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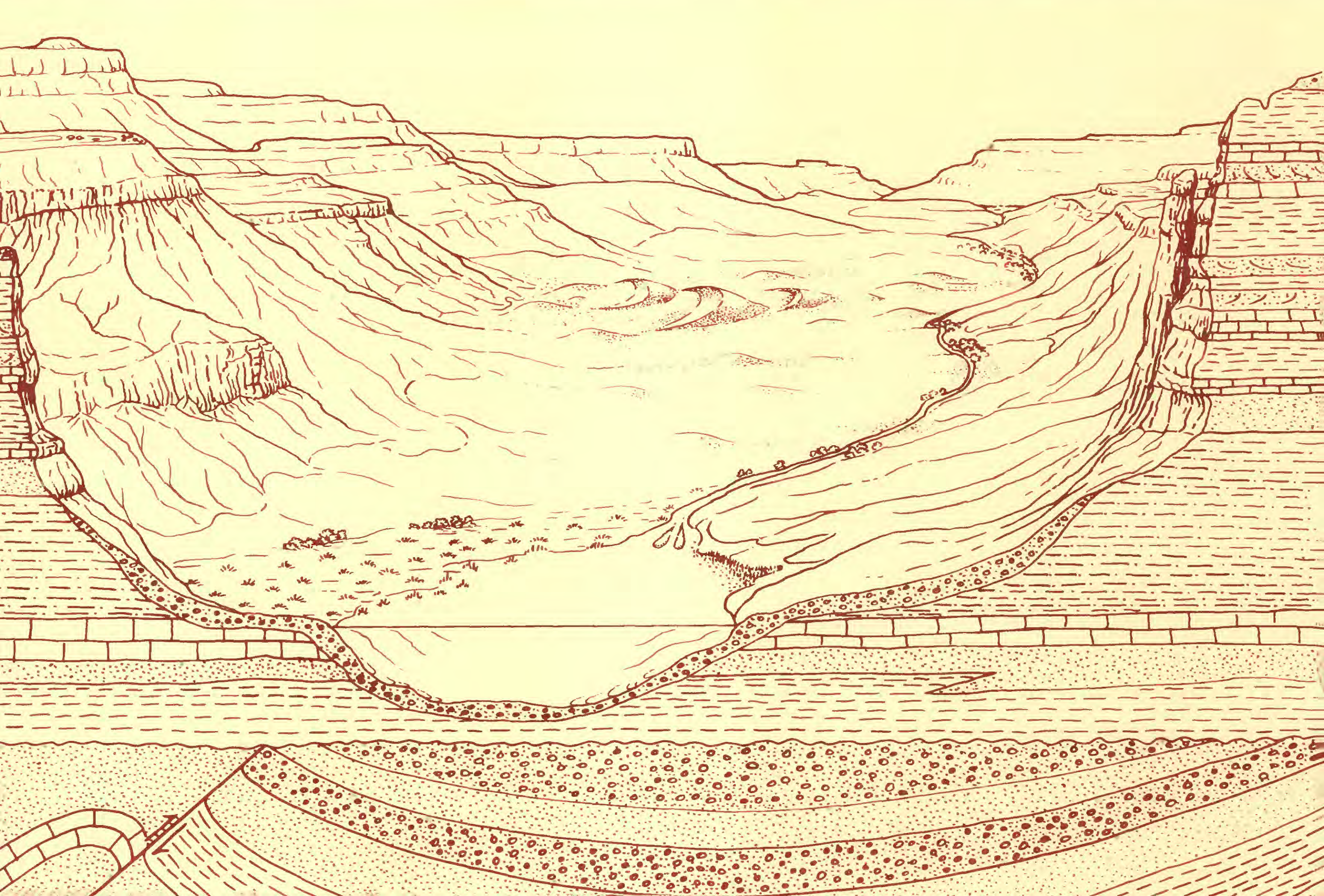

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EVOLUTION OF SEDIMENTARY BASINS—APPALACHIAN BASIN

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

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Chapter A

Horses in Fensters of the Pulaski Thrust Sheet, Southwestern Virginia: Structure, Kinematics, and Implications for Hydrocarbon Potential of the Eastern Overthrust Belt

By ARTHUR P. SCHULTZ

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1839

EVOLUTION OF SEDIMENTARY BASINS—APPALACHIAN BASIN

CONTENTS

FIGURES

TABLE

CONVERSION FACTORS FOR SOME SI METRIC AND U.S. UNITS OF MEASURE

To convert from	To	Multiply by
Feet (ft)	Meters (m)	0.3048
Miles (mi)	Kilometers (km)	1.609
Pounds (lb)	Kilograms (kg)	.4536
Degrees Fahrenheit (°F)	Degrees Celsius (°C)	Temp °C=(temp °F−32)/1.8

Horses in Fensters of the Pulaski Thrust Sheet, Southwestern Virginia: Structure, Kinematics, and Implications for Hydrocarbon Potential of the Eastern Overthrust Belt

By Arthur P. Schultz

Abstract

Highly deformed rocks of Cambrian through Devonian age are exposed in fensters of the Pulaski thrust sheet near the northern terminus of the southern Appalachian Valley and Ridge province. Detailed mapping of these outcrops shows a consistency of structural style—namely, faulted antiformal synclines having duplex geometry. Examination of strain data and cross sections suggests that the fensters expose rootless tectonic slices, or horses. Structural analysis of the rocks shows that cataclasis was the dominant deformation mechanism in thickly bedded carbonate rocks and sandstones. By contrast, isoclinal folding, cleavage, and boudinage were the dominant mechanisms in thinly bedded shales, sandstones, and limestones. Both the amount of tectonic thinning and the intensity of strain in the horses are dependent on lithotectonic units and the distance of transport from the root zone, which is perhaps a frontal tectonic ramp in the trailing part of the subjacent Saltville thrust sheet. Seismic studies indicate that this ramp is east of and below thrust sheets of the Valley and Ridge and western Blue Ridge provinces, an interpretation supported by structural studies of rocks in the fensters. Thermal maturation and geochemical data suggest that coal-bed methane in rocks of Mississippian age may exist below thermally overmature thrust sheets of the eastern Valley and Ridge and western Blue Ridge provinces. Rocks of Ordovician and Devonian ages in this area may have been source rocks but do not contain hydrocarbons.

INTRODUCTION

Regional-scale seismic studies of the Eastern Overthrust Belt have resulted in speculation about this frontier hydrocarbon province (Cook and others, 1979; Harris and Bayer, 1979; Milici and others, 1979; Harris and others, 1981, 1982). Hydrocarbon-bearing Paleozoic sedimentary rocks probably extend from surface exposures in the Valley and Ridge province of the Appalachian foreland eastward below thrust sheets of metamorphic rocks of the Blue Ridge and Piedmont provinces, but the hydrocarbon potential of these sedimentary rocks is very poorly known because drilling is nonexistent in the area and fensters are few.

This report describes certain complex structures associated with the Pulaski thrust sheet in southwestern Virginia (figs. 1, 2). These structures are tectonic slices or horses, many of which are exposed in fensters, and they have been termed "windows of dislodged slices" or schurflingsfensters (Tollman, 1968; Boyer and Elliot, 1982; Schultz and Anders, 1985). The tectonic rootless slices of sedimentary rocks of Cambrian through Devonian age are interpreted to have been derived from below the easternmost exposed rocks of the Valley and Ridge province and perhaps from below rocks of the Blue Ridge province.

Acknowledgments.—The author thanks Donald E. Anders of the U.S. Geological Survey (USGS) for geochemical analyses, Anita G. Harris and Randall Orndorff

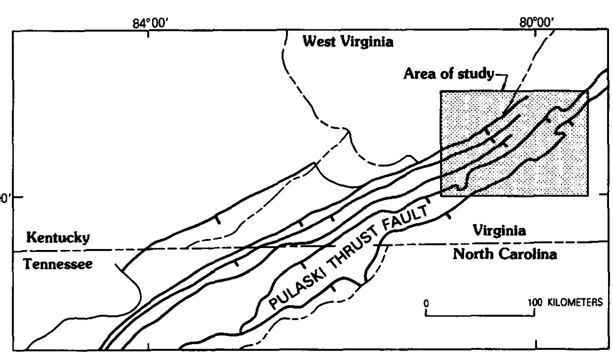

Figure 1. Major thrust faults of southern Appalachian Valley and Ridge province, Kentucky, Tennessee, West Virginia, Virginia, and North Carolina. Location of study area (fig. 2) also shown.

Manuscript approved for publication, 5/16/88

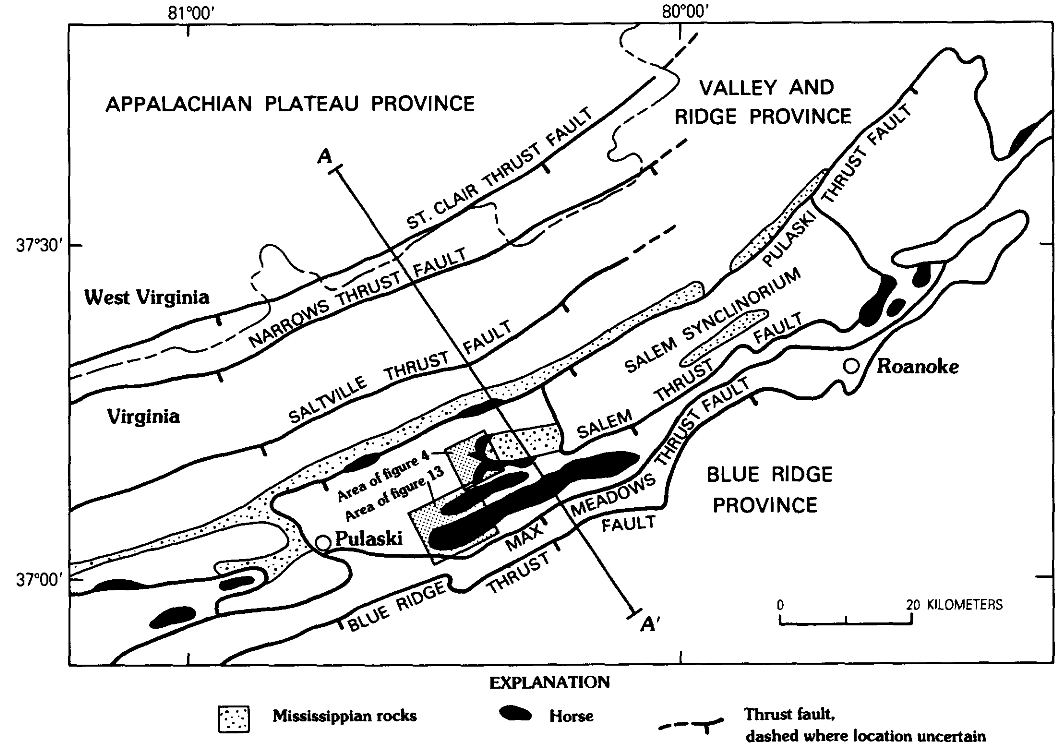

Figure 2. Major thrust faults of southern Appalachian Valley and Ridge province, horses of Pulaski thrust sheet, and distribution of Mississippian rocks discussed in report. Line of section *A–A'* (fig. 3) and locations of areas of figures 4 and 13 also shown. Modified from Bartholomew and others (1982).

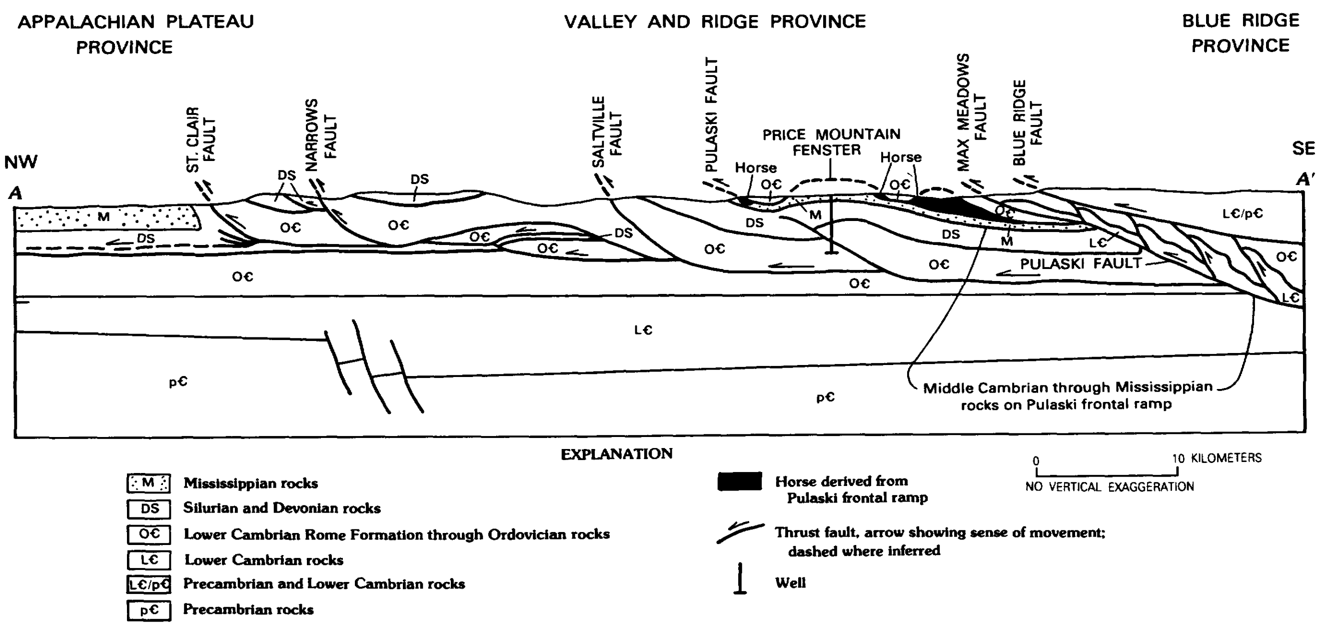

Figure 3. Cross section *A–A'* showing major frontal tectonic ramp of Pulaski thrust sheet, the proposed source of horses exposed in fensters. Modified from Gresko (1985) and Woodward (1985).

(USGS) for unpublished conodont data, and C. Scott Southworth (USGS), Robert C. McDowell (USGS), and Judith W. Stoeser (MESU Associates) for manuscript reviews.

GEOLOGIC SETTING

The Pulaski thrust fault (fig. 1) is one of several major, southeast-dipping thrust faults of the central and southern Valley and Ridge province and has been traced along strike for approximately 500 km (Cooper, 1970; Rodgers, 1970) from a terminus in central Virginia southwestward into Tennessee, where it is overridden by rocks of the Blue Ridge thrust sheet. Estimates of the displacement of the Pulaski thrust near the study area range from 15 (Cooper, 1970) to 50 km (Bartholomew, 1979). Near Pulaski, Va., the preserved thickness of the Pulaski thrust sheet is about 1,500 m, and the decollement of the Pulaski thrust is within shales and dolomites of the Lower Cambrian Rome Formation (fig. 3) and the Middle and Upper Cambrian Elbrook Formation. Rocks of Mississippian age are in the footwall of the Pulaski thrust sheet along its leading edge, in the Price Mountain fenster, and in the core of the Salem synclinorium (fig. 3).

Unique to the Pulaski thrust are thick, broken formations near the base of the thrust sheet (Cooper, 1970; Bartholomew and Lowry, 1979; Schultz, 1983), the unusual and widespread Max Meadows tectonic breccia (Cooper, 1970), and, in an area from near Pulaski to Roanoke, Va., a series of fensters and horses (fig. 2) (Butts, 1933, 1940; Cooper, 1939; Marshall, 1959; Bartholomew and Lowry, 1979; Schultz, 1979a, b; Bartholomew, 1981; Henika, 1981; Decker and others, 1985). Except for the Price Mountain fenster, the fensters expose thin, rootless tectonic slices or horses. Horses are also exposed along the leading edge of the Pulaski fault. Detailed structural and strain analysis (Schultz, 1979a,b, 1981) shows that deformation style and intensity in these horses are in striking contrast to those in footwall rocks below the Pulaski thrust sheet. Rocks of the horses are some of the most highly strained in the Appalachian Valley and Ridge province (Schultz, 1979a, b, 1981).

HORSES AND FENSTERS

The Price Mountain fenster (fig. 3) exposes a doubly plunging, fault-modified anticline of Mississippian rocks below Cambrian rocks of the Pulaski thrust sheet. Drilling of this structure (Bartholomew and Lowry, 1979; Stanley and Schultz, 1983) (fig. 3) shows a continuous, 3,000-m-thick section of rocks ranging from Middle Ordovician to Lower Mississippian in age. Stratigraphic thickening in the Ordovician and Devonian shales has been attributed to minor faulting within these stratigraphic sections (Harris and Milici, 1977). Structural interpretations based on seismic data (Gresko, 1985) collected across the Price Mountain anticline place basement rocks at a depth of 7,000 m, a depth consistent with projected thicknesses of rocks of Late Cambrian through Middle Ordovician age below available drill-hole data (Bartholomew and Lowry, 1979). The Price Mountain sequence is part of the Saltville thrust sheet (Bartholomew and Lowry, 1979; Gresko, 1985) (figs. 2, 3).

Complexly deformed horses ranging in age from Late Ordovician to Middle Devonian are located along the Pulaski fault between Cambrian rocks of the hanging wall and Mississippian rocks of the footwall. Many of these horses are exposed along the leading edge of the thrust and in fensters in the Pulaski and Roanoke areas (fig. 2). Horses along the southwestern edge of the Price Mountain fenster are discontinuous, faulted lensoid rock masses having duplex geometry (Schultz, 1979a, b) in which folded Cambrian rocks of the Pulaski thrust sheet form the roof thrust (figs. 4, 5). Irregular fault contacts separate individual horses in the duplexes, and much of the original stratigraphic sequence is missing. Inverted stratigraphic sequences predominate (Schultz, 1979a, b). Mesoscopic deformation in the horses increases in intensity with transport distance (Schultz, 1981). The smaller horses consist of Ordovician dolomite and Silurian sandstone clasts supported in a matrix of Ordovician and Devonian shales and siltstones (fig. 6). The more competent sandstone clasts of the fault zone have been internally deformed by a pervasive mesoscopic and microscopic brittle fracture or cataclasis, such that the original sedimentary fabric of the rock is obliterated (fig. 7). Cataclasis of transported sandstone clasts resulted in an extremely poorly sorted fabric of angular grains that have little to no preferred long-axis orientation and reduced mean grain size (Schultz, 1979a, b) (fig. 8). Cataclasis in Ordovician dolomite clasts (fig. 9) disrupted the original crystalline fabric and produced microbreccias. Intracrystalline deformation of the cataclastic rocks is minor and is similar to that of rocks away from the fault zone (fig. 10).

Penetrative, tectonically induced, mesoscopic melangelike deformation fabrics are in horses consisting of thinly bedded, alternating sequences of Ordovician and Devonian shales, sandstones, and limestones. These deformation fabrics consist of isolated, fractured, and flattened inclusions of more competent rock in a cleaved matrix of less competent shale. The melangelike inclusions are lensoid double boudinage and are 1 cm to 3 m long. In all cases, the boudin and matrix are of the same stratigraphic formation. Variably oriented extension fractures in the boudin suggest that the bedding from which the boudin were derived was extended in several directions. This conclusion is consistent with strain data (fig. 11), which show that tectonic flattening was the dominant deformation mechanism during formation of the melangelike fabric in the horses. The sequence in fabric development consists of

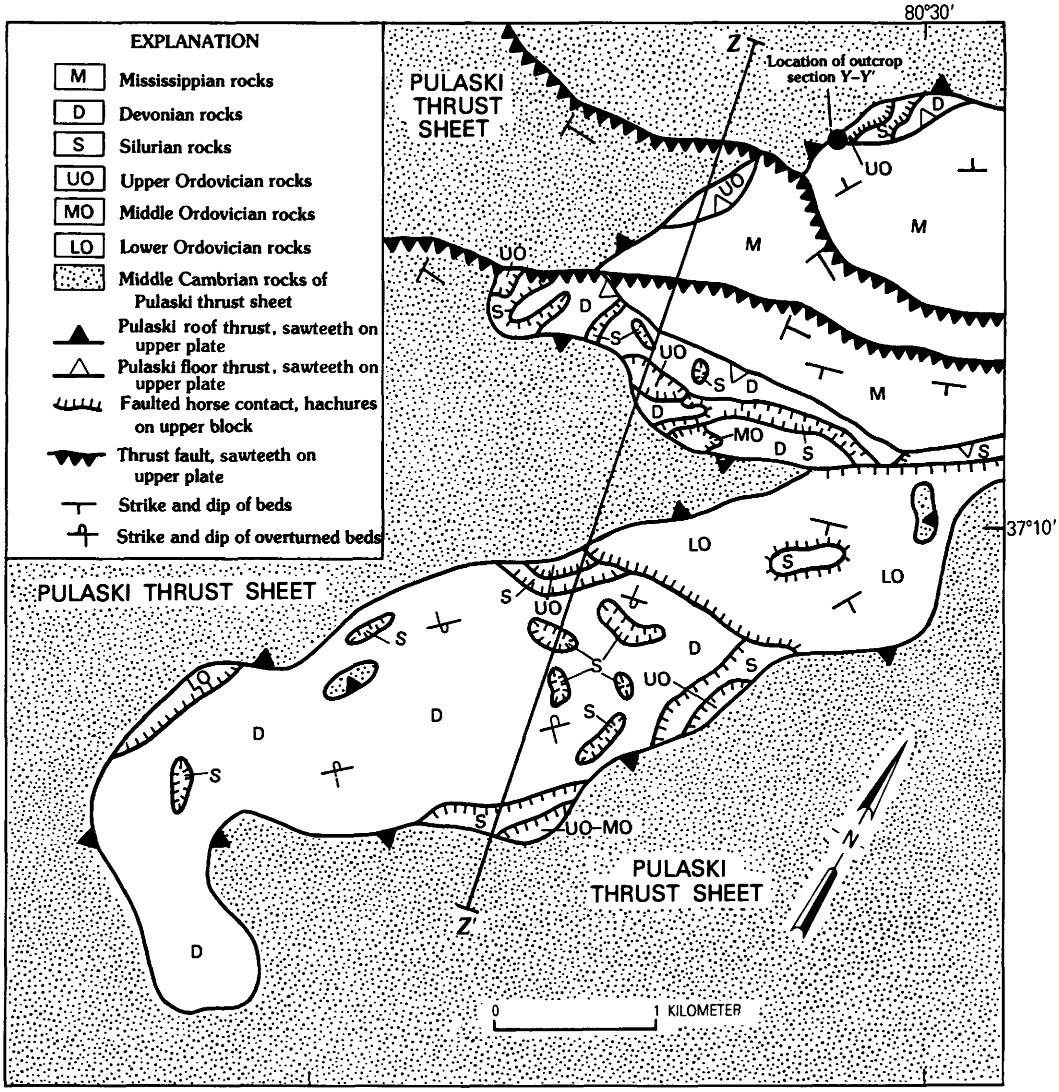

Figure 4. Western edge of Price Mountain fenster, including distribution of rooted Mississippian rocks and complexly deformed horses that lie below Cambrian rocks of Pulaski thrust sheet and above Mississippian rocks. Line of section *Z–Z′* (fig. 5) and location of outcrop section *Y–Y′* (solid circle) (fig. 6) also shown.

rotation (fig. 12), followed by transposition of early isoclinally folded rocks and formation of penetrative cleavage (Schultz, 1981). The southeasternmost fensters of the Pulaski thrust sheet in the Price Mountain area (fig. 3) expose rocks of similar structural complexity characterized by rootless and fault-bounded, stratigraphically attenuated slices (figs. 13, 14). In this area, lithologic variations are minimal, and the individual slices that compose the horses are more internally coherent; that is, mesoscopic deformation is limited to mesoscopic brittle faults (fig. 15).

Cross sections (figs. 3, 5, 14) drawn on the basis of existing drill-hole data and thickness constraints and available seismic interpretations (Stanley and Schultz, 1983; Gresko, 1985) suggest that rocks of Middle Cambrian through Devonian age in fensters in the study area lie structurally above a footwall of rocks of Mississippian age. This footwall may be continuous in the subsurface with southeast-dipping rocks on the southeastern limb of the Price Mountain anticline (figs. 3, 5). Interpretations of all other fensters of the Pulaski thrust sheet (Cooper, 1939; Marshall, 1959; Bartholomew, 1981; Henika, 1981; Decker and others, 1985) (fig. 2) are similar to those described near Pulaski (Schultz, 1979a, b). In all cases, highly deformed, rootless slices of stratigraphically older rocks are thought to lie above relatively less deformed younger footwalls.

A simple kinematic model for the origin and emplacement of horses (fig. 16) involves the interaction of an overriding thrust sheet with a subthrust syncline on or near a

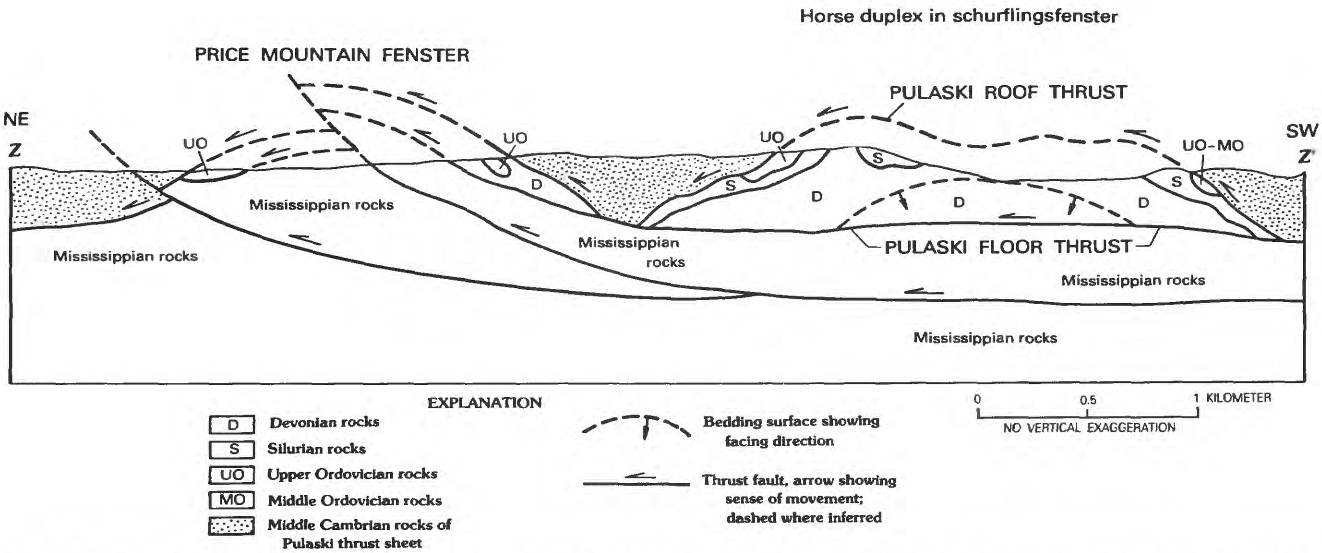

Figure 5. Cross section *Z–Z'* showing structural relationships between Mississippian rocks exposed in Price Mountain fenster, horses around edge of fenster, and Cambrian rocks of base of Pulaski thrust sheet. Horses below ground surface shown schematically.

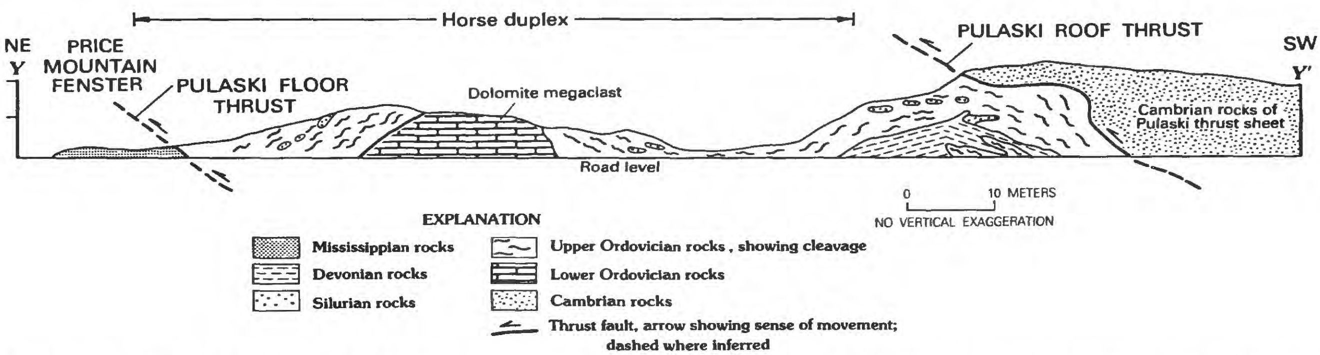

Figure 6. Outcrop along edge of Price Mountain fenster (line of section *Y–Y'*, fig. 4) showing relatively small horse duplex between Mississippian rocks of Price Mountain fenster and Cambrian rocks of Pulaski sheet. Rocks in duplex have undergone substantial amount of tectonic mixing and deformation during transport from their root zone. Drawn from photograph presented by Schultz (1979a).

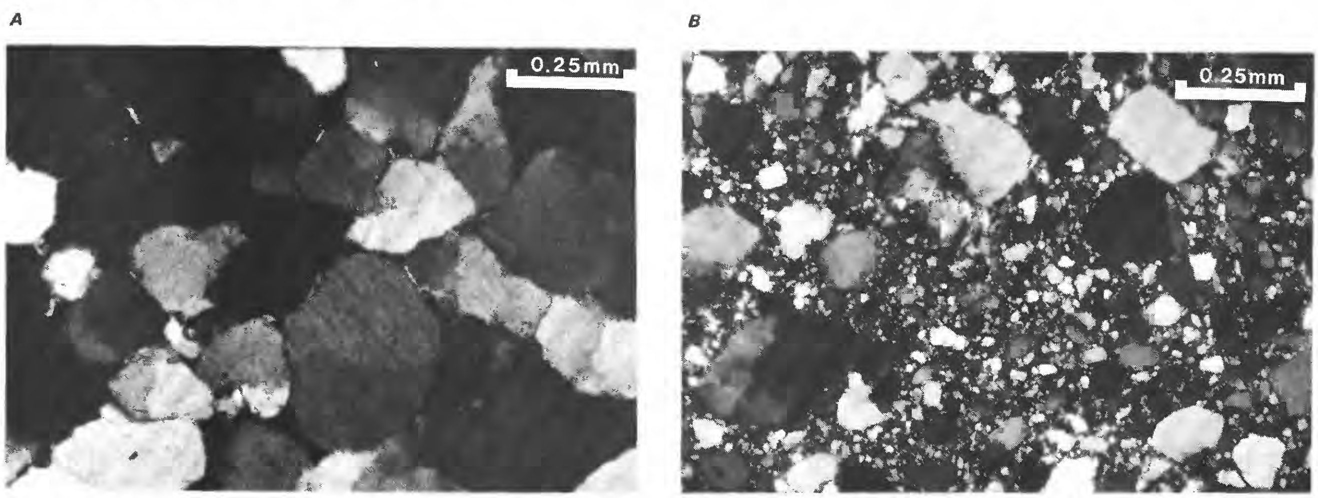

Figure 7. Photomicrographs of Silurian sandstones. *A*, Quartzite believed to be similar to undeformed protolith of cataclasites in horses of Pulaski thrust sheet. Sample collected on Saltville thrust sheet (fig. 2), about 10 km northwest of outcrop sketched in figure 6. *B*, Well-developed cataclastic fabric in Silurian sandstone from a horse of Pulaski thrust sheet. Development of poorly sorted fabric and angular grains indicates complete disruption of original sedimentary fabric. Sample collected at outcrop location *Y–Y'* (figs. 4, 6).

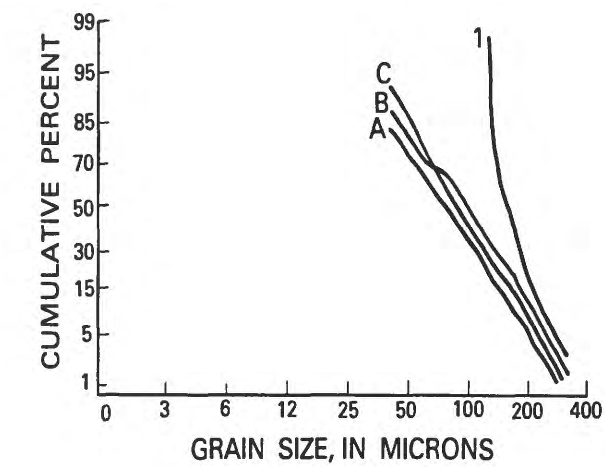

Figure 8. Cumulative frequency diagram showing grain size of Silurian sandstones in horses around Price Mountain fenster. Each curve based on 300 measurements of longest diameter of grains observed in thin section. Curves A, B, and C are based on counts from three mutually perpendicular thin sections of the same cataclastically deformed sandstone and indicate little or no preferred orientation of grains, an expected result of cataclasis. Curve 1 for undeformed sandstone shown in figure 7*A*. Method from Engelder (1974)

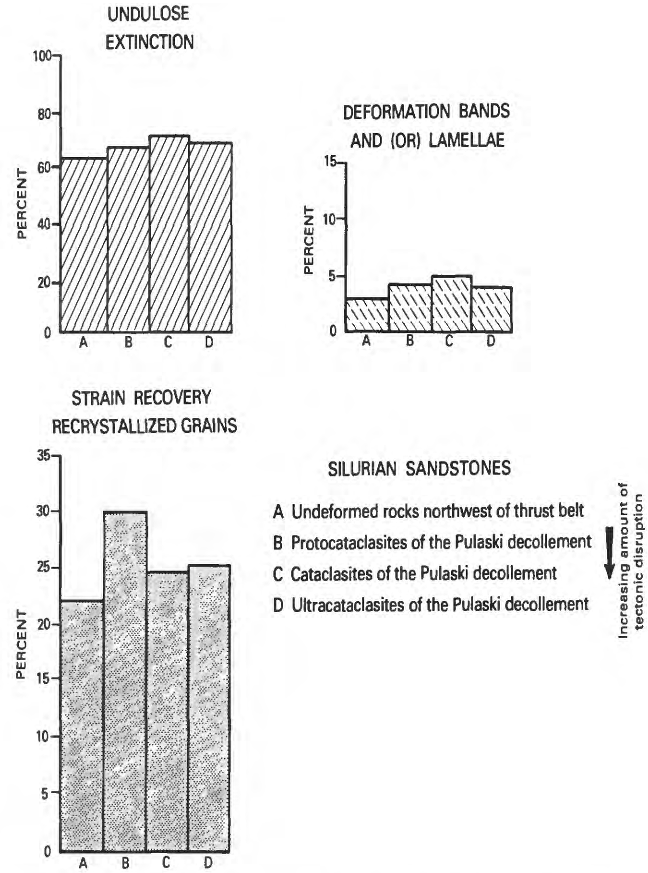

Figure 10. Histograms showing stages of intracrystalline deformation of Silurian sandstones resulting from increased amounts of cataclastic deformation. Percentage of detrital grains showing deformation is used as measure of deformation; 300 grains observed in each group of sandstones. Histograms show that no appreciable change occurred in amount of intracrystalline deformation as cataclasis intensified. Classification of stages of deformation from Sibson (1977).

tectonic frontal ramp. The first stage of horse development is footwall imbrication in a subthrust synclinal hinge and (or) in either the overturned limb or the normal limb of the syncline. The location of footwall thrusts determines the eventual facing of the horses. Detachment of the pieces (horse) from the footwall and their transport up the frontal ramp onto a decollement complete the early stages of horse development. Subsequent transport of the horses along the upper level decollement intensifies internal deformation fabrics and thins and tectonically mixes stratigraphic units.

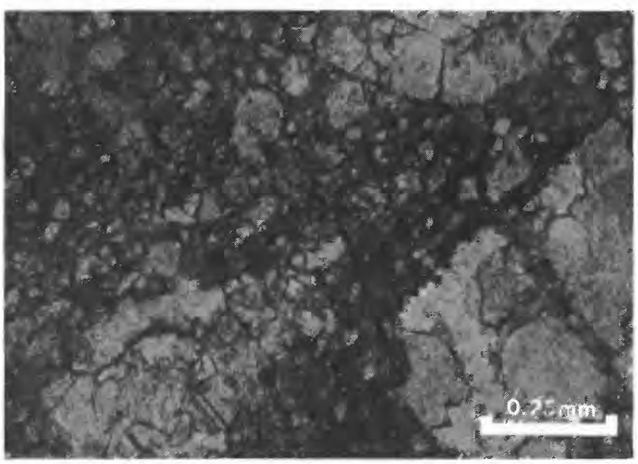

Figure 9. Photomicrograph of dolomite microbreccia from Ordovician horse. Angular fragments of dolomite have been plucked from the original crystalline fabric along cataclastic shears. Collected at outcrop location *Y–Y′* (figs. 4, 6).

IMPLICATIONS FOR HYDROCARBON POTENTIAL

The kinematic model for the evolution of horses in fensters of the Pulaski thrust sheet has important implications for hydrocarbon potential. If rocks of Devonian and (or) Mississippian age are below rocks in the fensters, they may also extend below the easternmost exposed Pulaski and Max Meadows thrust sheets of the Valley and Ridge province and perhaps below the westernmost part of the Blue Ridge province (fig. 3). This interpretation agrees well with regional seismic interpretations near this area that postulate undeformed foreland Paleozoic sedimentary rocks to the east of and below Precambrian metamorphic rocks of the Blue Ridge province (Milici and others, 1979; Harris and others, 1982).

In the study area, coals of Mississippian age below the Pulaski thrust sheet have proven coal-bed methane

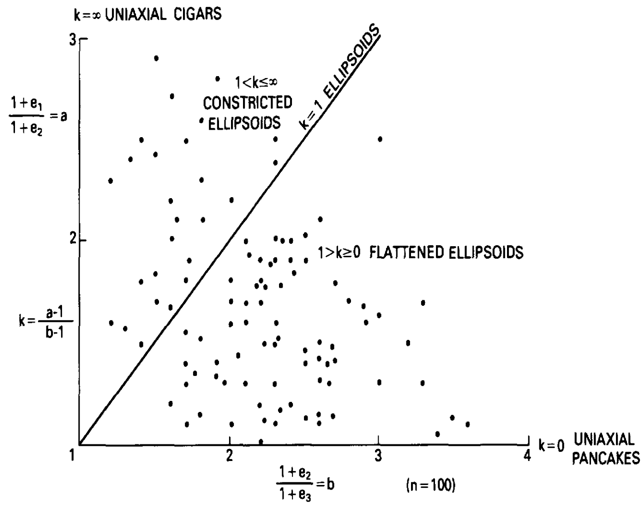

Figure 11. Flinn diagram of lensoid double boudinage showing distribution of strain in thinly bedded Ordovician rocks that are horses of Pulaski thrust sheet in area of study. Seventy-three percent of boudin fall within flattened ellipsoid field of diagram. e_1, e_2, and e_3, axes of principal extensions; a, ratio of elongations in e_1 and e_2 directions; b, ratio of elongations in e_2 and e_3 directions; k, slope of line defining strain types. Method from Cowan (1978).

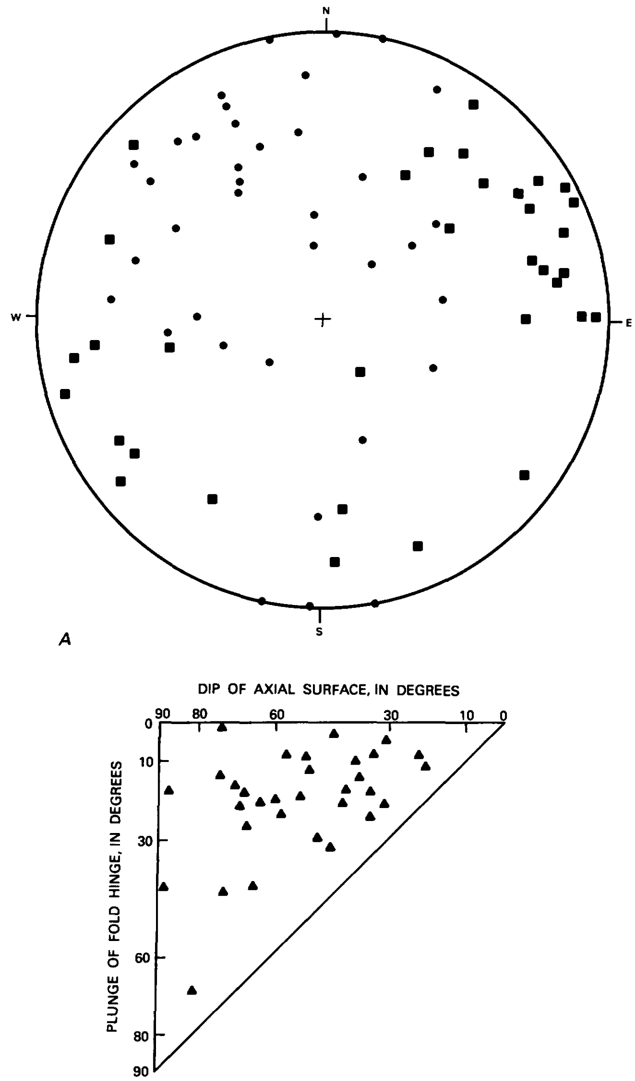

Figure 12. Structural plots for folds in thinly bedded Ordovician rocks in horses of Pulaski thrust sheet. *A*, Schmidt equal-area stereographic plot of pole to axial surface (solid circles) and fold axes (solid squares) in thinly bedded Ordovician rocks in horses of Pulaski thrust sheet. Variability of orientation reflects rotation of folds during formation of melangelike deformation fabric. Number of observations n=34. *B*, Fleuty diagram for folds in *A* shows that a wide range of fold styles is characteristic of melangelike deformation in horses. Method after Fleuty (1964).

potential (Stanley and Schultz, 1983). If rootless horses in the fensters southeast of the Price Mountain fenster overlie Mississippian rocks in the footwall. as the model presented herein suggests, then the area of coal-bed methane potential can be increased and may extend below the metamorphic rocks of the Blue Ridge province (fig. 3).

Results of Rock-Eval pyrolysis (fig. 17, table 1) of samples from Ordovician and Devonian horses of the Pulaski thrust sheet suggest that these rocks may have been potential source rocks of hydrocarbons. For a rock to be considered a potential source rock, the total organic carbon value must exceed 0.5 to 1.0 percent carbon (Tissot and Welte, 1984); 10 of the samples tested contain enough carbon to qualify. Hydrocarbon-generating capacity (or genetic potential) is expressed as the total hydrocarbon content (HC = S1 + S2) (table 1), and rocks containing more than 6 mg HC per gram of rock are considered to have good resource potential (Tissot and Welte, 1984). None of the samples analyzed, however, had a total hydrocarbon content above this value. Thermal maturation of the rocks, as measured by conodont color alteration index (CAI), is slightly higher (CAI 4) (fig. 18) than that of Mississippian coals in the Price Mountain fenster (CAI 3.5) (fig. 18) but is well within the upper limits of the dry gas window (Tissot and Welte, 1984). If coal-bearing Mississippian rocks extend to the east below thermally overmature thrust sheets (fig. 3), a viable coal-bed methane potential may exist below these rocks.

CONCLUSIONS

Fensters of the Pulaski thrust sheet in southwestern Virginia expose both rooted and rootless rocks. A simple kinematic model for the formation of horses in these fensters involves detachment and transport of thrust slices from footwall subthrust synclines. These subthrust synclines developed in a footwall composed of rocks of

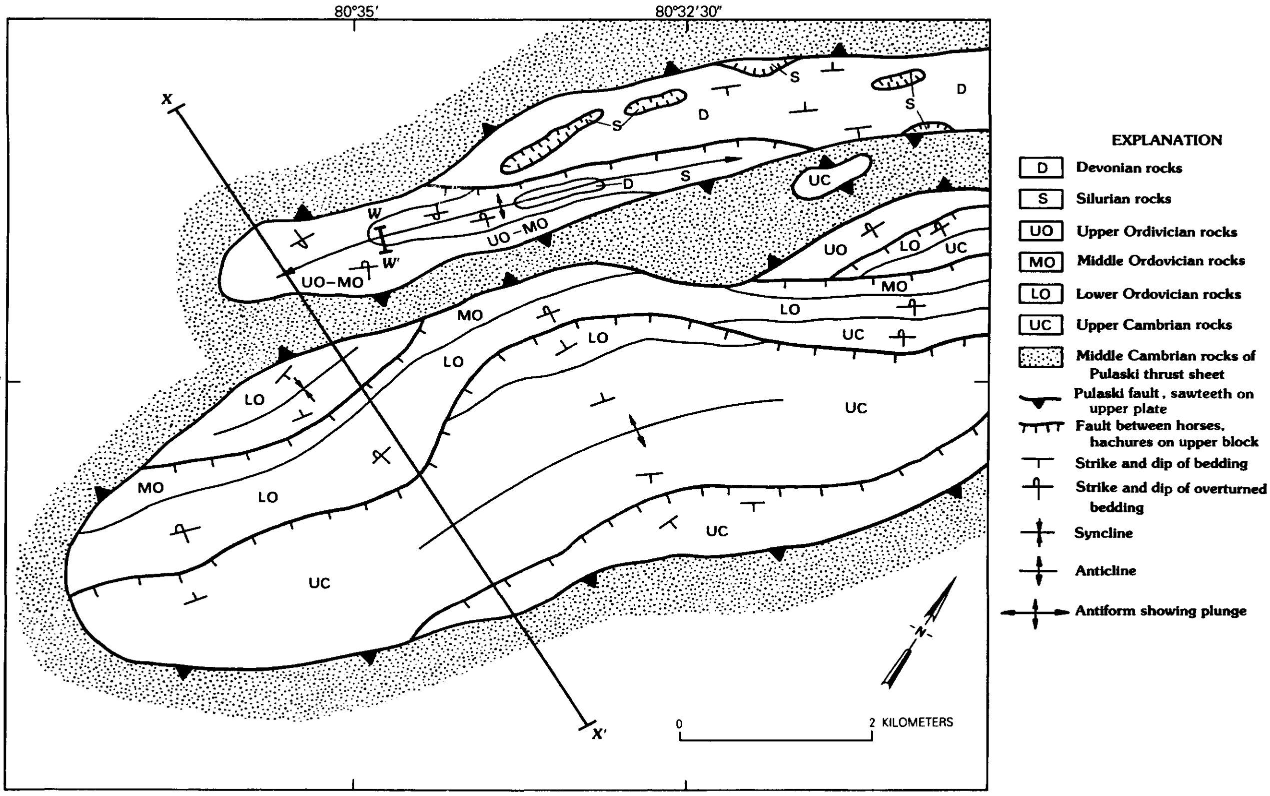

Figure 13. Horses exposed in fensters of Pulaski thrust sheet. Note juxtaposition of horses within each duplex along thrust faults contained within fensters. Location of map shown in figure 2; lines of section *X–X′* (fig. 14) and *W–W′* (fig. 15) also shown.

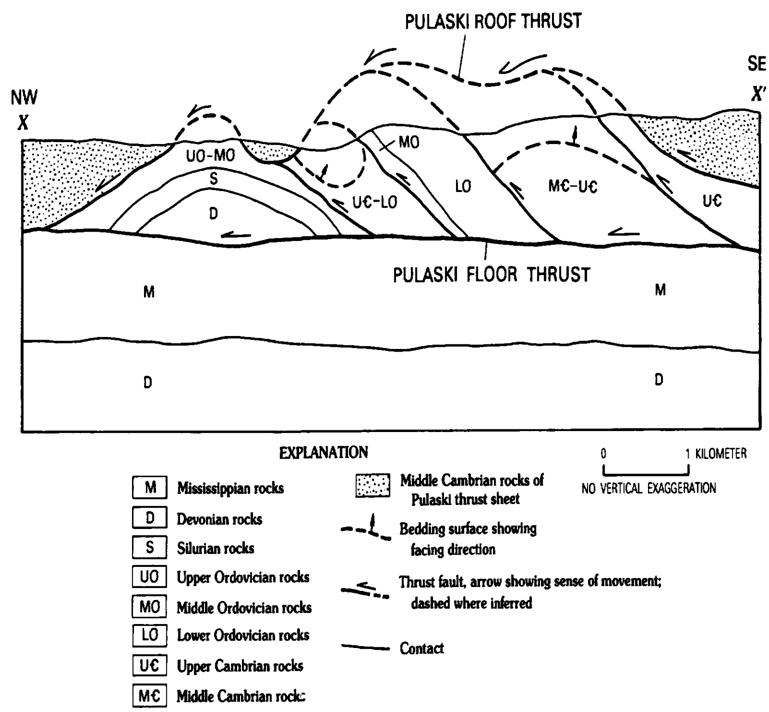

Figure 14. Cross section *X–X′* showing structural relationships between Devonian and Mississippian rocks of rooted footwall, horse duplexes, and Cambrian rocks of Pulaski thrust sheet. Line of section shown on figure 13.

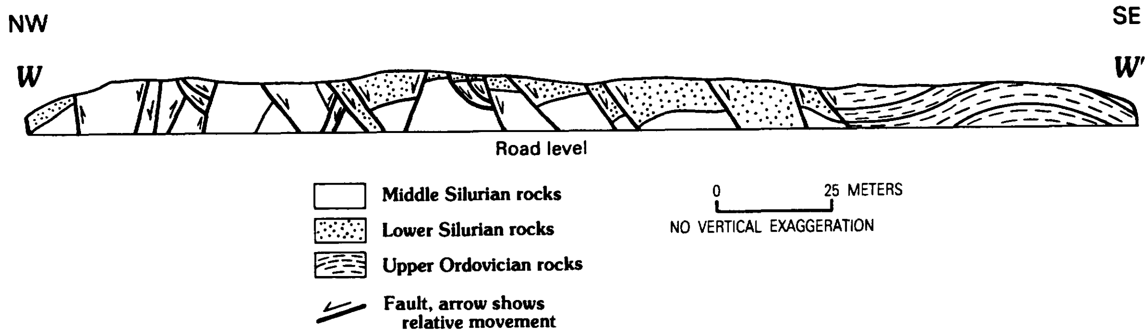

Figure 15. Sketch of outcrop section *W–W′* showing overturned, faulted core of antiform composed of Ordovician and Silurian rocks. Antiform is part of larger horse complex shown in figures 13 and 14. Line of section shown in figure 13.

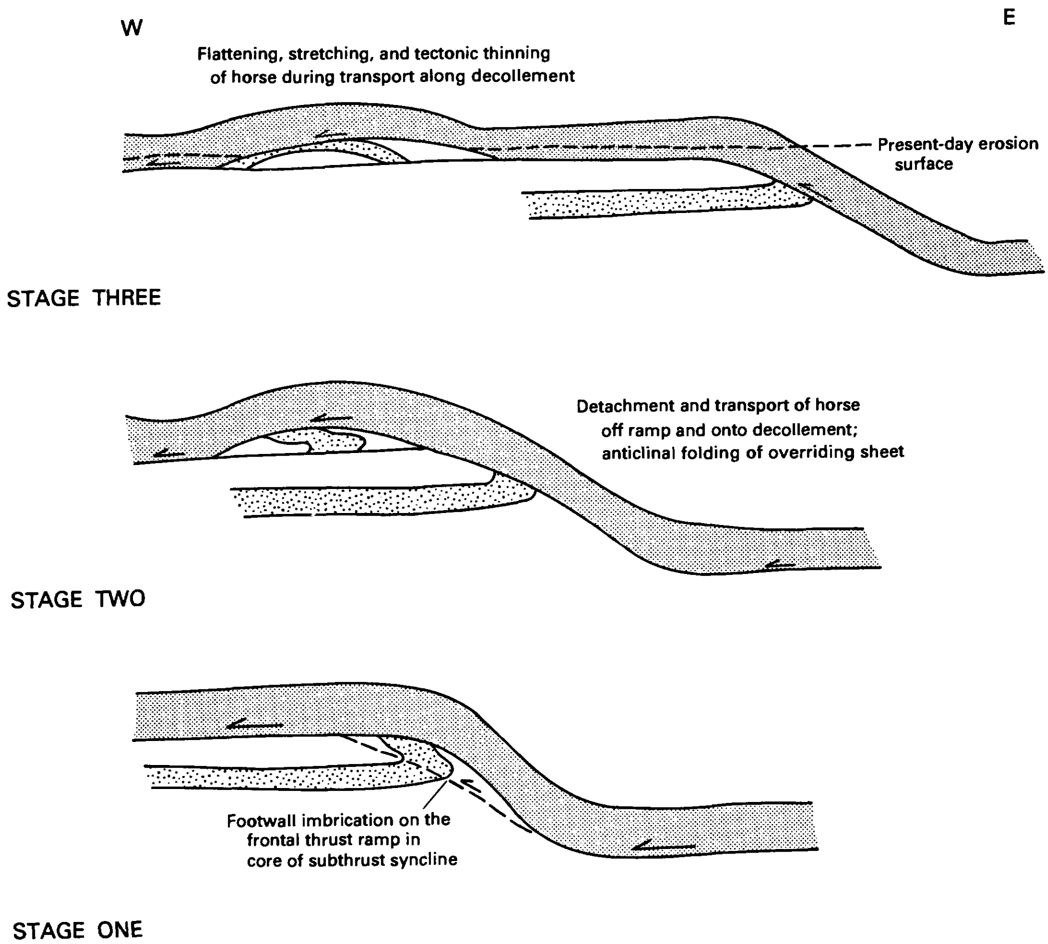

Figure 16. Simple kinematic model for horse derivation at frontal tectonic ramp of thrust sheet.

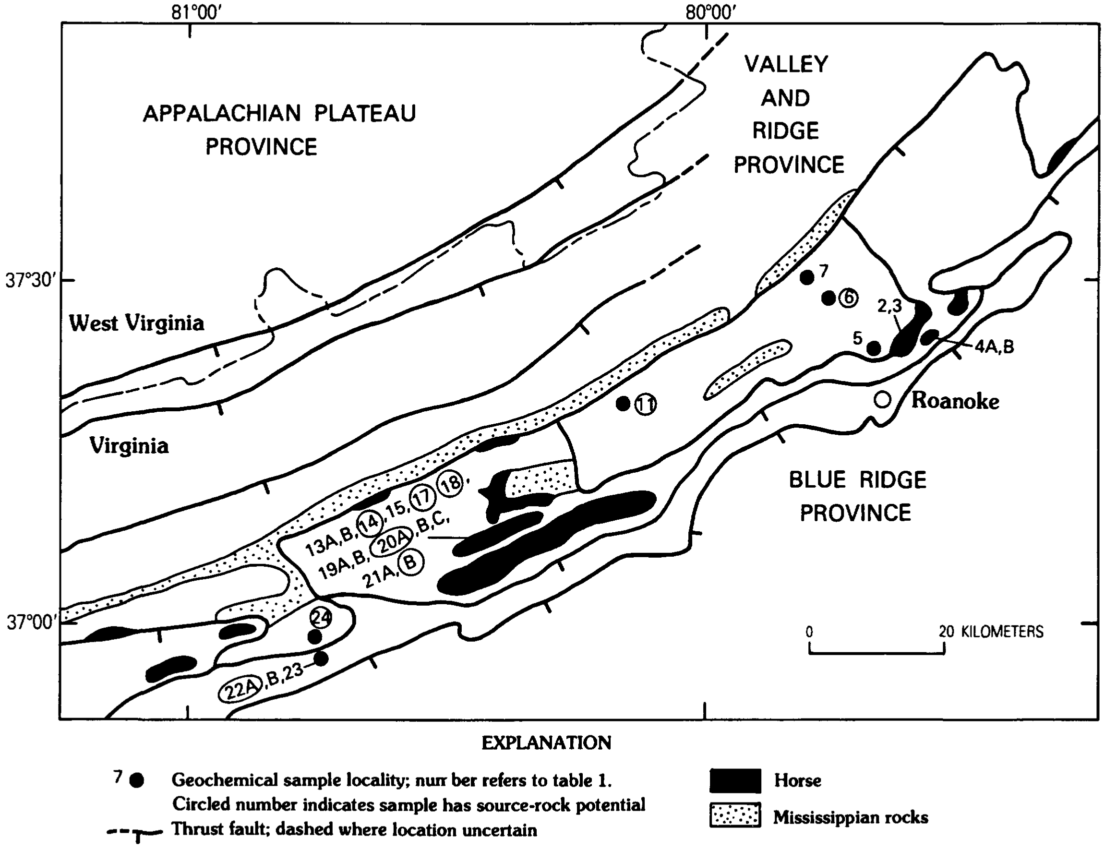

Figure 17. Location of geochemical samples and coal-bed methane test wells (Stanley and Schultz, 1983). Geochemical data for samples shown in table 1.

Cambrian through Mississippian age on the frontal tectonic ramp of the Pulaski thrust. This frontal ramp may extend eastward below the Blue Ridge province. This interpretation agrees well with regional-scale models for the evolution of the Eastern Overthrust Belt derived from seismic studies. Studies of the thermal maturity of horses in fensters in the Pulaski thrust sheet seem to indicate that rocks of similar age below thrust sheets of the Valley and Ridge and Blue Ridge provinces probably are in the upper part of the dry gas window. In addition, methane in Mississippian coals extending into this frontier hydrocarbon province may have an economic potential. Hydrocarbons probably are not in Ordovician and Devonian source rocks but may be elsewhere in this structurally complex area and may have been derived from the Ordovician and Devonian black shales.

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Table 1. Results of Rock-Eval pyrolysis of potential source rocks of Devonian and Ordovician age, Pulaski thrust sheet, southwestern Virginia

Sample number	Total organic carbon (in percent)	Free hydrocarbons S1[1] (mg/g of rock)	Pyrolyzed hydrocarbons S2[2] (mg/g of rock)
Devonian black shales			
6	2.59	0.01	0.16
14	1.37	.01	.05
17	2.12	.02	.07
18	2.59	.01	.03
24	1.01	0	.02
Ordovican black and gray shales			
2	0.22	0	0
3	.18	0	0
4A	.15	.01	.02
4B	.23	0	0
5	.26	0	0
7	.13	0	0
11	1.27	.02	.03
13A	.31	.01	0
13B	.11	0	0
15	.26	0	0
19A	.38	.02	.04
19B	.24	.03	.02
20A	.78	.01	0
20B	.43	.02	.02
20C	.06	.01	0
21A	.70	.02	.01
21B	1.04	.03	.02
22A	.68	.04	.11
22B	.36	.02	.04
23	.14	.01	.12

[1] S1, Quantity of organic matter existing in rock as free or adsorbed hydrocarbons.

[2] S2, Quantity of hydrocarbons.

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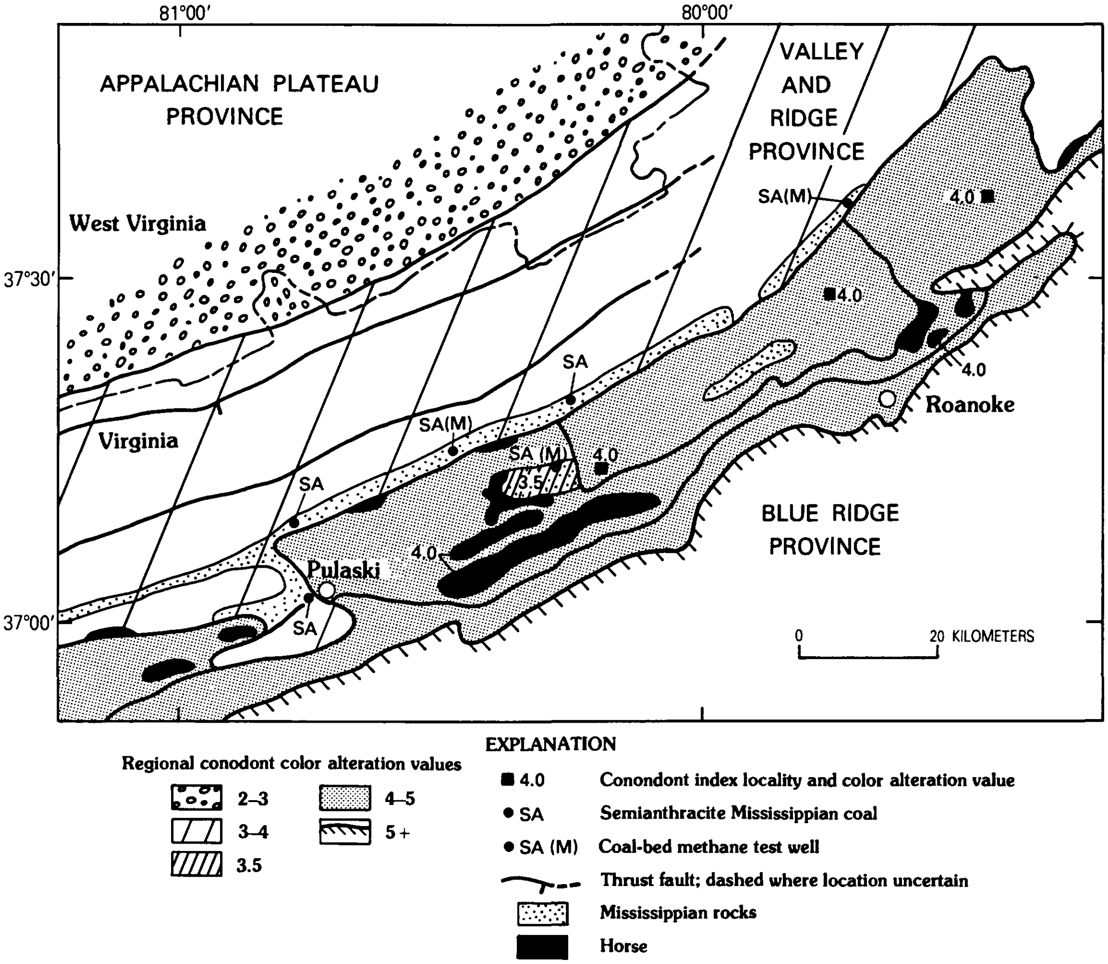

Figure 18. Thermal maturation level of rocks in study area based on conodont color alteration values of Epstein and others (1977) and A.G. Harris (unpublished data, 1985). Semianthracite coal localities from Stanley and Schultz (1983), Simon and Englund (1983), and Campbell (1925).

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Chapter B

Fluvial Deposition in the Central Appalachians During the Early Pennsylvanian

By CHARLES L. RICE and JOSEPH F. SCHWIETERING

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1839

EVOLUTION OF SEDIMENTARY BASINS—APPALACHIAN BASIN

CONTENTS

FIGURES

CONVERSION FACTORS FOR SOME SI METRIC AND U.S. UNITS OF MEASURE

To convert from	To	Multiply by
Feet (ft)	Meters (m)	0.3048
Miles (mi)	Kilometers (km)	1.609
Pounds (lb)	Kilograms (kg)	.4536
Degrees Fahrenheit (°F)	Degrees Celsius (°C)	Temp °C=(temp °F−32)/1.8

Fluvial Deposition in the Central Appalachians During the Early Pennsylvanian

By Charles L. Rice[1] *and* Joseph F. Schwietering[2]

Abstract

Development of a Pennsylvanian fluvial system in eastern North America following emergence of the craton in Late Mississippian time was controlled by a southwest-dipping paleoslope. Tectonism during the Late Mississippian and Early Pennsylvanian caused streams draining the Cincinnati arch toward the southwest to be captured and diverted to the south and southeast into the subsiding Appalachian basin. These drainage modifications resulted in a significant contribution of sediment to the Appalachian basin from source areas to the north and northwest.

INTRODUCTION

Arguments about the existence of a Mississippian-Pennsylvanian unconformity in individual outcrops or small areas in the central Appalachian basin have tended to overshadow accumulated data that indicate the existence of a well-developed fluvial drainage system in much of the area by latest Mississippian and earliest Pennsylvanian time. Numerous geologic reports, some of which date from the early part of the 20th century, describe the basal Pennsylvanian channels and rocks that crop out mostly along the northwestern border of the Appalachian basin. Although the varied nature of the Mississippian-Pennsylvanian contact and the lack of reliable data have generally precluded definitive subsurface interpretations for much of the Appalachian basin, a few local and regional subsurface studies of Carboniferous strata also support a fluvial interpretation for the basal Pennsylvanian. This report discusses these data and suggests a model of fluvial deposition for the Early Pennsylvanian of the Appalachian basin that is regionally consistent with that for the related Eastern Interior (Illinois) basin to the west.

Concepts of the shape and history of the Appalachian basin and of the character of deposition during Pennsylvanian time are influenced by a widely held perception that a sea existed northwest of the Appalachian orogenic belt and its northwest-facing deltas (Englund, 1974). Thick sequences of quartz arenites in the Lower Pennsylvanian of the Appalachian basin commonly are cited as evidence of that sea and of beach or barrier-bar deposition. We propose, however, that the quartz arenites, which commonly occur in channel deposits, are fluviatile. We also suggest that their distribution reveals a drainage pattern showing a significant contribution of sediment to the Appalachian basin during Early Pennsylvanian time, first from the northern flank of the basin and later, by means of stream capture, from cratonic sources north and northwest of the basin.

GEOLOGIC SETTING

Late Mississippian deposition in the Appalachian and Eastern Interior basins began with formation of shallow-water shelf carbonates (Greenbrier Limestone and equivalent strata), which, in northern Kentucky and adjacent areas, contain numerous exposure features and diastems indicative of frequent subaerial exposure (Rice and others, 1979). Predominantly terrigenous strata (Mauch Chunk Group and equivalents) subsequently were deposited by south- and west-prograding deltas. Subsidence in the Appalachian basin during Late Mississippian time resulted in deposition of a wedge of sediments that thickens southeastward and is as thick as 5,000 ft in southeastern West Virginia (Arkle, 1974). Thickness projections of Upper Mississippian rocks suggest, however, that the Cincinnati arch was emergent during the Late Mississippian in most of western Ohio, north-central Kentucky, and eastern Indiana (Pryor and Sable, 1974).

During Late Mississippian or Early Pennsylvanian time, a eustatic lowering of sea level resulted in the emergence of most, if not all, of the craton in eastern North America. The sea retreated from the craton toward the southwest (Swann, 1964), and southwest-flowing rivers cut valleys as deep as 450 ft in both the Eastern Interior basin (Siever, 1951) and the Appalachian basin (Mrakovich,

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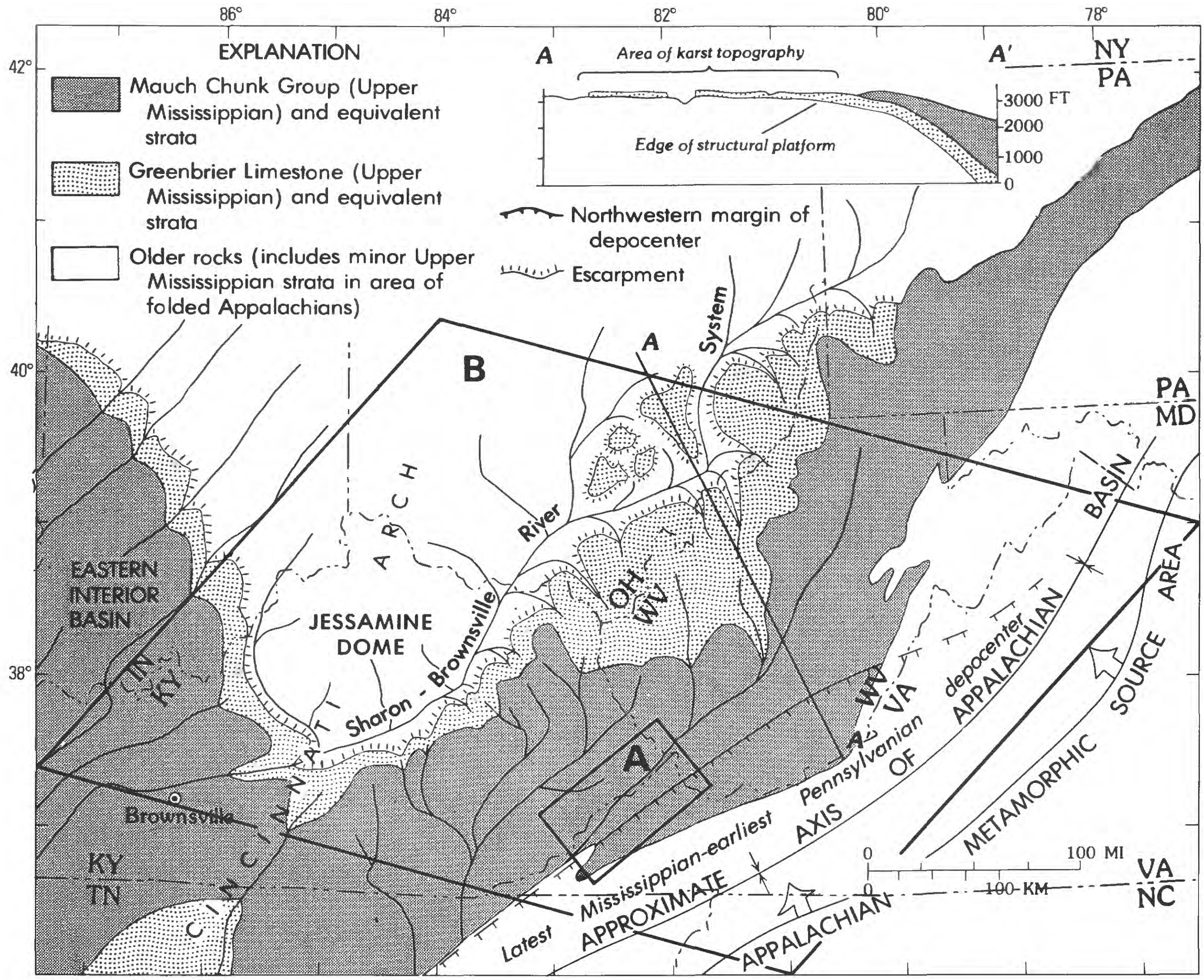

Figure 1. Distribution of Upper Mississippian rocks and inferred Late Mississippian–Early Pennsylvanian drainage system, Kentucky, Ohio, West Virginia, and parts of adjacent States. Locations of areas A and B depicted in figure 7 also shown.

1969). Erosion truncated progressively older strata northward, so that Pennsylvanian rocks directly overlie Ordovician strata in northern Illinois and Devonian strata in New York. Upwarping of the Cincinnati arch and erosion of less competent shales and siltstones above and below the more competent Mississippian carbonate rocks (Greenbrier Limestone and its equivalents) resulted in the formation of a low north-facing escarpment that defined the open shape of the south-plunging arch and, in particular, the northwestern edge of the Appalachian basin (fig. 1). Remnants of that escarpment are buried beneath Pennsylvanian rocks in southwestern Pennsylvania and southeastern Ohio (Wanless, 1975). The escarpment locally has been exhumed by erosion and is represented today, in part, by the Cumberland Escarpment and by Muldraughs Hill (a northeast-facing escarpment) in central Kentucky (Lobeck, 1929) and its extension in Indiana.

Emergence of the craton and upwarping of the Cincinnati arch during Late Mississippian and Early Pennsylvanian time were accompanied by relative downwarping of the Appalachian basin. Although Rice (1985) has suggested that an unconformity between Mississippian and Pennsylvanian strata extends throughout the central Appalachian basin, subsidence and sedimentation apparently continued in southeasternmost West Virginia and adjoining parts of Virginia, areas in which Englund (1974, 1979) reported that strata of the Pocahontas Formation (basal Pennsylvanian) (fig. 2) conformably overlie Mississippian strata.

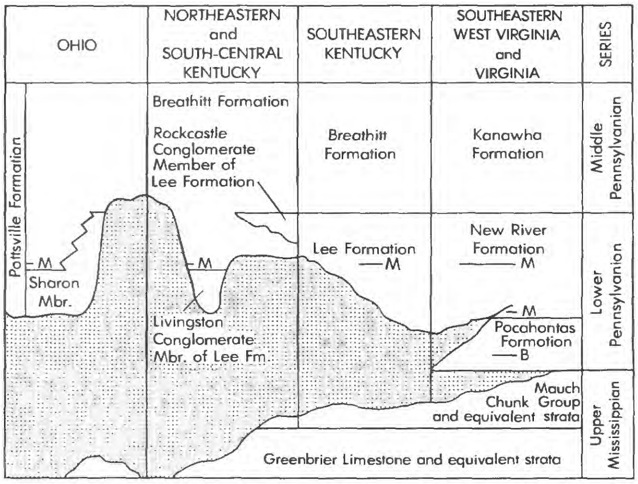

Figure 2. Lower and Middle Pennsylvanian and Upper Mississippian stratigraphic units used in report. Pattern indicates missing strata; M, horizon containing restricted marine fauna; B, horizon containing brackish-water fauna. Data from Arkle (1974), Englund (1974), Rice (1984), and Wanless (1975).

Figure 3. Crossbedded sets of Pennsylvanian quartz-pebble conglomerate and pebbly quartz arenite on Pilot Knob, Levee 7½-minute quadrangle, east-central Kentucky. These deposits and those of adjacent Rotten Point are west of carbonate escarpment shown in figure 1 and comprise a channel fill as thick as 165 ft that rests on Lower Mississippian rocks (McDowell, 1978). Current direction is southwest. Location of Pilot Knob shown in figure 6. Brunton compass shown for scale.

SEDIMENT DISPERSAL PATTERNS FOR THE PENNSYLVANIAN

In a detailed analysis of the paleogeography of Pennsylvanian rocks in the Appalachian basin in Pennsylvania and adjacent States, Meckel (1967) identified two distinct source areas for detritus in the Appalachian basin: (1) a "tectonic" source area along the southeastern margin of the basin in an area of rapid uplift and erosion and (2) a stable "cratonic" source area in southern Canada and northern New York. Detritus from the tectonic source is characterized by sedimentary and metamorphic rock fragments and generally angular to subrounded polycrystalline quartz grains, whereas detritus from the cratonic source is composed predominantly of well-rounded monocrystalline quartz grains, best typified by the quartz arenite of the Sharon (conglomerate) Member of the Pottsville Formation (fig. 2). Meckel's model suggests that sediment-dispersal patterns were controlled in part by a "thalweg," or linear topographic low, that extended southwestward from the general area of southwestern Pennsylvania. Clastic materials from the two source areas were carried by tributaries to the topographic low and ultimately toward a sea that, whenever subsidence exceeded deposition, extended northeastward into Pennsylvania from areas in West Virginia and Ohio.

Although Meckel's depositional model fits the general pattern of Pennsylvanian sedimentation, especially with regard to the two source areas, it neither conforms to nor explains major aspects of Early Pennsylvanian deposition. For example, marine incursions did not extend into western Pennsylvania until the middle part of Middle Pennsylvanian time, and marine fauna, generally of a restricted nature, have been identified only in one to three thin stratigraphic zones (generally only inches thick) in Lower Pennsylvanian rocks of Ohio, West Virginia, Virginia, and Kentucky (Rice, 1984) (fig. 2). In the general area of Meckel's topographic low, Middle Pennsylvanian rocks commonly overlie Lower Mississippian rocks. During the Early Pennsylvanian, these areas probably were uplands and more subject to erosion than to deposition (Wanless, 1975).

DRAINAGE SYSTEMS

Most studies of current directions in basal Pennsylvanian strata in eastern North America indicate a southwesterly transport direction (see, for example, Siever and Potter, 1956). Along the northwestern margin of the Appalachian basin, sub-Pennsylvanian valleys and channels have been described in northern Ohio (Lamb, 1911), in western Pennsylvania (Ingham and others, 1956), in southern Ohio (Fuller, 1955; Couchot, 1972), in northeastern Kentucky (Englund and Windolph, 1971), in south-central Kentucky (Wixted, 1977; Rice, 1984), and in the Eastern Interior basin (Bristol and Howard, 1971). The studies cited describe the valley- and channel-fill deposits as Pennsylvanian stream deposits, many of which are composed of pebbly or conglomeratic quartz arenite that indicates southerly current directions parallel with the valleys or channels (see, for example, figs. 3, 4). The basal quartz arenite deposits, although widely separated, are postulated by Rice (1984) to derive from the same southwest-flowing river system that included the basal Pennsylvanian deposits of the Brownsville paleovalley in the Eastern Interior basin (Pryor and Potter, 1979). In south-central Kentucky, an area of

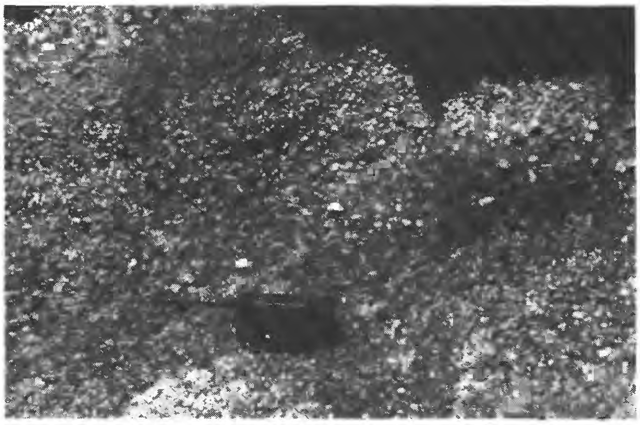

Figure 4. Detail of Pennsylvanian crossbedded quartz-pebble conglomerate on Pilot Knob, Levee 7 1/2-minute quadrangle, east-central Kentucky, shown in figure 3. Brunton compass shown for scale.

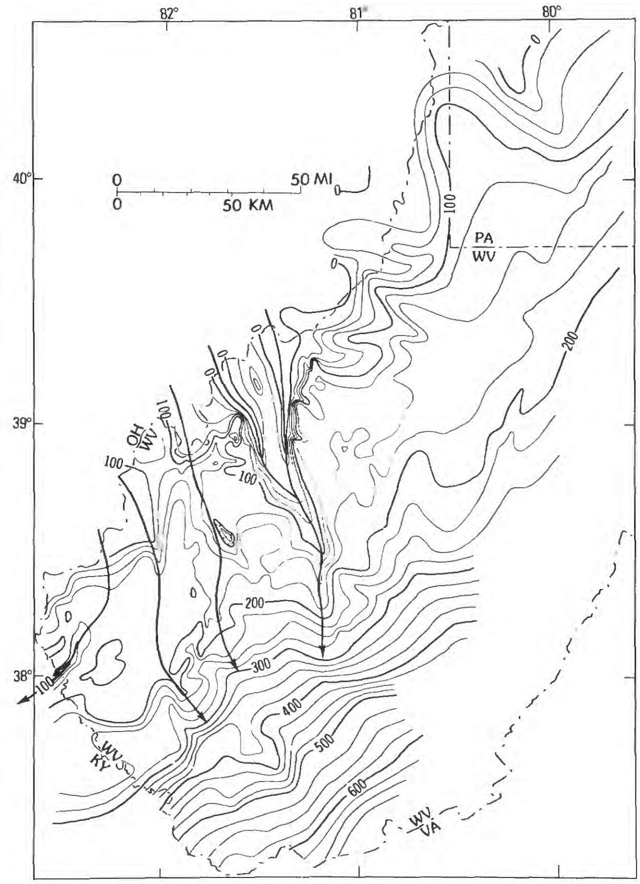

Figure 5. Isopach map of Mississippian Greenbrier Limestone in West Virginia showing traces and directions of flow of inferred paleochannels (indicated by arrows). Contour interval 25 ft. Modified from Flowers (1956, pl. 2).

extensive Pennsylvanian lag gravels (Miller, 1910) indicates where that river, herein called the Sharon-Brownsville river system (fig. 1), breached the Cincinnati arch. The stream pattern shown in figure 1 in the area of the Jessamine dome suggests that the southwest-dipping paleoslope was modified locally by upwarping of the Cincinnati arch in Late Mississippian time (Rice and Haney, 1980) and that the escarpment southeast of the Sharon-Brownsville river system was the drainage divide between the Appalachian and Eastern Interior basins at that time.

Paleocurrent directions and thickness contours show that the major Pennsylvanian depocenters were along the margin of the craton in the Appalachian basin in southeastern West Virginia and southwestern Virginia, in the Black Warrior basin of Mississippi and Alabama, and in the Arkoma basin of Oklahoma and Arkansas. Thus, in West Virginia and parts of Virginia along the eastern margin of the Appalachian basin, paleocurrent directions of basal Pennsylvanian strata are westerly or northwesterly from the evolving Appalachian orogenic belt (see, for example, Englund, 1974). In northeastern Kentucky, southeast-flowing streams at the base of the Pennsylvanian, such as the drainage system mapped by Englund and Windolph (1971), also carried detritus to the depocenter from the emergent southeastern flank of the Cincinnati arch. In southwestern Virginia, much of the depocenter is eroded away, and Early Pennsylvanian current directions shift from westerly to southwesterly and follow the margin of the craton in eastern Kentucky and Tennessee toward the southwest (Donaldson and others, 1979).

Although small channels cannot be traced in the subsurface by using available drill-hole data, several large paleovalleys have been distinguished at the base of the Pennsylvanian in West Virginia and easternmost Kentucky. Figure 5 is a modification of a map by Flowers (1956) showing the thickness of the Greenbrier Limestone in the subsurface of West Virginia. The configuration of thickness contours indicates that the upper surface of the limestone in northwestern West Virginia was beveled and locally deeply scoured by subaerial erosion. Depression contours indicate a huge sink hole and, together with Flowers' description of the systemic boundary, suggest development of a karst topography on the Greenbrier in that area in Late Mississippian and Early Pennsylvanian time. Flowers identified the large trough outlined by the 100-ft contour in the central part of the map as a river paleochannel and, because northwest-trending hanging valleys are tributary to the main channel, postulated that the channel and its fill of Pennsylvanian quartzose sandstone and conglomerate are the product of a northwest-flowing river. We believe, however, that the paleovalley was cut by a south-flowing river for several reasons: (1) the regional paleocurrent direction in Early Pennsylvanian time was southerly; (2) the paleovalley is large and is filled by quartzose sandstone and conglomerate; and (3) the paleovalley is cut in bedrock and was situated between a continental source of detritus and the rapidly subsiding Appalachian basin. Several other scours sugges-

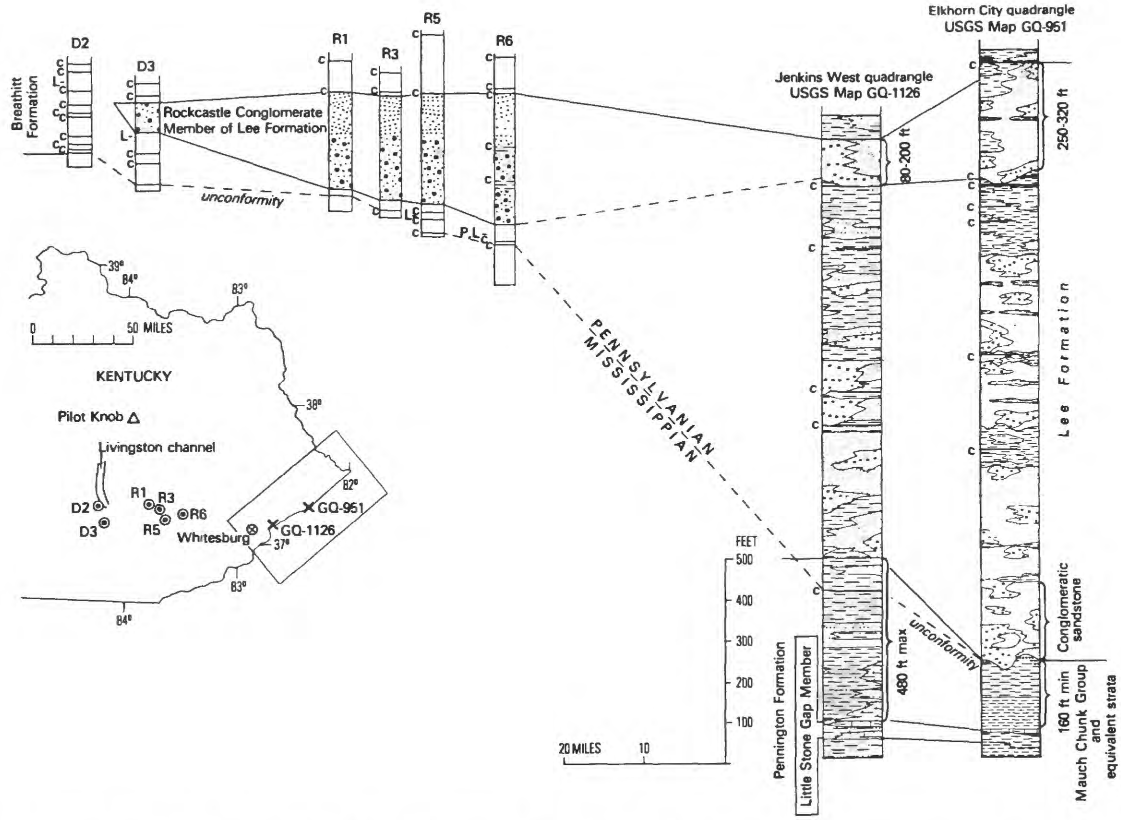

Figure 6. Westward onlap and pinchout of Pennsylvanian Lee Formation in eastern Kentucky. Generalized columnar sections from U.S. Geological Survey Geologic Quadrangle Maps GQ–951 (Alvord and Miller, 1972) and GQ–1126 (Rice, 1973). Subsurface data from core holes drilled for coal resource evaluation of Lower Pennsylvanian rocks (Bergeron and others, 1983). The Rockcastle Conglomerate Member of the Lee Formation was correlated with the upper sandstone member of the Lee Formation by Englund (1968) and by Rice and Smith (1980). c, coal bed; L, linguloid brachiopod; P, productoid brachiopod.

tive of paleochannels are indicated on the sub-Pennsylvanian surface in figure 5. Because the Greenbrier dips to the southeast (see fig. 1), the south-flowing streams cut progressively higher stratigraphic levels, and, south of their terminations shown in figure 5, the paleochannels are entirely in strata of the overlying Mauch Chunk Group.

A southwest-trending linear depression was identified in the subsurface at the base of the Pennsylvanian in eastern Kentucky (Coskren and Rice, 1979) and is shown in area A on figure 1 as a paleovalley. The extension of this paleovalley into southwestern Virginia was described by Rice (1985, 1986). The paleovalley is 10 mi wide and more than 300 ft deep and filled with pebbly and conglomeratic quartz arenite of the Lee Formation (fig. 2). The basal Pennsylvanian quartz arenites that occupy a portion of this paleovalley are locally brought to the surface by the Pine Mountain overthrust fault along part of the Kentucky-Virginia State line. Figure 6 contrasts a simplified geologic section for the Lee Formation in the central part of the paleovalley (Elkhorn City 7½-minute quadrangle) (Alvord and Miller, 1972) with one for an upland area west of the paleovalley (Jenkins West 7½-minute quadrangle) (Rice, 1973). The presence of a paleovalley at the base of the Pennsylvanian in the Elkhorn City quadrangle is corroborated by the difference in the thickness of the interval between the Mississippian Little Stone Gap Member of the Pennington Formation and the base of the Lee Formation in the two areas. In addition, a distinctive 200-ft-thick high-silica (>99.9 percent) conglomeratic sandstone unit at the base of the Lee Formation in the central part of the paleovalley in the Elkhorn City quadrangle is not in the upland area in the Jenkins West quadrangle.

DEPOSITIONAL MODELS

Depositional models for Lower Pennsylvanian rocks in the central Appalachian basin must explain the contrast between what might be called the "northwestern" and "southeastern" facies of the New River Formation (or equivalent strata of the Lee Formation) (fig. 2). The

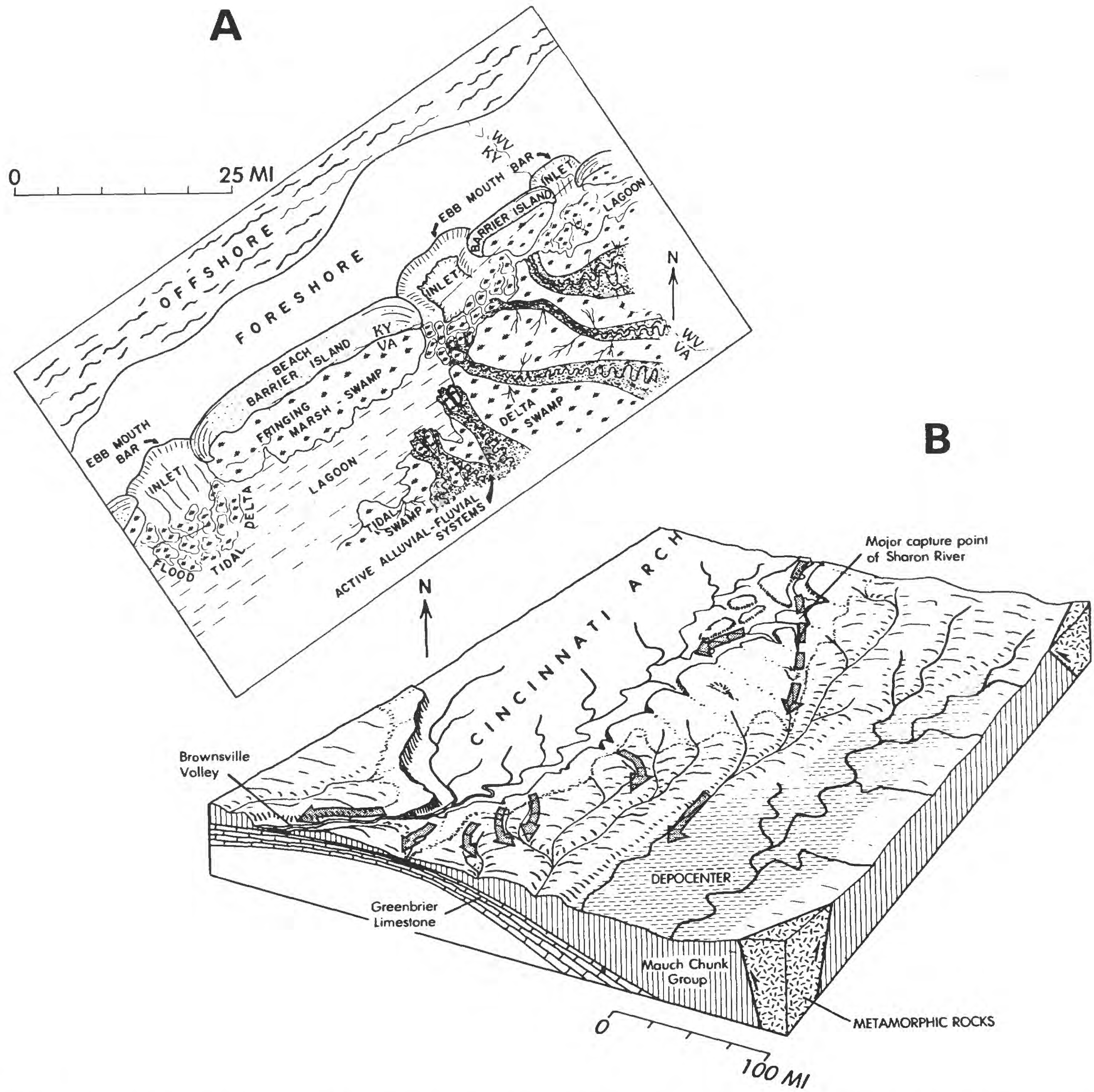

Figure 7. Two interpretations of Early Pennsylvanian paleogeography in the Appalachian basin. *A*, Area A in figure 1. Beach and barrier island model of Miller (1974, fig. 59) in parts of Kentucky, Virginia, and West Virginia. *B*, Area B in figure 1. Fluvial model presented in this report. Arrows indicate general location and paleocurrent directions of known deposits of basal Pennsylvanian quartz arenite; paleocurrent direction inferred for subsurface data (dashed) (Flowers, 1956; Hansen, 1984). Details of streams altered; vertical scale exaggerated for sake of perspective.

northwestern facies is dominated by quartz arenite units, which are broadly linear, trend southwest, and locally are more than 400 ft thick and 50 mi wide. The quartz arenite facies wedges out to the southeast or locally grades into the southeastern facies, which is dominated by subgraywacke, siltstone, and shale. Figure 7*A* (Miller, 1974) shows a model of the paleogeography during deposition of Lower Pennsylvanian strata in adjacent areas of Kentucky, Virginia, and West Virginia that is supported by the studies of Donaldson (1974, fig. 1), Englund (1974, 1979), Englund and others (1979, 1985, 1986), Ferm (1974a, b), Ferm and others (1971), Horne (1979), and Horne and others (1974). In this model, the two facies are genetically related: the northwestern facies is represented by the beach and barrier island complex and the southeastern facies by the back-barrier and alluvial complexes. However, marine units predicted by the model to represent the foreshore and offshore environments in Kentucky and West Virginia have never been identified in either State. Proponents of the model argue either that the Pennsylvanian quartz arenite is a facies of Mississippian marine shale and carbonate units (Ferm, 1974b; Horne and others, 1974) or that the northwestern marine equivalents of the quartz arenite have been eroded away (Englund, 1974). We believe that these hypotheses are untenable. Available data indicate that the Pennsylvanian quartz arenite units onlap the southeastern flank of the Cincinnati arch and either fill south- or southwest-trending channels in the Mississippian surface (such as the Livingston Conglomerate Member of the Lee Formation) or, as figure 6 shows, overlie or wedge out to the northwest (similar to the Rockcastle Conglomerate Member of the Lee Formation) into coal-bearing sequences of Pennsylvanian shale and siltstone of the Breathitt Formation. Depositional thinning of the lower part of the Lee Formation increases with westward onlap (fig. 6). Core hole D2 (fig. 6) was drilled on the western rim of the Livingston paleochannel, the base of which is at least 150 ft below the base of the Pennsylvanian section in the core hole (Brown and Osolnik, 1974). The Livingston channel is about 4 mi wide and is filled with interstratified and intergraded quartz sandstone and conglomerate deposited by a south- to southeast-flowing stream (Rice, 1984). Thus, data from the outcrop belts at both ends of the section shown in figure 6 suggest that the pre-Pennsylvanian surface was terrestrial and had local relief of at least 150 ft.

A continental environment of deposition for the basal Pennsylvanian strata is also indicated by Alvord and Miller (1972), who characterized quartz arenites of the Elkhorn City area as conspicuously cross stratified in large-scale sets and forming persistent channel-in-channel units that contain thin, lenticular bodies of interstratified clayey and silty sandstone and thin coal beds. Sedimentologic and paleohydrologic studies by BeMent (1976) of outcropping Lower Pennsylvanian quartz arenites in areas including area A (fig. 1) indicate that the arenites were deposited by a southwest-flowing braided river. A study by Miller (1974, p. 118) suggests that the abundant current and crossbedding structures of those strata are characteristically composed of tabular sets of uniformly dipping, planar crossbeds that mostly dip 15° to 25° south and southwest (fig. 8). Miller noted, however, that "a significant number of low-angle laminar and festoon cross-bedding features have a dip to the southeast or northwest." Although he attributed these latter structures to deposition in a marine beach or barrier-bar environment and explained their scarcity as resulting from destruction by southwest-migrating tidal channels, he was unable to explain the absence of shelly fossils in the arenites or associated strata. Confronted with data similar to the foregoing, Donaldson and others (1979) reevaluated the paleogeography of Lower Pennsylvanian strata and suggested that plant fossils, textural sequences, and sedimentary structures of the quartz arenites of the New River Formation in West Virginia indicate deposition in braided rivers.

Figure 8. Southeast-inclined tabular sets of crossbedded pebbly quartz arenite of basal part of Lee Formation, eastern Kentucky. U.S. Highway 119 at crest of Pine Mountain, about 3.2 mi south of Whitesburg, Ky. Crossbedding is unidirectional toward southwest. Location of photograph shown in figure 6.

Our fluvial model for Early Pennsylvanian deposition in the Appalachian basin, shown in figure 7*B*, indicates inferred drainage configurations and the locations and current directions of identified deposits of quartz arenite in paleovalleys at the base of the Pennsylvanian. We envision the following scenario for Early Pennsylvanian time. Deposition began in the central part of the basin (depocenter) and consisted of sequences of sand, silt, clay, and peat, which became the Pocahontas Formation (see fig. 2). Increased erosion of the uplifted cratonic source area in Canada and New York resulted in transport of great quantities of quartz sand and gravel into the Sharon-Brownsville valley and its alluviation. Headward erosion of streams along the southeastern margin of the carbonate escarpment flanking the Cincinnati arch led to the capture and diversion of the headwaters of the Sharon-Brownsville river into the Appalachian basin. The major capture was by way of the great valley cut into the Greenbrier Limestone described by Flowers (1956) and by us (fig. 5). Thick sequences of quartz arenite of the New River and Lee Formations represent clastic material transported from northern cratonic areas across West Virginia; these sequences truncate or disconformably overlie the Pocahontas in the northwestern part of its extent (Englund, 1974). Braided streams deposited coarse quartzose sediments on delta plains in the subsiding Appalachian basin, and the rapid aggradation resulted in construction of extensive sand sheets in the southern and western parts of the basin. Detritus in the central part of the basin came mostly from source areas to the southeast (Englund, 1974). The braided rivers were bordered mostly by freshwater lakes and swamps in which clay, silt, and peat were deposited. Several transgressive events during the Early Pennsylvanian are interpreted to represent the encroachment of seas into areas of rapid subsidence in the central part of the basin and the local extension of shallow marine or brackish water into certain river valleys (Rice, 1984). As regional subsidence continued in the Appalachian basin, south-trending Sharon channels were alluviated and abandoned. West-flowing streams built deltas into the basin, and the delta plain extended progressively west from the rising Appalachians. These deltaic deposits did not completely displace the Sharon system and bury the remnants of the carbonate escarpment in northeastern Kentucky until Middle Pennsylvanian time.

CONCLUSIONS

Integration of stratigraphic and sedimentologic information within the Early Pennsylvanian tectonic framework for eastern North America suggests that, at the beginning of the Pennsylvanian, much of the area was emergent and had a southwest-dipping paleoslope. Earliest Pennsylvanian deposition in southeastern West Virginia and southwestern Virginia was accompanied by headward erosion of streams draining the southeastern flank of the developing Cincinnati arch and by the capture of major rivers originating in the southeastern part of the Canadian Shield and their diversion into the subsiding Appalachian basin. A reevaluation of Flowers' (1956) subsurface study of the Greenbrier Limestone in West Virginia, including his identification of a large south-trending paleovalley at the base of the Pennsylvanian that is filled with pebbly and conglomeratic quartz arenite, provides the necessary link between cratonic source areas in the Sharon drainage system and vast deposits of Lower Pennsylvanian pebbly quartz arenite in the Appalachian basin. The channel identified by Flowers is the largest of those that diverted streams from the Eastern Interior basin into the Appalachian basin, and it greatly affected both depositional patterns and facies distribution in the Appalachian basin during Early Pennsylvanian time. Our fluvial model and the sedimentation history for the Appalachian and Eastern Interior basins furnish a new basis for intraregional and interregional correlation of Lower Pennsylvanian strata and for analysis of large and small tectonic events in eastern North America during the Early Pennsylvanian.

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Chapter C

Disturbed Zones: Indicators of Subsurface Faults and Possible Hydrocarbon Traps in the Valley and Ridge and Appalachian Plateau Provinces of Pennsylvania, Maryland, Virginia, and West Virginia

By HOWARD A. POHN and TERRI L. PURDY

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1839

EVOLUTION OF SEDIMENTARY BASINS—APPALACHIAN BASIN

CONTENTS

FIGURES

CONVERSION FACTORS FOR SOME SI METRIC AND U.S. UNITS OF MEASURE

To convert from	To	Multiply by
Feet (ft)	Meters (m)	0.3048
Miles (mi)	Kilometers (km)	1.609
Pounds (lb)	Kilograms (kg)	.4536
Degrees Fahrenheit (°F)	Degrees Celsius (°C)	Temp °C=(temp °F−32)/1.8

Disturbed Zones: Indicators of Subsurface Faults and Possible Hydrocarbon Traps in the Valley and Ridge and Appalachian Plateau Provinces of Pennsylvania, Maryland, Virginia, and West Virginia

By Howard A. Pohn *and* Terri L. Purdy

Abstract

Disturbed zones are sequences of severely thrust faulted and folded rocks either in the hanging walls or footwalls adjacent to thrust faults or between closely spaced pairs of thrust faults. They are common in the central Appalachian Valley and Ridge province and are surface manifestations of imbricate thrust faults that are rooted to detachments at depth. The zones are tens to hundreds of meters thick and a few kilometers to tens of kilometers long. Although they commonly form in units composed of alternating siltstone and shale, some are in more competent units. The intense folding and faulting in disturbed zones may localize domains of high fracture porosity in the subsurface, which, when sealed from the surface, may produce potential hydrocarbon traps.

INTRODUCTION

The gross aspects of the structural geology of folded and faulted Paleozoic rocks of the central Appalachian Mountains have been fairly well described by using seismic analyses and geologic mapping (Rodgers, 1963; Gwinn, 1964, 1970; Harris and Milici, 1977; Perry, 1978). One type of structural feature, herein referred to as a "disturbed zone," has been frequently described (Rickard, 1952, p. 517), but the relationship between these zones and the regional tectonic framework has been given little attention. This report discusses the occurrence, morphology, and sequential development of these zones.

The disturbed zones described in this paper are in the Valley and Ridge and Appalachian Plateau provinces of the Appalachian Mountains from central Pennsylvania to northern West Virginia (fig. 1). In this area, a series of folded and thrust-faulted Paleozoic rocks trend east-northeast to northeast. The sedimentary sequence comprises predominantly carbonate rocks of Cambrian through Ordovician age and clastic rocks of Ordovician through Pennsylvanian age and is 7,800 to 10,200 m thick.

Seismic profiles and drilling data indicate that both the Valley and Ridge province and a large part of the Appalachian Plateau province are underlain by large thrust sheets that have been translated westward along a thrust system consisting of extensive bed-parallel flats (decollements), ramps, and imbricate splay faults (fig. 2). This type of structural architecture is indicative of thin-skinned tectonic systems in which the deformation is concentrated above the basal detachment and the basement is virtually undeformed (Rodgers, 1963; Gwinn, 1964; Dahlstrom, 1970; Boyer and Elliott, 1982; Butler, 1982). Disturbed zones are common throughout the study area, and we believe that such structures are characteristic of thrust belts worldwide.

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CHARACTERISTICS AND MORPHOLOGY

The term "disturbed zone" was first used by Rickard (1952, p. 517) to describe precisely the structures discussed below. Disturbed zones consist of intensely folded and thrust-faulted beds either in the hanging wall or footwall adjacent to a thrust fault or in a zone between a closely spaced pair or within a series of approximately parallel thrust faults (fig. 3). Beds within a disturbed zone are intensely deformed, whereas beds adjacent to the zone are relatively undeformed. Disturbed zones are tens to hundreds

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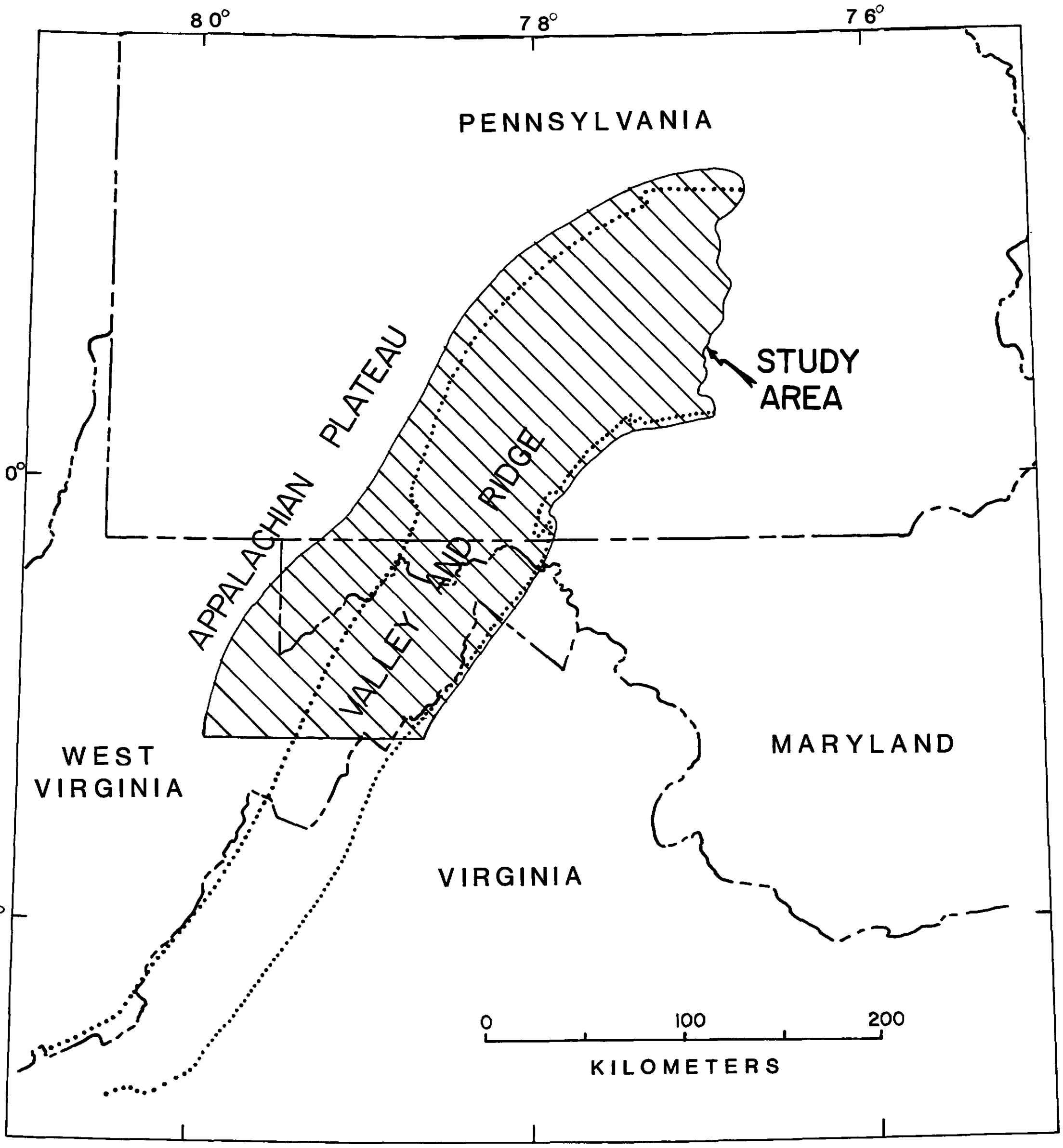

Figure 1. Location of study area in Valley and Ridge and Appalachian Plateau provinces of Appalachian Mountains, Pennsylvania, Maryland, Virginia, and West Virginia. Boundaries of Great Valley (east) and Appalachian structural front (west) indicated by dotted lines.

of meters thick and commonly can be traced for a few kilometers to tens of kilometers along strike. They can be distinguished from horse blocks or duplexes (fig. 2) because horse blocks and duplexes are not necessarily intensely folded or faulted in the fault-bounded block.

The thrust faults that bound disturbed zones can be either bed parallel or bed oblique. Although bed-parallel disturbed zones are similar in appearance to drag folds, they are different from drag folds in that disturbed zones are not restricted to the limbs of a host fold, generally contain more intensely deformed rocks, and may show opposite senses of rotation of axial planes of folds within the fault blocks.

Field mapping in the study area demonstrates an abundance of disturbed zones. At several locations, the entire width of a zone is exposed, and the morphology of the zone can be described in detail. An excellent example of a well-exposed disturbed zone occurs at Towanda, Pa., 80 km north of the study area (fig. 4). This bed-oblique disturbed zone is bounded by a pair of thrust faults, and the total displacement to the south along the faults is greater than 15 m. The antithetic or back-thrusted disturbed zone, in the siltstone and shale of the Devonian Lock Haven (Chemung) Formation, evolved from a series of horse blocks that imbricated successively in a piggyback fashion

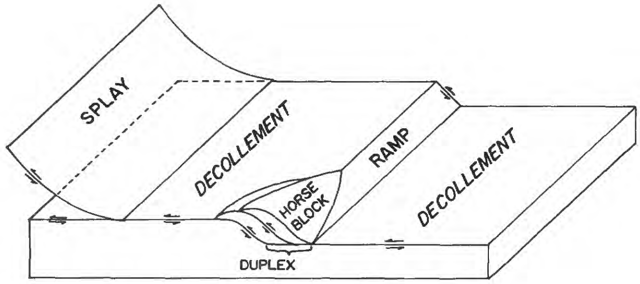

Figure 2. Structural elements in thrust system.

(fig. 5). Individual horse blocks were internally deformed by compression and drag, and concomitant thickening occurred. Many folds within individual horse blocks are asymmetric, and one limb commonly is vertical to overturned. These folds may themselves be cut by thrust or extension faults. Shaly beds generally have been deformed in response to disharmonic folding between resistant units.

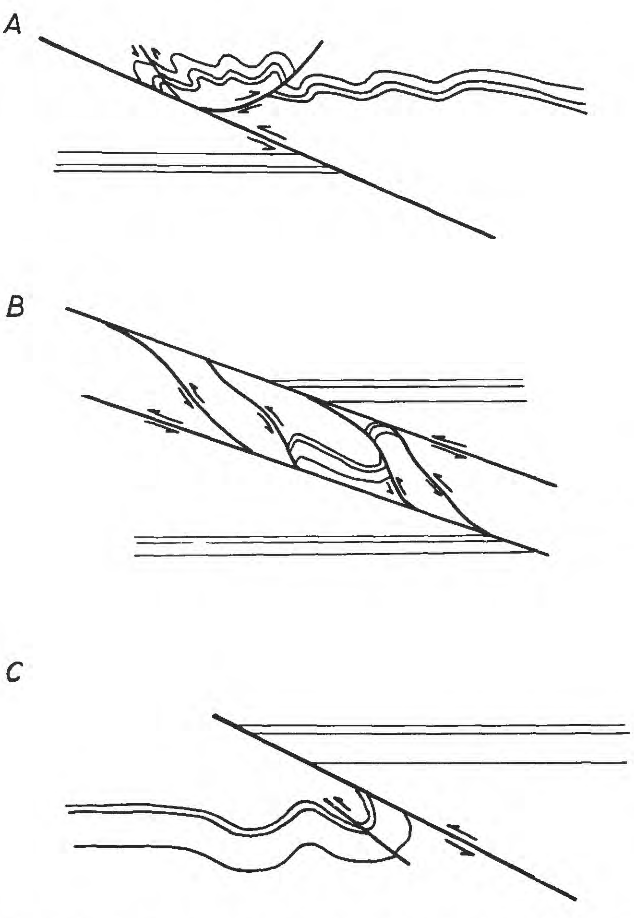

Figure 3. Formation of disturbed zones. *A*, In hanging wall of thrust fault. *B*, Between pair of thrust faults. *C*, In footwall of thrust fault.

REGIONAL IMPLICATIONS

Disturbed zones have been noted by many field geologists and identified as "crumpled" (Root, 1977), "tightly folded or otherwise contorted on a small scale" (Miller, 1959; Conlin and Hoskins, 1962; Dyson, 1963; deWitt, 1974), or "contorted" (Hoskins, 1976). These structures have never before been interpreted as being the surface expressions of regional fault systems, but, in our opinion, they are precisely that for the following reasons. First, many disturbed zones are associated with mapped faults. Figure 6 shows a map of surface thrust faults in part of the Hyndman 7½-minute quadrangle, Pennsylvania (deWitt, 1974). Most of the disturbed zones that we mapped in this area occur along faults mapped by deWitt (1974). Second, many disturbed zones are found along extensions of mapped faults (fig. 7). Third, disturbed zones commonly occur along upward extensions of faults that were mapped in the subsurface on the basis of well control or seismic interpretation. Gwinn (1964, p. 872), for example, showed that thrust faults in the subsurface, as determined from seismic and drill-hole data, are found on both sides of the Deer Park anticline in Preston County, W. Va., and we mapped disturbed zones along the surface projections of these faults (fig. 8). Fourth, disturbed zones commonly occur along contacts of disharmonically folded stratigraphic units. Figure 9 shows an area in Huntingdon County, Pennsylvania, in which numerous disturbed zones are in Silurian rocks along the contacts between the Clinton Group and the Mifflintown Formation and between the Bloomsburg Formation and the Wills Creek Formation. The same formational contacts show disharmony throughout much of Pennsylvania, Virginia, and West Virginia, and extensive disharmonic fold patterns strongly suggest the presence of decollements (James Farley, oral communication, 1980;

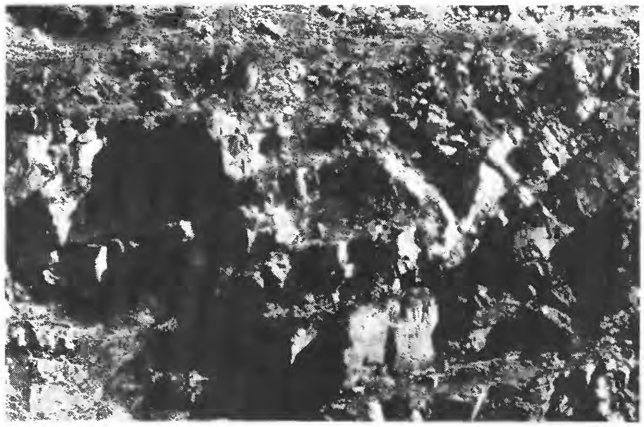

Figure 4. Disturbed zone in Devonian Lock Haven (Chemung) Formation at Towanda, Pa., about 80 km north of the study area. Details of geometry of this bed-oblique disturbed zone that formed between a pair of thrust faults are shown in figure 5.

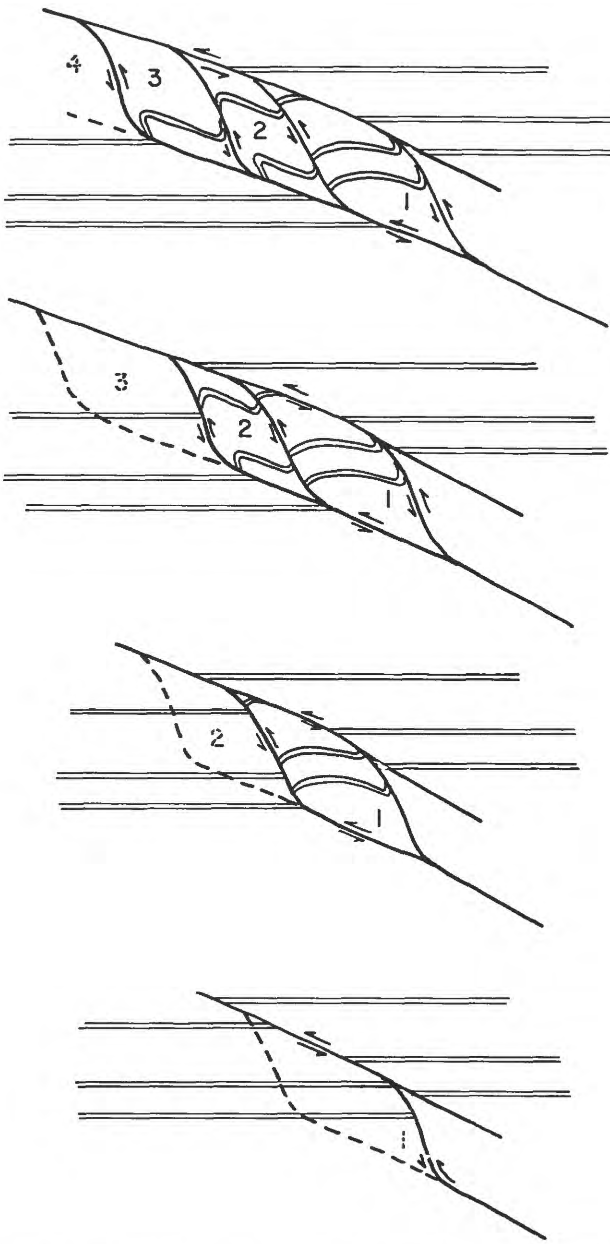

Figure 5. Evolution of disturbed zone at Towanda, Pa. Zone is shown in figure 4.

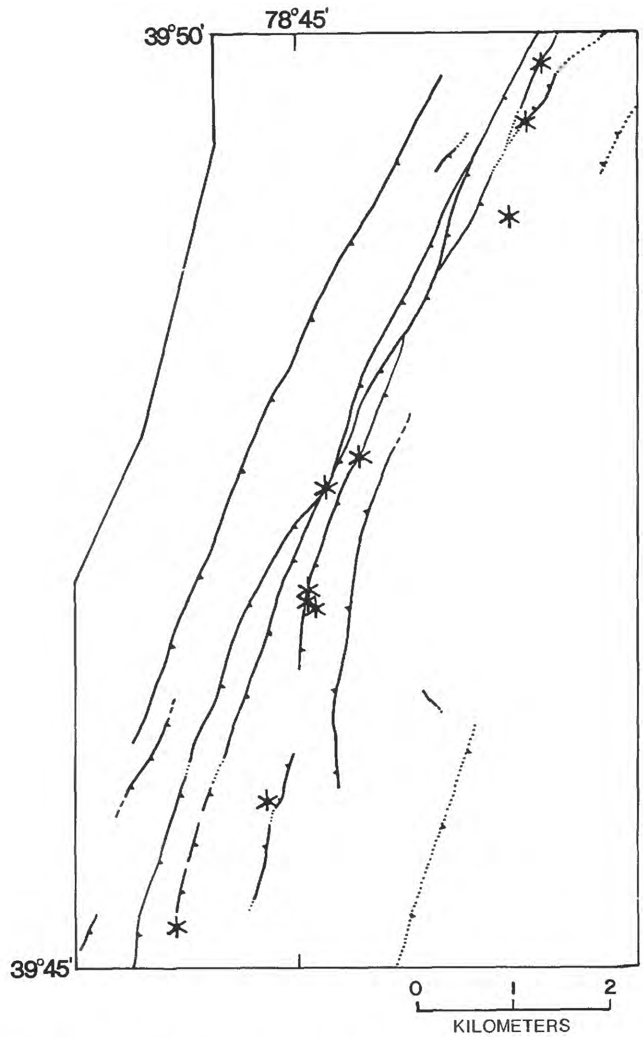

Figure 6. Distribution of faults in part of Hyndman 7½-minute quadrangle, Pennsylvania. Asterisks, disturbed zones; solid lines, faults (barbs on upper plate); dashed lines, inferred faults; dotted lines, concealed faults. Modified from deWitt (1974).

Pohn and Purdy, 1982). In the example shown in figure 9, the decollements (bed-parallel disturbed zones) have been folded.

These examples are evidence that disturbed zones are surface expressions of thrust faults rooted in the subsurface. We believe that, in areas where disturbed zones and mapped flexures are coincident, these flexures represent duplication of the stratigraphic sequence by faulting. An example of the association of flexures and disturbed zones occurs in the Hyndman 7½-minute quadrangle, Pennsylvania (de Witt, 1974) (fig. 10). If a line is drawn between the two flexures in the Keyser Limestone (locations A and B, fig. 10), it will pass directly through the disturbed zone at location C; we believe that the presence of the disturbed zone indicates that the flexures result from duplication by a thrust fault denoted by the disturbed zone. This conclusion is supported by Wallace deWitt, Jr. (oral communication, 1982), who originally mapped the zone as "tightly folded rocks."

MAGNITUDE OF DISPLACEMENT

Many disturbed zones are intraformational in that rocks in the hanging wall and footwall belong to the same stratigraphic unit and therefore appear to have only small displacement; however, intraformational faults may have large displacements. Stacked anticlines in the Valley and Ridge province (fig. 11) are similar to those in the Canadian

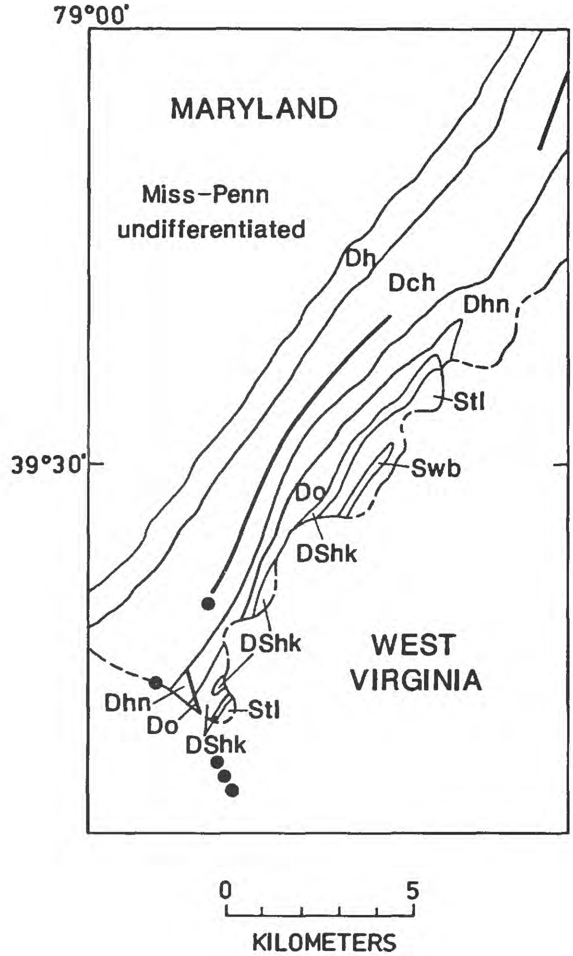

Figure 7. Locations of disturbed zones along extensions of mapped faults in part of Allegheny County, Maryland. Solid circles, disturbed zones; heavy lines, faults. Dh, Hampshire Formation; Dch, Chemung Formation (including Parkhead Sandstone, Brallier Formation, and Harrell Shale); Dhn, Hamilton Group; Do, Ridgeley Sandstone and Shriver Chert; DShk, Helderburg Formation and Keyser Limestone; Stl, Tonoloway Limestone; Swb, Wills Creek Shale and Bloomsburg Formation. Compiled from geologic maps of West Virginia (Cardwell and others, 1968) and Maryland (Cleaves and others, 1968; used with permission of Maryland Geological Survey). Fault extending toward three disturbed zones in West Virginia is not shown on West Virginia geologic map.

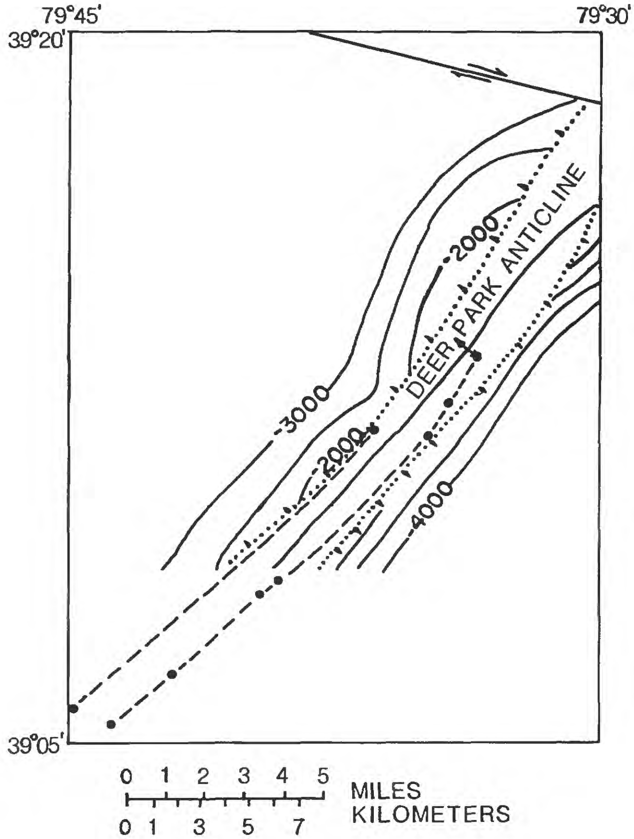

Figure 8. Structure of Oriskany Sandstone along part of Deer Park anticline, Preston County, West Virginia. Contours are of depth to top of Oriskany Sandstone; contour interval, 1,000 ft. Dotted lines, uplimb thrusts mapped by Gwinn (1964) from seismic reflection and drill-hole data; solid circles, disturbed zones; dashed lines, surface representation of faults as inferred from locations of disturbed zones. Modified from Gwinn (1964).

Rocky Mountains that have been described as adjacent anticlines juxtaposed by thrust faulting (Dahlstrom, 1970).

In the study area, we identified numerous examples of stacked anticlines in which the apparent intervening syncline is occupied by faults or by disturbed zones. Figure 11 shows two examples of stacked anticlines that have virtually identical map patterns but considerably different displacements along the intervening faults. Seismic reflection surveys or closely spaced drill holes may be required to determine the amount of displacement on these faults.

LITHOTECTONIC ASSOCIATIONS

Disturbed zones in the study area generally are in incompetent, thick sequences of shale and thin-bedded siltstone, including the Lock Haven (Chemung), Brallier, and Marcellus Formations of Devonian age. In more competent units, such as the thick-bedded sandstone of the Catskill Formation of Late Devonian age, clusters of wedge faults (fig. 12) are in extensive exposures that otherwise contain unfaulted beds. The subjacent Lock Haven (Chemung) Formation contains many more disturbed zones than any other formation in the study area. Although some of these faults most likely continue upward, relatively few disturbed zones are in the Catskill Formation. We believe that disturbed zones in the incompetent units manifest themselves as large (meters to tens of meters displacement) wedge faults in competent units.

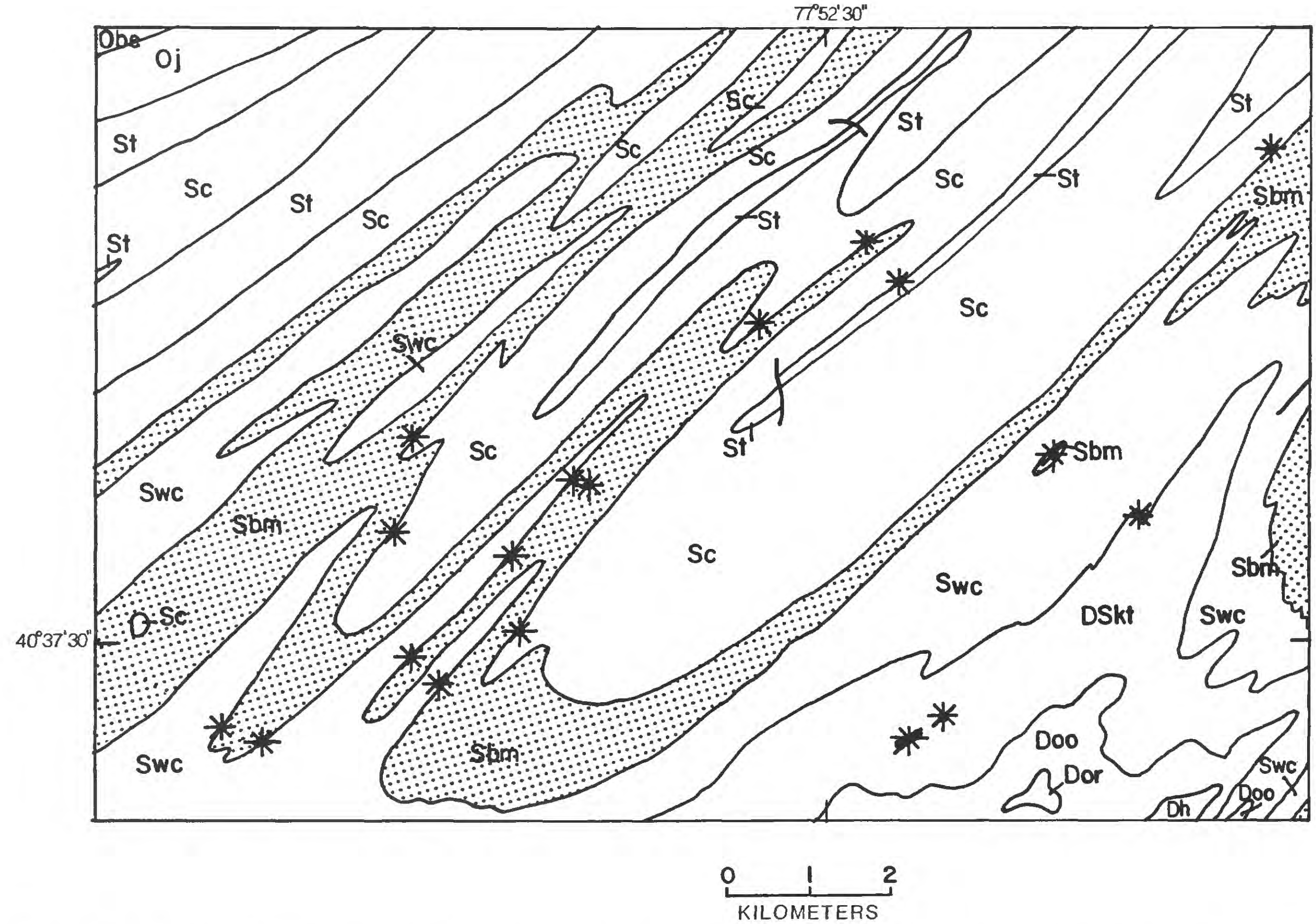

Figure 9. Disharmonic fold patterns of formations and relationship between formational contacts and disturbed zones in parts of Pine Grove Mills, McAlevy's Fort, Donation, and Allensville quadrangles, Huntingdon County, Pennsylvania. Asterisks, disturbed zones; heavy lines, faults. Dh, Hamilton Group; Doo, Onondaga and Old Port Formations, undivided; Dor, Ridgely Member of the Old Port Formation; DSkt, Keyser and Tonoloway Formations, undivided; Swc, Wills Creek Formation; Sbm, Bloomsburg and Mifflintown Formations, undivided; Sc, Clinton Group; St, Tuscarora Formation; Oj, Juniata Formation; Obe, Bald Eagle Formation. Geology modified from Berg and Dodge (1981).

ASSOCIATION OF DISTURBED ZONES AND HYDROCARBON OCCURRENCES

Field mapping shows the coincidence of concentrations of disturbed zones and lines of gas wells, which are slightly offset from and parallel with the concentrations of disturbed zones (figs. 13, 14). This association can be understood by examining a schematic cross section of such a concentration (fig. 15). Folding and extreme wedge faulting in a competent formation such as the Oriskany Sandstone considerably increase the fracture porosity of the formation. The same faults that fracture competent formations are taken up by flowage and concomitant disharmonic folding in superjacent incompetent shale beds, such as the Needmore and Marcellus Formations, and produce disturbed zones that serve to seal the reservoir. Detailed mapping of disturbed zones in overthrust belts will result in a better understanding of both the structural setting of disturbed zones and the relationship between these zones and certain hydrocarbon traps.

CONCLUSIONS

Disturbed zones are intensely folded and thrust-faulted beds in the hanging wall or footwall of thrust faults or in zones between closely spaced pairs or series of approximately parallel thrust faults. They are surface expressions of thrust faults rooted in the subsurface to detachments or ramps. The zones are tens to hundred of meters thick and kilometers to tens of kilometers long.

Disturbed zones are common throughout the central Appalachian Valley and Ridge and Appalachian Plateau provinces, and we believe that such structures are characteristic of thrust belts worldwide. They are more abundant in incompetent units and are manifested as wedge faults in competent units. Although concentrations of disturbed

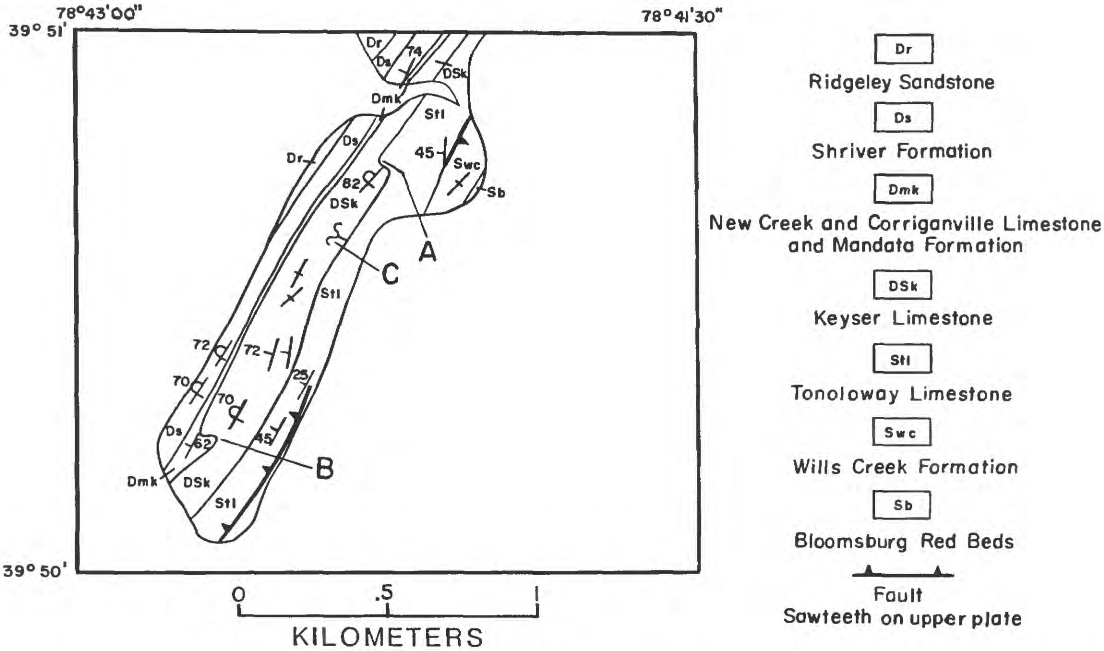

Figure 10. Relationship between formational flexures (A, B) and disturbed zone (C) in part of Hyndman 7½-minute quadrangle, Pennsylvania (deWitt, 1974). Symbol at letter C is deWitt's symbol for "tightly folded rocks."

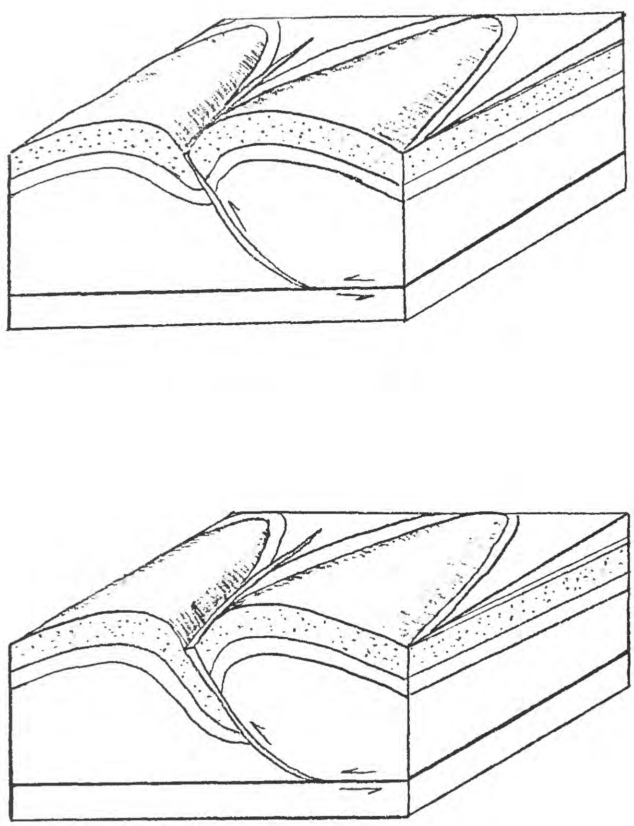

Figure 11. Stacked anticlines that have identical surface configurations but considerably different displacements on intervening faults.

zones are commonly associated with hydrocarbon occurrences, the converse is not necessarily true, and careful mapping of disturbed zones may be used to augment hydrocarbon exploration techniques in thrust belts.

Figure 12. Zone of wedge faults in Upper Devonian Catskill Formation of Pennsylvania. Wedge faults in competent units probably are structural equivalents of disturbed zones in incompetent units. Note open wedge fractures, higher joint density, and shattered sandstone in region of wedge faults, all of which lead to increases in fracture porosity.

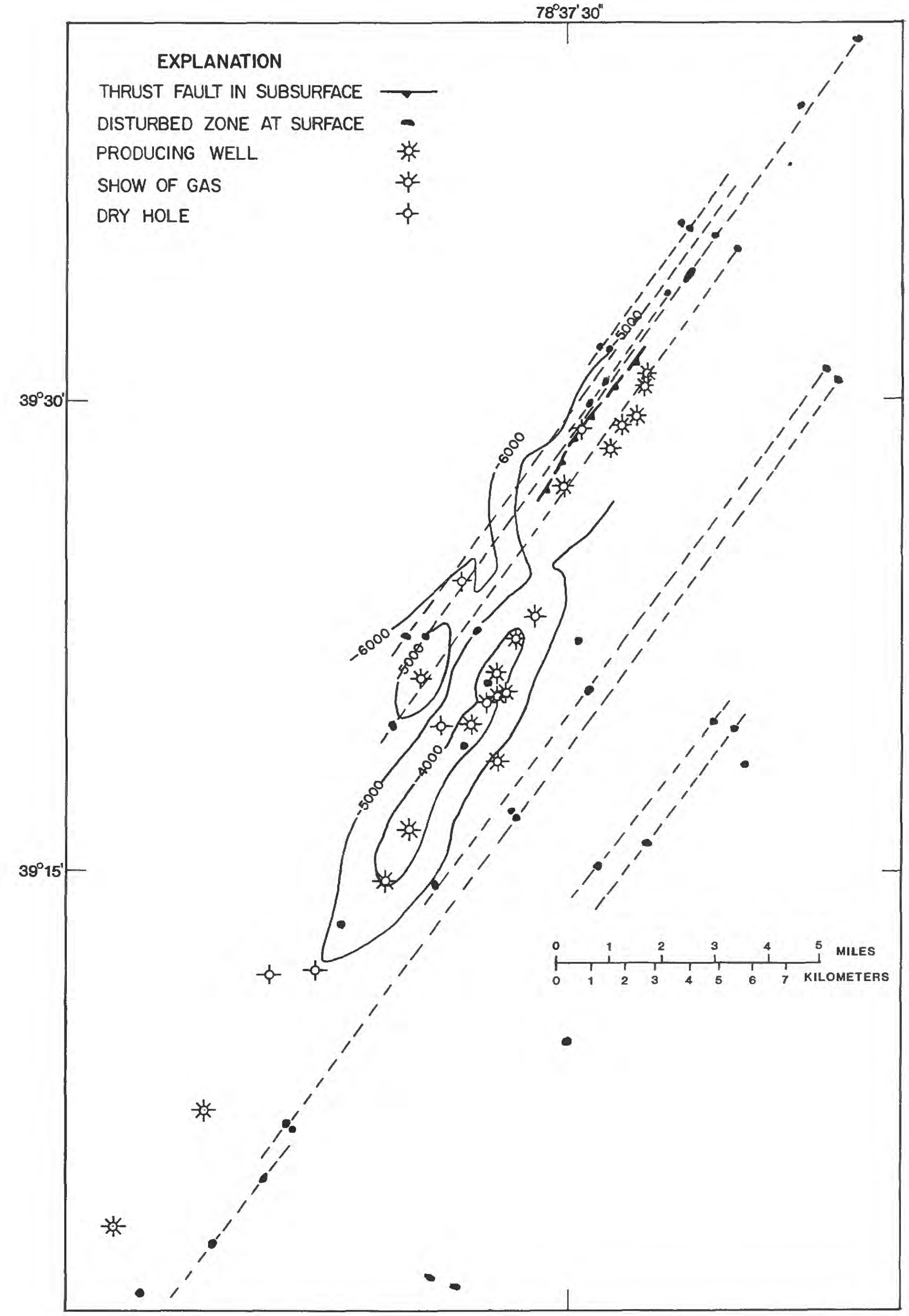

Figure 13. Locations of surface exposures of disturbed zones, structure contours (interval 1,000 ft) of top of Onondaga Formation or equivalent, and locations of subsurface thrust fault and oil and gas wells. Modified from Cardwell (I982).

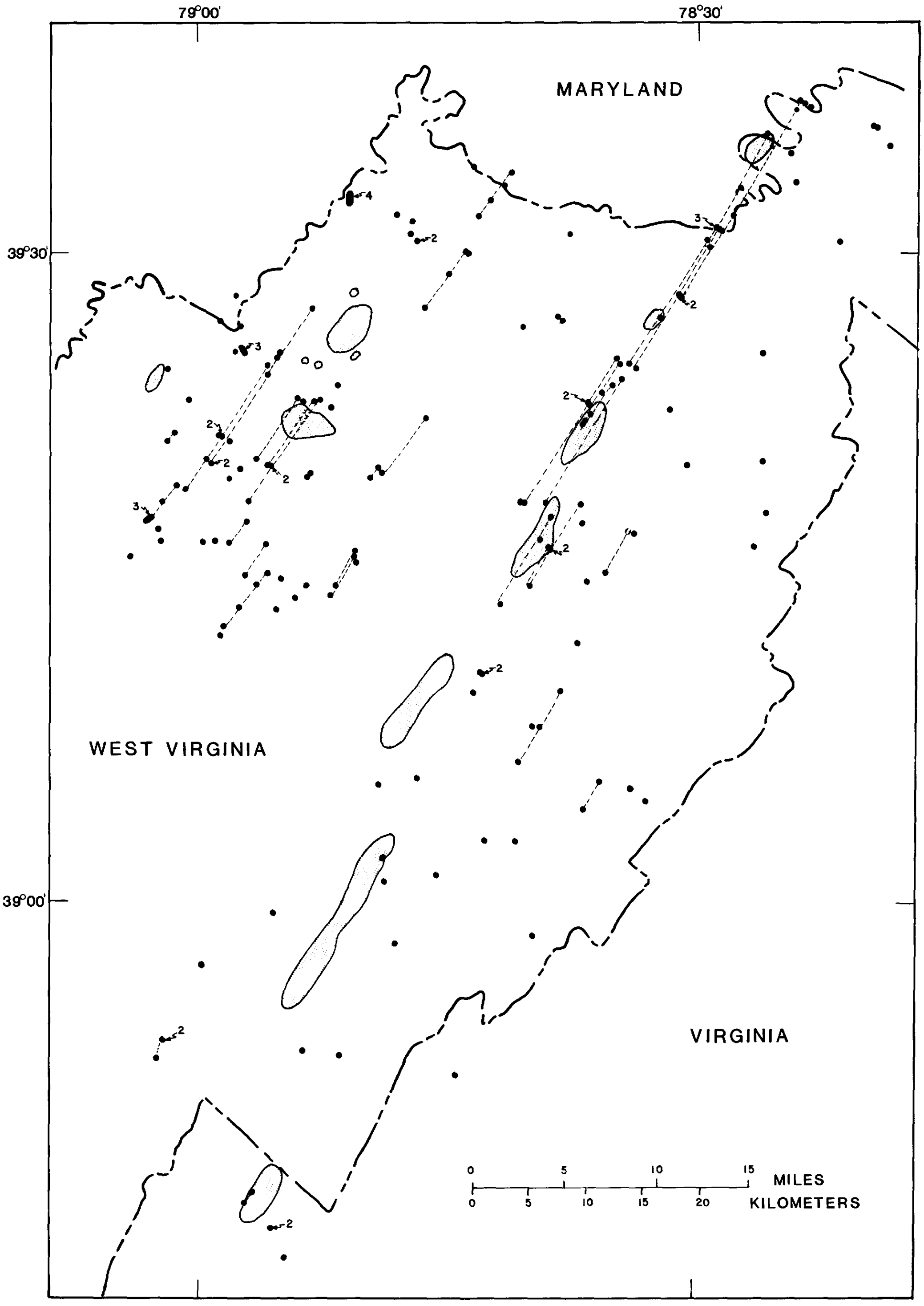

Figure 14. Relationship between disturbed zones (solid circles and dashed lines) and gas fields (patterned areas), West Virginia panhandle. Numerals indicate number of disturbed zones.

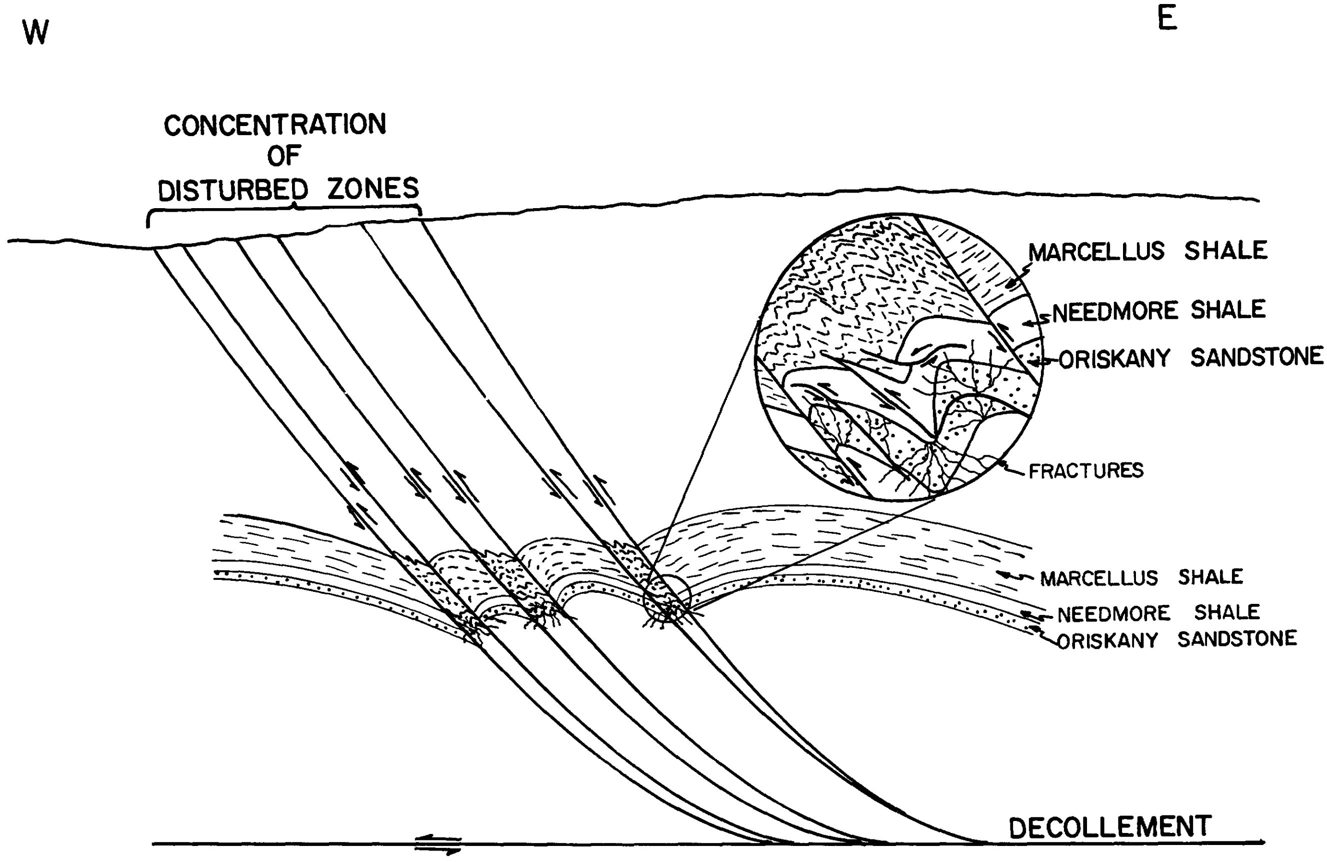

Figure 15. Relationship between concentrations of disturbed zones and areas of high fracture porosity in Oriskany Sandstone and reservoir seals in Marcellus and Needmore Shales.

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CHAPTER D

Reevaluation of Conodont Color Alteration Patterns in Ordovician Rocks, East-Central Valley and Ridge and Western Blue Ridge Provinces, Tennessee

By RANDALL C. ORNDORFF, ANITA G. HARRIS, and ARTHUR P. SCHULTZ

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1839

EVOLUTION OF SEDIMENTARY BASINS—APPALACHIAN BASIN

CONTENTS

FIGURES

TABLE

CONVERSION FACTORS FOR SOME SI METRIC AND U.S. UNITS OF MEASURE

To convert from	To	Multiply by
Feet (ft)	Meters (m)	0.3048
Miles (mi)	Kilometers (km)	1.609
Pounds (lb)	Kilograms (kg)	.4536
Degrees Fahrenheit (°F)	Degrees Celsius (°C)	Temp °C=(temp °F−32)/1.8

Reevaluation of Conodont Color Alteration Patterns in Ordovician Rocks, East-Central Valley and Ridge and Western Blue Ridge Provinces, Tennessee

By Randall C. Orndorff, Anita G. Harris, *and* Arthur P. Schultz

Abstract

An anomalously low conodont color alteration index (CAI) has been reported for Ordovician rocks in the Tuckaleechee Cove window of the Blue Ridge province in previous investigations. These data encouraged hydrocarbon explorationists to consider the eastward extension of Valley and Ridge rocks beneath thrust sheets of the Blue Ridge as a potential hydrocarbon province. Reevaluation of old and new CAI data in the easternmost thrust belt of the Valley and Ridge province and in windows through the Blue Ridge in central eastern Tennessee shows that, although the CAI anomaly in the Tuckaleechee Cove window is of less magnitude than first reported, CAI values for rocks in the window are still lower than those in correlative rocks northward and northwestward at the eastern limit of the Valley and Ridge province. CAI patterns in Lower and lower Middle Ordovician rocks in central eastern Tennessee are more complex than those shown by earlier investigations, and the patterns may be related to primary depositional and burial trends in Middle and Upper Ordovician chiefly clastic rocks. CAI values in Ordovician rocks of the Tuckaleechee Cove window are slightly lower than those in correlative rocks in nearby windows; a similar pattern exists in the Dumplin Valley thrust belt opposite the windows and may reflect thickness patterns of Middle and Upper Ordovician rocks. The area of hydrocarbon potential for Valley and Ridge rocks beneath the crystalline rocks of the Blue Ridge is somewhat less than previous estimates; these rocks, however, still have thermal potential for natural gas but are probably beyond the thermal limit for liquid hydrocarbons.

INTRODUCTION

Maps showing thermal maturation patterns in Paleozoic rocks in the Appalachian basin based on conodont color alteration indices (CAI) were first presented by Epstein and others (1977). Subsequently, Harris and others (1978) published more detailed maps of the same area. These early studies showed that, in most of the Valley and Ridge province, thermal maturation patterns in Paleozoic rocks are generally related to overburden thickness established before Alleghanian thrusting. In general, CAI values increase eastward and reflect the eastward increase in thickness of Paleozoic rocks. Some exceptions that are structurally controlled are in Lower and Middle Ordovician rocks along the eastern limit of the Valley and Ridge province. CAI values in the westernmost thrust sheet of the Taconic allochthon in New York, in the Jutland klippe in New Jersey, and in the Hamburg klippe in Pennsylvania (Harris and others, 1978; Harris, 1979) are all significantly lower than those in parautochthonous rocks with which they are juxtaposed. Thus far, the only other noteworthy reversal in thermal maturation patterns near the eastern limit of the Valley and Ridge province has been found in the western Blue Ridge province, in windows through the Great Smoky thrust sheet in central eastern Tennessee (figs. 1, 2). An anomalously low CAI value of 2 reported from Ordovician rocks of the Tuckaleechee Cove window (Epstein and others, 1977; Harris and others, 1978) indicates thermal potential for hydrocarbons in sedimentary rocks that underlie crystalline rocks of the Blue Ridge thrust sheets (fig. 3). The CAI of rocks in this window was reported to be two indices lower than values in correlative rocks 15 to 20 km to the west at the eastern limit of the Valley and Ridge province. Regional structural interpretations (Woodward, 1985) show that rocks in the windows are thrust slices having duplex geometry (fig. 3). The slices were derived from a tectonic ramp below the western part of the Blue Ridge province. A similar interpretation was put forth for rocks in the windows of southwestern Virginia (Schultz and Anders, 1985; Schultz, this volume), but, in that area, CAI values and geochemical data (Schultz, this volume) indicate that little to no hydrocarbon potential exists east of the western edge of the Blue Ridge province. Thus far, the Tuckaleechee Cove thermal low has not been explained either structurally or sedimentologically. The apparent

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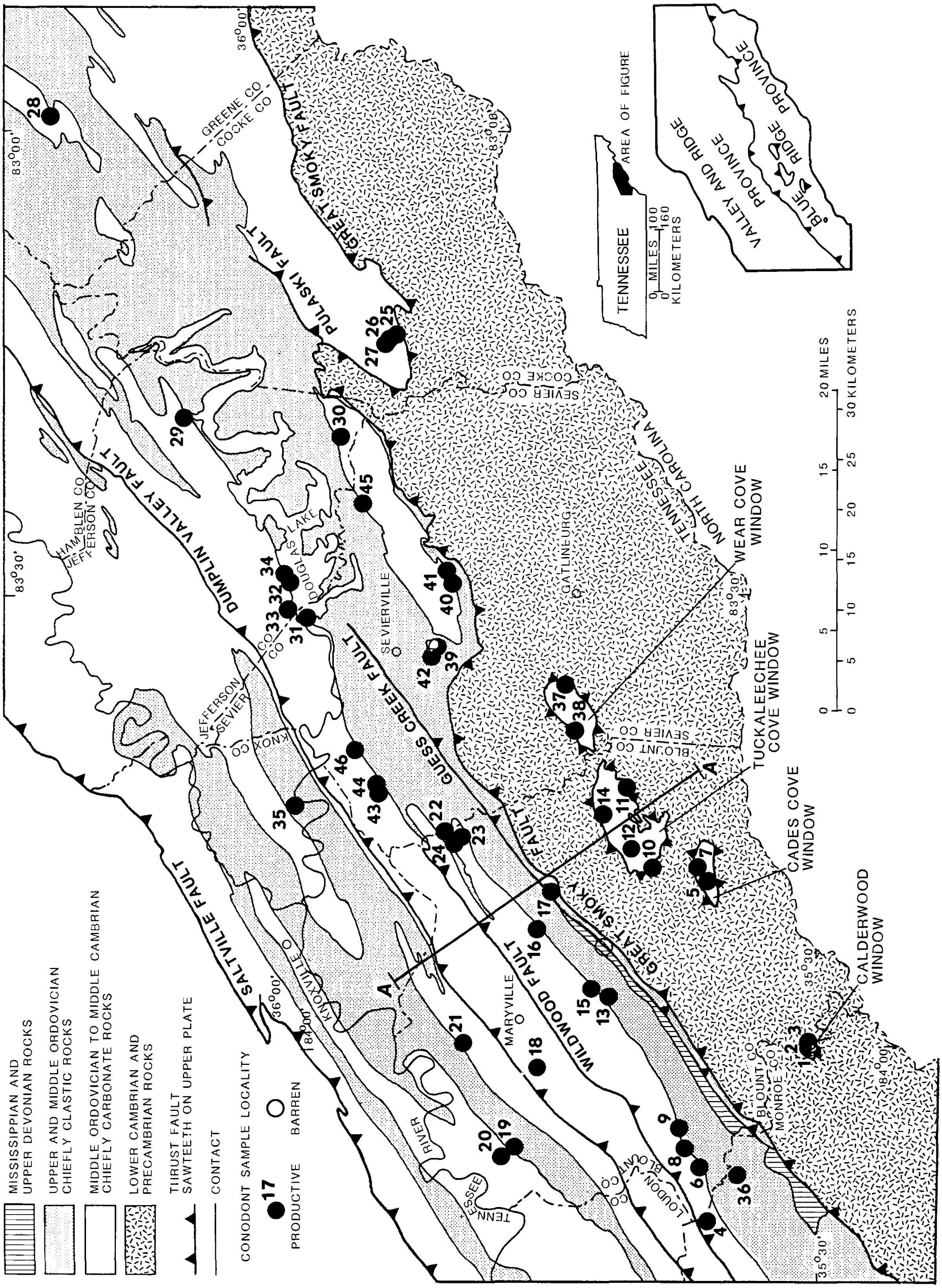

Figure 1. Generalized geologic map of central eastern Tennessee showing conodont color alteration index sample localities. Detailed geographic and stratigraphic data are shown for each numbered sample locality in table 1. Line of section *A–A'* (fig. 3) is also shown. Geology modified from Hardeman (1966).

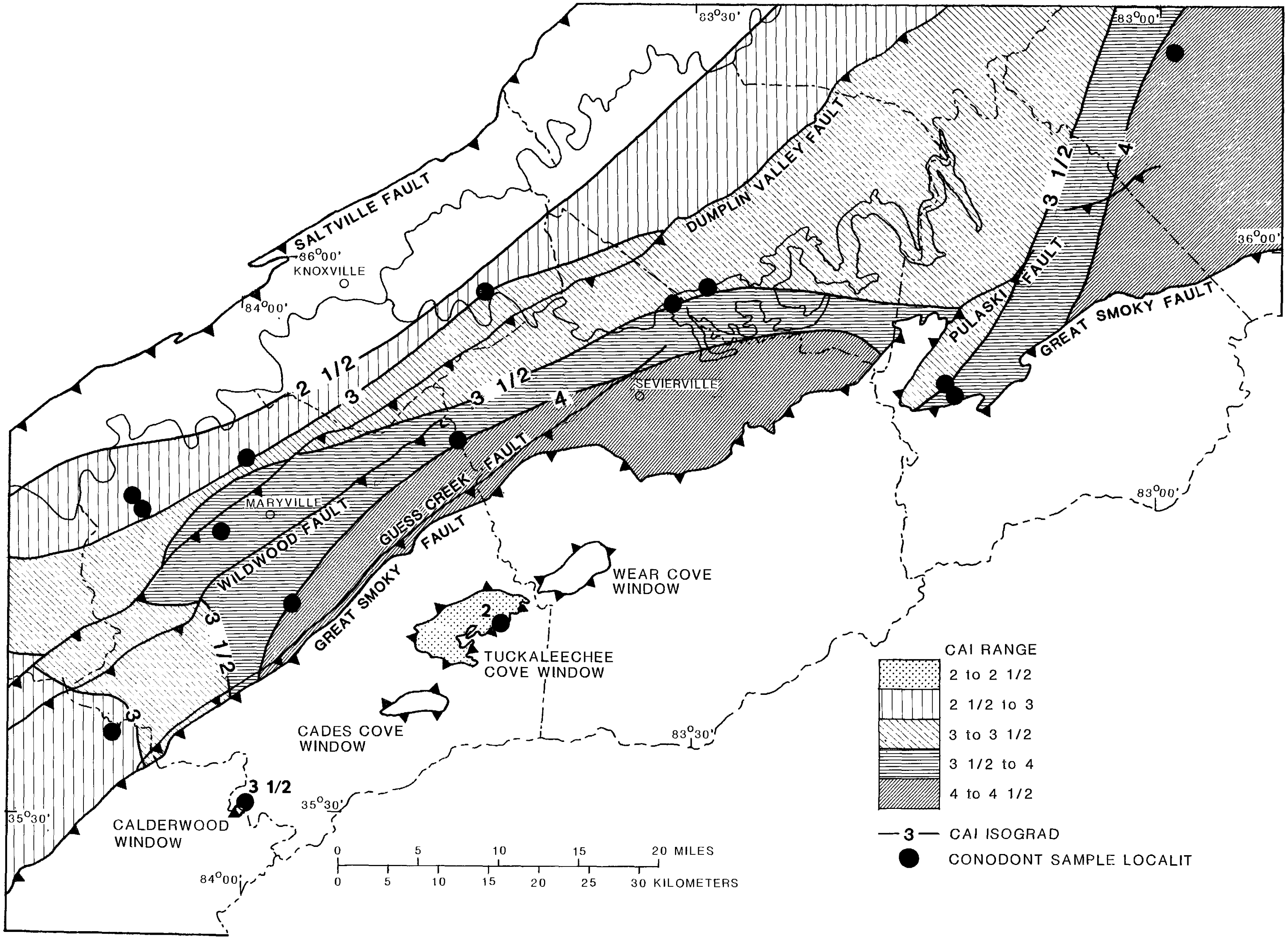

Figure 2. Conodont color alteration index localities and isograds for Ordovician carbonate rocks east of the Saltville fault, central eastern Tennessee. Slightly modified from Harris and others (1978).

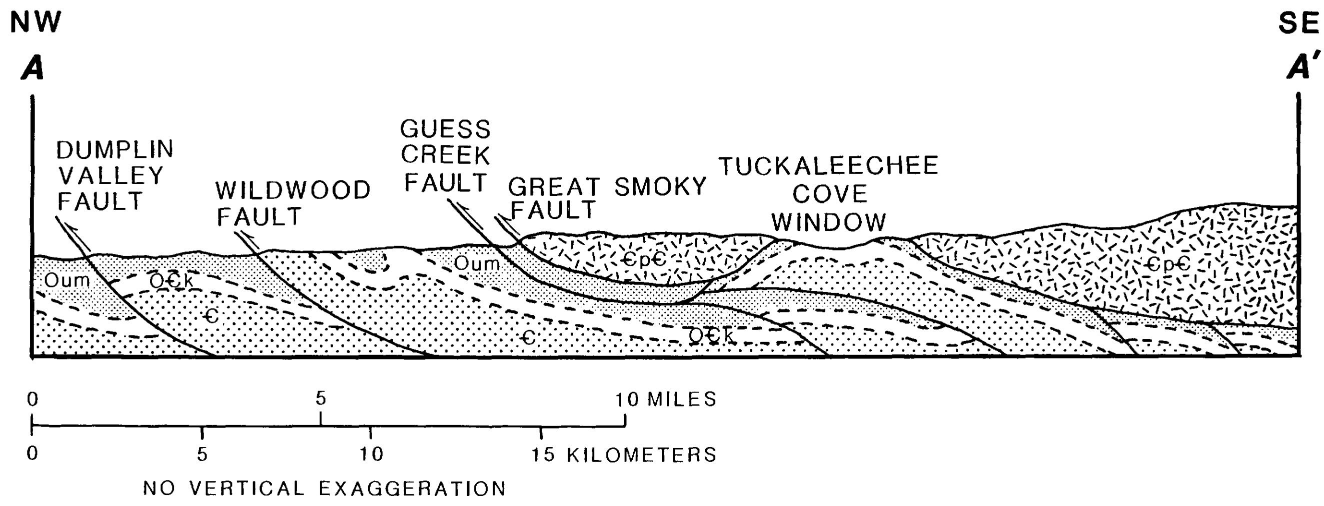

Figure 3. Generalized cross section from the Dumplin Valley fault through the Tuckaleechee Cove window. €p€, Precambrian and Lower Cambrian rocks; €, Cambrian rocks of the Rome Formation through the Conococheague Limestone; O€k, Upper Cambrian and Lower Ordovician rocks of the Knox Group; Oum, Middle and Upper Ordovician rocks. Line of section is shown in figure 1. Modified from Roeder and others (1978) and Woodward (1985).

thermal anomaly may be the result of rapid eastward thinning of overburden above the Ordovician rocks exposed in the window. Alternatively, geochemical and (or) physical factors may have kept these rocks from reaching the same thermal maturity as correlative rocks both along strike to the north or across strike to the west at the eastern limit of the Valley and Ridge province. The Canning basin in Australia, for example, contains as much as 6,500 m of post-Precambrian sedimentary rocks that are flat lying to gently deformed. In a study of the geothermal history of this basin, Nicoll and Gorter (1984) showed that differences in CAI values at equivalent depths in bore holes having similar stratigraphy are not related to overburden but rather to differences in thermal conductivity of basin sediments, hydrology, and heat flow patterns. Similar factors could have produced local variations in CAI patterns early in the evolution of the Appalachian basin.

The relatively low organic maturation levels reported from Ordovician rocks that structurally underlie the chiefly crystalline rocks of the western Blue Ridge in central eastern Tennesee have encouraged hydrocarbon explorationists to consider this area a potential natural gas province (Harris and others, 1981). In addition, seismic interpretations of this region (Cook and others, 1979, 1983; Harris and Bayer, 1979; Milici and others, 1979) have encouraged further speculations concerning this frontier hydrocarbon province. Hydrocarbon-bearing Paleozoic sedimentary rocks appear to extend from surface exposures in the Valley and Ridge province of the Appalachian foreland eastward below thrust sheets of metamorphic rocks of the Blue Ridge and Piedmont provinces. Palinspastic reconstructions of the eastern thrust belt in Tennessee (Harris and others, 1981) show that the area of hydrocarbon potential in the subsurface may equal that of known production to the west. A less optimistic view was presented by Hatcher (1982), who summarized a variety of geologic data and concluded that the area of hydrocarbon potential was limited to a relatively narrow zone in the westernmost Blue Ridge province in the southern half of Tennessee, western North Carolina, and northern Georgia. Despite this view, others (Cook and others, 1983) have continued to speculate that a sizable part of the subsurface beneath the Blue Ridge and Piedmont provinces has commercial potential for natural gas. The purpose of this investigation was to verify and explain the anomalously low CAI of Ordovician rocks of the Tuckaleechee Cove window. This anomalously low value has important implications for understanding the geologic framework of the area and its implications for hydrocarbon potential.

Acknowledgments.—We wish to thank R.D. Hatcher Jr., (Department of Geological Sciences, University of Tennessee) and R.C. Milici (Virginia Division of Mineral Resources) for technical review of the manuscript. We also wish to thank the U.S. Park Service for access to Cades Cove.

EVALUATION OF COLOR ALTERATION INDEX DATA

Examination of the CAI data base used by Harris and others (1978) shows that conodonts from rocks in only two windows through the Great Smoky thrust sheet were indexed (fig. 2); of these, only rocks in the Tuckaleechee Cove window produced an anomalously low CAI value in comparison with values in the adjacent Valley and Ridge province. Moreover, correlative rocks in the easternmost

Table 1. Ordovician conodont color alteration index (CAI) localities used in this report

[Sample localities and geologic information shown in fig. 1. Localities without U.S. Geological Survey (USGS) collection numbers are from the collections of S.M. Bergström and are reposited in the Department of Geology and Mineralogy, Ohio State University, Columbus, Ohio. Asterisk indicates sample was collected for this study; all others are from Harris and others (1978). Dolostone was sampled at localities 7, 15, 16, and 34; all other samples are from limestone]

Locality no.	Field no. (USGS colln. no.)	County	7-minute quadrangle	Latitude/longitude (N./W.)	Series	Stratigraphic unit	CAI value
1	*SOCW-30 (10451-CO)	Blount	Calderwood	35°30.6′/83°59.4′	Lower	Knox Group	3
2	T-O-77 (10576-CO)	do.	do.	35°30.7′/83°59.9′	do.	Jonesboro Limestone	3½
3	T-O-76 (10575-CO)	do.	do.	35°30.4′/83°59.6′	do.	do.	3½
4	*SOVO-50 (10549-CO)	do.	Vonore	35°35.7′/84°11.3′	do.	Chepultepec Dolomite	3
5	*SOCC-26 (10449-CO)	do.	Cades Cove	35°36.1′/83°49.1′	do.	Jonesboro Limestone	3½
6	*SOVO-49 (10548-CO)	do.	Vonore	35°36.4′/84°07.7′	do.	Mascot Dolomite	2½
7	*SOCC-25 (10448-CO)	do.	Cades Cove	35°36.7′/83°48.1′	do.	Jonesboro Limestone	3
8	*SOTA-51 (10550-CO)	do.	Tallassee	35°36.9′/84°06.7′	do.	Mascot Dolomite	2½
9	70B9-4	do.	Binfield	35°37.4′/84°06.7′	Middle	Whitesburg Limestone	3
10	*SOTC-23 (10447-CO)	do.	Kinzel Springs	35°38.8′/83°48.3′	do.	Lenoir Limestone	3
11	*SOTC-16 (10444-CO)	do.	Wear Cove	35°40.2′/83°43.1′	do.	do.	3
12	*SOTC-53 (10552-CO)	do.	Kinzel Springs	35°40.2′/83°46.9′	Lower	Jonesboro Limestone	3
13	70B11-2	do.	Blockhouse	35°41.0′/83°57.0′	Middle	Blockhouse Shale	3½-4
14	*SOTC-18 (10445-CO)	do.	Kinzel Springs	35°41.5′/83°45.8′	do.	Lenoir Limestone	3
15	*SOBH-48 (10547-CO)	do.	Blockhouse	35°42.1′/83°56.6′	Lower	Mascot Dolomite	3
16	*SOBH-52 (10551-CO)	do.	do.	35°44.0′/83°53.7′	do.	do.	2½-3
17	*SOLR-34 (10453-CO)	do.	Kinzel Springs	35°44.2′/83°49.4′	Middle	Tellico Formation	3
18	70B29-2	do.	Louisville	35°45.0′/84°01.0′	do.	Lenoir Limestone	2½-3
19	64B6-2	do.	do.	35°45.8′/84°07.3′	do.	Arline Formation	2½-3
20	71B8	do.	Concord	35°46.2′/84°07.8′	do.	Lenoir Limestone	2½-3
21	74B36-3	do.	Maryville	35°47.0′/83°59.0′	do.	do.	2½
22	70B10-5	do.	do.	35°48.1′/83°45.3′	do.	do.	3½-4
23	*SOWW-45 (10546-CO)	do.	do.	35°48.8′/83°46.3′	do.	do.	3
24	*SOWW-44 (10545-CO)	do.	do.	35°49.5′/83°46.8′	do.	do.	3½
25	T-O-79 (10577-CO)	Cocke	Hartford	35°52.4′/83°13.5′	do.	do.	3½-4
26	T-O-40 (10574-CO)	do.	Newport	35°52.7′/83°13.3′	do.	do.	3-3½
27	*SONE-60 (10559-CO)	do.	do.	35°53.0′/83°13.1′	Lower	Chepultepec Dolomite	3½
28	T-O-11 (10573-CO)	Greene	Mosheim	36°10.9′/82°58.9′	Middle	Blockhouse Shale	4
29	*SOWP-59 (10558-CO)	Jefferson	White Pine	35°04.0′/83°19.0′	Lower	Chepultepec Dolomite	3½
30	*SOCH-62 (10560-CO)	do.	Chestnut Hill	35°55.7′/83°20.3′	do.	do.	4
31	73B8-2	do.	Douglas Dam	35°58.0′/83°20.3′	Middle	Lenoir Limestone	3-3½
32	T-O-81 (10578-CO)	do.	do.	35°58.3′/83°30.1′	do.	do.	3½-4
33	*SODD-57 (10556-CO)	do.	do.	35°58.3′/83°31.5′	Lower	Chepultepec Dolomite	3
34	*SOSG-58 (10557-CO)	do.	do.	35°58.4′/83°29.9′	do.	Kingsport Dolomite	3
35	74B38-1	Knox	Boyds Creek	35°58.5′/83°44.0′	Middle	Lenoir Limestone	3
36	70B8-2	Monroe	Vonore	35°34.3′/84°08.0′	do.	Chota Formation	2½-3
37	*SOWC-38 (10455-CO)	Sevier	Gatlinburg	35°43.5′/83°37.5′	Lower	Jonesboro Limestone	3½
38	*SOWC-10 (10443-CO)	do.	Wear Cove	35°43.8′/83°39.3′	Middle	Lenoir Limestone	3½
39	*SOPF-43 (10544-CO)	do.	Pigeon Forge	35°49.5′/83°33.5′	Lower	Mascot Dolomite	3-3½
40	*SOFG-4 (10440-CO)	do.	Richardson Cove	35°49.7′/83°29.8′	do.	Jonesboro Limestone	4
41	*SOFG-5 (10441-CO)	do.	do.	35°50.0′/83°28.7′	Middle	Not known	3½-4
42	*SOPF-42 (10543-CO)	do.	Pigeon Forge	35°50.7′/83°34.7′	do.	Lenoir Limestone	3-3½
43	*SOBC-55 (10554-CO)	do.	Boyds Creek	35°53.5′/83°43.5′	Lower	Mascot Dolomite	3
44	*SOBC-56 (10555-CO)	do.	do.	35°53.9′/83°42.4′	Middle	Lenoir Limestone	2½
45	*SOSG-63 (10561-CO)	do.	Shady Grove	35°54.5′/83°24.6′	do.	do.	3½
46	*SOBC-54 (10553-CO)	do.	Boyds Creek	35°55.0′/83°40.3′	do.	do.	3

thrust belt (Dumplin Valley thrust belt) of the Valley and Ridge closest to the Tuckaleechee Cove window were indexed at only two localities (fig. 2). In order to understand and explain the Tuckaleechee Cove window anomaly, additional CAI data were required. Ordovician rocks were sampled in all windows in the Great Smoky thrust sheet in central eastern Tennessee and at geologically appropriate spacings in the Dumplin Valley thrust belt.

Thirty new localities were sampled for CAI evaluation (table 1); except for a single locality at which Mississippian rocks were sampled, all were productive. The 29 new localities in Lower and Middle Ordovician rocks increased the CAI data base in the Dumplin Valley thrust belt (between the southern limit of Blount County and northern Jefferson County) and the Calderwood, Cades Cove, Tuckaleechee Cove, and Wear Cove windows (compare figs. 2 and 4). For consistency, we also reindexed the conodont collections used by Harris and others (1978) in their study for central eastern Tennessee; as a result, some earlier CAI values have been changed, chiefly because of changes in indexing methodology. Changes of one-half index in the eastern part of the Saltville and the western part of the Dumplin Valley thrust belts produced minor changes in the formerly consistent eastward increase in CAI values. The most significant change, however, is for rocks in the Tuckaleechee Cove window, now indexed as 3 (fig. 4), an increase of one index over the former value. The previous CAI value of 2 for rocks in this window (Epstein and others, 1977; Harris and others, 1978) was based on a few relatively thin walled Middle Ordovician conodonts. Our experience has shown that such conodonts generally yield lower CAI values than do thicker walled conodonts in a sample. Lower and Middle Ordovician rocks at four localities in the Tuckaleechee Cove window all produced conodont collections having CAI values of 3, which are still lower than those from localities indexed by Harris and others (1978) in the nearby Dumplin Valley thrust belt to the west.

Ordovician rocks in the Cades Cove and Wear Cove windows (fig. 4) have CAI values of 3½, slightly higher than those of correlative strata in the Tuckaleechee Cove window. Ordovician rocks in the Calderwood window, about 20 km south of the Tuckaleechee Cove window, have intermediate CAI values of 3 to 3½. Thus, inspection of CAI values in the windows alone shows no apparent trend or relationship between CAI values and inferred tectonic or depositional patterns.

On the basis of seven CAI localities along a 120-km-long strike belt of the Dumplin Valley thrust sheet, Harris and others (1978) showed that CAI values gradually decrease southwestward, northwestward, and northeastward from the eastern limit of the thrust belt in Sevier County. The 21 new localities in the Dumplin Valley thrust belt add complexity to the CAI patterns in this area (compare figs. 2 and 4), and some intriguing relationships emerge. The CAI values of 3½ in Ordovician rocks of the Wear Cove and Cades Cove windows are opposite equivalent values in the Dumplin Valley thrust belt to the west. Likewise, the slightly lower CAI values in Ordovician rocks of the Tuckaleechee Cove window are opposite an area of similarly lower CAI in the Dumplin Valley thrust belt.

GEOLOGIC INTERPRETATION

We suspect that CAI patterns in lower Middle and Lower Ordovician rocks in the Dumplin Valley thrust belt and in windows to the east chiefly reflect primary depositional trends of Middle and Upper Ordovician predominantly clastic rocks that have been shown to be thickest in Blount and Sevier Counties and that may be even thicker in eastern Jefferson and Cocke Counties (fig. 5). The thickness of post-Lenoir Ordovician deposits in the eastern Valley and Ridge province of part of central eastern Tennessee was compiled from a variety of published reports (fig. 5). This task proved difficult because (1) Upper Ordovician rocks are partly eroded from the Saltville thrust belt and almost totally absent from the Dumplin Valley thrust belt, (2) Middle Ordovician clastic deposits are incompletely preserved or incompletely exposed in the Dumplin Valley thrust belt, and (3) the area of probable thickest pelitic deposition north of Sevierville is probably the most structurally complex area in the Dumplin Valley belt, so that thickness data are unavailable or speculative. Consequently, only generalized unrestored thicknesses could be plotted for post-Lenoir Middle Ordovician rocks south of Sevierville in the Dumplin Valley thrust belt and for post-Lenoir Middle Ordovician rocks and part of the Upper Ordovician rock succession in the Saltville thrust belt (fig. 5). Interestingly, these data mimic CAI trends in the same area. Moreover, these thickness trends appear to extend eastward toward the CAI values in the windows. This projection may be inappropriate, however, because Ordovician rocks in the windows are now 15 to 20 km east of correlative rocks in the Dumplin Valley thrust belt as a result of tectonic juxtaposition (fig. 3). In addition, palinspastic reconstructions based on existing interpretations (fig. 3) place these rocks at least 8 km farther eastward. Thus, it is likely that these parallel CAI trends, although possibly produced by the same processes, may not be part of a single depositional pattern.

CAI data from the single outcrop belt of younger Upper Devonian and Mississippian rocks in the Dumplin Valley thrust belt (fig. 1) would be useful, but, thus far, three samples from these dominantly clastic deposits have not produced conodonts. If CAI values for these younger rocks are considerably lower than those for the Lower and lower Middle Ordovician rocks that lie beneath the thick post-Lenoir Ordovician deposits in the same vicinity, then a primary depositional origin for the CAI patterns in the older Ordovician rocks could be established.

North of the Blount–Sevier County border in the Dumplin Valley thrust belt, CAI values are higher and appear to be more consistent. These higher values coincide with the broadening belt of Middle and Upper Ordovician chiefly clastic rocks in the same area (see Hardeman, 1966). Although thicknesses for these deposits are unavailable, the higher CAI values north of Blount County, as compared with those along strike to the south, strongly indicate thicker Ordovician deposits northward and eastward. We do not believe that these CAI trends are related to thickness patterns of post-Ordovician Paleozoic rocks or to major differences in thickness of tectonic overburden along strike.

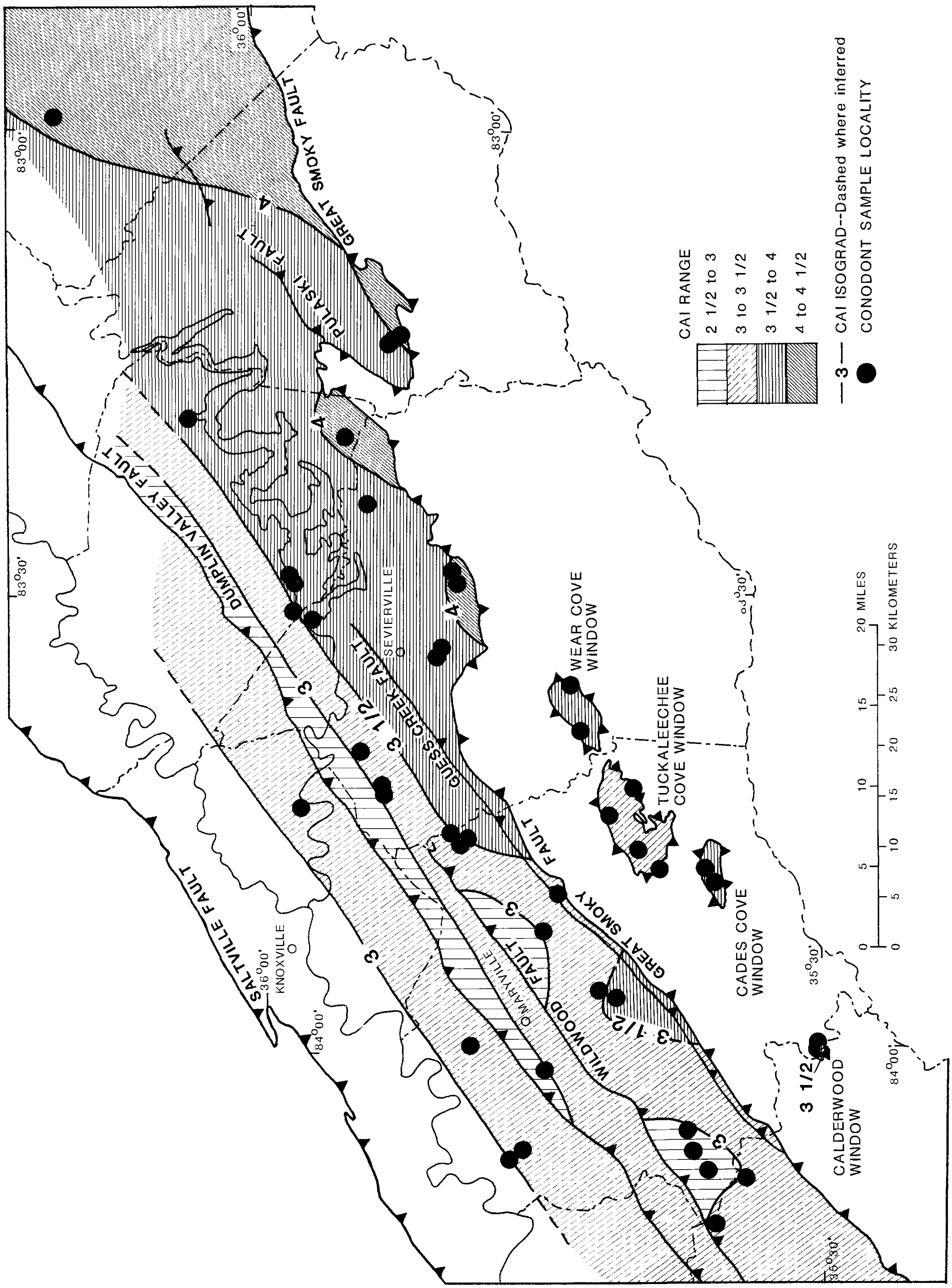

Figure 4. Conodont color alteration index localities and revised isograds for Ordovician carbonate rocks east of the Saltville fault, central eastern Tennessee.

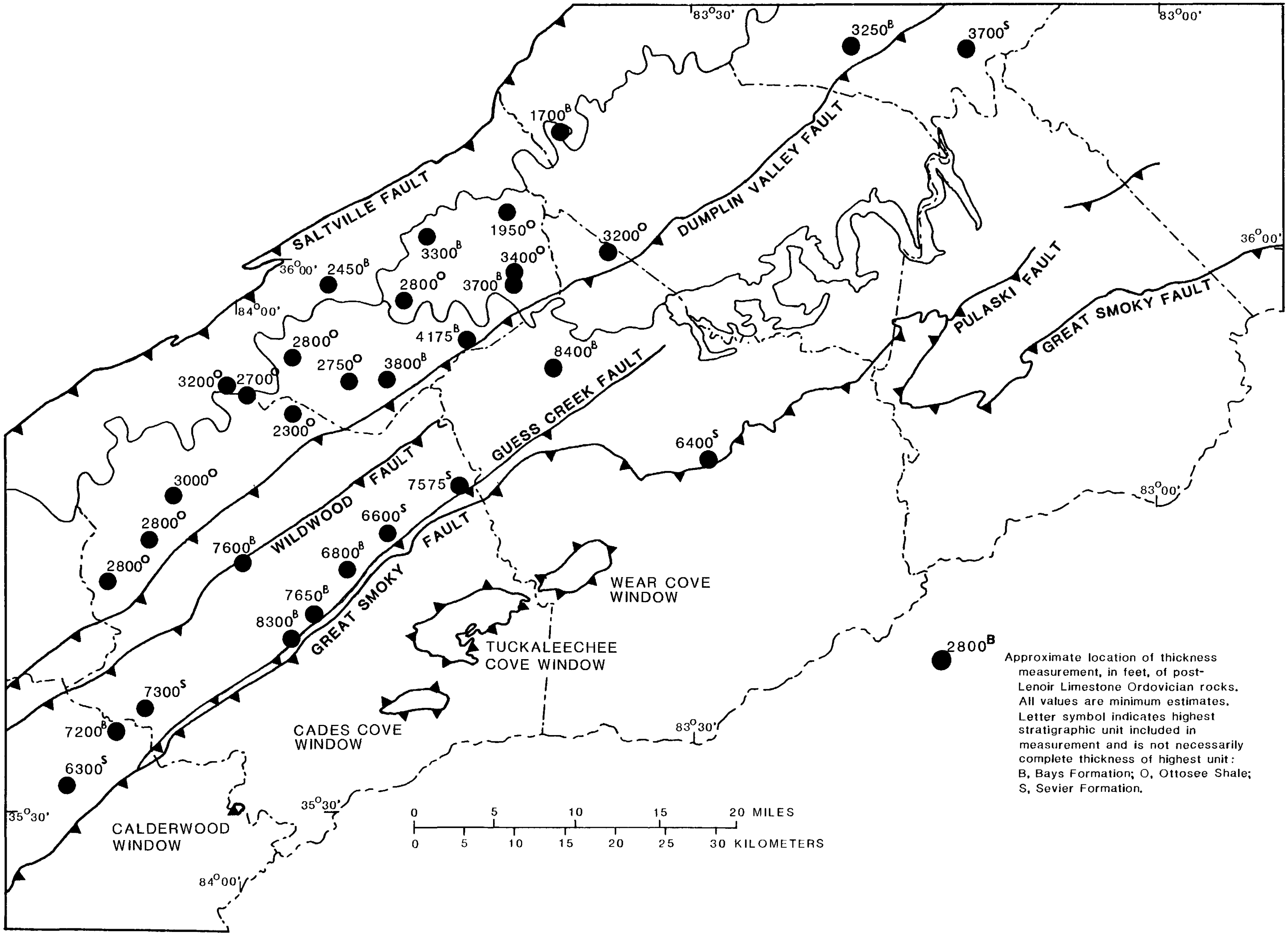

Figure 5. Unrestored thickness of Ordovician rocks younger than the Lenoir Limestone in the Saltville and Dumplin Valley thrust belts, central eastern Tennessee. Thickness data compiled from Bridge (1956), Cattermole (1955, 1958, 1960, 1962, 1966), Hamilton (1961), Bridge and Hatcher (1973), Keith (1896a,b, 1901), Milici and others (1979), Neuman (1955, 1960), Neuman and Wilson (1960), Swingle and others (1967), and Walker and others (1983).

CONCLUSIONS

This study shows that:

1. The "anomalously" low CAI value for Ordovician rocks of the Tuckaleechee Cove window is not as low as that reported by earlier investigators (Epstein and others, 1977; Harris and others, 1978) and is anomalous only with respect to CAI values in correlative rocks northward and northeastward at the eastern limit of the Valley and Ridge province.
2. CAI patterns in Lower and lower Middle Ordovician rocks in central eastern Tennessee are more complex than those shown by earlier investigators; these patterns appear to be related chiefly to primary depositional trends in Middle and Upper Ordovician rocks.
3. CAI values in Ordovician rocks of the Tuckaleechee Cove window are slightly lower than those in correlative rocks in nearby windows. A similar pattern persists in correlative rocks in the Dumplin Valley thrust belt opposite the windows and appears to mimic thickness patterns of Middle and Upper Ordovician rocks in the same area. These depositional patterns may persist eastward toward the windows and could account for the difference in CAI values of rocks in the windows.
4. Regardless of these changes in CAI values and their inferred geologic causes, the data still indicate thermal potential for hydrocarbons in the eastward extension of Valley and Ridge rocks beneath the chiefly crystalline rocks of the Blue Ridge. Reevaluation of CAI patterns, however, somewhat decreases the area of this potential hydrocarbon province and virtually restricts its potential to natural gas.

More detailed sampling and mapping of CAI values will provide a higher resolution and probably increase the complexity of thermal maturation patterns in the Appalachian basin. Such studies may help to better understand the tectono-depositional framework of the basin, particularly along its eastern exposed margin, where such data can be projected into the eastward extension of the sedimentary succession beneath the Blue Ridge province.

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