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THE ROLE OF MACROSCALE THRUSTS IN THE DEFORMATION OF THE ALLEGHANIAN ROOF SEQUENCE IN THE CENTRAL APPALACHIANS: A RE-EVALUATION

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ABSTRACT. The roof sequence to the blind Alleghanian foreland thrust duplexes of the central Appalachians in Maryland, Virginia, and West Virginia is commonly interpreted to be dominantly deformed by macroscale thrusts. The present contribution argues that these faults are not abundant because: (1) Most geologic map data indicate that macroscale thrusts are not abundant in the roof sequence. (2) A prediction that thrusts are ubiquitous proves incorrect when tested with a set of seismic reflection data. (3) Thrusts are not common along strike for the roof sequence in Maryland and Pennsylvania. (4) The upper part of the roof sequence, which lacks the previously interpreted abundant macroscale thrusts of the lower part of the roof sequence, also lacks compensatory deformation at the micro- and outcrop scales. (5) If gas fields are indicators of macroscale-thrust frequency, their limited distribution implies that the faults are rare. This revised interpretation has three major implications: (1) Much less deformation is partitioned at the macroscale in the roof sequence, and no cross section through the central Appalachians can be balanced without the inclusion of shortening by structures smaller than the scale of the cross section, where the cumulative effect of outcrop-scale deformation is the most difficult to quantify. (2) Comparisons of the previous structural interpretations with abundant macroscale thrusts to analog models and shortening assessments of those macroscale structural profiles by fractal analysis should be reconsidered. (3) The roof sequence is not the displacement sink for the 60+ km translation of the North Mountain thrust sheet from the hinterland.

INTRODUCTION

The deformed Paleozoic sedimentary rocks of the central Appalachian foreland in the contiguous parts of Maryland, Virginia, and West Virginia contain a thrust belt characterized by blind duplexes beneath a roof sequence (figs. 1, 2) decoupled by a roof detachment in the Martinsburg Formation. The fundamental kinematic problem for a blind duplex is the shortening response of the overlying roof sequence to formation of the underlying blind faults (Dunne and Ferrill, 1988; Geiser, 1988a; Jadoon, Lawrence, and Lillie, 1994). A roof sequence either deforms in advance of the blind thrusts by forethrusting, deforms coevally above the blind thrusts by local compensation, or is translated hinterlandward along blind thrusts by backthrusting. In the central Appalachians, opinions converged in mid-1980's toward one geometric configuration for forethrusting (Knotts, Buckley, and Dunne, 1985; Kulander and Dean, 1986; Mitra, 1986): A roof sequence of upper Ordovician to Pennsylva-

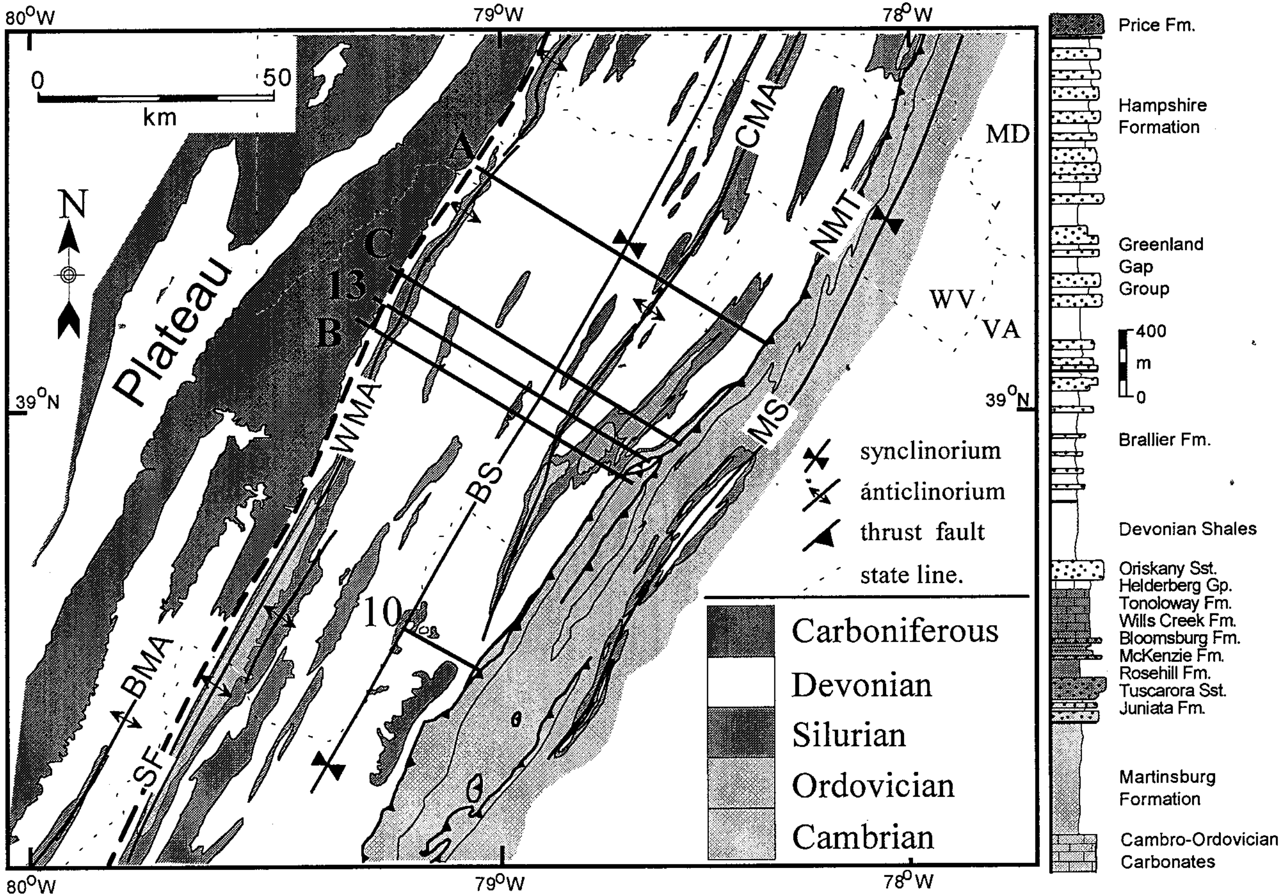


Fig. 1. Geologic map of central Appalachians for a portion of Maryland (MD), Virginia (VA), and West Virginia (WV) with a stratigraphic column that highlights the stratigraphy of the roof sequence from the upper Ordovician Juniata Formation to the Mississippian (Carboniferous) Price Formation. BMA—Browns Mountain anticline; SF—Alleghany structural front; WMA— Wills Mountain anticlinorium; BS—Broadtop synclinorium; CMA Cacapon Mountain—Adams Run anticlinorium; NMT—North Mountain thrust; MS—Massanutten synclinorium; A, B, and C—location of section lines in figure 2; 10—location of figure 10; 13—location of figure 13.

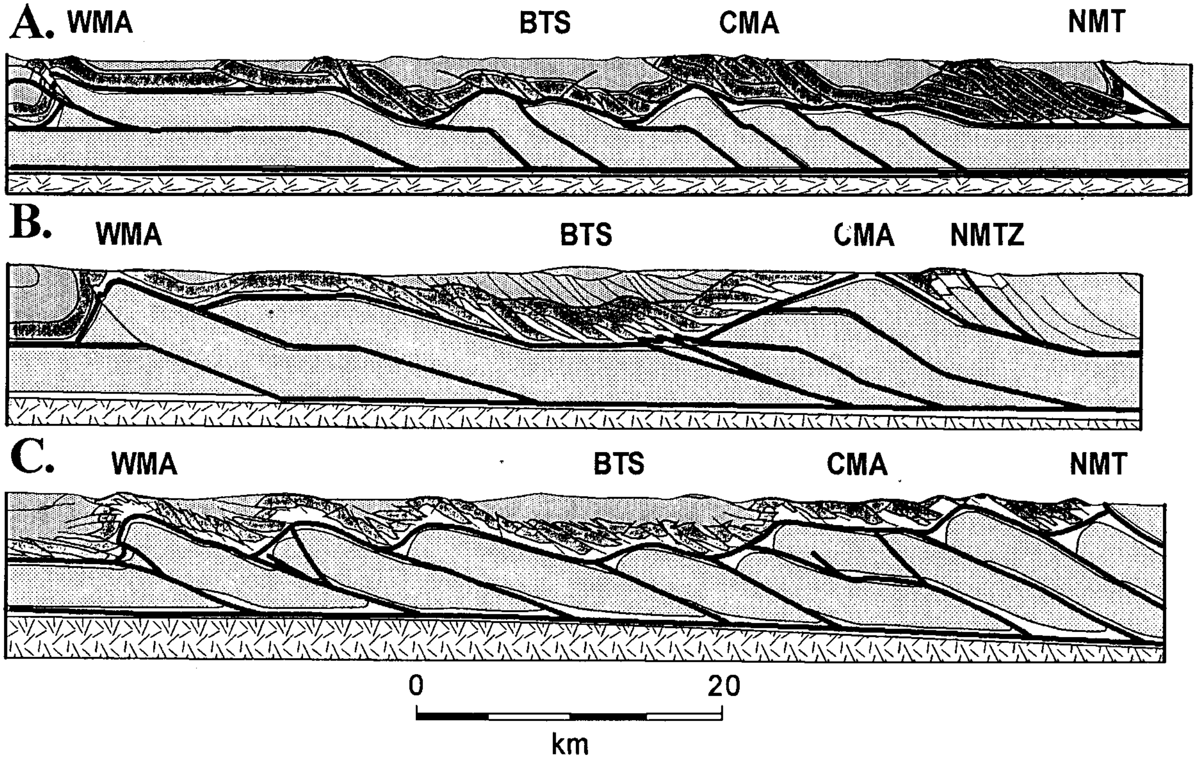


Fig. 2. Regional cross sections for the central Appalachians; for locations see figure 1. (A) modified from Knotts and others (1985), (B) modified from Mitra (1986); and (C) modified from Kulander and Dean (1986). WMA—Wills Mountain anticlinorium; BTS—Broadtop synclinorium; CMA—Cacapon Mountain—Adams Run anticlinorium; NMT or NMTZ—North Mountain thrust. Light gray—Cambro-Ordovician carbonates, dark gray—lower part of roof sequence with upper Ordovician Juniata Formation to lower Devonian Oriskany Sandstone, and medium gray—middle Devonian to Mississippian rocks of upper part of roof sequence.

nian rocks deformed primarily by macroscale thrusts with additional shortening contributions from outcrop-scale structures and microscale deformation mechanisms. This interpreted configuration indicated that shortening by macroscale imbrication in the roof sequence with subsidiary small-scale structures matched the shortening by the underlying blind thrusts (figs. 1, 2). Achieving this match is a non-trivial problem because blind thrust systems shorten the Cambro-Ordovician carbonates about 40 percent, or 40 to 50 km (Billman, Dunne, and Johnston, 1989; Wilson and Shumaker, 1992). Further, some workers (Kulander and Dean, 1986; Mitra, 1986) believe that the roof sequence also accommodates a 60+ km displacement (Evans, 1989) by the North Mountain thrust sheet from the southeast (figs. 1, 2). If this supposition is true, a roof sequence now only 50 to 75 km wide absorbed much of 100+ km of displacement (figs. 1, 2). Layer-parallel shortening by microscale deformation is only 10 to 20 percent, accommodating 5 to 14 km shortening (Bowen, 1985; Dunne and others, 1988; Ferrill and Dunne, 1989; Nair and others, 1991; Couzens and others, 1993; Onasch, 1994). Additionally, layer-parallel shortening of 5 to 10 percent across the 250 km width of the Appalachian Plateau to the northwest (fig. 1) accommodated an additional 12 to 25 km of shortening during forethrusting (Engelder and Engelder, 1977; Engelder, 1979; Engelder and Geiser, 1979; Geiser, 1988a,b). Outcrop-scale deformation is locally intense but does not account for the remaining 70 to 85 km of shortening (Cloos, 1951; Perry, 1971, 1978a; Geiser, 1974; Perry and DeWitt, 1977; Lessing, 1987; Mitra, 1987; Ferrill and Dunne, 1989; Markley and Wojtal, 1990; Meyer and Dunne, 1990; Scott and Dunne, 1990). Thus, macroscale thrusts are almost a necessity if the roof sequence accommodated over 100 km of shortening.

Common subsequent usage demonstrates the popularity of this thrust-dominated configuration for roof-sequence deformation. The geometry and abundance of macroscale faults are a focus of some field trips across the region (Spencer, Bell, and Kozart, 1989; Lessing, Dean, and Kulander, 1991), define a standard of comparison for analog modeling (Liu and Dixon, 1990, 1991), provide a basis for determining whether regional shortening is fractal (Wu, 1993), and provide an example for determining whether duplexes develop with a fractal relationship between frequency and displacement (Wojtal, 1994). In contrast, the purpose of this contribution is to demonstrate that macroscale thrusts play a much lesser role in shortening the roof sequence. This result will be used: (1) to re-emphasize the contribution of deformation at scales smaller than regional cross sections for the central Appalachians and other blind thrust belts, and (2) to reconsider whether the roof sequence accommodates the displacement from the North Mountain thrust sheet.

REGIONAL GEOLOGY

The Paleozoic stratigraphy of the central Appalachian foreland (figs. 1, 2) consists of five lithostructural units (Currie, Patnode, and Trump, 1962; Wiltschko and Chapple, 1977; Kulander and Dean, 1986). Lower Cambrian and older rocks form the autochthonous base to the blind foreland thrust belt (Perry, 1971, 1978a). The Waynesboro Formation is inferred to contain the floor thrust. The blind thrust systems or duplexes deform Cambro-Ordovician carbonates with a roof thrust in the upper Ordovician Martinsburg Formation. The upper Ordovician to Pennsylvanian rocks above this detachment constitute the roof sequence for the blind duplexes.

The Alleghanian foreland thrust belt consists of two provinces: the Valley and Ridge province to the east is separated from the Appalachian Plateau province to the west by the Alleghany structural front (fig. 1). The Valley and Ridge province to the east of the North Mountain thrust largely exposes Cambro-Ordovician carbonates at the surface and is referred to as the Great Valley. The western part of the Valley and Ridge between the North Mountain thrust and the Structural Front exposes Ordovician to Carboniferous strata at the surface. The present paper is primarily concerned with the latter, although deformation to the east and west will also be discussed.

Kulander and Dean (1986) and Mitra (1986) reached different conclusions about the geometry of blind duplexes in the Cambro-Ordovician carbonates, although both had access to proprietary seismic data (fig. 2). Kulander and Dean (1986) interpreted the data to indicate that duplexes consist of numerous horses with relatively small displacements (fig. 2C). Mitra (1986) believed that horses are less abundant but have relatively large displacements (fig. 2B). Published seismic data (Jacobeen and Kanes, 1974, 1975; Wilson, 1989; Wilson and Shumaker, 1992) support the interpretation that horses of Cambro-Ordovician carbonates are less numerous with larger displacements of up to 20 km, producing blind duplexes with flat-on-flat geometries (Geiser, 1988b).

The Cacapon Mountain and Wills Mountain duplexes are the two main blind thrust systems in this portion of the thrust belt. They form culminations that fold the overlying roof sequence, producing anticlinoria in the surface geology of the roof sequence (figs. 1, 2). Where the Cambro-Ordovician carbonates are unduplicated between the duplexes, the overlying roof sequence forms synclinoria. The major folds of the roof sequence in the study area are the Cacapon Mountain-Adams Run anticlinorium, Broadtop synclinorium, and Wills Mountain anticlinorium (figs. 1, 2).

Knotts, Buckley, and Dunne (1985) applied a very simplistic approach to incorporating macroscale thrusts into the roof sequence. They used surface data about lithology and structural geometry with a regional gravity survey to infer large duplexes in the lower part of the roof sequence. Individual horses were displaced up to 10 km and imbricate primarily Silurian rocks (fig. 2A). Although this interpretation contributed to developing the hypothesis that macroscale thrusts are abundant in the roof sequence, it is inferior to two later interpretations (fig. 2B,C) and is not discussed further.

Mitra (1986) also applied a duplex geometry to macroscale faults in the roof sequence (fig. 2B). For example, a Broadtop duplex is interpreted to imbricate the lower part of the roof sequence in upper Ordovician to lower Devonian rocks beneath the Broadtop synclinorium. Ramps would have spacings of about 1.5 km and displacements of 1 to 2.5 km. An imbricate fan branches from the roof thrust of the Broadtop duplex into Devonian and Mississippian rocks with a spacing between faults of about 1 km and displacements of a few 100 m's. Consequently, macroscale shortening by thrust faults is interpreted to be much greater in the lower part of the roof sequence than in the upper part.

Kulander and Dean (1986) made an important modification of macroscale thrust geometry in the roof sequence. They realized as other workers had (Cloos, 1951; Nickelsen, 1963; Perry, 1971; Knotts, Buckley, and Dunne, 1985; Mitra, 1986) that the lower part of the roof sequence is an irregular mixture of sandstones, shales, and limestones (fig. 1). These rocks contain folds of several size orders, faults of many different sizes, and varying cleavage development that change vertically through the sequence as a function of lithology and bed thickness. They believed that this lithologic variation prevents the lower part of the roof sequence from acting as a single mechanical member that forms duplexes. Instead, macroscale thrusts imbricate all or part of the lower part of the roof sequence, are fore- or backthrusts, and are rooted or isolated (fig. 2C, 3). For example, in their detailed cross section (Dean, Kulander, and Ressing, 1985; Kulander and Dean, 1986) (fig. 3), macroscale thrusts are interpreted to offset the top of the Silurian Tuscarora Sandstone at a spacing of 850 m and an average displacement of 160 ± 75 m. These imbricate thrusts are absent in most of the upper part of the roof

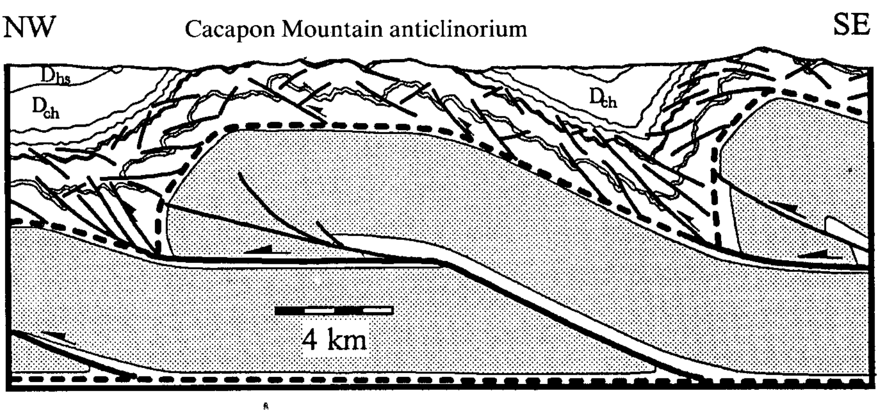


Fig. 3. Cross section showing the detailed interpretation of the subsurface structure beneath the Cacapon Mountain anticline from figure 4 in Kulander and Dean (1986). Thick light gray layer—Cambro-Ordovician carbonates, thin light gray layer—Silurian Tuscarora Sandstone, and thin dark gray layer—Devonian Oriskany Sandstone. Dch—Greenland Gap Group, and Dhs—Hampshire Formation.

sequence of middle Devonian to Mississippian rocks. So, they interpreted the upper part of the roof sequence to be much less deformed by macroscale thrusts as had Knotts, Buckley, and Dunne (1985) and Mitra (1986).

BRIEF REVIEW OF EVIDENCE FOR ABUNDANT MACROSCALE THRUSTS

The appearance in the literature during the mid-1980's of interpretations with abundant macroscale thrusts in the roof sequence was not simply a convenient solution to a kinematic problem in regional cross sections. Data existed to support this hypothesis (fig. 4). The upper Ordovician to lowest Devonian rocks (that is, the lower part of the roof sequence) in the Smokes Holes and Petersburg regions of West Virginia

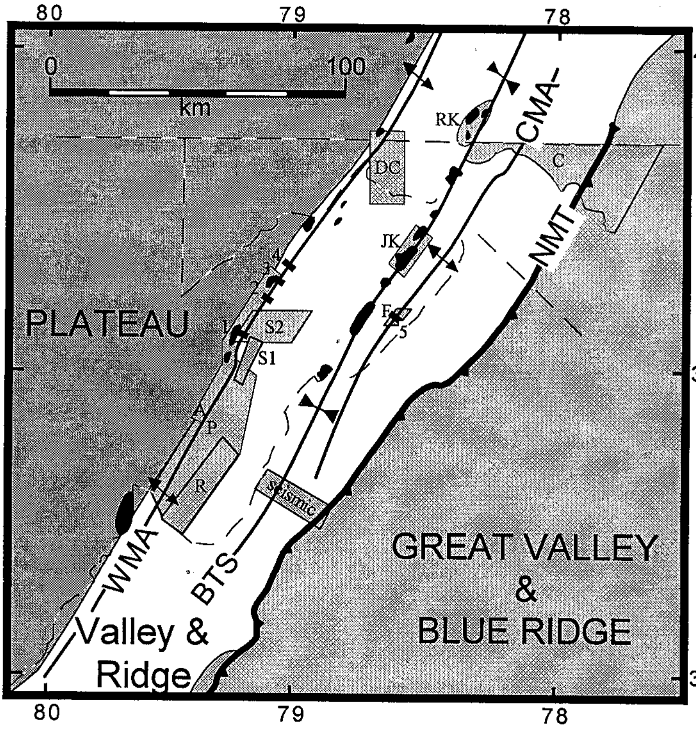


Fig. 4. Location map for studies cited in the text. Irregular black spots, gas fields in Devonian Oriskany Sandstone; 1 to 5, location of water gaps with extensive exposures of Tuscarora Sandstone (table 1); areas studied: A—Adamson (1992), C—Cloos (1951), DC—DeWitt and Colton (1964), F—Ferrill (1987; Ferrill and Dunne, 1989), JK—Jacobeen and Kanes (1974), P—Perry (1971, 1978b), R—Rohaus (1987), RK—Rowland and Kanes (1972), S1—Sites (1971, 1973) and Gerritsen (1988), S2—Sites (1978), seismic—location of seismic reflection profile in figure 10, WMA—Wills Mountain anticlinorium, BTS—Broadtop synclinorium, CMA—Cacapon Mountain—Adams Run anticlinorium, and NMT—North Mountain thrust.

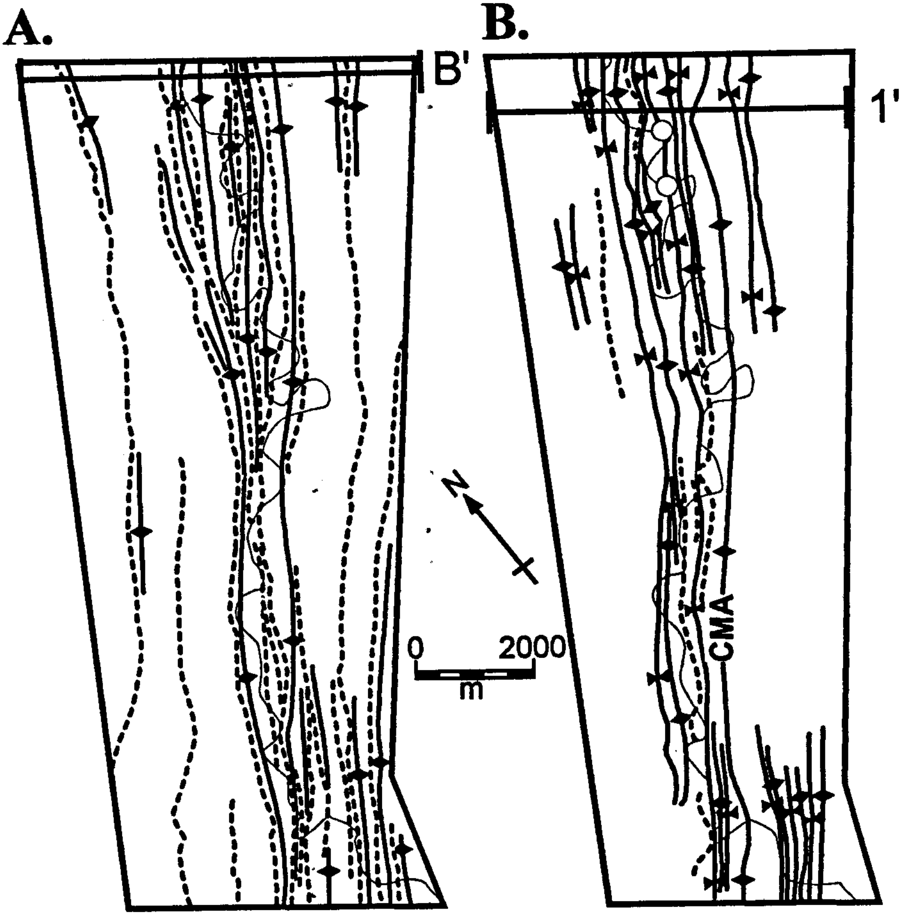


Fig. 5. Structural maps for the Smoke Holes region of West Virginia, showing the interpreted positions of thrusts and fold axes (for location, see fig. 4). (A) Sites (1971, 1973); (B) Gerritsen (1988). Dashed lines—thrusts, Thick solid curving lines—folds, thin solid curving line—trace of the South Branch of the Potomac River, CMA—Cave Mountain anticline, B′—section line position for Sites (1971), 1′—section line position for Gerritsen (1988), two small white circles in upper part of figure 5B are locations of photographs in figure 9.

(Sites, 1971, 1973, 1978) were interpreted as extensively faulted (figs. 5A, 6A). These proposed faults have 500 to 1000 m spacing and displacements of 100 to 1000 m and branch from a detachment in the Ordovician Martinsburg Formation. Surface mapping of Devonian rocks above the Augusta gas field in the Broadtop synclinorium (fig. 4) also revealed one major thrust and several minor ones (Jacobeen and Kanes, 1974).

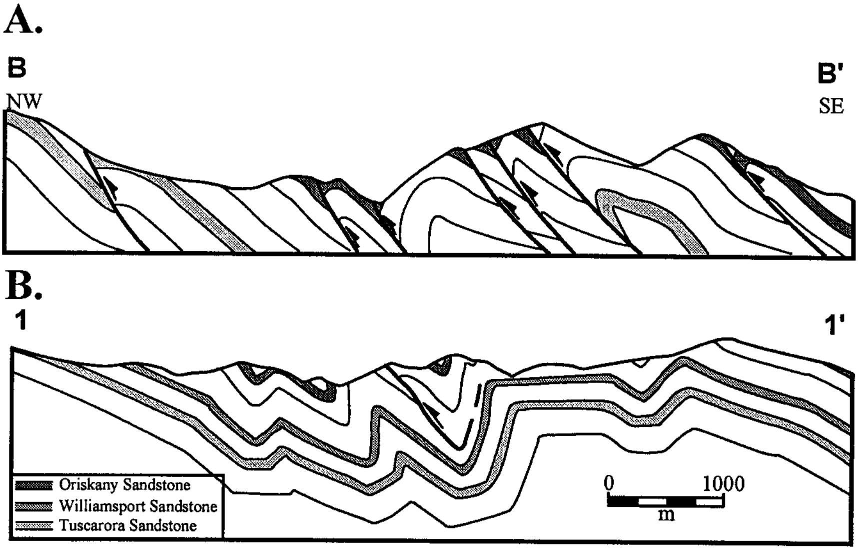


Fig. 6. Cross sections through the Smoke Holes region of West Virginia, showing the structural interpretations of (A) Sites (1971, 1973) and (B) Gerritsen (1988). Section lines located in figure 5.

Well and seismic reflection data (Rowland and Kanes, 1972; Jacobeen and Kanes, 1974, 1975) indicate that gas fields with reservoirs in the Devonian Oriskany Sandstone are situated in imbricate fans of the roof sequence (fig. 7). The faults were interpreted to have spacings of 500 to 1500 m and displacements of 100 to 300 m. They were interpreted to branch from a detachment in the Martinsburg Formation and offset upper Ordovician to Devonian rocks.

Another key type of evidence for macroscale faults is the abundance of outcrop-scale thrusts. For example, Mitra (Mitra, 1986, fig. 12) uses an outcrop thrust with about 5 m displacement in the upper Devonian Hampshire Formation to infer the existence of macroscale faults with displacements of a few 100 m (fig. 2B) in the same unit. Many outcrop-scale thrusts occur in spectacular exposures (fig. 8) that have been extensively studied along roads, railroads, rivers, and canals (Cloos, 1951; Perry, 1971; Dunne and Schultz, 1986; Mitra, 1987; Scott and Dunne, 1990). A potentially reasonable approach would be to apply Pumpelly's Rule (1918) and infer that these abundant faults with displacements of 1 to 20 m indicate the existence of numerous macroscale thrusts with similar geometry. A more formal test of this inference was recently attempted, using a variant of figure 3 for a profile-shape fractal analysis (Wu, 1993). Thus, some map data, well logs, seismic reflection data, and outcrop-scale structural style could support a hypothesis of abundant macroscale thrusts in the roof sequence.

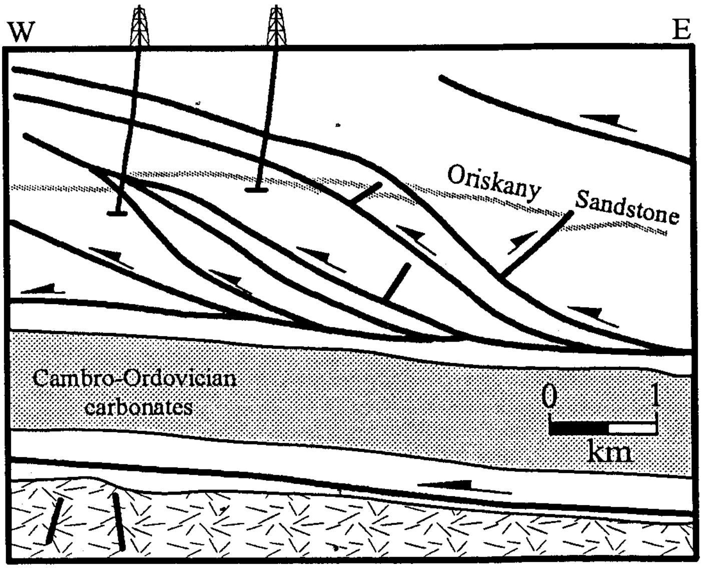


Fig. 7. Interpretation of subsurface structure for the Augusta gas field in the Broadtop synclinorium from Jacobeen and Kanes (1974) from published seismic data. Well symbols and approximated ground surface from the original figure.

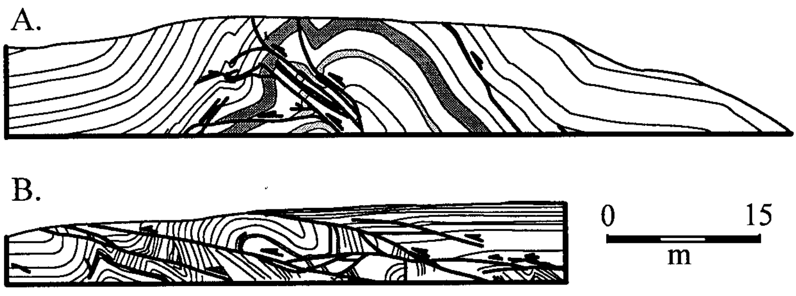


Fig. 8. Examples of thrust-related deformation at the outcrop scale in the roof sequence. (A) Cedar Cliff, Maryland, in the Silurian McKenzie to Wills Creek Formations (Mitra, 1986; Scott Dunne, 1990). (B) Bergton, Virginia, in the Greenland Gap Group (Mandros, 1985; Pohn and Purdy, 1987; Dunne, 1989; Nair and others, 1991).

EVIDENCE FOR LIMITED OCCURRENCE OF MACROSCALE THRUSTS

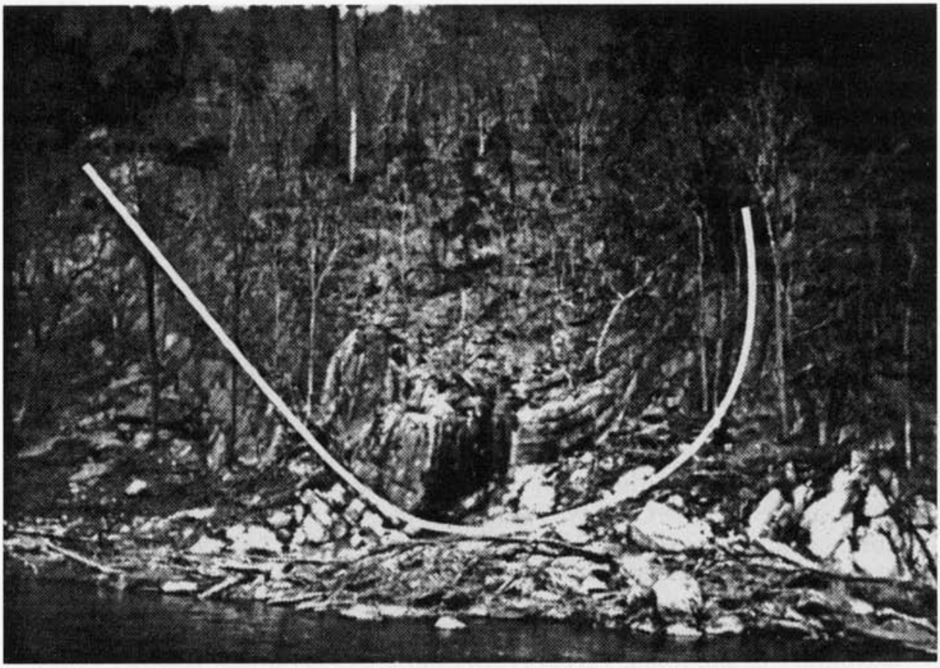
Abundance of macroscale thrusts in geologic maps.—Several geological maps published prior to the mid-1980's contain detailed descriptions of the structural geology and show macroscale thrusts to be uncommon in the roof sequence. Cloos (1951) identified three macroscale thrusts but found folds to be the dominant structures around the Cacapon Mountain anticlinorium in Washington County, Maryland (fig. 4). Examining the

Evitts Creek and Pattersons Creek 7.5-min quadrangles, DeWitt and Colton (1964) found a few macroscale thrusts at the transition from the Wills Mountain anticlinorium to the Broadtop synclinorium (fig. 4). Cross sections for the Evitts Creek quadrangle are about 12 km long and contain 4 to 5 thrusts in the Silurian to Devonian rocks, but only one or two faults have displacements greater than 25 m. Thrusts are absent in the Pattersons Creek quadrangle. Perry (1971, 1978a,b) mapped an extensive portion of the Wills Mountain anticlinorium in Pendleton County, West Virginia (fig. 4). He found one major thrust, the Castle Mountain thrust, with over 700 m displacement and several macroscale contraction and extension faults in the northwestern limb of the anticlinorium. Otherwise, macroscale thrusts are absent in his study area.

Several recent maps also show a lack of macroscale thrusts in the roof sequence of upper Ordovician to Pennsylvanian rocks. Rohaus (1987) re-examined the southeastern portion of the Wills Mountain anticlinorium in Pendleton County, West Virginia (fig. 4) and confirmed the absence of thrusts (Perry, 1978a). Adamson (1992) examined the northwestern limb of the anticlinorium in Pendleton and Grant counties, West Virginia (fig. 4) and found the region to be dominated by folds related to the parasitic Hopeville anticline with very few macroscale thrusts that are secondary to the folds. Ferrill (1987; fig. 2 in Ferrill and Dunne, 1989) found a similar absence of macroscale thrusts across the Cacapon Mountain anticline in the Baker-Wardensville area of West Virginia. In an immediately adjacent area, the West Virginia portions of five 7.5-min quadrangles show no macroscale thrusts (Dean, Kulander, and Lessing, 1985). This result is interesting because the detailed cross section for the area (Dean, Kulander, and Lessing, 1985; Kulander and Dean, 1986; fig. 3 in the present text) shows an abundance of macroscale thrusts in the roof sequence. This increase of thrust abundance from geologic map to cross section (Dean, Kulander, and Lessing, 1985) is achieved by a sharp decrease in fault spacing from outcrop to subcrop in the lower part of the roof sequence (fig. 3). This increase of macroscale thrusts from geologic map to cross section occurs again for a four-quadrangle area of Hardy County, West Virginia (Dean and others, 1991).

Gerritsen (1988) intended to use the map by Sites (1971, 1973) of the Smoke Holes region in West Virginia as the basis for investigating finite strain in the roof sequence where macroscale thrusts are abundant. However, the catastrophic flood of November, 1985 (Clark and others, 1987; Miller and Parkinson, 1993), greatly reshaped the South Branch of the Potomac River in the Smoke Holes, exhuming bedrock in both cutbanks and channel floors. As a result, Gerritsen (1988) found many exposed syncline hinges (figs. 5B, 6B, 9) that were previously mapped as thrust faults (figs. 5A, 6A) and a structural style dominated by folds rather than thrusts. He did find six mappable thrusts with 100 to 250 m displacements that root in different decollement horizons, including the Helderberg Group, Wills Creek, and Martinsburg Formations. However, the six faults have limited lateral extent along regional strike (fig. 5B).

A.



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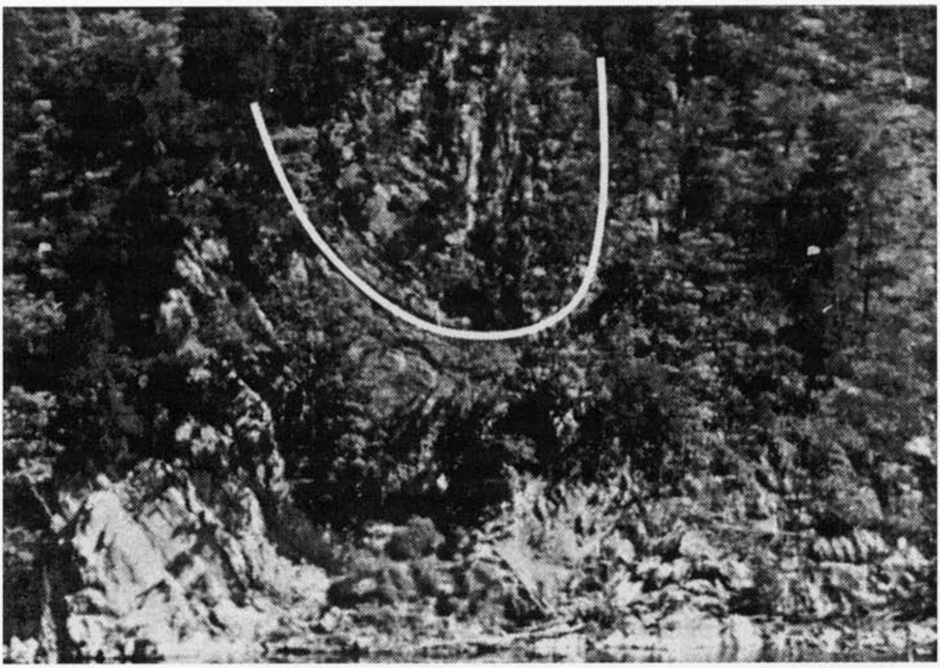

Fig. 9. Photographs of syncline hinges in the Smoke Holes region of West Virginia (locations in fig. 5B) (modified from Gerritsen, 1988). (A) Syncline hinge in the Silurian Tonoloway Formation exhumed in a cutbank of the South Branch of the Potomac by the 1985 flood. (B) Sub-isoclinal hinge in the Siluro-Devonian Helderberg Group.

Consequently, one of the cornerstone areas for the interpretation that macroscale faults are abundant in the roof sequence is actually fold-dominated (figs. 6B, 9).

Examining Tuscarora Sandstone in spectacular water-gap exposures across major anticlines provides another surficial indication for the lack of macroscale thrusts in the roof sequence in West Virginia. According to figure 3, macroscale thrusts should have a spacing of about 850 m and displacements of about 160 m through the Tuscarora Sandstone. Five of these outcrops (fig. 4; table 1) with a total exposure length of over 6850 m showed no macroscale thrusts (Ferrill, 1987; Adamson, 1992). Each exposure did have one or two thrusts with 5 to 20 m displacement. In summary, the preponderance of geologic mapping data demonstrates that macroscale thrusts occur but are not abundant in the roof sequence.

TABLE 1

Number of macroscale faults offsetting Tuscarora Sandstone in major water gaps

*	Location	Arc-length (m)	Number
1	North Fork Gap	2200	0
2	Greenland Gap	1300	0
3	Cosner Gap	1300	0
4	Kline Gap	1300	0
5	Hanging Rock	750	0

*Location numbers positioned in figure 4

Macroscale thrusts in seismic reflection data.—One prediction from the hypothesis of abundant macroscale thrusts is that the structures should be ubiquitous in any section across the region (secs 1 through 8, Kulander and Dean, 1986). Figure 10 is a test of this prediction where seismic reflection data (fig. 10) across the Broadtop synclinorium in Rockingham County, Virginia (fig. 4) are compared to a collinear segment of section 4 (fig. 11) from Kulander and Dean (1986). The cross-section segment shows an almost evenly distributed set of 18 thrusts in the upper Ordovician to lower Devonian rocks of the roof sequence. The seismic reflection data show that long portions of the Silurian to lower Devonian rocks are represented by continuous reflectors and are unfaulted at macroscale. Although two portions of the reflection data for the sequence are complicated by thrusts (left-hand edge and center of fig. 10B), the faults are much less common and have much less total displacement than predicted. Thus, at least one example of seismic reflection data exists where the macroscale thrusts are not ubiquitous in the roof sequence.

An additional observation is that seismic reflectors for the Cambro-Ordovician carbonates are nearly continuous across the seismic line (fig. 10). They contain only one disruption from a ramp with a few 100 m's of displacement (fig. 10), as opposed to three predicted ramps each with a 1

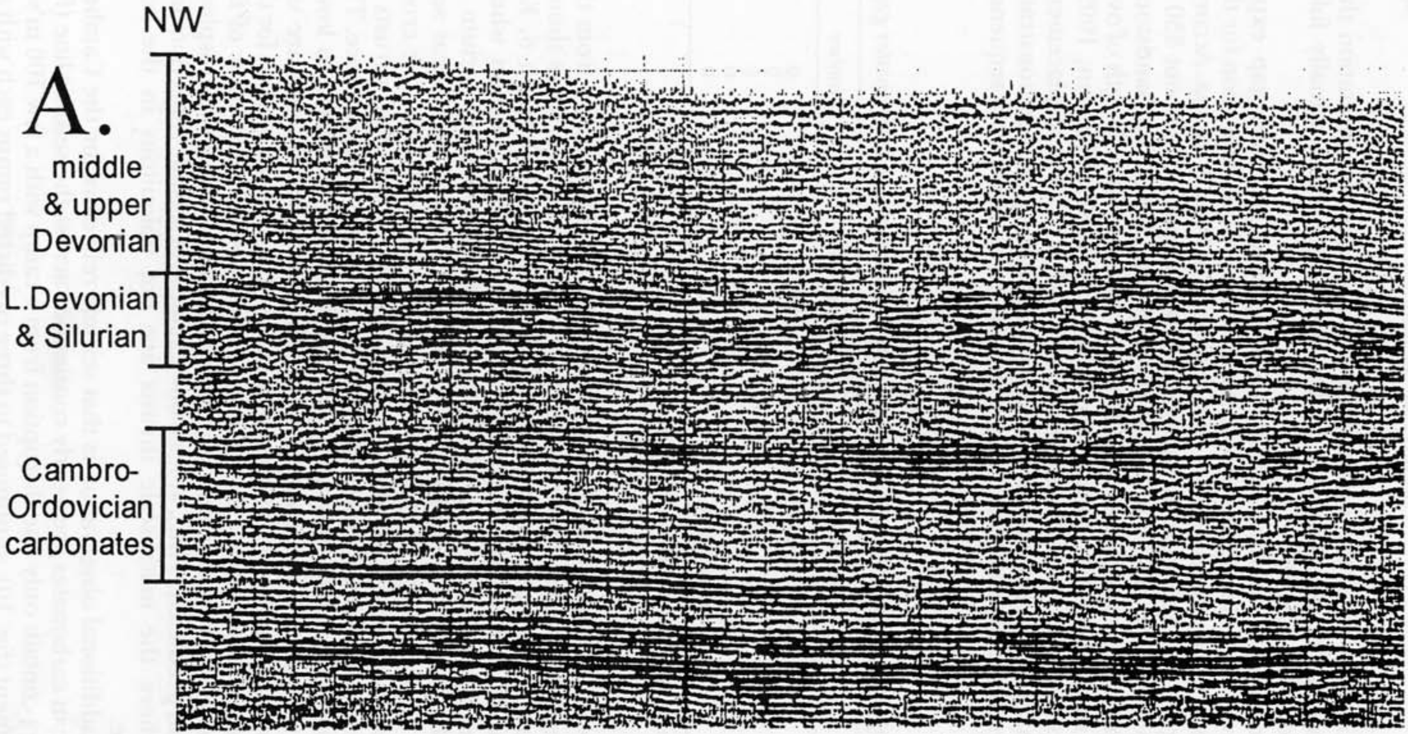

Fig. 10. Seismic reflection profile across the Broadtop synclinorium between the North Mountain thrust (surface outcrop location is shown near left-hand edge of data in B) and Wills Mountain anticlinorium (see fig. 1 for location). (A) Uninterpreted.

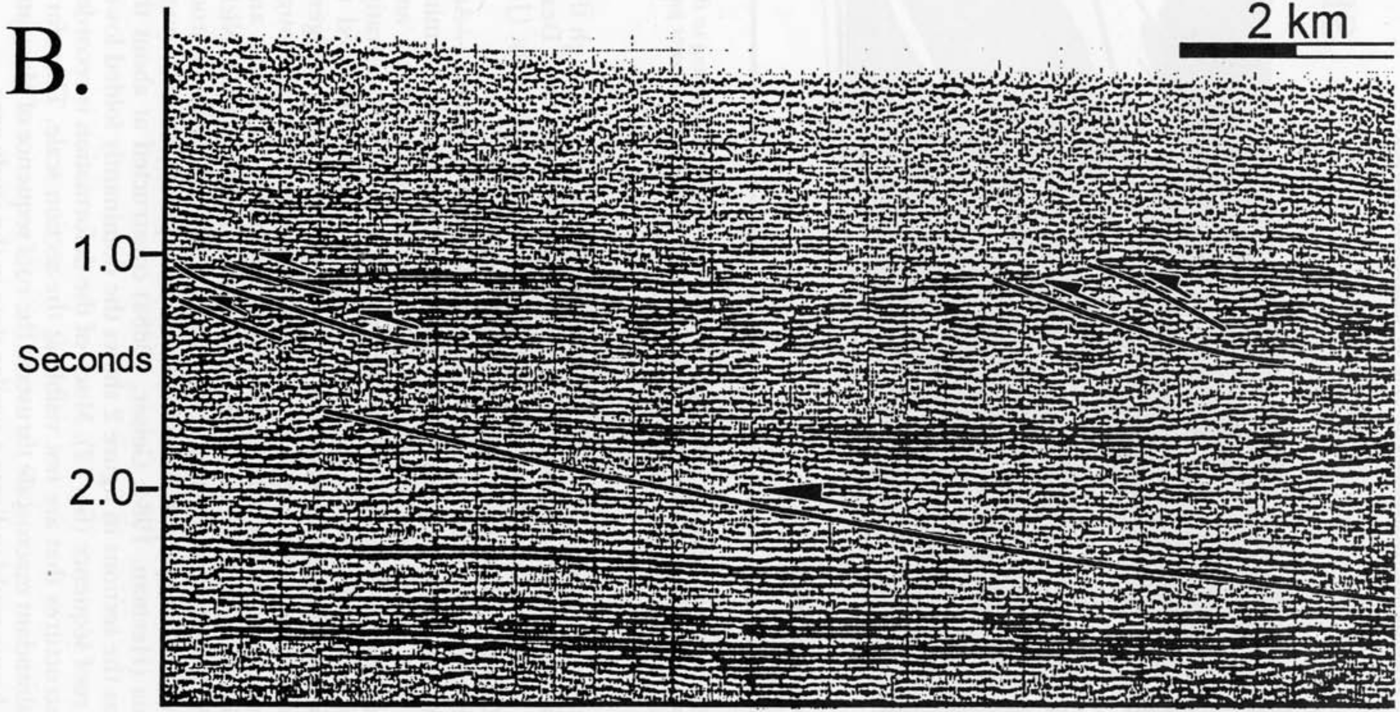

Fig. 10(B) Interpreted to show locations of likely thrusts, although exact details of fault geometry are only approximated. Note the continuity of reflectors at both levels of the Cambro-Ordovician carbonates and the lower part of the roof sequence of Silurian to lower Devonian rocks. NMT—surface trace of North Mountain thrust.

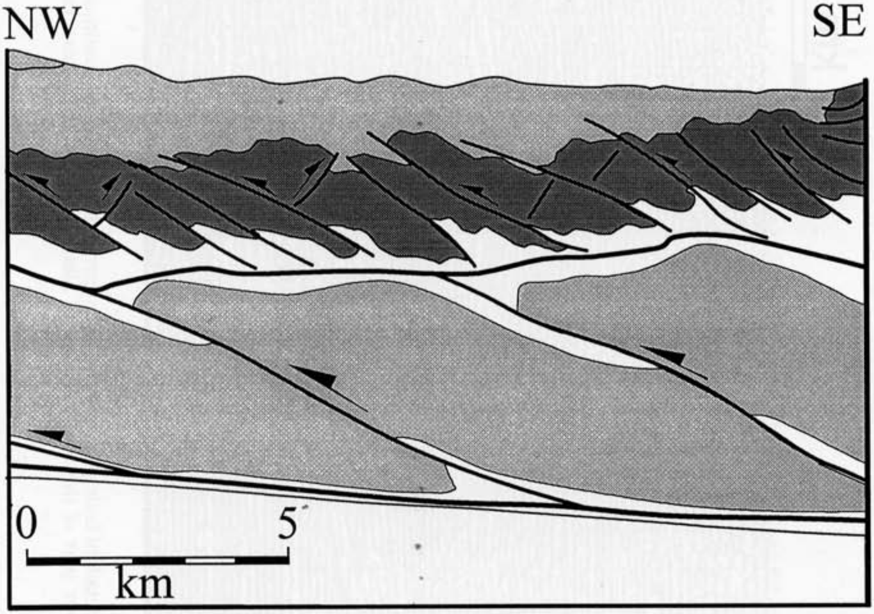

Fig. 11. Segment from section 4 of Kulander and Dean (1986) corresponding to the location of figure 10. Light gray—Cambro-Ordovician carbonates, dark gray—lower part of roof sequence, and medium gray—upper part of roof sequence.

to 3 km displacement (fig. 11). Thus, ramps are fewer here through the Cambro-Ordovician carbonates than interpreted by Kulander and Dean (1986) but are more consistent with other published seismic data (Jacobeen and Kanes, 1974, 1975; Wilson and Shumaker, 1992).

Occurrence of macroscale thrusts in Maryland and Pennsylvania.—Another test for the presence of abundant macroscale thrusts is to examine the lower part of the roof sequence along strike in Maryland and Pennsylvania, where these units crop out continuously. This lithostratigraphy is essentially the same along strike and has been subjected to similar burial conditions and tectonic shortening (Colton, 1970; Rodgers, 1970), so similar structural style is a reasonable expectation. Although these rocks contain a few macroscale thrusts (Cleaves, Edwards, and Glaser, 1968; Berg and others, 1980), most workers (Cloos, 1951; Nickelsen, 1963; DeWitt and Colton, 1964; Faill, 1969; 1973) found rock structure dominated by up to five orders of folds. A cross section through Pennsylvania (Herman, 1984; Geiser, 1988a) constructed at about the same time as the sections in figure 2 shows the dominantly folded lower part of the roof sequence (fig. 12). Much of the deformation is recorded in smaller structures that are not visible at the section scale. Therefore, the lack of abundant macroscale thrusts in the roof sequence of Maryland and Pennsylvania could indicate a similar state in the study area.

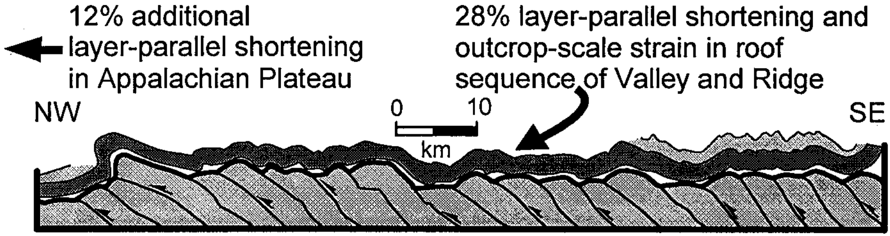

Fig. 12. Cross section through the Juniata culmination of Pennsylvania by Herman (1984). Light gray—Cambro-Ordovician carbonates, dark gray—lower part of roof sequence, and medium gray—upper part of roof sequence.

Effect of vertical change in fault intensity and finite strain.—The interpretations of the regional structure in figure 2 seem to show that thrusts with significant displacement are restricted to the lower part of the roof sequence. Mitra (1986) believed that an imbricate fan (fig. 2B) shortened the middle Devonian to Mississippian rocks of the upper part of the roof sequence, but this thrust system has much less displacement than the underlying Broadtop duplex in the lower part of the roof sequence. Recent mapping (Schultz, 1995) and seismic reflection data such as figure 10 support the interpretation that macroscale thrusts are uncommon in the upper part of the roof sequence. If the entire roof sequence shortened uniformly to accommodate the formation of the blind duplexes, the upper part of the roof sequence must be deformed by structures other than macroscale thrusts to match the shortening by macroscale faults in the lower part.

One possibility is that microscale deformation is more intense in the upper rather than in the lower part. This possibility was tested by measuring finite strains in sandstones at different stratigraphic levels in the roof sequence from Maryland, Virginia, and West Virginia (Dunne and others, 1988; Billman, 1989; Johnston, 1989; Billman, Dunne, and Johnston, 1989). Compositionally, samples from the Price Formation, Oriskany, and Tuscarora Sandstones are entirely quartz arenites, whereas samples from the Hampshire Formation, Greenland Gap Group, and Juniata Formation are either quartz arenites or quartzwackes. Samples from the Hampshire and Juniata Formations included up to 10 percent hematitic cement and detrital grains. Thus, sandstones have an overall lithologic similarity between the lower and upper parts of the roof sequence, and strain measurements would not be perturbed by differences in rock composition between the two stratigraphic levels.

More than 200 quartz grains were used as strain markers in each of three mutually perpendicular thin sections per sample. Grain boundaries were digitized, grain centers calculated, and finite strain ellipses measured with the normalized Fry method (Erslev, 1988) for each thin section. Strain ellipsoids were calculated from the sets of three ellipses per sample (Gendzwill and Stauffer, 1981). Strain factorization (Couzens and others, 1993) demonstrated that strain histories involving flexural flow or horizontal flattening after folding do not produce the measured finite strain ellipsoids (Billman, 1989; Johnston, 1989), because measured strain magnitudes are not a function of the angle of bedding dip (Dunne and others, 1988; Billman, Dunne, and Johnston, 1989). Factorization indicates that the strain histories of the sandstones are dominated by pre-tectonic diagenetic compaction and tectonic layer-parallel shortening in the regional transport direction. Microstructural suites consisting of bed-normal and bed-parallel microfractures, bed-normal and bed-parallel stylolites, grain-to-grain solution penetrations, deformation lamellae, and deformation bands (Billman, 1989; Onasch, 1990; Onasch and Dunne, 1993) support this mathematical interpretation. Strain factorization also demonstrates that layer-parallel shortening of about 20 percent does not vary as a function of stratigraphic level in the roof sequence (table 2). Although table 2 only shows the partitioned layer-parallel shortening for the endmember case where all tectonic deformation is by solution with volume loss, the similarity of tectonic shortening between stratigraphic level occurs in all sets of calculations. Hence, the upper part of the roof sequence is not more deformed at the microscale than the lower part of the sequence.

TABLE 2

Factorized layer-parallel shortening as a function of stratigraphic level

	Stratigraphic Unit	Number of samples	Layer-parallel shortening ($-100\%\Delta V$)
Upper roof sequence	Mississippian Price Formation	5	21%
	Devonian Hampshire Formation	11	19%
	Devonian Greenland Gap Group	12	16%
Lower roof sequence	Devonian Oriskany Sandstone	19	17%
	Silurian Tuscarora Sandstone	8	23%
	Ordovician Juniata Formation	3	18%

The upper part of the roof sequence could be more deformed than the lower at the outcrop scale. Certainly, locally intense sites of deformation occur in Devonian rocks of the upper part of the roof sequence (Mitra, 1986; Pohn and Purdy, 1987; fig. 8B in the present paper). Recent mapping in the Broadtop synclinorium of West Virginia (Schultz, 1995) also found abundant outcrop-scale folds and faults through the upper part. However, sites of similarly intense deformation exist in the lower part of the sequence (Cloos, 1951; Perry, 1978a; Rohaus, 1987; Mitra, 1987; Ferrill and Dunne, 1989; Scott and Dunne, 1990). At present, no field-based studies have demonstrated that outcrop-scale deformation is consistently greater in the upper rather than in the lower part of the roof sequence. The lack of assessment of relative deformation intensity reflects a lack of fieldwork rather than an inability to evaluate existing data. Such fieldwork is presently out of favor, but very necessary to the overall understanding of deformation in these foreland thrust systems. Consequently, the upper part may not be more deformed at the outcrop-scale than the lower part. If the upper part of the roof sequence lacks greater micro- or outcrop-scale deformation, either shortening does not match vertically or the macroscale thrusts do not exist in the lower part of the roof sequence.

Distribution of gas fields and abundance of macroscale thrusts.—All producing and storage gas fields in the Oriskany Sandstone of the roof sequence are thrust-related in the Valley and Ridge province of the study area (figs. 4, 5) (Rowland and Kanes, 1972; Jacobeen and Kanes, 1974; Bagnell, Beardsley, and Drabish, 1978; Cardwell, 1982; Adamson, 1992). Almost all gas fields are in two linear zones on the forelandward (northwest) side of the Cacapon Mountain and Wills Mountain anticlinoria (fig. 4). These two locations are forelandward and adjacent to the leading branch lines for the underlying Cacapon Mountain and Wills Mountain duplexes.

The Oriskany Sandstone is a quality reservoir rock because of secondary porosity from tectonic fractures and dissolved cement (Cardwell, 1982). The Sandstone is overlain by lower Devonian shales that form both an effective top seal and potential source rock for gas. Consequently, any antiformal structure containing Oriskany Sandstone would have the potential to be a hydrocarbon target. Experience has shown that anticlines related to thrusts are the folds that actually contain economical gas accumulations, perhaps reflecting locally intense fracture porosity related to thrust formation (Rowland and Kanes, 1972; Jacobeen and Kanes, 1974; Bagnell, Beardsley, and Drabish, 1978; Cardwell, 1982).

The thrusts in the gas fields are interpreted to develop during intense local deformation of the roof sequence adjacent to the leading branch lines due to displacement transfer from the underlying blind duplexes. Such a forelandward concentration of deformation is consistent with the forelandward sequence of regional deformation in the region (Perry, 1978a; Engelder and Geiser, 1979; Ferrill and Dunne, 1989). The lack of gas fields elsewhere in the Oriskany Sandstone is inferred to result from a lack of abundant macroscale thrusts elsewhere in the roof sequence. If this interpretation is correct, the implication is that such faults developed only locally in the roof sequence adjacent to leading branch lines for the blind duplexes.

DISCUSSION

An alternative interpretation.—The central thesis of this contribution is that the roof sequence of the blind foreland thrust belt in the central Appalachians lacks abundant macroscale thrusts. The reasons for this opinion are: (1) The preponderance of geologic map data indicates that macroscale thrusts occur but are not abundant in the roof sequence. (2) The prediction of ubiquitous thrusts fails at least one subsurface test when compared to seismic reflection data. (3) The thrusts are not common along strike in the roof sequence of Maryland and Pennsylvania.

(4) The upper part of the roof sequence, which lacks the previously interpreted abundant macroscale thrusts of the lower part of the roof sequence, also lacks clear evidence for more intense compensatory deformation at the micro- and outcrop scales. (5) If gas fields are indicators of macroscale-thrust frequency, their limited distribution in the roof sequence implies that the faults also have limited occurrence.

Applying this thesis, a regional cross section should contain few macroscale thrusts and some macroscale parasitic folds in the roof sequence (fig. 13). Important components of regional shortening in the roof sequence are indicated in the text above the section (figs. 12, 13), not by structures illustrated in the section. These components are deformations recorded by structures that are too small to be illustrated in the section.

Comparison of figure 13 to the sections in figure 2 leads to two important points: (1) much less deformation is partitioned at the macroscale in figure 13 and may indicate that the total shortening is less in the roof sequence as compared to figure 2. (2) Quantification of shortening from smaller structures may eliminate the kinematic need to include macroscale structures during section construction. Other points from the comparison are: (1) A hydrocarbon exploration strategy based on the positions of macroscale thrust-related anticlines in the roof sequence would find a more restricted number of sites in figure 13 than in figure 2. (2) An attempt to apply fractal analysis to the structural geometries (Wu, 1993) in figure 13 would find much less small-scale deformation as opposed to figure 2. (3) An investigation of seismic activity in an actively deforming blind thrust belt would reveal a more limited distribution of earthquakes for the roof sequence in figure 13 as opposed to figure 2. All these comparisons are potentially applicable to the roof sequences of younger blind thrust belts, which have mostly been examined at the macroscale (Suppe, 1983; McMechan, 1985; Wallace and Hanks, 1990; Humayon, Lillie, and Lawrence, 1991).

The text attached to the section in figure 13 contains two uncertainties about this portion of the central Appalachians. Unlike Pennsylvania, where strain was extensively measured in the Plateau (Engelder and Engelder, 1977; Engelder, 1979; Engelder and Geiser, 1979), strain data have not been collected regionally across the Plateau of West Virginia. Consequently, the amount of micro- and outcrop-scale deformation in this part of the Plateau is not well constrained. Secondly, no one has attempted to quantify the regional shortening contribution from outcrop-scale structures. The lack of such an attempt is not surprising, given the limitations of exposure, lack of abundant distinctive markers in the Devonian stratigraphy, dependence of outcrop-scale structural style on stratigraphic level, and need for much fieldwork. Yet the lack of this quantity further limits the complete description of the regional shortening in the roof sequence. In essence, Alleghanian deformation in the central Appalachians will never be sufficiently described until the significant contributions of micro- and outcrop-scale structures are quantified.

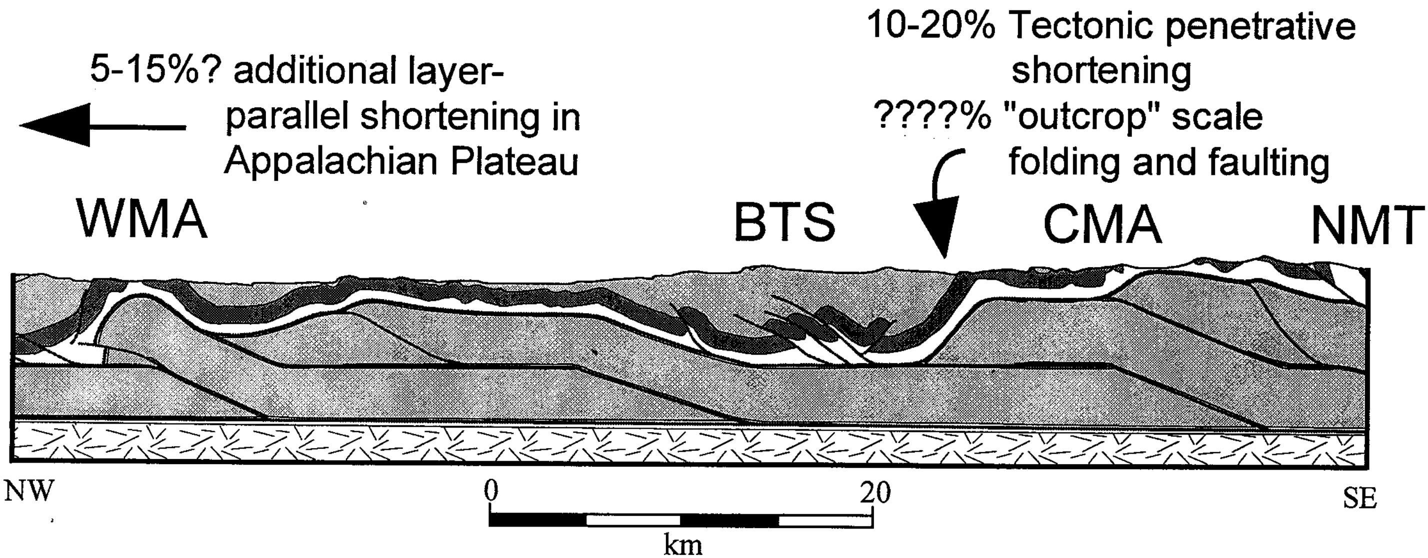

Fig. 13. Proposed cross section (located in fig. 1) for a portion of the blind thrust belt in the central Appalachian foreland. The section contains few thrusts in the roof sequence and has text to note the contribution of deformations at scales smaller than the cross section. Light gray—Cambro-Ordovician carbonates, dark gray—lower part of roof sequence, and medium gray—upper part of roof sequence. Section constructed without access to seismic reflection data.

Hence, quantification of only macroscale deformation by techniques such as constant bed-length section balancing is an insufficient description of regional shortening in this or any roof sequence.

Implications for the North Mountain thrust.—The upper Ordovician to Pennsylvanian rocks of the Appalachian Plateau and Valley and Ridge province contain insufficient deformation to accommodate 100+ km of displacement from blind thrusts in the Cambro-Ordovician carbonates, if macroscale thrusts are not abundant in the roof sequence (fig. 13). Geiser (1988a,b) reached a similar conclusion along strike for the roof sequence in Pennsylvania. The lack of sufficient roof-sequence deformation requires a smaller displacement magnitude for the blind thrusts beneath the present study area. One geometry that would decrease the displacement is if displacement of the North Mountain thrust sheet was transferred into the eroded portion of its hangingwall above the North Mountain thrust (Evans, 1989), rather than into the subsurface roof flat of the Martinsburg Formation (Kulander and Dean, 1986; Mitra, 1986).

Evans (1989, 1990) has cogently made the case from mapping and seismic reflection data that the hangingwall ramp of the North Mountain thrust sheet is eroded above the surface trace of the North Mountain thrust rather than resting on the roof flat in the Martinsburg Formation (for example, as shown in fig. 2B). Two additional points can be made to support Evans's viewpoint. First, the roof sequence adjacent to the leading branch lines of the frontal hangingwall ramps for the Wills Mountain and Cacapon Mountain duplexes contains several macroscale thrusts (Jacobeen and Kanes, 1974; Bagnell, Beardsley, and Drabish, 1978; Cardwell, 1982). If these two duplexes are representative, macroscale thrusts should occur in the roof sequence adjacent to the North Mountain thrust sheet if its leading branch line was on the roof flat. The faults are rare (fig. 10). Specifically, the Broadtop duplex (Mitra, 1986) is absent in the lower part of the roof sequence in this region. The duplex was postulated to exist so as to accommodate slip from the North Mountain thrust (Mitra, 1986) but is absent here adjacent to the surface trace of the fault (NMT in fig. 10B). Hence, if the Broadtop duplex exists, it is not regionally extensive and is not a major sink for displacement transfer from the North Mountain thrust to the roof sequence.

Second, layer-parallel shortening of crinoid ossicles on sandstone bedding surfaces in the Greenland Gap Group increases southeastward across the Broadtop synclinorium to a maximum of 36.5 percent adjacent to the Cacapon Mountain anticlinorium and underlying Cacapon Mountain duplex (Nair and others, 1991). This increase in LPS correlates with the appearance of macroscale thrusts in the roof sequence near the leading branch line of the Cacapon Mountain duplex. Layer-parallel shortening does not increase toward the North Mountain thrust sheet (Nair and others, 1991), which correlates with the paucity of subsurface thrusts in the roof sequence adjacent to the branch line for the North Mountain thrust (fig. 10). Consequently, the lack of an increase in microscale shortening and the rarity of macroscale thrusts in the roof sequence are interpreted to indicate that the hangingwall ramp for the North Mountain thrust sheet is not on a thrust flat below the roof sequence. Instead, as Evans (1989, 1990) argued, the hangingwall ramp was translated up the North Mountain thrust and subsequently eroded.

CONCLUSIONS

1. Macroscale thrusts are *not* abundant in the roof sequence of the central Appalachians. They are locally important as with the Castle Mountain thrust (Perry, 1971), Cave Mountain thrust (Gerritsen, 1988), Woods fault (Lessing, Dean, and Kulander, 1992) and subsurface faults in the Augusta gas field (Jacobeen and Kanes). The roof sequence above the blind Alleghanian foreland thrust systems deformed mainly by macroscale folding with significant shortening contributions from microstructures and outcrop-scale folds and faults. In fact, the roof sequence records more deformation by micro- and outcrop-scale structures than by macroscale thrusts in a regional cross section.

2. This interpretation may affect comparison of macroscale geometry in the central Appalachians to analog models (Liu and Dixon, 1990, 1991) and would significantly change the results from an attempted fractal analysis of macroscale structural profiles in the central Appalachians (Wu, 1993). Also, the results indicate that the contribution of deformation at less than section scale must be considered when examining the kinematic interaction between any roof sequence and its related blind thrust belt.

3. The lack of more intense deformation in the roof sequence adjacent to the North Mountain thrust sheet is interpreted to support the theory that the hangingwall ramp of the sheet is displaced up the North Mountain thrust and not into the foreland under the roof sequence.

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