp.

Mitra,S.,1982, Controls of deformation mechanisms and fracturing on local and regional hydrocarbon potential in the Central Appalachian overthrust belt (abs.): Bull. Am. Assoc. Pet. Geol., v.67, no.3, pp. 516.

Morris,A.P.,1981, Competing deformation mechanisms and slaty cleavage in deformed, quartzose meta-sediments : J. Geol. Soc. London, v.90, pp. 455-462.

Mullenax,R.H.,1975, Surface expression of the Parsons lineament, southwestern Tucker County, West Virginia : M.S. Thesis, West Virginia Univ., 62 pp.

Mullenax,A.C.,1981, Deformation features within the Martinsburg Formation in the St. Clair and Narrows thrust sheets, Giles County, Virginia : M.S. Thesis, VPI&SU, 131 p.

Mussman,B.,1982, The middle Ordovician Knox unconformity, Virginia Appalachians - transition from passive to convergent margin : M.S. Thesis, VPI&SU, 160 p.

Oder,C.R.L.,1927, Geology of the northcentral and northeastern portions of the Harrisonburg Quadrangle, Virginia : M.A. Thesis, Univ. Va., 178 p.

Perry,W.J.,Jr.,1978, Sequential deformation in the central Appalachians: Amer. Jour. Sci., v.278, pp. 518-542.

Pilant,W.L., and Likiak,E.G.,1982, Fracture zones in the basement and exposed crystalline rocks and possible expressions in the overlying and adjacent sedimentary rocks of the Valley and Ridge and Plateau province : Guidebook for 2nd meeting of ABIA, Knoxville, Tennessee, Fall 1981.

Rabchevesky,1963, Contribution to the geology of the Adams Run Anticline, Hardy County, West Virginia : M.S. Thesis, George Washington Univ.

Rader,E.K., and Perry,W.J.,Jr.,1976, Reinterpretation of the geology of Brocks Gap, Rockingham County, Virginia : Virginia Minerals, v.22, no.4, pp. 37-45.

Ramsay,J.G.,1967, Folding and fracturing of rocks : McGraw Hill, New York, 568 p.

Read,J.F.,1980, Carbonate ramp-to-basin transitions and foreland basin evolution, Middle Ordovician, Virginia Appalachians : Bull. Am. Assoc. Pet. Geol., v.64, p. 1575-1612.

Reks,I.J.,1981, Strain, mesoscopic structure and cleavage in the Pulaski thrust sheet, southwestern Virginia, M.S. Thesis, VPI&SU, 158 pp.

Rich,J.L.,1934, Mechanics of low-angle overthrust faulting as illustrated by Cumberland thrust block, Virginia, Kentucky, and Tennessee : Bull. Am. Assoc. Pet. Geol., v.18, p. 1584-1596.

Sites,R.S.,1978, Structural analysis of the Petersburg lineament, central Appalachians : Ph.D. Dissertation, West Virginia Univ., 274 pp. (Ann Arbor, Michigan, Univ Microfilms).

Simmons,N.G.,1983, Fracture intensities of systematic joints associated with the Parsons lineament in the Broadtop synclinorium, Rockingham County, Virginia : in Structural Analysis of the Valley and Ridge extension of the Parsons lineament, M.S. Thesis, VPI&SU (second paper).

Spears,D.B.,1983,Syntectonic fibers pressure fringes from the Massanutten synclinorium - implications for fold development : M.S. Thesis, VPI&SU.

Trumbo,D.B.,1976, The Parsons lineament, Tucker County, West Virginia : M.S. Thesis, West Virginia Univ., 81 p.

Wheeler,R.L.,1978, Fracture intensity predictions for eastern gas shales : Eastern Gas Shales Open-File Report 137, 78 pp., available from U.S. Department of Energy, Morgantown Energy Technology Center, Morgantown, West Virginia.

Wheeler,R.L.,1980, Cross-strike structural discontinuities -possible exploration tool for natural gas in Appalachian overthrust belt : Bull. of Am. Assoc. Pet. Geol., v.64, no.12, p. 2166-2178.

Wheeler,R.L., and Dixon,J.M.,1980, Intensity of systematic joints : methods and applications : Geology, v.8, pp. 230-233.

Wheeler,R.L., and Holland,S.M.,1978, Style elements of systematic joints - an analytic procedure with a field example : in O'Leary,D.W. and Earle, J.L., Proceedings of the Third International Conference on Basement Tectonics, pp. 393-404.

Wheeler,R.L.,Mullenax,R.H.,Henderson,C.D.,and Wilson,T.H.,1974, Cross-strike structural discontinuities, possible exploration tool in detached forelands (abs.) : Geol. Soc. America Abs. with Programs, v.8, p. 298.

Wheeler,R.L., and Sites,R.S.,1977, Field studies of Parsons and Petersburg structural lineaments, West Virginia (abs.) : Am. Assoc. Petroleum Geologists Bull., v.61, p. 840-481.

White,S.H., and Knipe,R.J.,1978, Microstructure and cleavage development in selected slates : Contrib. Mineral. & Petrol., v.66, pp. 165-174.

Wickman,J.S.,1973, An estimate of strain increments in naturally deformed carbonate rock : American Jour. Sci., v.273, p. 23-47.

Wilson,T.H.,1980, Cross-strike structural discontinuities - tear faults and transfer zones in the central Appalachians of West Virginia, Ph.D. dissertation, W. Va. Univ., 248 p.

Wise,D.U.,1982, Linesmanship and the practice of linear geo-art : Geol. Soc. Amer. Bull., v.93, no.9, pp. 886-888.

Young,R.S., and Harnesberger,W.T.,1955, Geology of Bergton gas field, Rockingham County, Virginia : Bull. Am. Assoc. Pet. Geol., v.39, no.3, pp. 317-327.

Young,R.S., and Rader,E.K.,1974, Geology of the Woodstock, Wolf Gap, Conicville and Edinburg quadrangles, Virginia : Va Division of Mineral Resources Rept. Inv., no.35, 67 p.

Zietz,I., Calvert,J.L., Johnson,S.S., and Kirby,J.R.,1977, Aeromagnetic map of Virginia : U.S.G.S. Pub. Map GP-916.

Zietz,I., Gilbert,F.P., and Kirby,J.R.,Jr.,1980, Aeromagnetic map of Delaware, Maryland, Pennsylvania, West Virginia, and parts of New Jersey and New York : U.S.G.S. Pub. Map GP-927.

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