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THE IMPORTANCE OF REGIONAL AND LOCAL STRUCTURE TO DEVONIAN SHALE GAS PRODUCTION FROM THE APPALACHIAN BASIN

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ABSTRACT

The recent energy shortage within the United States of America has drawn governmental interest toward unconventional sources of natural energy. The black, organic-rich gas shales of Devonian and Mississippian age in the continental interior present a huge resource base for that area. The Devonian shale has produced high-quality gas from the Appalachian basin in eastern Kentucky and West Virginia for nearly 100 years, yet little is known of the relationships between the geology and production. This is true because the wells are shallow, and they are drilled largely on a random basis related to available acreage and adjacent production. Geologic structure and production from this area is being studied to determine if there is a relationship between the two. Analyses of oriented cores taken in the shale suggest that most commercial production relates to the presence of highly organic shale and natural fractures, and that optimum production is found where mineralized fractures occur within the highly organic layers. Slickensided fractures formed in response to Appalachian stress within the areas of commercial production further suggest that differential tectonic shortening (detachment) across the shales is important to development of fracture permeability. Three transitional zones of movement have been found that can be characterized by their fracture patterns within the shales:

(1) an outer or cratonic zone of tensional joints with no evidence of differential movement within the shale,

(2) a foreland zone of inclined (slickensided) shear fractures and tensional fractures, and

(3) a foreland zone of recognizable tectonic transport defined by mineralized and slickensided bedding plane fractures.

The commercial gas production lies with zone 2 of the foreland area. Fortunately, this foreland area coincides with the depositional center of the highly organic Devonian shales. Maximum production occurs within the zone above the margin of basement block faults where unique stress fields occurred during Appalachian deformation. The stress fields developed an extremely porous fracture facies within the organic shales. In this unique trap the shale acts as the source and seal, and the mineralized fractures, probably developed in ancient high-pressure zones, serve as the reservoir.

A program which utilizes geomorphology, detailed subsurface structure analyses, geochemistry, and high-resolution seismic investigations is being developed to help formulate an exploration rationale. Results of our study may help geologists to locate fractured reservoirs in other foreland troughs, and in particular where the reservoirs are organic rich shales.

Introduction

The Devonian shale is an informal stratigraphic name applied to a body of organic clay-rich sediments that extend across nearly '25% of the North American continent. This black and gray shale generally lies between Mississippian sands or shales and Middle Devonian limestones. The shale onlaps these carbonates along an erosional surface of low relief.

In basins of the western plain states the thin shale is usually called the Woodford shale. In the Illinois basin (Figure 1) the shale is called the New Albany shale (30-100 meters thick), and in the Michigan basin it is called, the Antrim shale (25-40 meters thick). Within the western Appalachian basin the thick shale sequence (up to 400 meters thick) is usually called either the Ohio shale or the Chattanooga shale (Figure 2). Stratigraphic problems arise east of this area, within the central portion of the Appalachian basin, where the shales change facies to interbedded sands and silts of the Appalachian deltaic sequence (Figure 3).

Production

The highly organic portions of the Devonian shale sequence usually give up minor amounts of gas and some oil when penetrated by the drill. Occasionally the gas produced will be of sufficient quantity to warrant completion as a commercial gas well. However, it is only within the Appalachian basin that the shale produces large quantities of gas. The *major* areas of production are in eastern Kentucky in a blanket-like deposit and as discreet fields in southwestern West Virginia (Figure 4). It is this area that is the subject of this report. These fields have produced over one trillion cubic feet during the last fifty years, but the shale has produced shallow gas for local consumption for over 100 years in several areas of the eastern United States. Exploratory gas wells are shallow, being located randomly, either in proximity to other producing wells or on the basis of available acreage in the productive area. Even though nearly 10,000 wells are producing shale gas in eastern

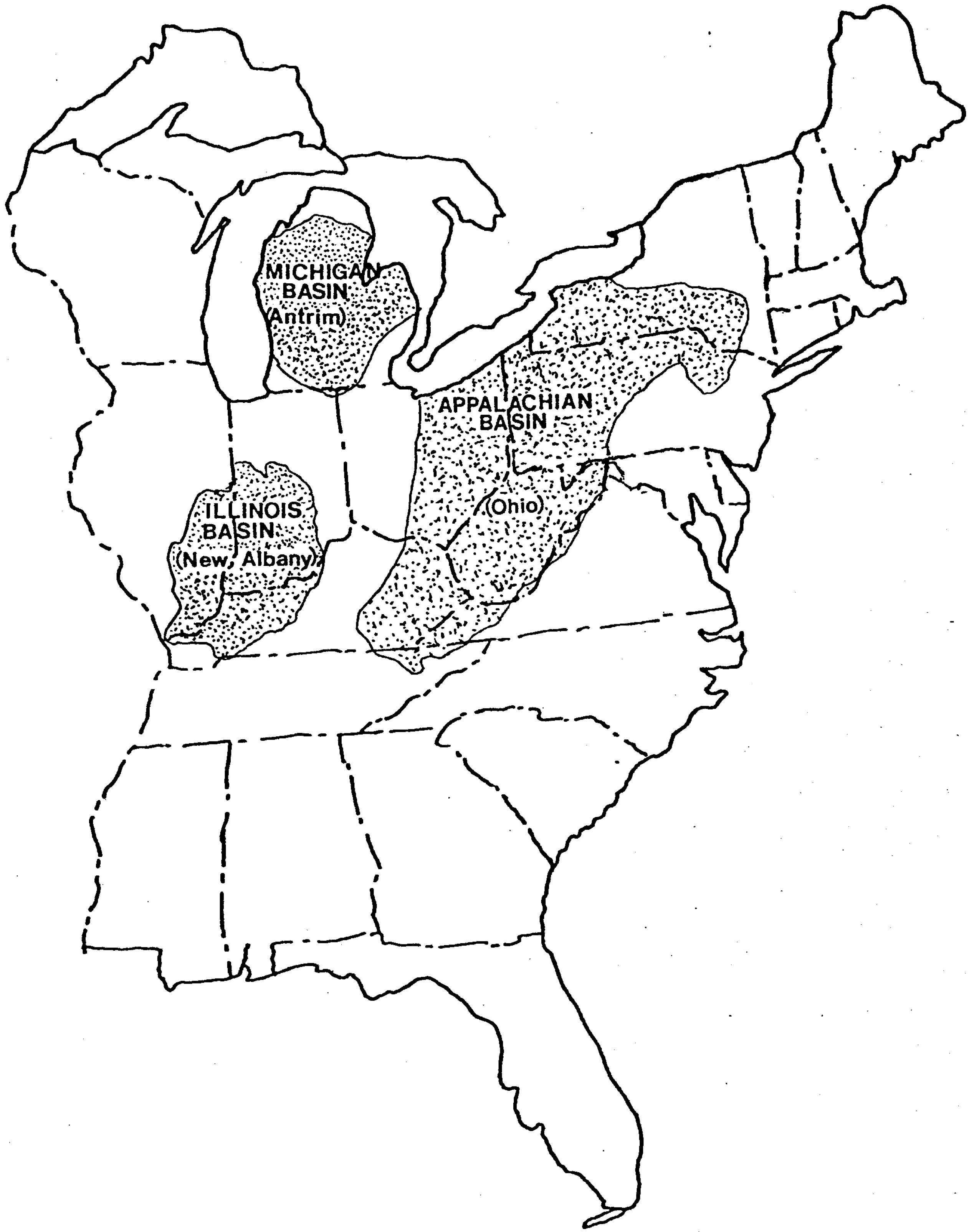

Figure 1. Distribution of Devonian shale within eastern basins

ystem	Series	Units of New Albany Shale in S.IN.-W.KY.		Units of Ohio Shale in OH.-E.Ky.			Units of Chattanooga Shale in W.VA.-E.TENN.	
Miss.	Lower Miss.	Rockford Limestone		Sunbury Shale			Big Stone Gap Member	CHATTANOOGA SHALE
		Jacob's Chapel Bed Henryville Bed Underwood Bed Falling Run Bed	NEW ALBANY SHALE	Bedford Berea Sequence				
DEVONIAN	UPPER DEVONIAN	Clegg Creek Member		Cleveland Shale		OHIO SHALE	Middle Gray Siltstone Member	
		Camp Run Member		Three Lick Bed	Partial Chagrin Shale Equi-valent			
		Morgan Trail Member		Upper Member Middle Member Lower Member	HURON SHALE		Lower Black Shale Member	
		Selmier Member		Olentangy Shale				
			Central Ky. Boyle ls./ch.	Marcellus Shale				
	Mid. Dev.	Blocher Member		Onondaga Limestone/ Huntersville Chert/ Needmore Shale			Absent.	

de Wys, 1979

Figure 2. Devonian shale nomenclature: Appalachian basin

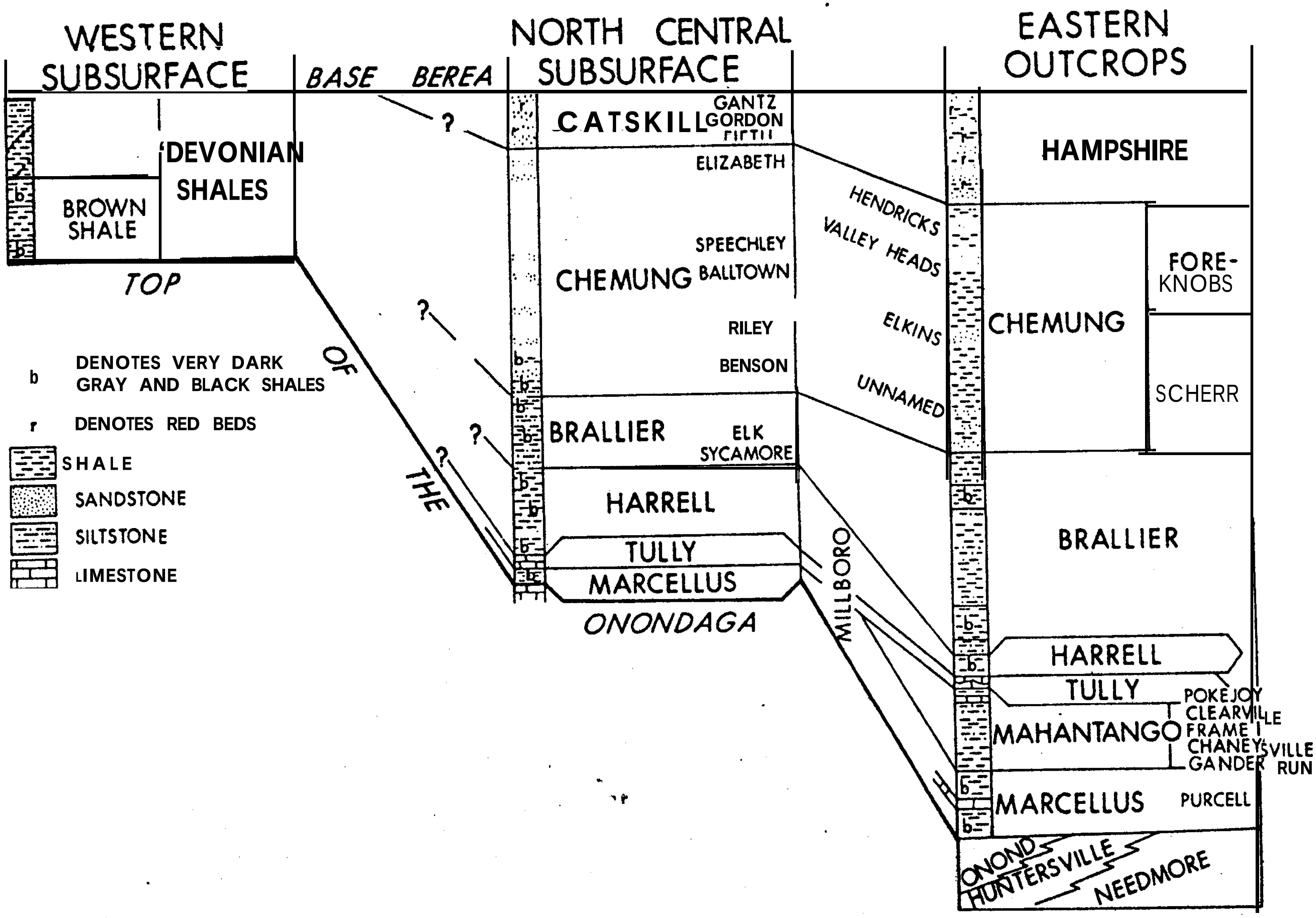

Figure 3. Devonian shale **facies** relationships: Appalachian basin

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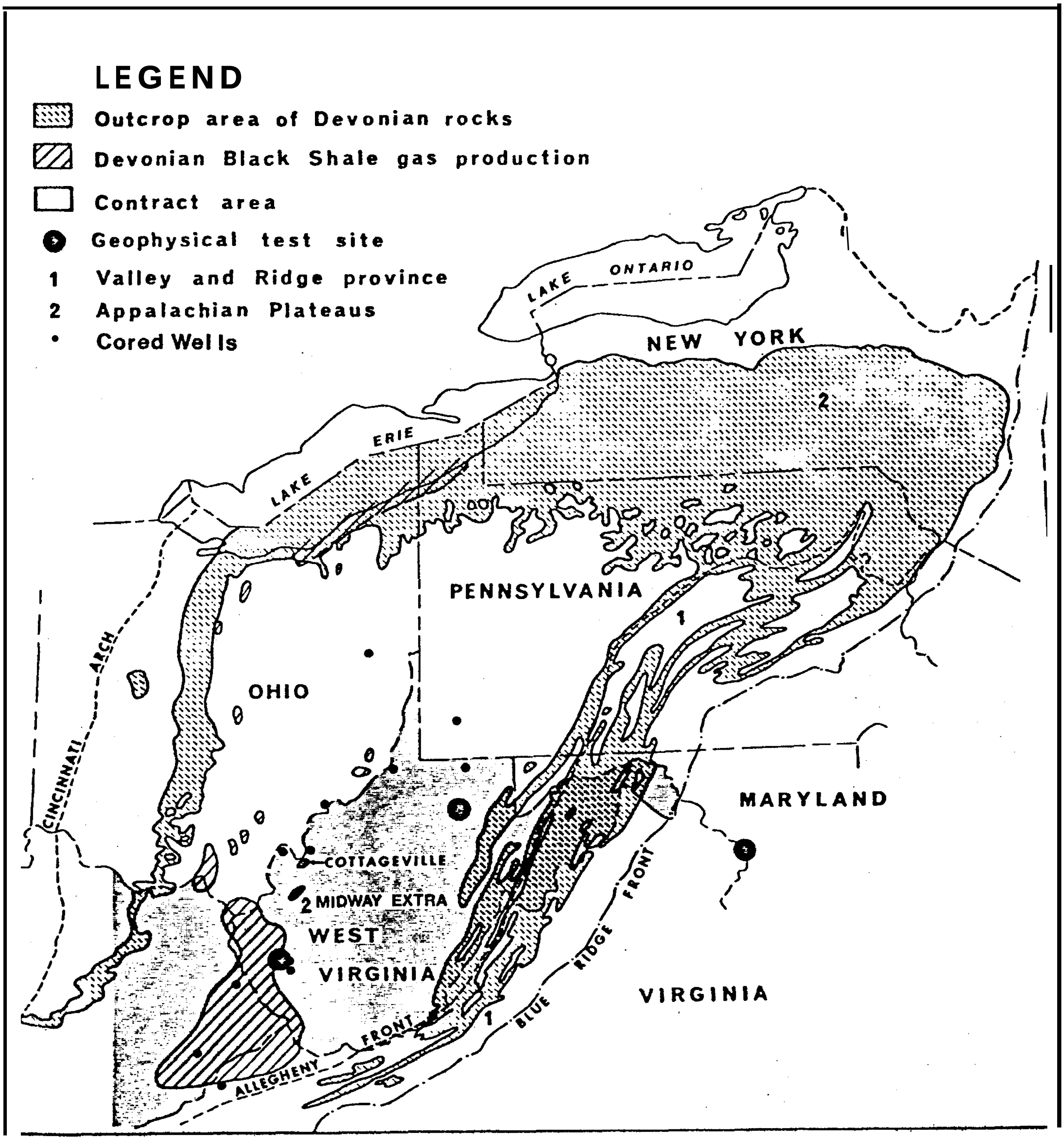

Figure 4. Study Area - structural parameters that affect Devonian shale gas production

Kentucky and West Virginia, very little was known about the geology of the shale or the cause for its commercial production. Geologists have generally reasoned that fractures create the permeability within the shale necessary to release gas in commercial quantities. However, some geologists have maintained that thin silt stringers in the shale are the reservoir, and a few maintain that matrix porosity in the shale is significant to account for all of the production. Our work supports the interpretation that natural fractures are most important for commercial production.

Background

The recent energy shortage in the United States has focused governmental interest on domestic unconventional sources of natural energy, and the productive Devonian shales contain a huge resource potential of high quality natural gas within the energy starved eastern and mid-continent regions. The magnitude of the potential can easily be seen by calculating the total amount of gas which potentially could naturally escape from the shale. By doing so one arrives at an astronomical figure of between 225 trillion cubic feet and 1861 trillion cubic feet of gas that is locked up within the shale in the Appalachian basin alone (N.P.C., 1979), and it is clear that there is a far greater resource of natural gas locked up within the shale within the other basins of the continental interior. Unfortunately, under present technology, only between 8 and 15 trillion cubic feet of this shale gas is available in the Appalachian basin. The range of 8 to 15 TCF is largely dependent upon the price the producer will receive for the gas: a lower price deters exploration in marginally commercial areas, whereas a high figure would make exploration in these areas more likely.

The United States Department of Energy has funded research designed to evaluate existing production and the future potential of Devonian shales in order to evaluate the potential of the shale and with the ultimate goal of expanding production. All aspects of gas production from the shale are under study in this governmental program, but this report includes only those aspects of the structural geology which affects production.

Before embarking on a discussion of these results, it should be understood that an essential ingredient for commercial production is the presence of a sufficient thickness of highly organic shale and a maturation of that shale which is sufficient to liberate hydrocarbons. Both of these prerequisites are fulfilled over much of the continental interior, and they are both fulfilled throughout the study area. Therefore, the key variables for production from Devonian shale in the study area are its lithology and the structure.

Two aspects of a broadly based structural study have been particularly interesting in regard to understanding the relationships between shale gas production and geologic structure. The first result comes from the study of fractures found in oriented cores of the shale, and the other comes from the geologic analysis of two producing shale gas fields.

The evaluation of fractures found in oriented shale cores taken from within the study area in the Appalachian basin (Figure 4) has shed light on the distribution of fractures in an orogenic foreland. Even though several of these cores were taken in what intially was considered undeformed foreland sediment, they all contained natural fractures, joints, to depths of over 6000 feet, and most surprisingly, these cores contained slickensided fractures. In general, systematic joints from these cores form three sets: one related to present day in-situ stress which is thought to be Mesozoic in age (Evans, 1980), and the other two which form an orthogonal, cross and longitudinal, joint system that is Alleghenian in age. The slickenlines of small faults trend parallel to the cross joint strike which support the Alleghenian age of the orthogonal system. Shumaker (1978) suggested that open and mineralized fractures were most prevalent in the highly organic portions of the shale based on studies of the first few oriented cores. Evans (1980) showed that the open and mineralized joints within the shale were most numerous in the highly organic portions of the section based on 13 wells, and he supported the proposal (Shumaker, 1978) that production comes from a porous fracture facies within the highly organic shales in the lower portion of the Devonian shale. This mineralized and more intensely fractured shale section in the commercially productive area is interpreted to be a decollement zone, or perhaps more aptly, a zone of differential shortening. The differential shortening is found in the distal portion of a more extensive area of transport and shortening above decollement surfaces that extends deeper into the section in the more deformed eastern Appalachian basin (Figure 5). An important feature for production from the organic shales is that the fractures are limited vertically so that the enclosing shale forms both the source and the seal for the reservoir and the interconnected fractures form the permeability. It is essential to maintain this relationship during well completion treatment and stimulation so that water from adjacent formations does not enter the chemically sensitive reservoir. The vertical joints'presumably form the main channels of permeability, whereas, the small faults probably do not greatly enhance permeability (Heald and Larese, 1978). In plotting the area1 distribution of fracture types, it was found that most of the present day commercial production falls within an area of limited tectonic transport as defined by the inclined slickensided fractures, whereas, production from the zone of tectonic transport ranging up to several miles is characterized by higher than normal pressure in blowout zones of little sustained production. Horizontal slickensides predominate in the major transport zones, but inclined slickensides are also very common. Poles to slickensided surfaces plot in a girdled distribution with maxima related to the primary and Reidel shear directions in the large transport areas. In the area of minimal transport a shear system asymmetrically distributed about the horizontal stress direction prevails. A reduction in production is

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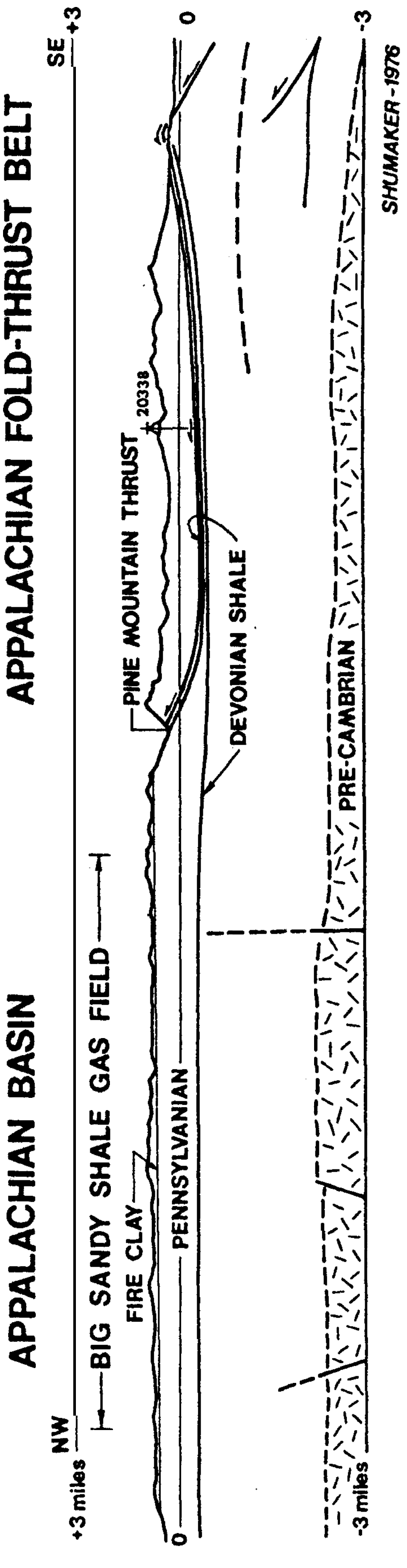


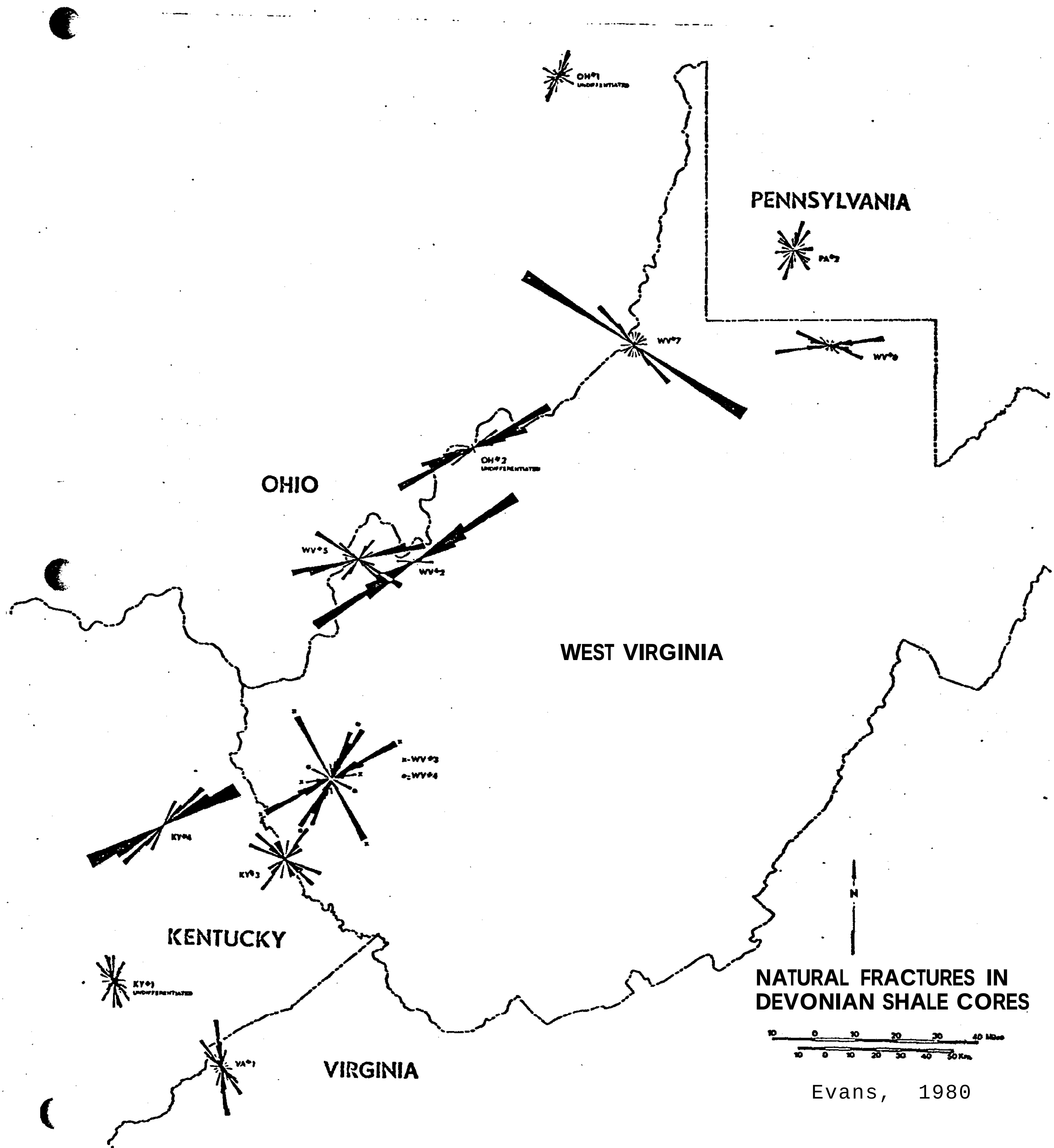
Figure 5. Structural cross section: eastern Kentucky

found cratonward of the commercial production. Cores taken of the shale in that area show a lack of slickensided surfaces and a decrease in frequency of open or mineralized joints; thus, there is a distinct zone of maximum production related to the distribution of fractures in the organic shales.

A second aspect of our investigation that has application to shale gas exploration comes from a study of two productive fields within the study area of the Appalachian basin. Production data from three fields within the Appalachian basin are available for study, and two, the Midway-Extra and Cottageville fields (Figure 4) have been thoroughly analyzed for this report. The third field is presently under study.

Detailed investigations of the Midway-Extra field of Putnam County, West Virginia, by William W. Schaefer (1979) established a direct relationship between production from the organic portion of the Devonian shale (the lower Huron shale) and the structural trend of the field. Schaefer was able to confirm that initial and final open flows, flows after explosive frac, from wells at Midway-Extra are greatest along the northwestern limb of the Midway anticline; that is, in the adjacent syncline, off structure. He also found a lesser increase in production along the southeastern limb. The striking similarities of high flow rates with structural position along the fold is forcibly brought out by comparing Figures 10 and 11 taken directly from Schaefer's text (1979). Furthermore, he showed that the thickening of the lower Huron shale, the primary reservoir, into the adjacent syncline (Figure 12) suggests growth of the structure during sedimentation. He interpreted this to mean that basement deformation was an important factor in the formation of the Midway anticline. From these data (Figures 10, 11, 12, and 13) at the Midway-Extra field, one cannot be absolutely certain if it is the thicker lower Huron organic shale or if it is fracturing associated with the folding which contributes most to the noticeable increase of off-structure flow rate. One might argue that even if fractures are present, they are not necessarily structural in origin. Such fractures could be caused either by lithologic factors or as the result of differential compaction of thin shale on and thick shale off structure. Regardless of the cause, an empirical exploration rationale was proposed based on Schaefer's study (1979). Direct evidence for the exact and underlying cause for this increased production of off-structure wells was elusive even though Schaefer had made a major guiding breakthrough for an empirical exploration rationale.

If, however, one combines the data from the Midway-Extra field with what is known of the Cottageville field (de Wys and Shumaker, 1978), then additional insight is gained into the specific cause of commercial shale gas production for that portion of West Virginia (Figure 9). At first glance, the structural similarity between Cottageville (Martin and Nuckols, 1976; Nuckols, 1979; and de Wys and Shumaker, 1978) and the Midway-Extra field is not striking. Structurally, the Cottageville field



Evans, 1980

Figure 6. Natural fractures in Devonian shale cores

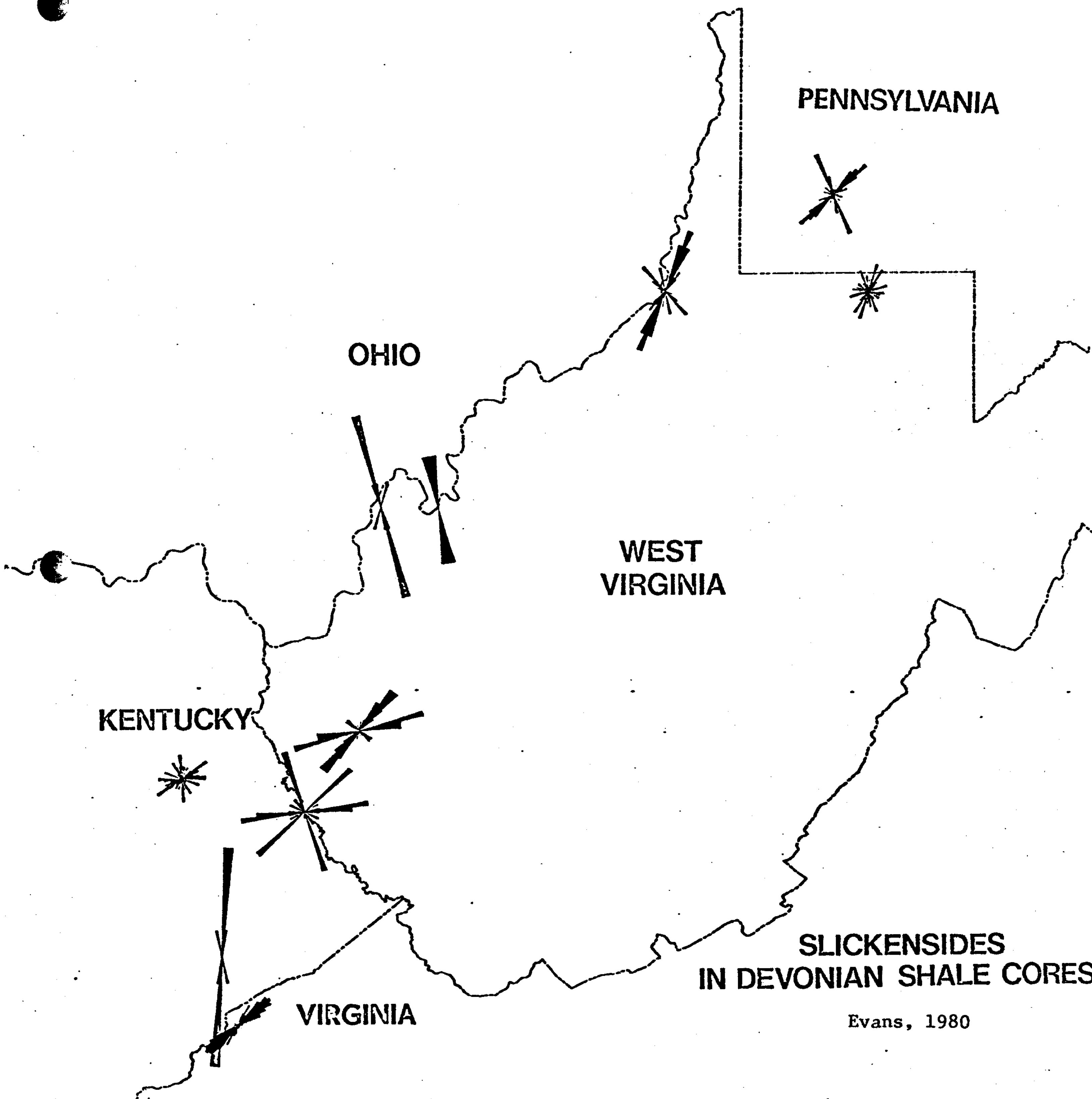


Figure 7. Slickenside surfaces from Devonian shale cores

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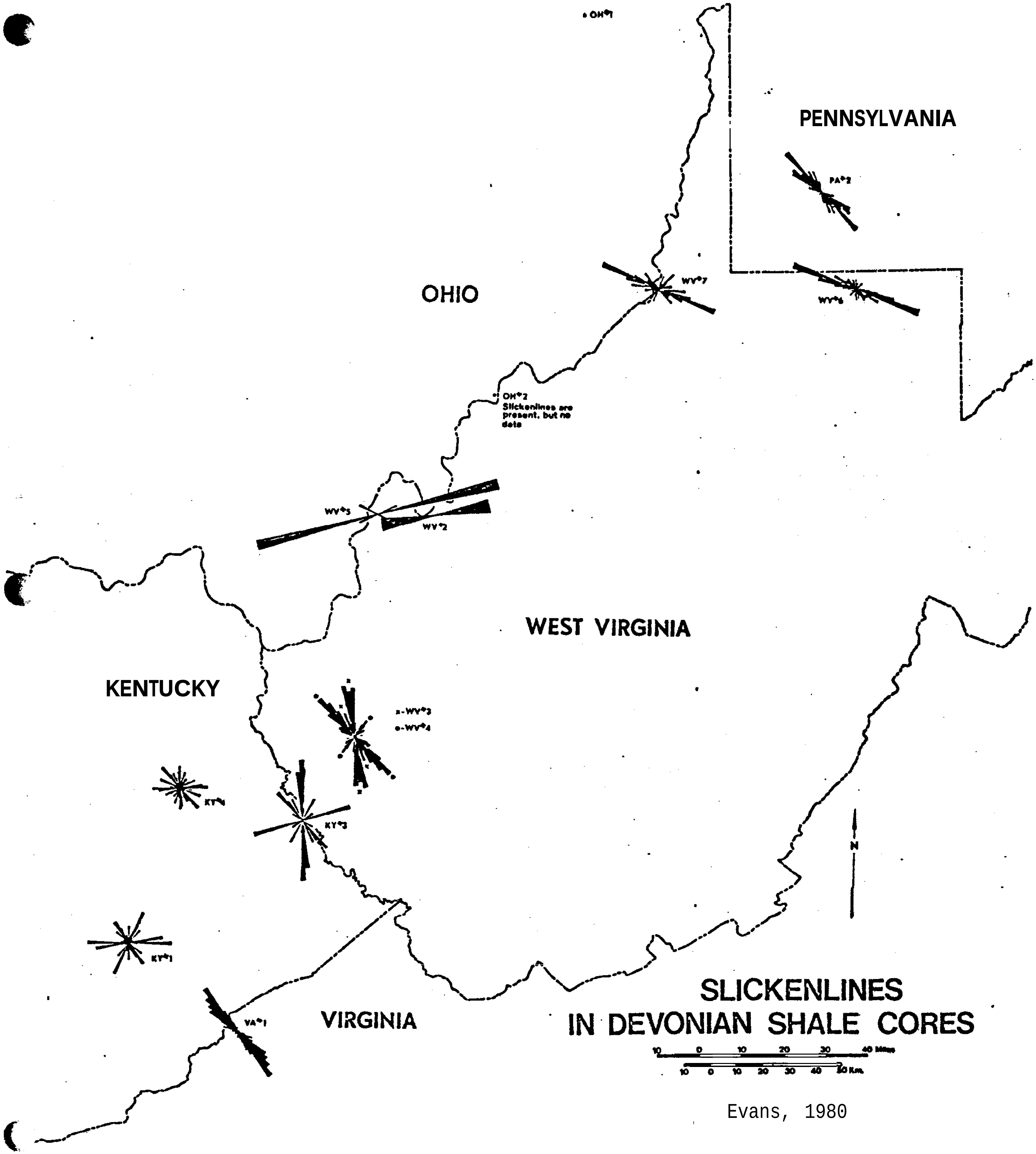


Evans, 1980

Figure 8. Slickenlines trends in Devonian shale cores

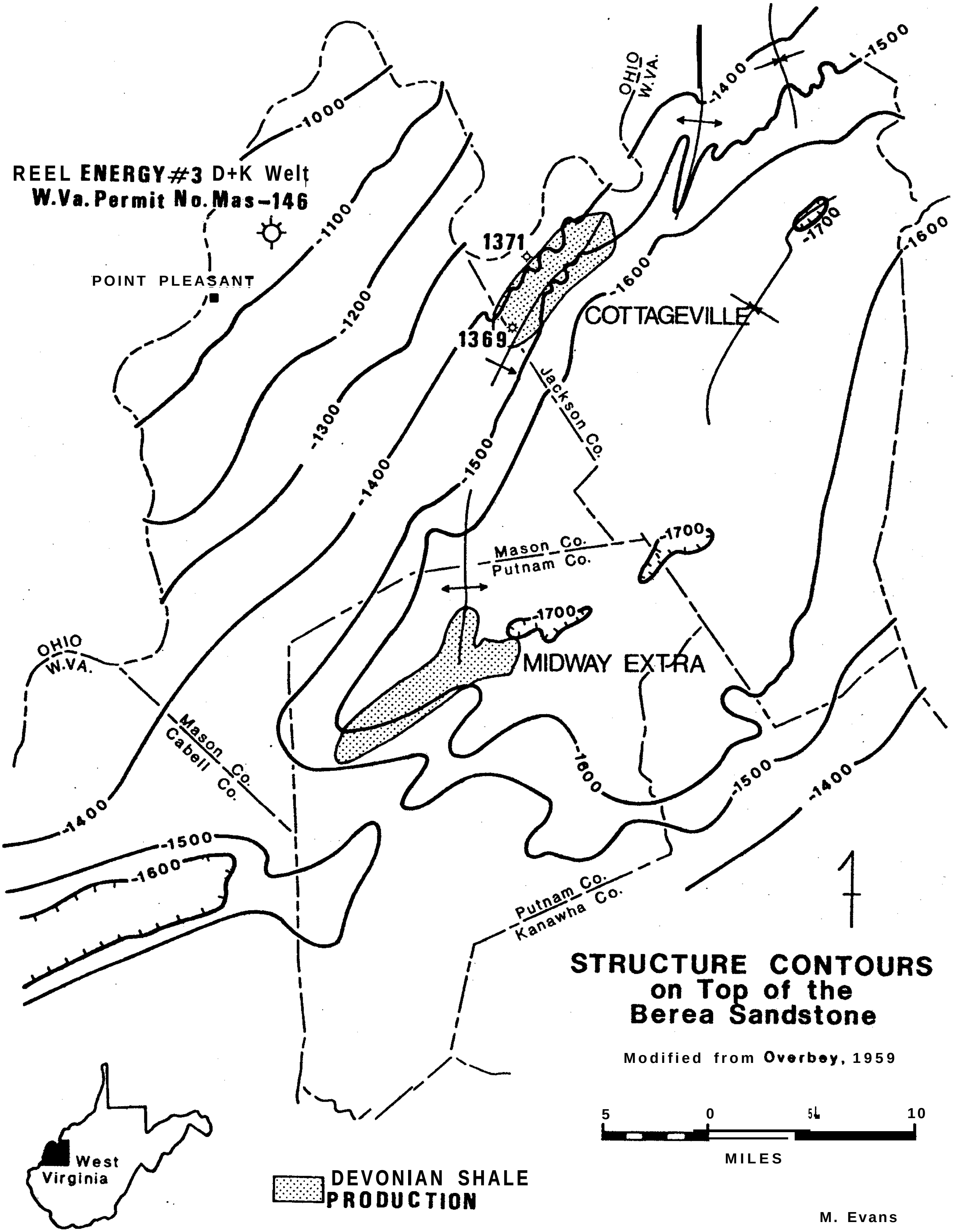
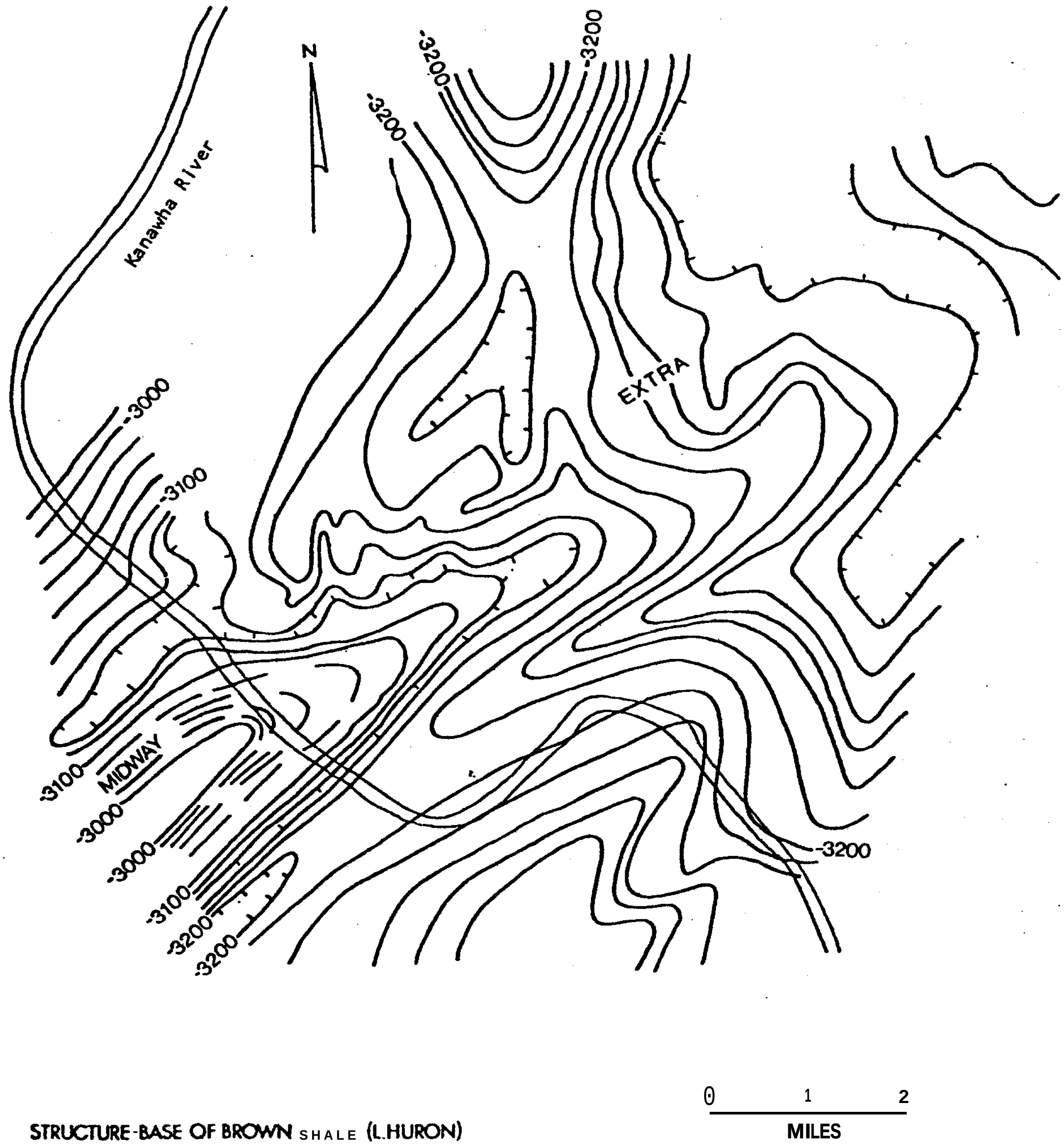


Figure 9. Midway-Extra and Cottageville shale gas field area .



STRUCTURE-BASE OF BROWN SHALE (L.HURON)

Midway-Extra Field
Putnam County, W. Va.

Figure 10

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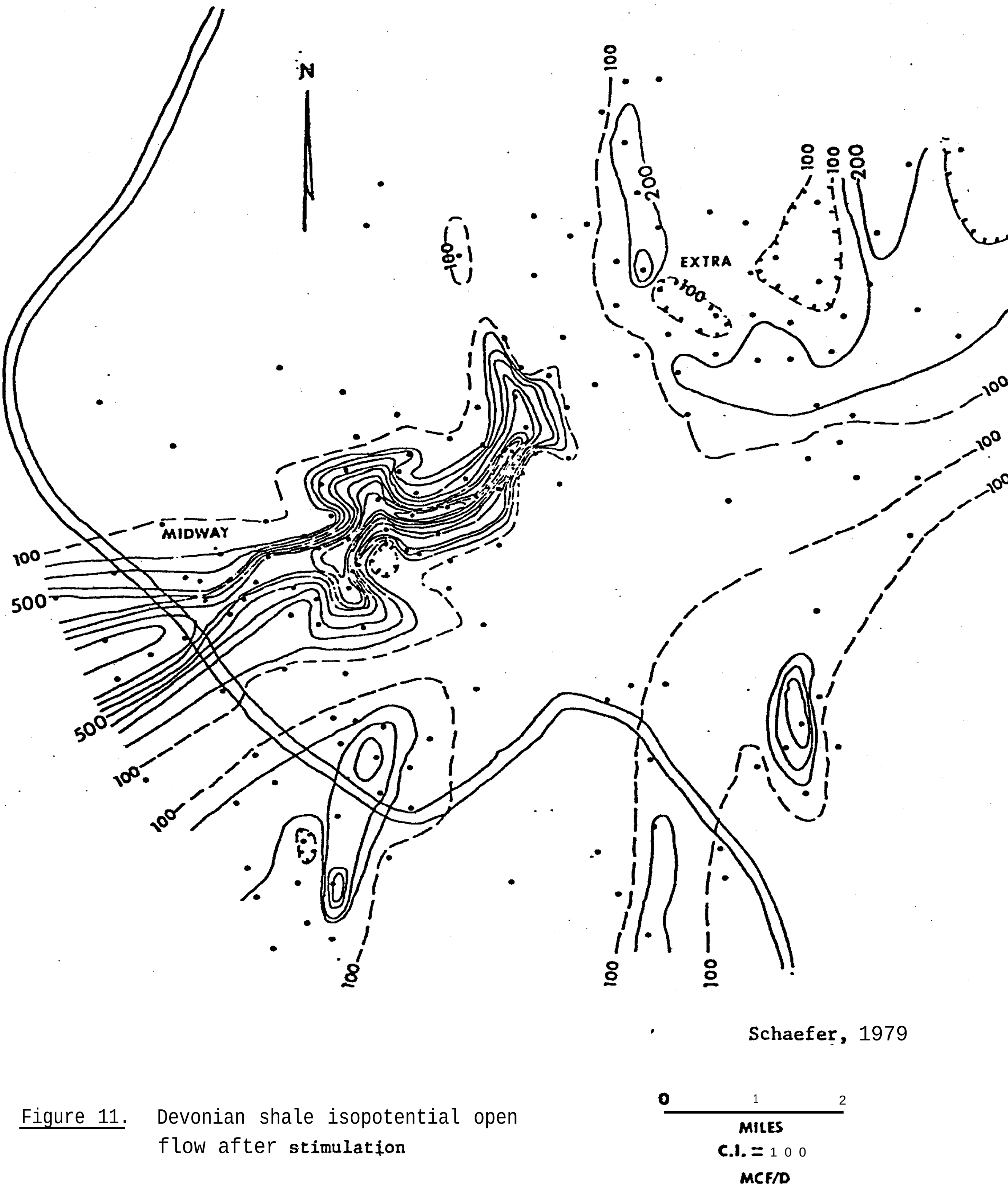


Figure 11. Devonian shale isopotential open flow after stimulation

LOWER HURON ISOPACH MAP

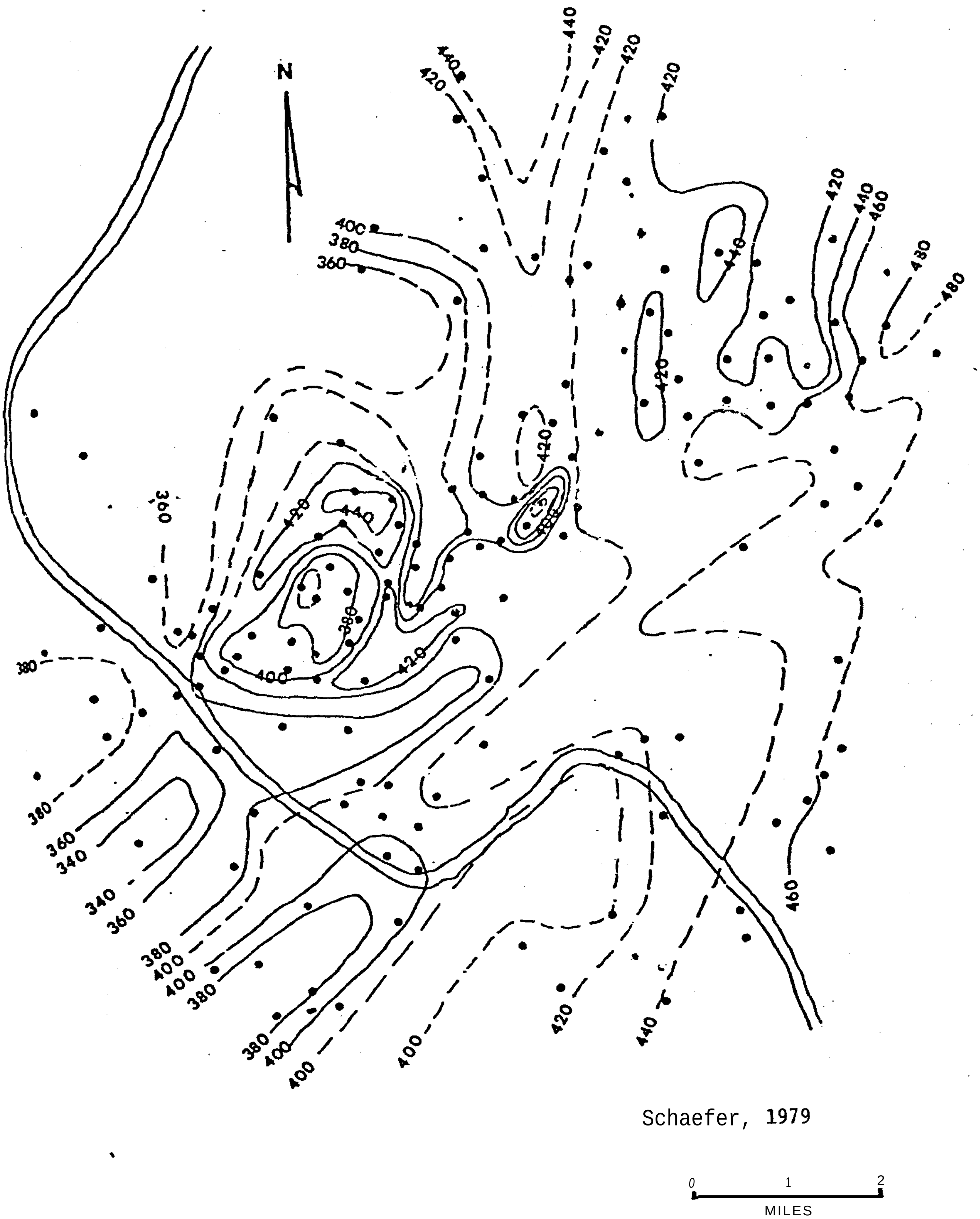
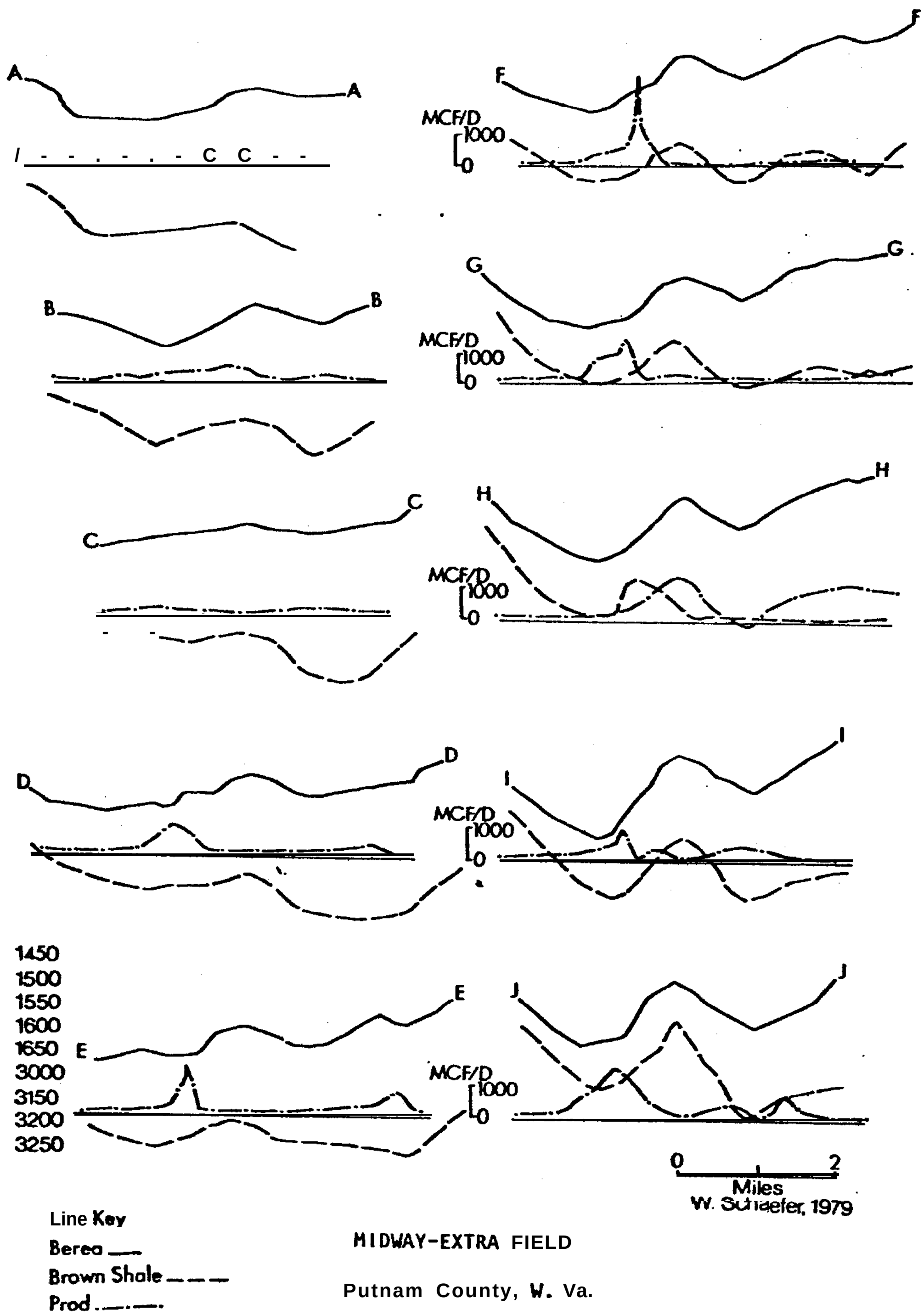


Figure 12. Organic-rich Devonian shale (lower Huron)

STRUCTURE AND ISOPOTENTIAL CROSS SECTIONS



MIDWAY-EXTRA FIELD

Putnam County, W. Va.

Figure 13

appears to lie along a very low relief monoclinal flexure on a southeast dipping regional slope. The cause for the flexure was inferred to be a basement fault (Martin and Nuckols, 1976; and Shumaker, unpublished maps). Detailed interpretation of seismic data collected by Geophysical Services, Incorporated, by Glenn Sundheimer (1978 and 1979) confirmed the presence of the flexure in the sediments and a basement fault directly under the trend of the most productive wells along the southeastern flank of the Cottageville field (compare Figures 14 and 15). Note the southeast regional dip and the subdued flexure including a syncline just updip, northwest from the fault (Figure 14). These structures are similar to, although not identical to, ones mapped by E. B. Nuckols III (1979) from detailed subsurface geologic data. Nuckols has found that sedimentary patterns of the organic shales are complex around this structure. His maps (ibid., 1979) also show that the best production does not uniquely follow the thickest lower Huron organic shale section. The best production lines up with the fault as mapped by Sundheimer (Figure 14). If one eliminates the regional dip from Sundheimer's isotime structure map, then the Cottageville field becomes a low fold with flanking synclines. It is only now that the Cottageville field appears similar to the Midway-Extra field, but Cottageville has far less relief. Keeping this in mind, compare the position of the fault, the fold crestal trace, and the trace of the flanking northern syncline with the production trends at Cottageville as mapped by de Wys and Shumaker (Figures 16, 17, and 18). There is a marked similarity of final open flow trends at Midway-Extra with production as mapped at Cottageville. This similarity is noted by lower productivity along the crest of both structures. At Cottageville there is a near coincidence of productive trends shown on the summary trend map (Figure 19) above and parallel to the basement fault. The trends are not nearly as numerous for the northern syncline (Figures 14 and 19) which, incidentally, may be the southwest terminus of another buried fault. In the case of Cottageville, the identity between structure and production seems far more conclusive than that at Midway-Extra simply because of the greater quality and quantity of data. At Cottageville it is clear that better wells, by all production statistics, occur off structures, and that the best wells generally occur directly above the basement fault. De Wys and Shumaker (1978) contoured the production data at Cottageville (Figures 15 thru 18) with a mechanical style, attempting to avoid bias in their contouring. Had they contoured the production data as Schaefer did with final open flows at Midway-Extra, and if-they had both Schaefer's results and Glenn Sundheimer's map when contouring the Cottageville data in 1977, then they would have contoured the Cottageville data to a more linear trend, and the identity of structure and production trends would be more striking.

Using re-interpreted Cottageville as background, one can now go back to Midway-Extra and re-interpret the northwestern flank of the anticline suggesting that it. is faulted at the basement level. The justification for this interpretation is the growth aspect of the structure and location

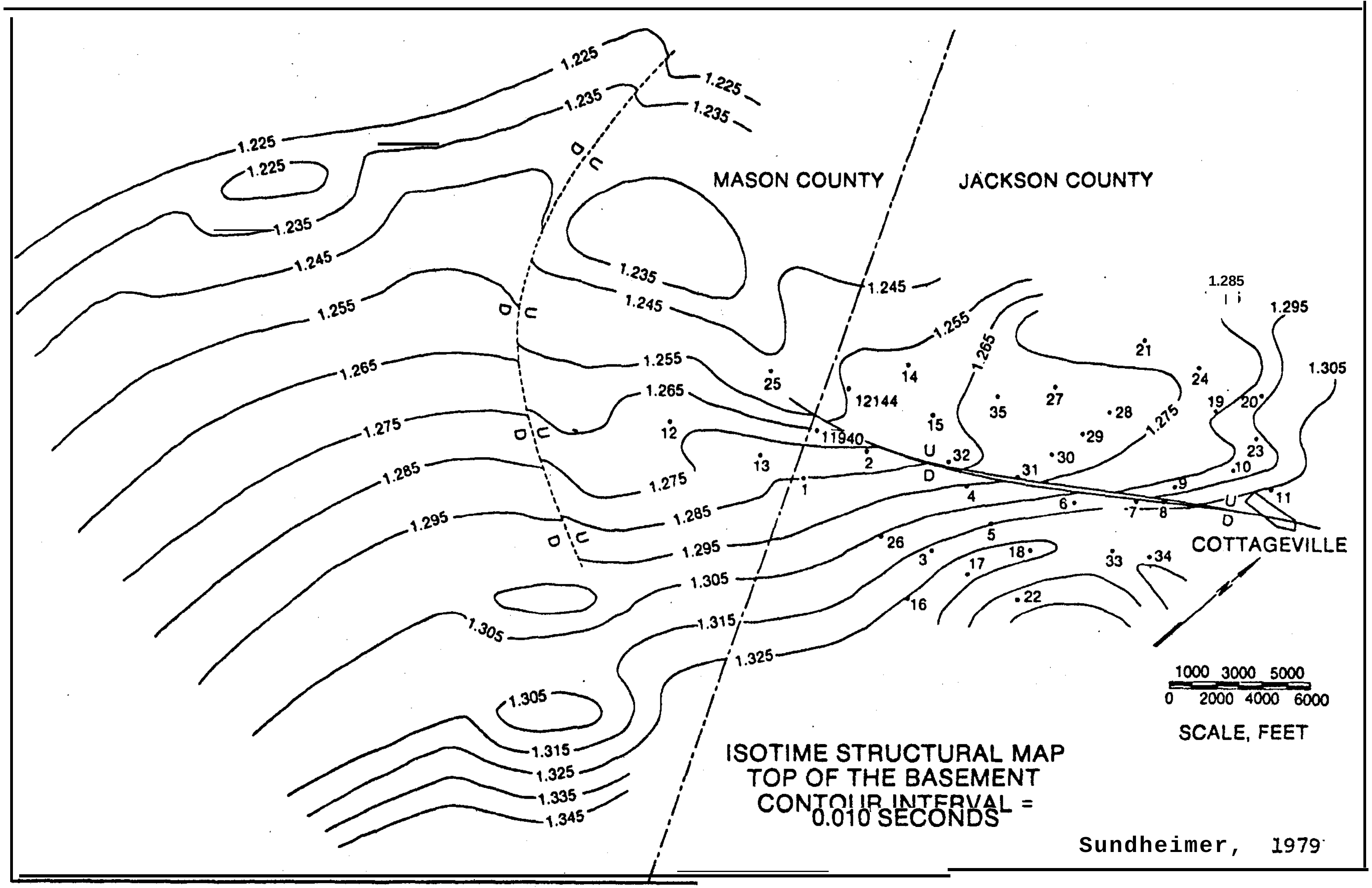
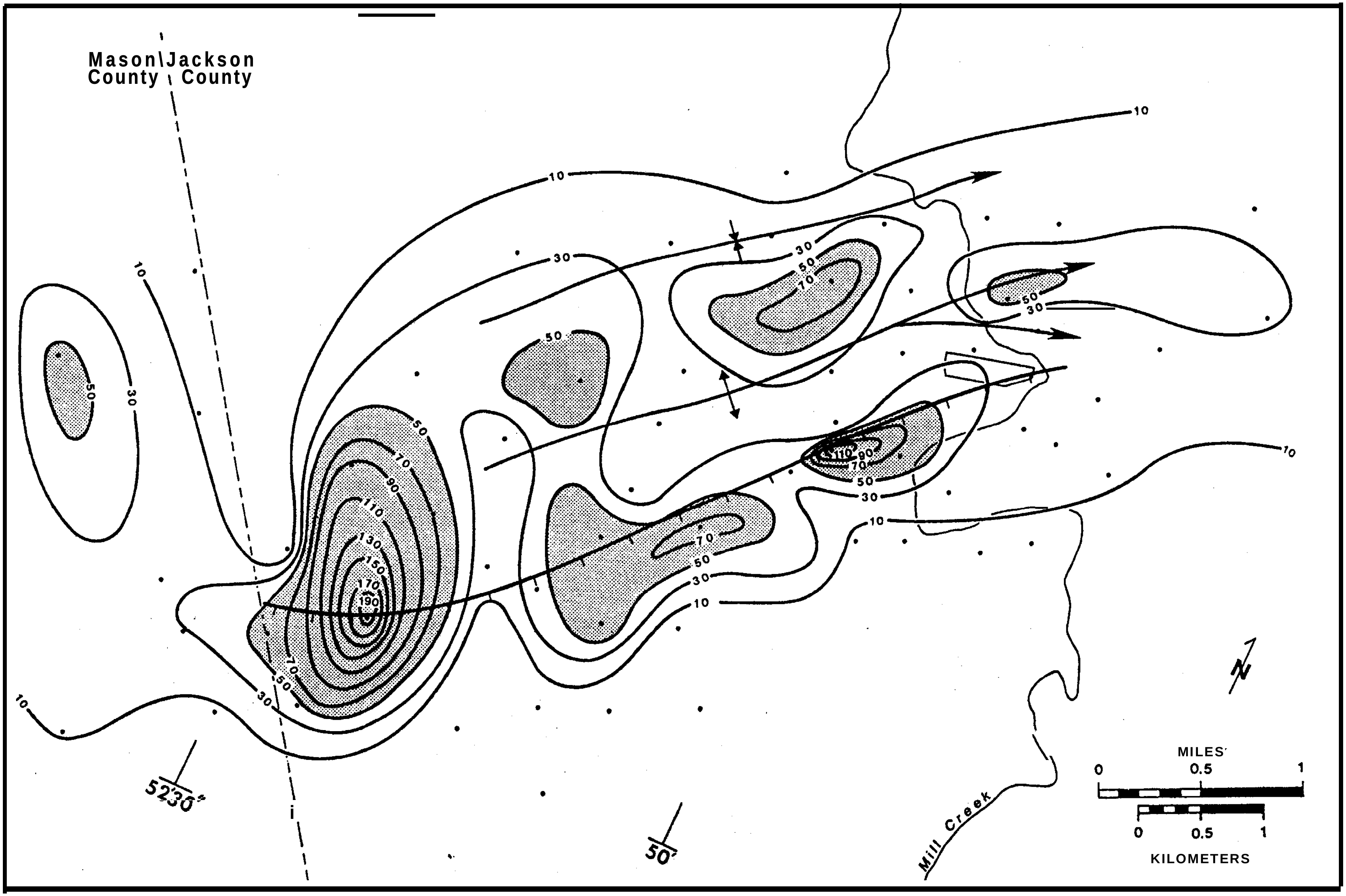
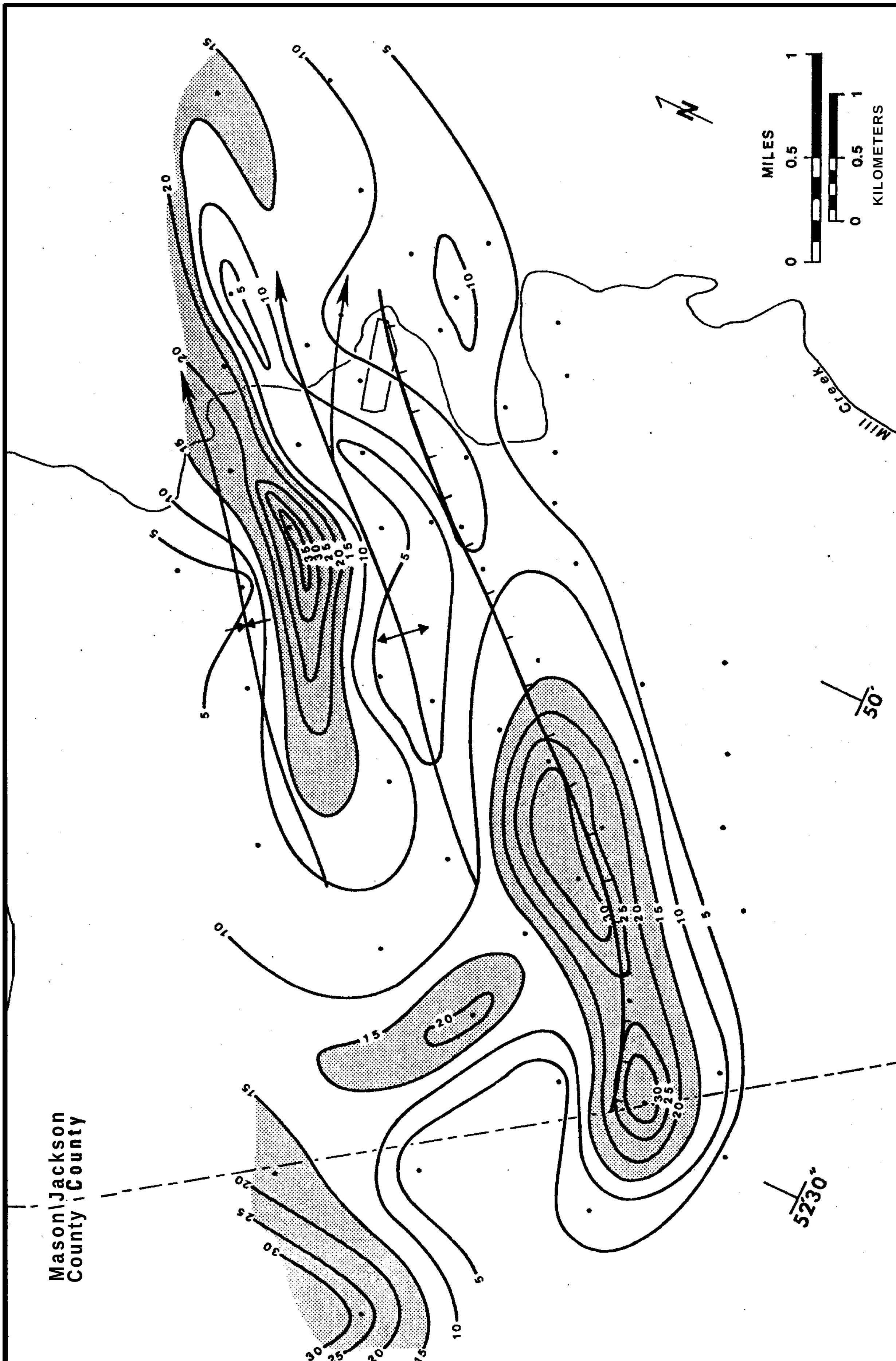


Figure 14. Isotime structural map top of the basement: Cottageville field



de Wys and Shumaker, 1978

Figure 15. Cottageville - isocontours of highest annual production. (1st or 2nd year production)



de Wys and Shumaker, 1978

Figure 16. Cottageville - isocontours of mean annual gas production

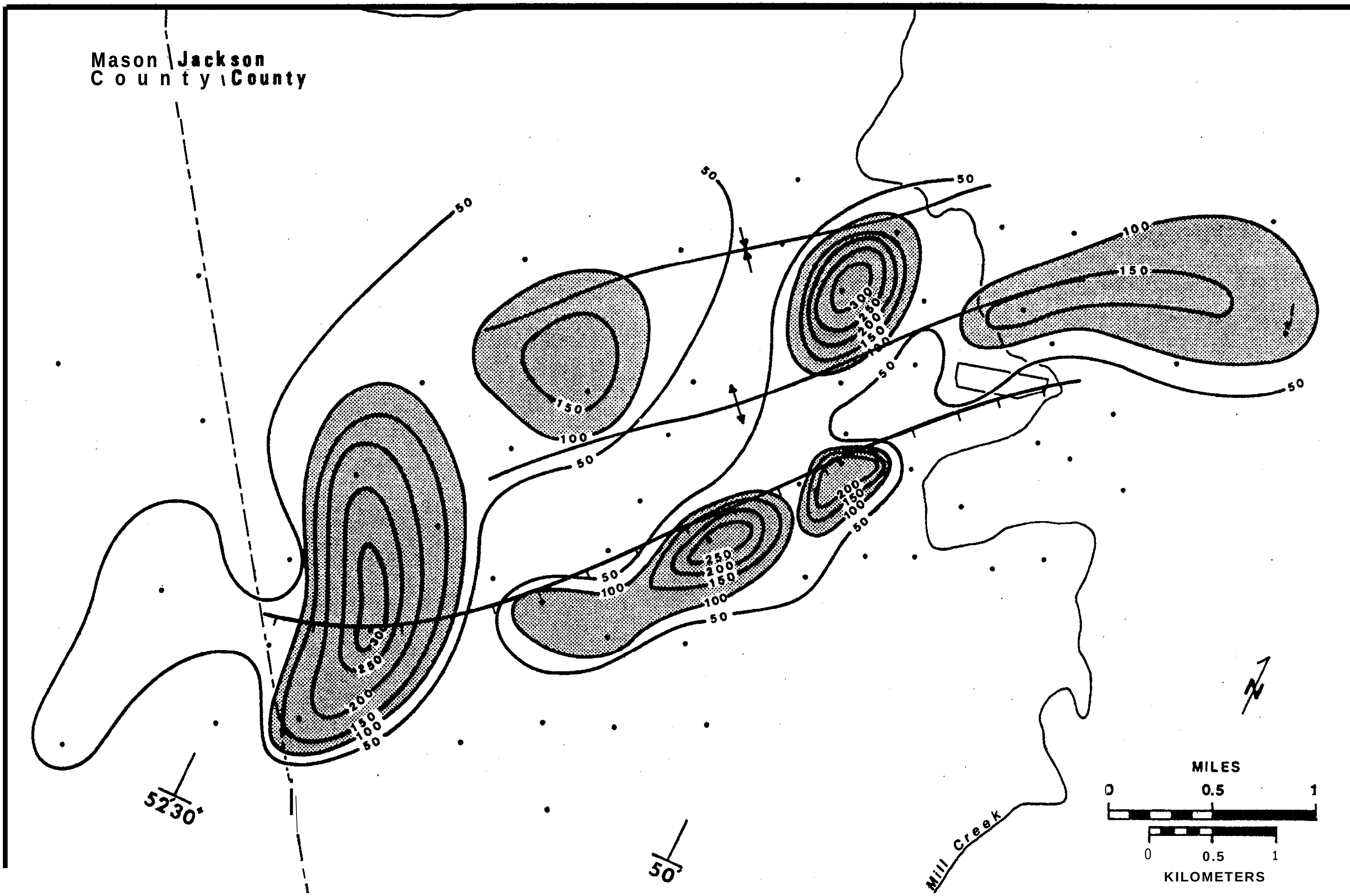


Figure 17. Cottageville - isocontours of first five years accumulated gas production - de Wys and Shumaker, 1978

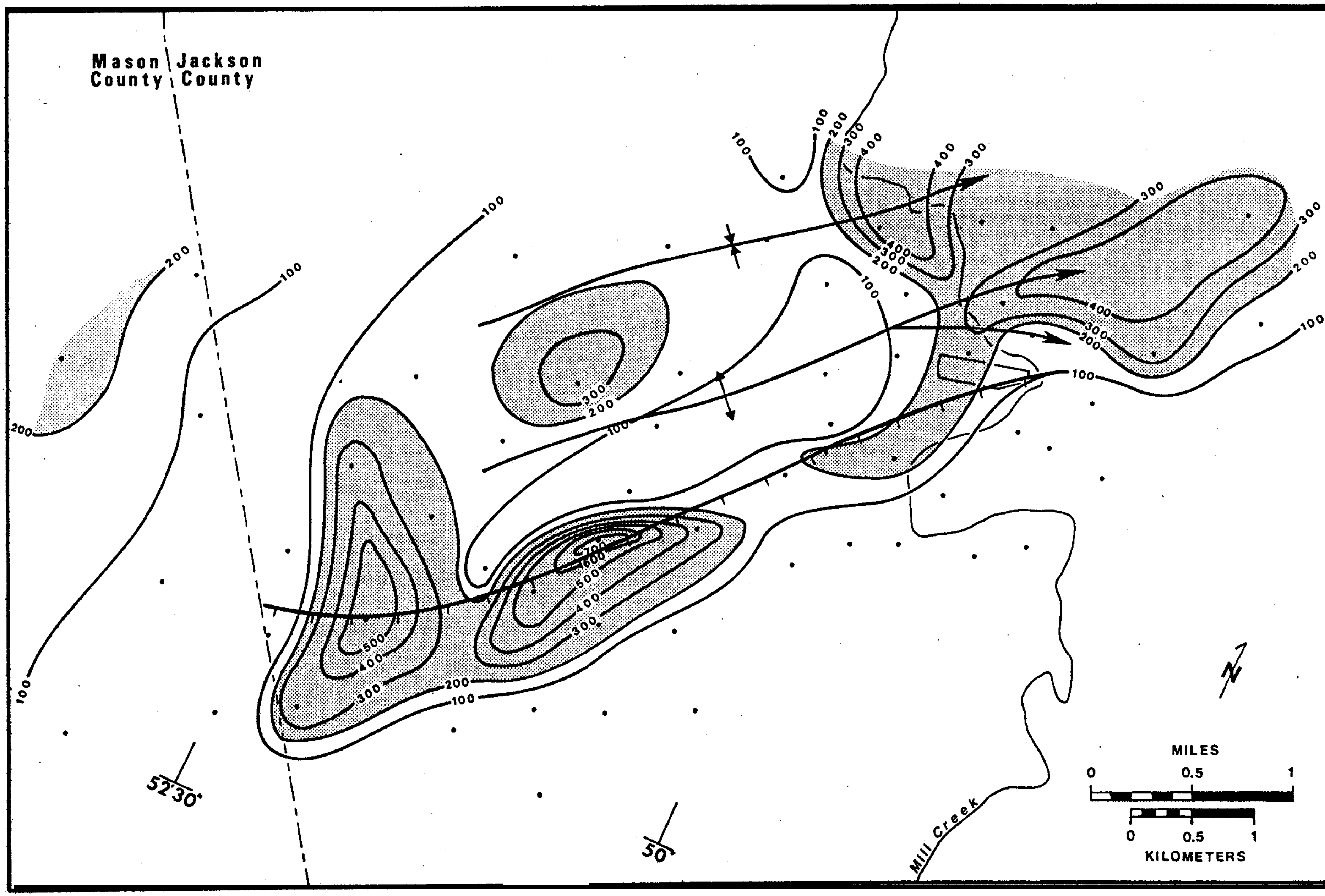


Figure 18. Cottageville - isocontours of total accumulated production de Wys and Shumaker, 1978

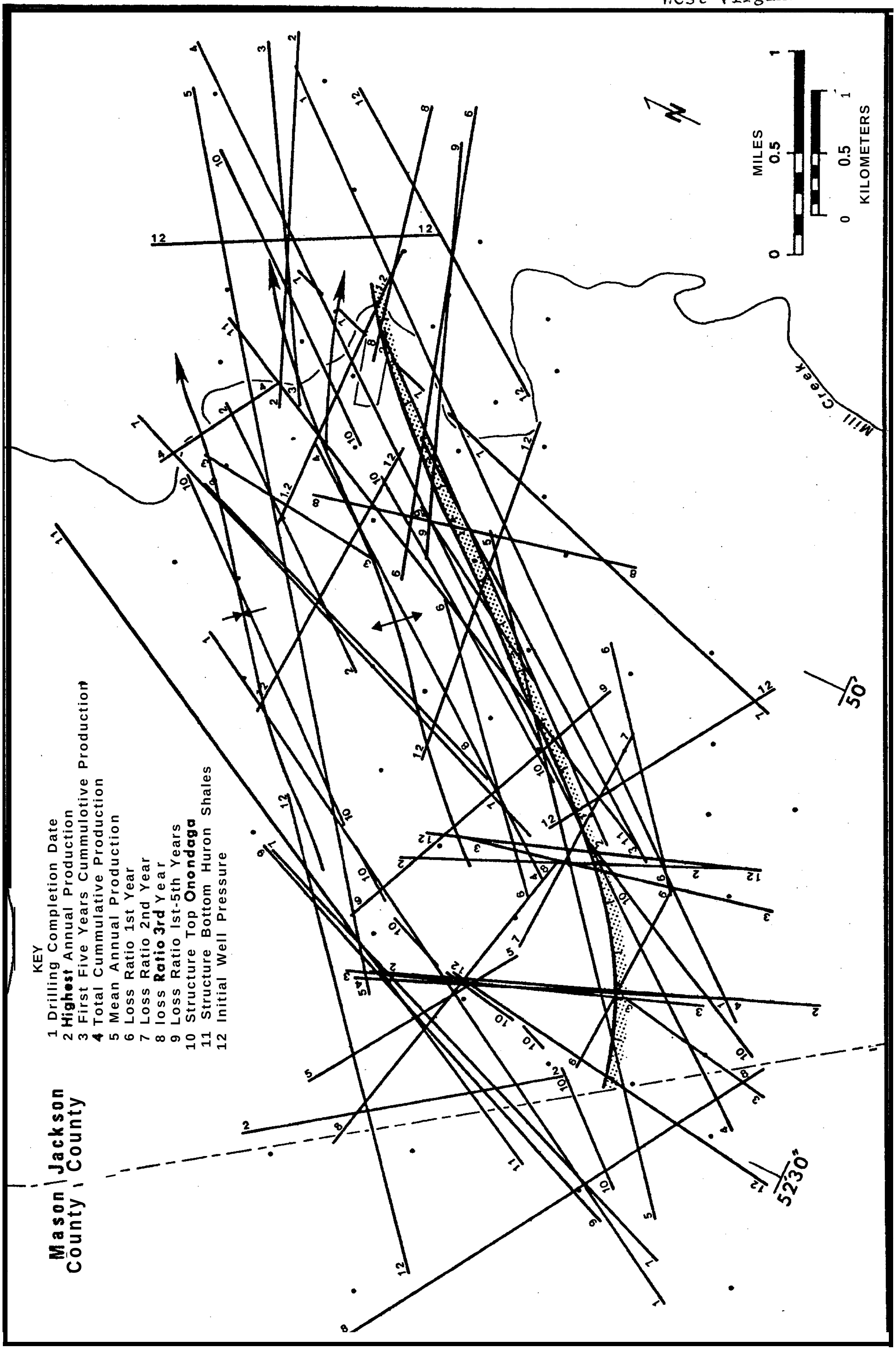


Figure 19. Cottageville - axial trends of contours from production maps de Wys and Shumaker, 1978

of the high productivity wells. At Cottageville such'wells are located along and above a proven basement fault. If one concludes that the Midway-Extra field is faulted on both flanks then the marked asymmetry of production is puzzling. This asymmetry may relate to Alleghenian stress being concentrated on the western flank of that structure to create anomalously fractured shale in the detached reservoir horizon along that trend. Clearly Midway-Extra and Cottageville document the importance of geologic structure and specifically, basement faulting, to high production from the shale. The productive asymmetry suggests an interplay with detached Alleghenian deformation along the margin of the pre-existing basement derived faults. It further suggests that the permeability in the detachment horizon, the porous fracture facies, is not a blanket permeability for this part of West Virginia. If it were, then production would be found on the'crest of structures. The interplay of basement and detached deformation has been suggested for this area based on other geologic data in an independent study (Shumaker, 1979).

Conclusions

There are a multitude of ways to develop fractures, and thereby potential fracture permeability; to mention a few: basement deformation, detached deformation, compaction, sedimentary diagenesis, overburden removal, etc. Based on analyses of producing shale gas fields in the Appalachian basin, it is concluded that basement growth faulting is the. most effective means of producing commercially effective porosity within West Virginia. The importance of this understanding and the application of these exploration guidelines to southwestern West Virginia are heightened by a substantiating observation made by Don Neal (1979) concerning the coincidence of higher initial open flows from shale gas wells located on the flanks of geologic structures from the adjacent area of southern West Virginia. We are presently extending our structural analysis into eastern Kentucky, and preliminary results suggest that linear highly productive trends within a more blanket-like production in eastern Kentucky are related to the interplay of basement faults and detachment deformation. Based on analysis of shale cores it is further concluded that the organic portions of the Devonian shale contain a porous fracture facies that forms the major reservoir horizon for shale gas production. Commercial production in the Appalachian basin coincides with a zone of limited tectonic transport at the terminus of more extensive movement found to the east. This commercial zone is characterized by inclined slickensided fractures and mineralized and open vertical joints. Marked asymmetry of production along the flanks of producing structures suggest that the interplay of horizontal transport at the margin of basement-derived faults is the area for maximum development of open fractures in the organic shales.

It is not suggested that the rationale developed thru analysis of the Appalachian basin is a unique solution for the location of fracture porosity in organic shales found in all foreland basins. However, it is a model that may have application to other geologically similar areas, and it therefore should be tested in those areas.

The application of the rationale to the interior basins of the continental United States which lack detached horizontal transport is open to question. It would appear, based on the results of this study, that the flanks of basement structures, particularly at intersecting basement fault trends, appear most prospective. However, if the shale acts as a seal in such areas, it also seems reasonable to presume that faults of small throw and/or monoclinal flexures are the most prospective structural features. If such flanking structural positions do hold higher potential, it is essential that well completion fracture treatments of limited size be designed to preserve that seal to limit entry of formation water from adjacent units. Chemically foreign water placed in the shale generally will severely damage the reservoir and invalidate any commercial success.

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