DOE/METC-121

EVALUATION OF DEVONIAN SHALE POTENTIAL IN EASTERN KENTUCKY/TENNESSEE

Morgantown
United States Department of Energy
Technology
Center

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OF
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IN
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Prepared for publication by:

TETRA TECH, INC.
Columbus, Ohio
under U.S. Department of Energy
Contract Number DE-AC21-79MC10389

NOTICE

PREFACE

This report is a geologic screening effort to evaluate areas within eastern Kentucky and Tennessee that contain sufficient geologic and geochemical characteristics to warrant industry exploration activity. The results are an integration of contractor report data, maps, and logs generated in the Eastern Gas Shales Project. The areas outlined as favorable in this report are those in which the likelihood of encountering gas is greater than elsewhere. Within these areas, local geologic and geochemical factors must be considered as they can dictate success or failure. It is hoped that this information will guide industry activity to the areas of high shale gas potential.

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Eastern Gas Shales

ACKNOWLEDGEMENTS

Participants in the accumulation, synthesis, and interpretation of data for the eastern Kentucky/Tennessee screening report included:

Tetra Tech, Inc.

The assistance and cooperation received from representatives of all Federal, State and local agencies is gratefully acknowledged.

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INTRODUCTION

Dark, organic-rich Devonian shales--distributed across more than 10 states from Illinois to Pennsylvania and Michigan to Mississippi, in the contiguous Appalachian, Illinois, and Michigan basins--represent an important natural gas resource. A recent authoritative estimate indicates in-place reserves of gas in the Appalachian basin, entrapped in the matrix and fracture systems of the shale, at 277 to 900 trillion cubic feet (Tcf). Of this, about 20 Tcf of gas are expected to be recoverable using presently available methods (Pulle and Seskus, 1980).

Although geologic and engineering evidence indicates that the volume of natural gas in the eastern Devonian shales is enormous, little of the gas can be recovered by conventional methods. Production to date has been limited to areas where fracturing is present and geochemical parameters are favorable. As a result, although production of gas from Devonian black shales began in 1821 with the drilling of a well near Fredonia, New York, only about 2.5 Tcf of gas have been produced; most (2 Tcf) came from the Big Sandy gas field in eastern Kentucky (Hunter and Young, 1953). Additional production of gas from these eastern gas shales depends on identifying favorable areas for exploration and developing new stimulation techniques that will enhance the rate of gas recovery.

To evaluate the potential of the Devonian shale as a source of natural gas, the U.S. Department of Energy (DOE) has undertaken the Eastern Gas Shales Project (EGSP). The EGSP is designed not only to identify the resource, but also to test improved methods of inducing permeability to facilitate gas drainage, collection, and production. The ultimate goal of this project is to increase the production of gas from the eastern shales through advanced exploration and exploitation techniques.

The purpose of this report is to inform the general public and interested oil and gas operators about EGSP results as they pertain to the Devonian gas shales of the Appalachian basin in eastern Kentucky and Tennessee. Geologic data and interpretations are summarized, and areas where the accumulation of gas may be large enough to justify commercial production are outlined.

Locations of Chattanooga Shale gas-producing areas are on the index map (plate 1), which was compiled using information taken from McFarlan (1950) and Wilson and Sutton (1976). Other useful sources for reporting current activity in shale exploration were recent issues of Petroleum Information (1980 a and b).

Publications by Provo and others (1977 and 1978) describe subsurface subdivisions of the Chattanooga Shale; these subdivisions were based largely on gamma-ray curve signatures from well logs. Dillman in Blackburn (1980) described the extent and thickness variations of the Provo subdivisions. Ettensohn, et al. (1979) and Wilson and Ettensohn (1976 and 1979) used gamma-ray log curves to make semiregional correlations within eastern Kentucky. Roen (1980) used the same type curves to make long-range correlations with classic Devonian units in New York.

Semiregional structural interpretations were guided by works of McFarlan (1950), Dever and others (1977), and Fulton (1979). Stress and fracture pattern analyses have been made by Overby (1976), Komar (1978), and McKetta (1980).

General geochemical presentations are based on information provided in articles by Dow (1977) and Harwood (1977) and in texts by Tissot and Welte (1978) and Hunt (1979). Quarterly status reports by Mound Facility plus work by Streib (1980) provided area-specific information.

Because the data presented in this report are generalized and not suitable for evaluation of specific sites for exploration, the reader should consult the various reports cited for more detail and discussion of the data, concepts, and interpretations presented.

SUMMARY AND CONCLUSIONS

Organic carbon contents from fairly widely distributed data points throughout eastern Kentucky/Tennessee indicate sufficient richness to encourage exploration for gas. On the other hand, indicators of basin maturity, such as thermal alteration indices of 1+ to 2 and vitrinite reflectance of less than 0.6, suggest thermal immaturity (which, in some respects, contradicts widespread existing dry gas production). Overall, given proved production and established organic richness, additional drilling for gas in Devonian shales should be undertaken, particularly along suspected fracture zones associated with structural anomalies. The most favorable areas are located where adequate thicknesses of black shale and interbedded greenish-gray shales occur along with fractures.

GEOLOGIC SETTING

Much of the eastern Kentucky/Tennessee portion of the Appalachian basin lies within the maturely dissected Allegheny or Cumberland Plateau capped principally by Pennsylvanian strata. To the northwest, the Chattanooga Shale offlaps the Lexington Dome in a visible outcrop, which physiographically forms the boundary between the Bluegrass region and the Appalachian Plateau (Swager, 1978, and Haney, 1979). In Tennessee, except for a small area around Flynn Creek in southern Jackson County, the offlap along the southeast flank of the Nashville Dome is concealed beneath Mississippian strata (Hardeman, 1966, and Hershey, 1970). Uppermost units of the Devonian shale extend westward across the Cumberland saddle between the two domes where patchy outcrops occur in central-southern Kentucky.

In southeasternmost Kentucky from Bell to Pike Counties, the Chattanooga Shale is exposed at the base of the Pine Mountain Fault. East of the Pine Mountain/Emery River Fault System, the Chattanooga Shale appears to thicken to the east as it extends into the Valley and Ridge Province featured by folded and thrust-faulted strata. The easternmost counties of Tennessee lie within the Blue Ridge Province where rocks exposed at the surface have undergone metamorphism, though there are windows in the metamorphosed rock which reveal relatively undisturbed strata.

STRATIGRAPHY

The name Chattanooga has been applied to the Upper Devonian shale sequence. Other formation names, adopted before the term Chattanooga gained wide acceptance, are in use in neighboring states (Conant and Swanson, 1961). The variation in nomenclature between areas is best shown by figure 1, from Provo, et al. (1980).

Except where locally absent in south central Tennessee, the Chattanooga or Devonian shale sequence characteristically is composed of black and greenish-gray shales. The greenish-gray shales generally are more porous than the black shales, which establishes an inherent reservoir-source bed relationship. (Fractured black shales alone, however, may serve as both reservoir and source beds.) The black shales appear to have relatively greater density of fractures than the greenish-gray shales (Potter, et al., 1980), thereby allowing gas to migrate from the black source-bed shales into the greenish-gray reservoir shales. While the relationship between black shales and greenish-gray shales is important, the focus of this report is principally on the distribution of black shale.

The gamma-ray log, commonly run in exploratory wells in the Appalachian area, indicates zones of high natural radioactivity, which is considered indicative of organic-rich hydrocarbon source beds. Based on sample color, these organic-rich source beds usually are referred to as black shales, in contrast to the low radioactive, greenish-gray shales with which the black shales are interbedded. Because of the sharp contrasts on gamma logs, the stratigrapher can easily identify and correlate individual Devonian black shales.

The Chattanooga or Ohio Shale is considered Upper Devonian in age. However, in parts of eastern Tennessee, eastern Kentucky, and western Virginia, the Chattanooga contains beds of Kinderhook age, Early Mississippian in the upper part, making it both Devonian and Mississippian in this area. Favorable Middle Devonian black shales do not extend as far west as eastern Kentucky. They do, however, probably occur in the less studied, complexly distorted parts of eastern Tennessee east of the Emery River Fault System. Figure 2 shows an unnamed radioactive unit, probably a Middle Devonian black shale, at the base of the regional profile. Figures 3, 4, and 5 show the areal extent of Upper Devonian black shale targets and how eastern Kentucky/Tennessee fits into the overall Appalachian pattern.

Devonian black shales in eastern Tennessee are highly radioactive on gamma-ray logs, but aggregate thicknesses as low as 25 to 50 feet between the Nashville Dome and the Emery River Fault System suggest a meager drilling target. Plate 2 shows a significant aggregate thickening of Devonian black shales east of the Pine Mountain/Emery River system. In this complexly distorted region, the black shales should be amply fractured, thus enhancing production potential. However, Zafar and Wilson (1978) have pointed out that black shales in samples taken near Big Stone Gap, Wise County, Virginia, show a southeastward decrease in radioactivity without a corresponding diminution in black color. (The decrease may relate to changing proportions of marine versus terrestrial kerogens; hydrocarbon producing potential may remain undiminished.)

Figure 6 is a detailed stratigraphic chart by Provo, et al. (1977). Units of the Chattanooga Shale, clearly identifiable in outcrop, often can be correlated with counterpart gamma-ray log units in the subsurface so that widespread correlations are possible. (Figure 6 incorporates Upper Devonian units of the classic New York section.) The shale units, in stratigraphically descending order, are the Cleveland, Three Lick, upper Huron,

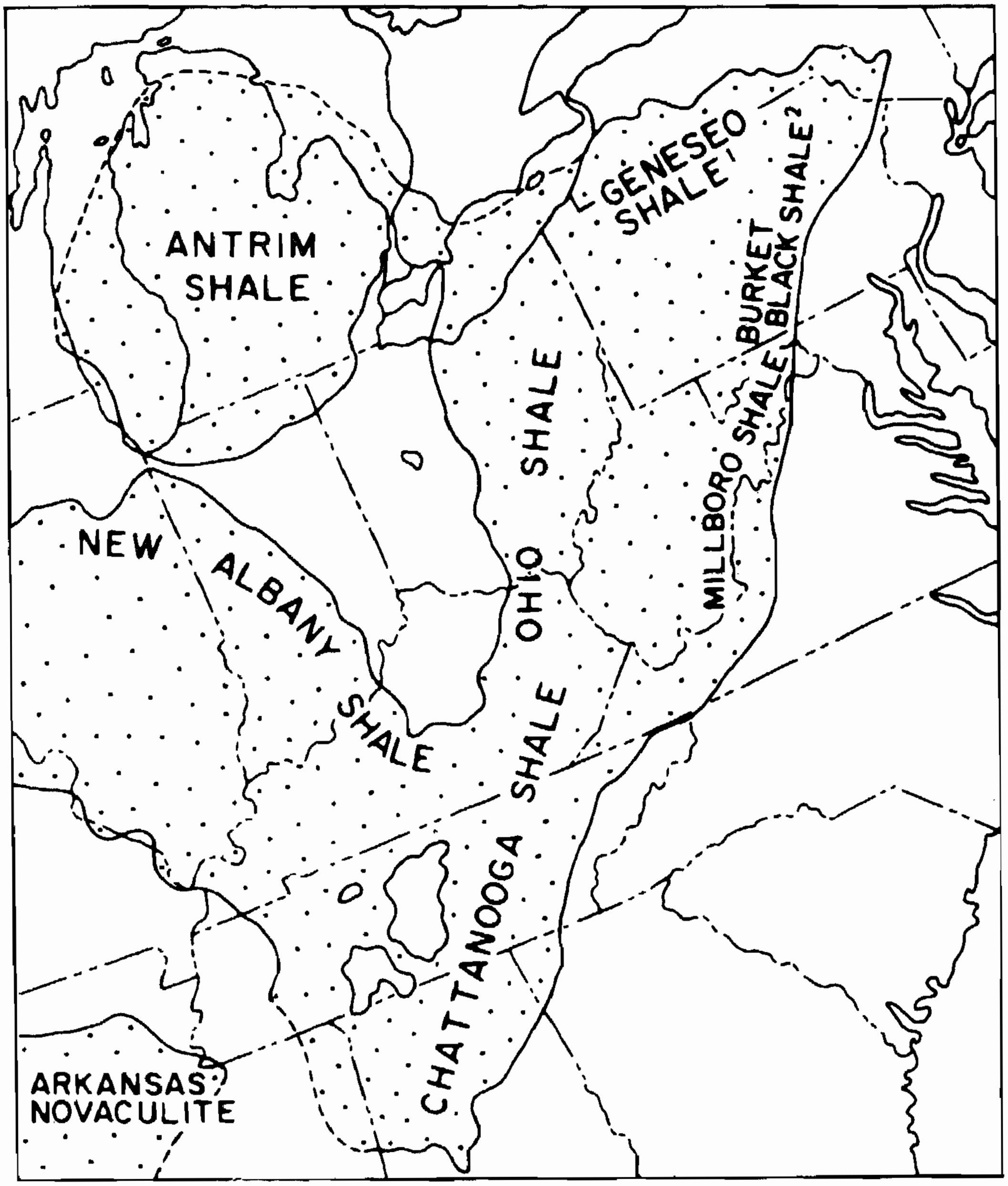


Figure 1. Map showing areal variations in formation name for Devonian shale. After Provo, et al. (1978).

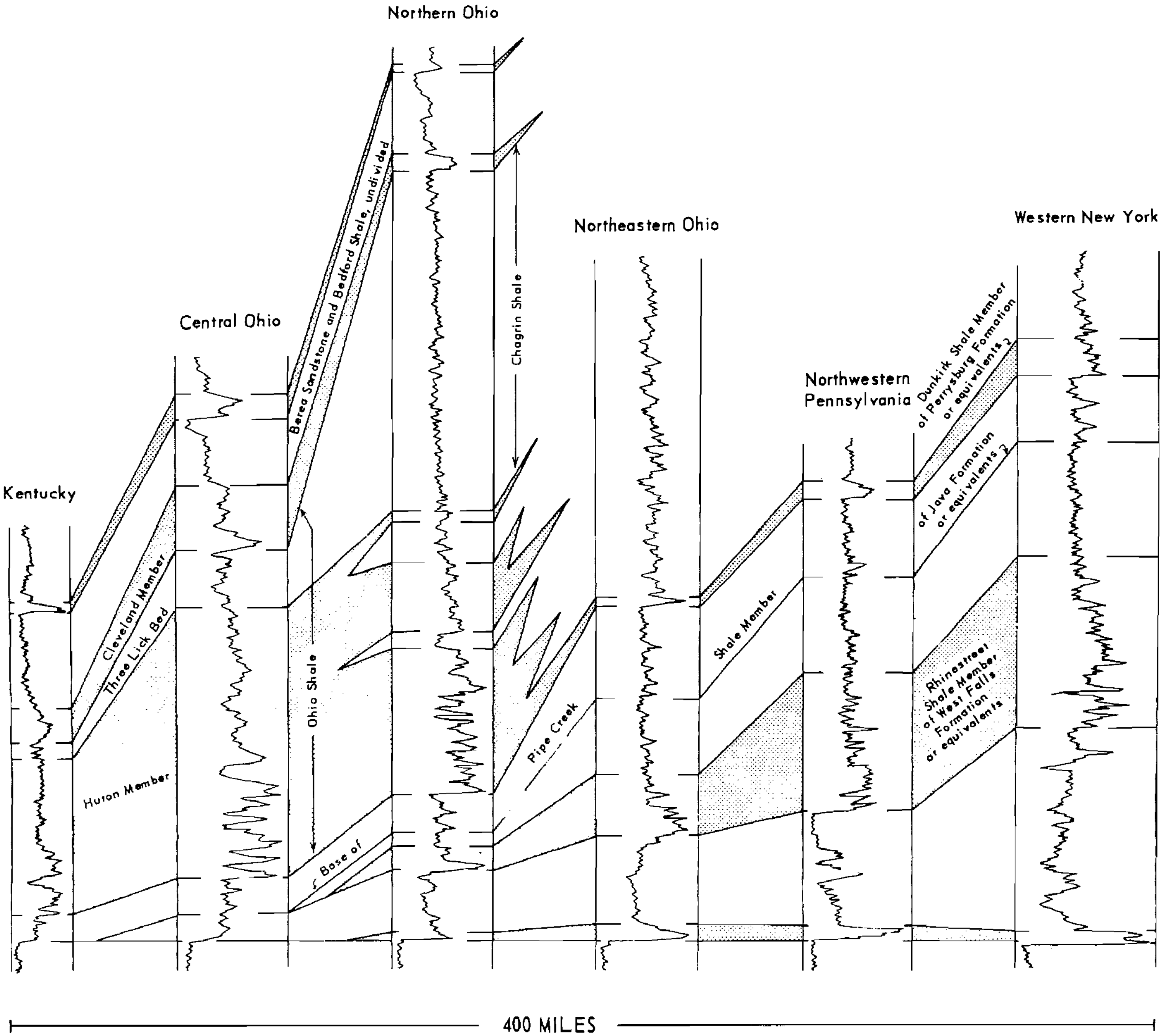


Figure 2. Regional Upper Devonian correlations based upon gamma-ray signatures, Kentucky to New York. After Roen (1980).

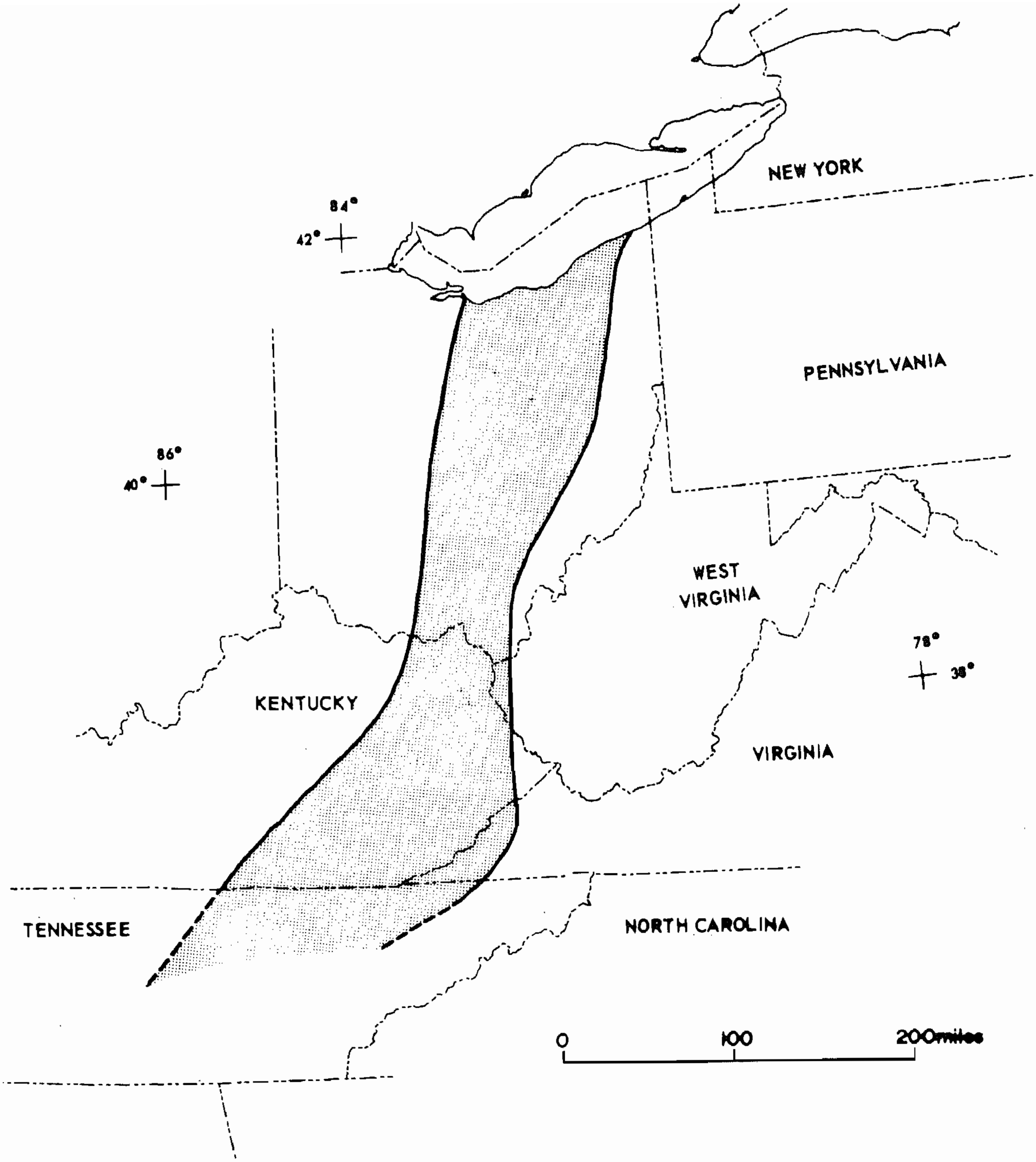


Figure 3. Map showing areal extent of the Cleveland Shale (Unit I) and its equivalents. After Roen (1980).

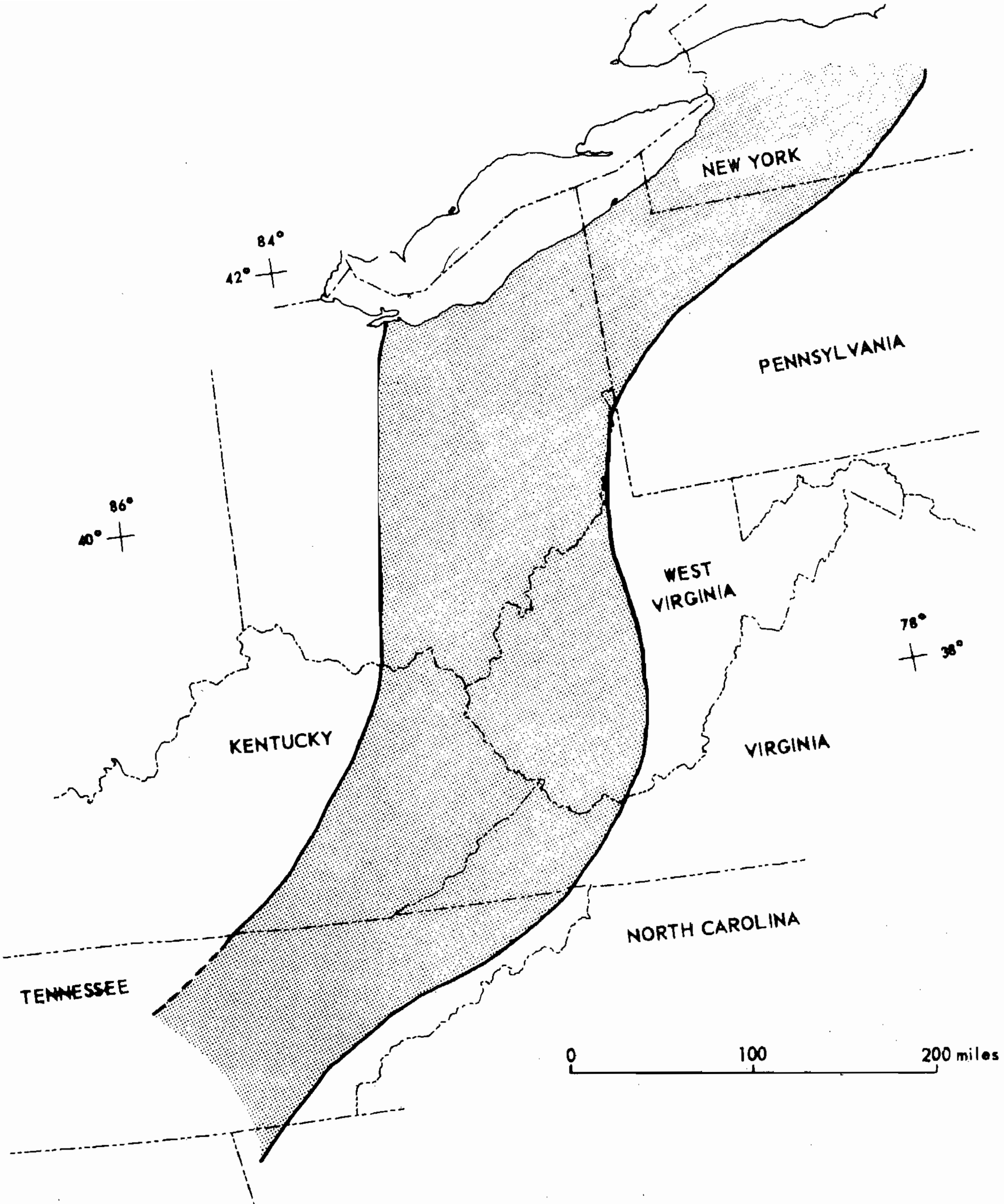


Figure 4. Map showing areal extent of the Dunkirk Shale (Unit 5) and its equivalents. After Roen (1980).

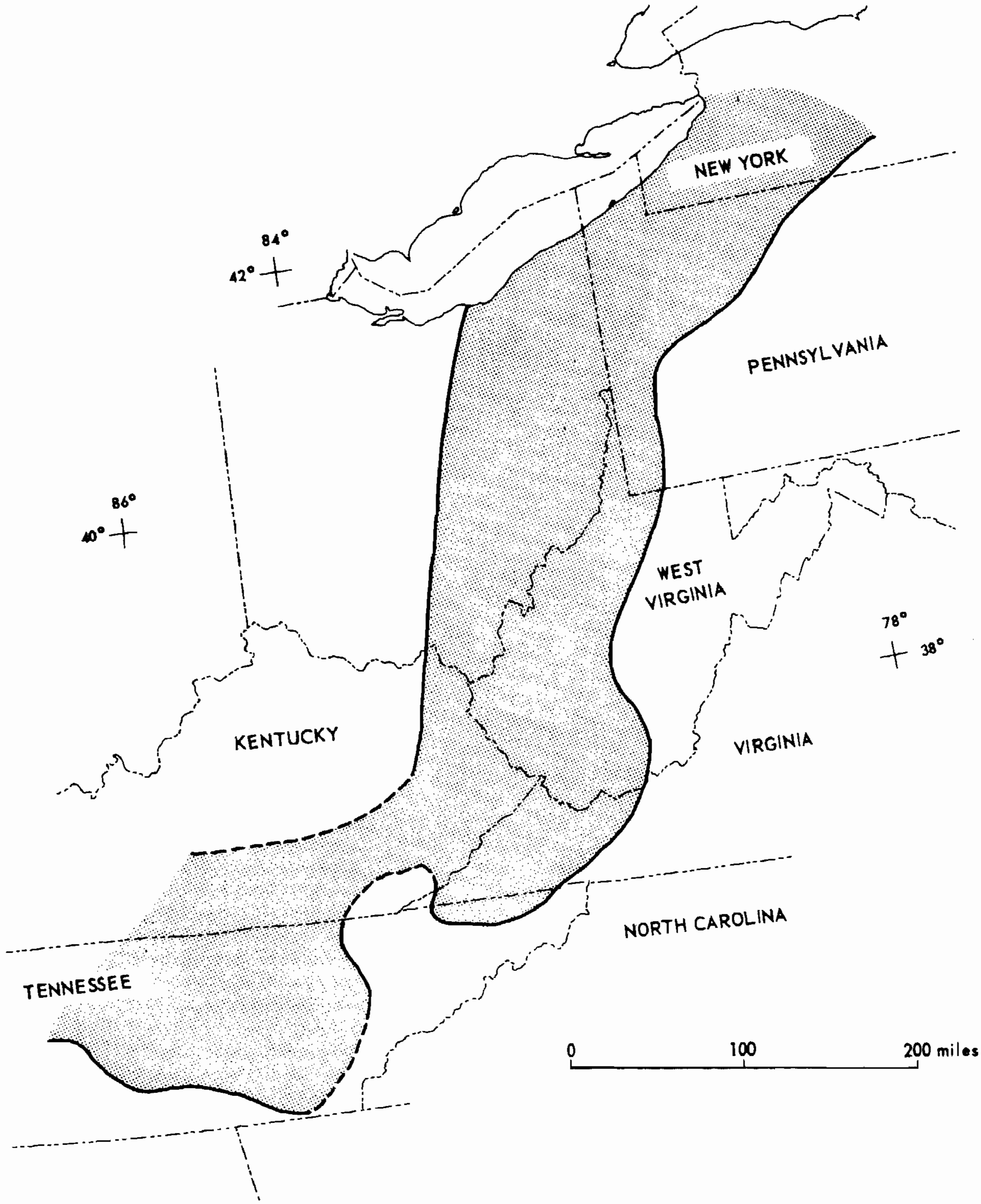


Figure 5. Map showing areal extent of the Rhinestreet Shale (Unit 7) and its equivalents. After Roen (1980).

SAMPLE LOG-STRATIGRAPHIC CHART

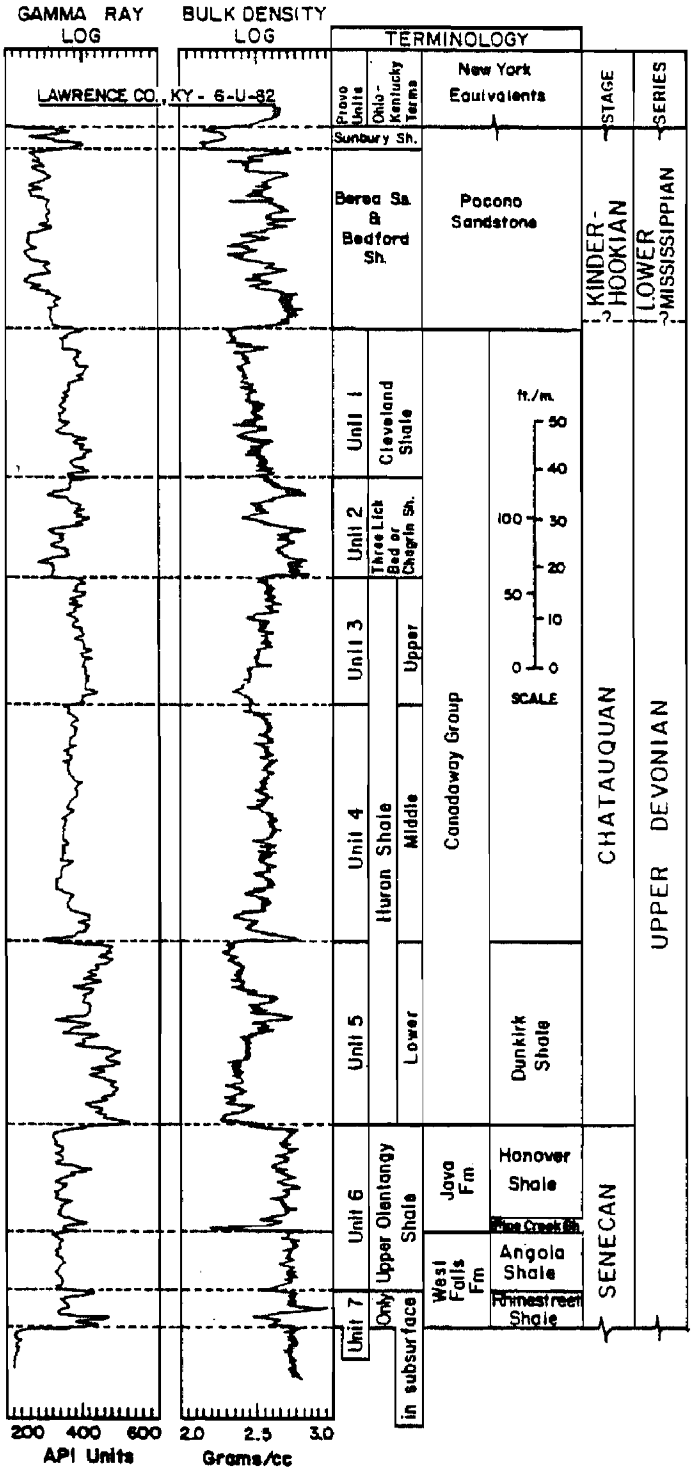


Figure 6. Chattanooga (Ohio) Shale stratigraphic chart. After Provo, et al. (1977).

middle Huron, lower Huron, Olentangy, and Rhinestreet Shales. The Cleveland, upper Huron, lower Huron, and Rhinestreet are members showing comparatively strong radioactive characteristics.

Cleveland Shale

The Cleveland Shale, Provo's Unit 1, along the Bell and Knox County boundary, undergoes an apparent lateral gradation from the Gassaway Member of the Chattanooga Shale in Tennessee (Provo, et al., 1977; Conant and Swanson, 1961). The Cleveland grades from organic and black shales with phosphate nodules in west-central Kentucky to greenish-gray shales in eastern Kentucky.

The Cleveland ranges from 40 feet thick in Lewis County in north-central Kentucky to 10 feet thick in Cumberland County in south-central Kentucky. (All descriptions of unit thicknesses in this report are taken from Dillman and Ettensohn, 1980b.) In various parts of Kentucky, the Cleveland is radioactive. An eastward thickening in the Cleveland accompanies a loss in radioactive character; also, it becomes increasingly difficult to distinguish upper and lower boundaries. Eastward, it is possible that the Cleveland grades into the greenish-gray shales of the Chagrin.

Three Lick Member

The Three Lick Member, Provo's Unit 2, characterized by its greenish-gray color, is a distinctive member lying directly beneath the Cleveland Shale. Dillman in Blackburn (1980) reports a maximum thickness of 136 feet in southwestern Martin County and a minimum of 3 feet in Cumberland County. In the central outcrop area, thicknesses range from 3 feet in Cumberland County to 16 feet in Lewis County. To the east, facies change and the gamma-ray signature is lost (Provo, et al., 1977). Nowhere does the Three Lick exhibit any radioactivity. Several descriptions of the Three Lick Member have been published. Some publications include descriptions of remaining units of the Upper Devonian Chattanooga Shale. See Provo, et al. (1977 and 1978); Ettensohn, et al. (1979); Blackburn (1980); and Dillman and Ettensohn (1980a).

Upper Huron Shale

Parts of the upper Huron, Provo's Unit 3, have black shale facies and are radioactive. Unit 3 ranges from 9 feet thick in Clinton County in south-central Kentucky to 134 feet thick in Pike County in the east. The shale thickens rapidly toward the east and grades into the greenish-gray Chagrin. With the diminution of black color comes the loss of gamma-ray signature, which makes interpreting lower and upper member limits difficult.

Middle Huron Shale

The middle Huron, Provo's Unit 4, is a nondescript greenish-gray shale member attaining a maximum thickness of 465 feet in southeastern Pike County. Along the outcrop belt, it ranges from 2 feet thick in Cumberland County to 65 feet thick in Lewis County. Nowhere is the middle Huron radioactive. Unit 4 is the lowest stratigraphic unit that extends across the Cincinnati Arch (Dillman and Ettensohn, 1980b).

This member is significant because of the presence of the fossil algae Foerstia, which had a brief but flourishing life only in middle Huron time (Schopf and Schwietering, 1970). The algae marks a time-stratigraphic zone that has been mapped throughout the basin. Placement of Foerstia at a particular depth in a well bore could be indexed to an event on a gamma-log curve, which might be useful since sharp, distinctive gamma curve anomalies themselves are uncommon in the middle Huron portion of the Upper Devonian Shale.

Lower Huron Shale

The lower Huron, Provo's Unit 5, a black shale facies extending over a large area, is distinguished by its high radioactive signature on gamma-ray curves, which allows easy mapping. In the northern outcrop belt, Unit 5 is 54 feet thick; in the southern outcrop belt, it is absent. Maximum thickness exceeds 251 feet in southeastern Pike County. The relative thickness of the lower Huron, compared with that of overlying units, suggests that, during its depositional cycle, the basin was subsiding more rapidly and had a greater influx of fill material (Provo, et al., 1977). As with other Devonian black shale units, the interspersed lower Huron unit may reflect an interlude of relatively greater distal crustal downbuckling. To the east, a correlative interlude of proximal Catskill clastic overloading might have occurred (Murany, 1980).

Olentangy Shale

The Olentangy Shale, Provo's Unit 6, is greenish gray and shows no radioactivity. In Pike County, Kentucky, Unit 6 is more than 325 feet thick and perhaps 20 feet thick in Lewis County some 100 miles to the northwest. The thick Olentangy is composed of the Angola Shale member of the West Falls Formation and the overlying Java Formation. The Pipe Creek Shale of the Java Formation, where it can be identified, differentiates the Java from the Angola. Since the Pipe Creek Shale can be correlated for many miles, it serves as a useful stratigraphic marker within the Appalachian basin.

Rhinestreet Shale

The Rhinestreet in Kentucky and Tennessee, Provo's Unit 7, is the lowest and least widespread member of the Devonian shale system. Like the overlying Olentangy, it has a fairly characteristic gamma-ray curve and, therefore, can be mapped over the approximately 3,600 square miles where it is present in the easternmost part of Kentucky. In eastern Kentucky, the upper part of the Rhinestreet is radioactive, as indicated on wireline logs. In Martin and Pike Counties, the member is 150 feet thick.

Correlations

As shown in figure 6, the radioactive Pipe Creek Shale has a distinct gamma-ray signature. Because of this, the Pipe Creek can be locally useful in tracking the pre-Chattanooga facies. See figure 7.

The Three Lick Member, Provo's Unit 2, correlates with the middle unit of the Gassaway Member of the Chattanooga Shale in Tennessee and with the lower part of the Camp Run Member of the New Albany Shale in north central Kentucky and southern

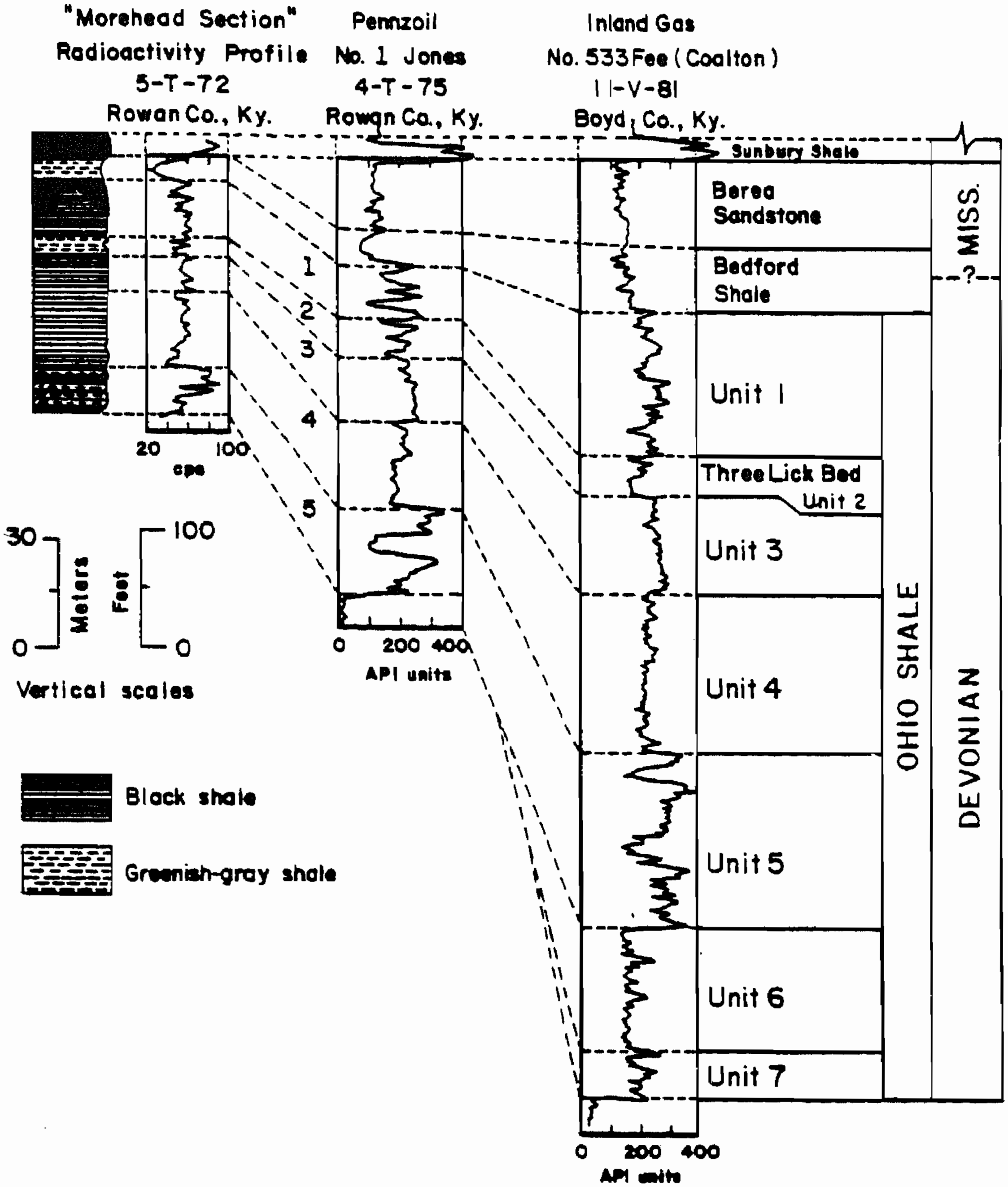


Figure 7. Cross section showing basal westward truncation of Chattanooga (Ohio) Shale in eastern Kentucky. After Dillman in Blackburn (1980).

Indiana. See Conant and Swanson (1961); Lineback (1968); and Provo, et al. (1978). Also, the Three Lick is considered equivalent to parts of the Chagrin Member of the Ohio Shale (Swager, 1978).

STRUCTURE

The study area is one where major structural trends intersect. The Rome trough and related parallel features appear related to the transcontinental 38th parallel lineament as shown in figure 8 (Heyl, 1972). The Lexington fault system appears to overlie the north-south boundary of the Grenville facies in basement rocks (fig. 9).

A north-south, probably basement-related, hinge line extends from Lewis County to Bell County (plate 1) (Dillman and Ettensohn, 1980a, p. 32). Another north-south feature, a major strike slip fault extending through Martin County (fig. 10), has been described by Lee (1980). Also, the Pine Mountain-Emery River Thrust Fault complex falls within the study area.

Interestingly, the study area is marked by a conspicuously high amplitude anomaly on a satellite-derived bulk magnetization map of the United States (fig. 11), though this remains unevaluated in this report.

In eastern Tennessee and, more particularly, eastern Kentucky, regional southeast dip off the foreland flank of the Appalachian basin is interrupted by a number of regional and semiregional structural anomalies. Productive capacity of the Devonian Shale appears to be related to relatively localized fracture permeability. Since fracturing in the shale is at least partly related to emplacement and movement of structural features, the regional and semiregional anomalies are important. Time of emplacement and movement also are important, particularly post-Devonian activity.

Waverly Arch

The Waverly Arch extends from northern Ohio into northeastern Kentucky. The arch appears to have been either a low relief feature or an axis of resistance to subsidence as early as Cambrian and Ordovician time (Dever, et al., 1977, and Woollard and Joesting, 1964). The arch generally was the site of renewed uplift in later Paleozoic time beginning as early as lower Mississippian time (Dever, et al., 1977, and Dohm, 1963).

Plate 1 shows two segments of the Waverly Arch offset by the Kentucky River Fault System. The northern of the two segments appears to have undergone relatively greater uplift in Carboniferous time (Dever, et al., 1977). Because of this, a greater degree of fracturing in the Devonian Shale might be expected in the northern block, accompanied by correspondingly better prospects for hydrocarbon production.

Paint Creek Uplift

Movement along the Paint Creek Uplift began in Devonian time and increased during Mississippian, Pennsylvanian, post-Pennsylvanian, and Cretaceous time (Hudnall and Browning, 1924 and 1949). The uplift is a north-south trending structure, with about 250

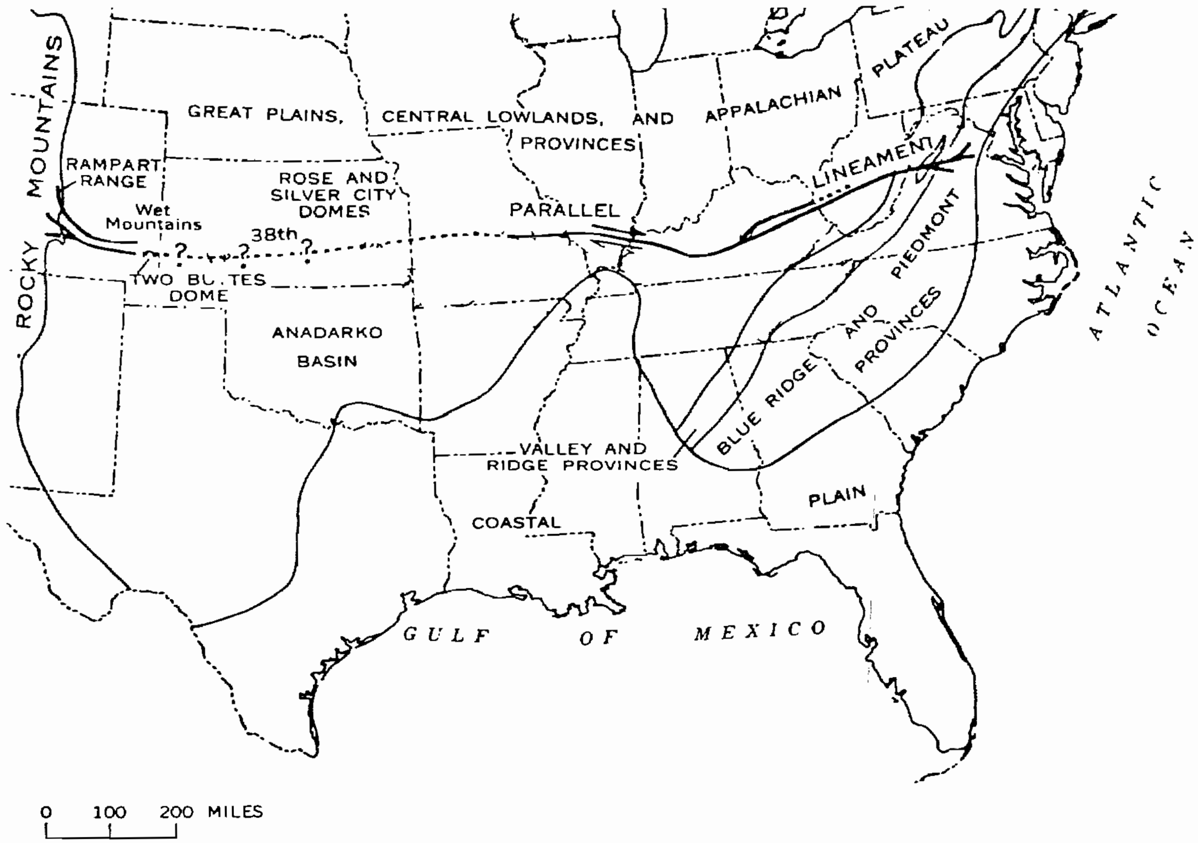


Figure 8. Location of Kentucky in relation to 38th parallel lineament. After Heyl (1972).

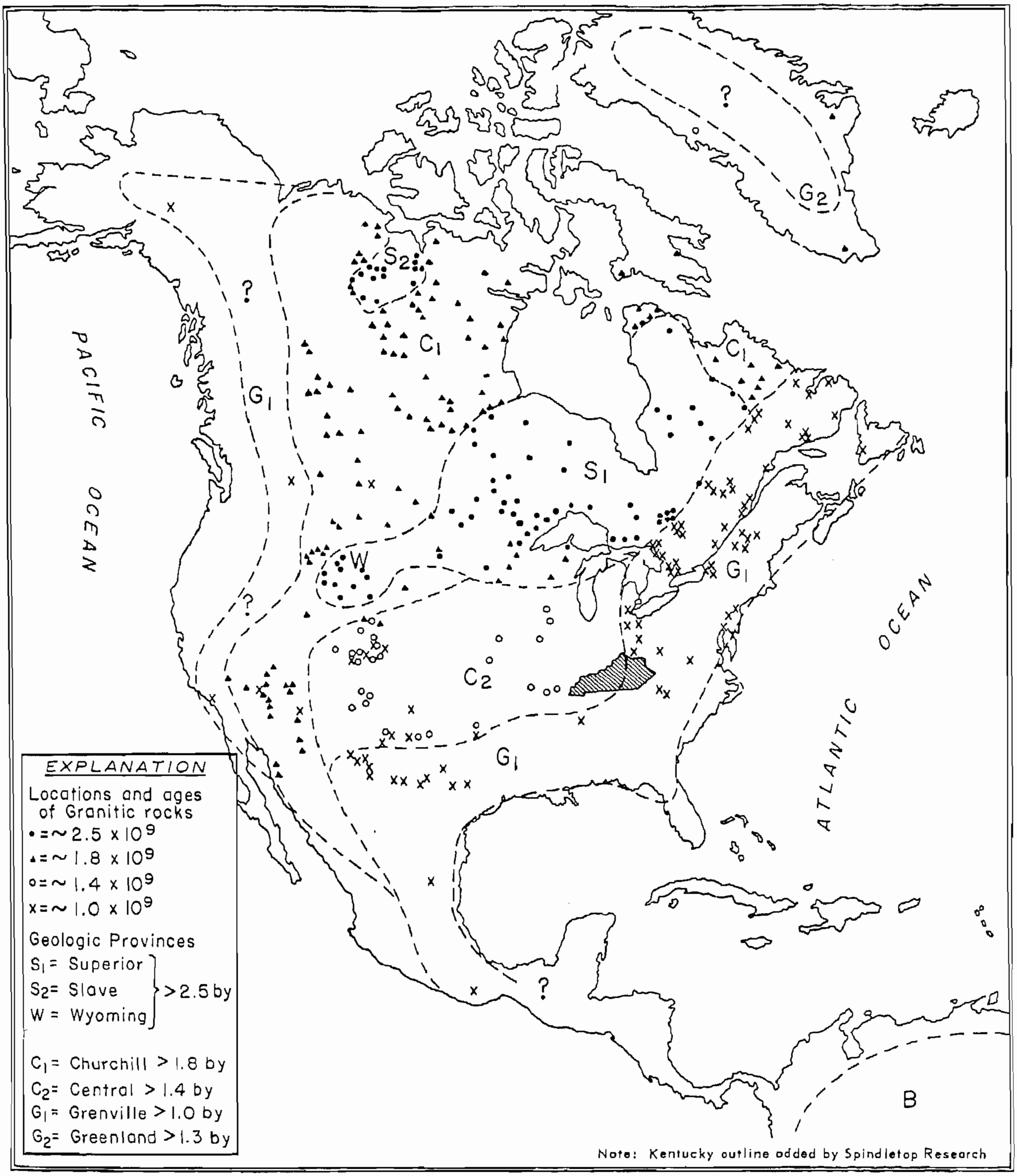


Figure 9. Location of Kentucky in relation to Precambrian Grenville boundary. After Spindletop Research Center (1963). From Engle (1963).

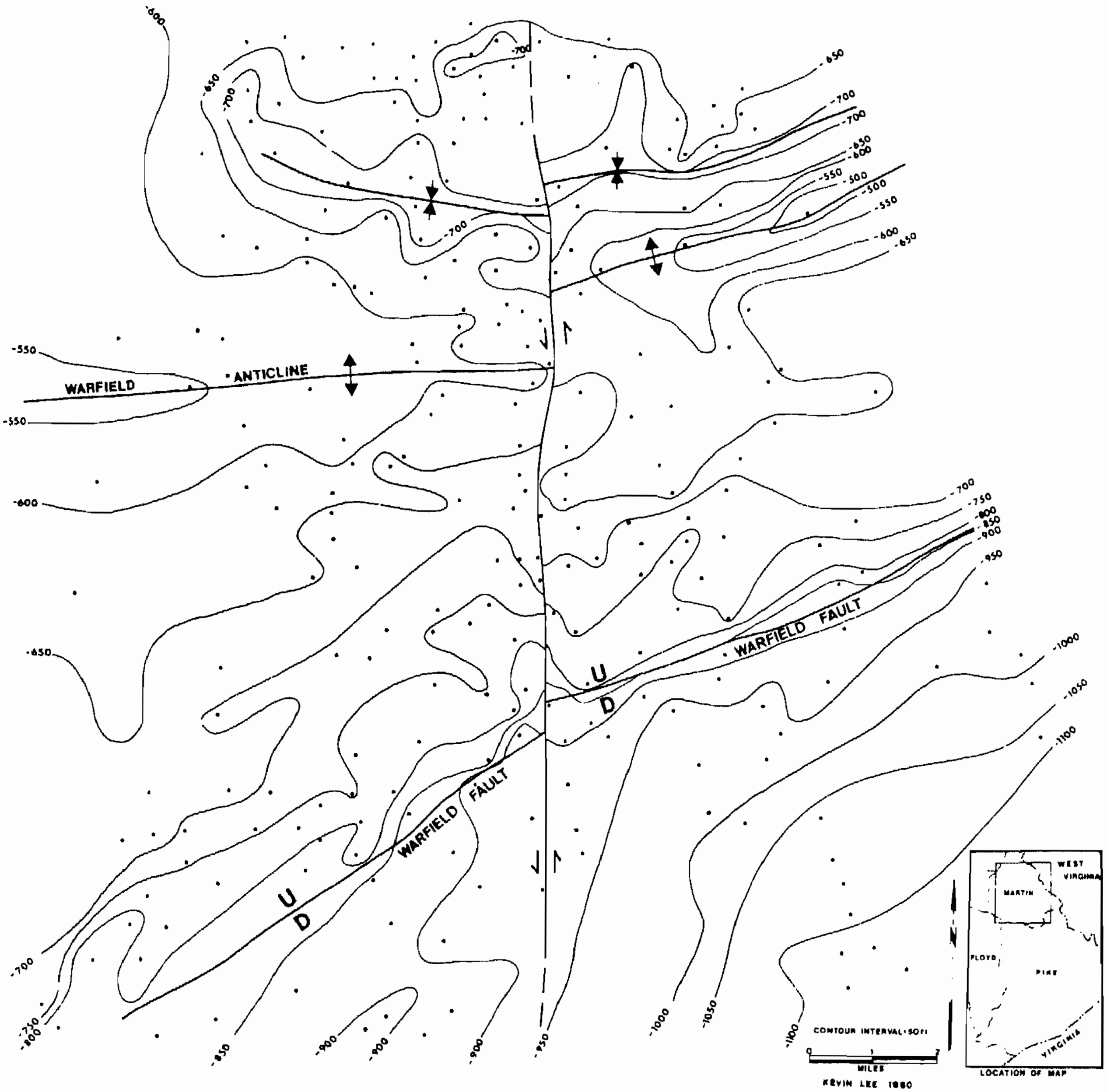


Figure 10. Map showing regional north-south, strike-slip fault in Martin County, Kentucky. After Lee (1980).

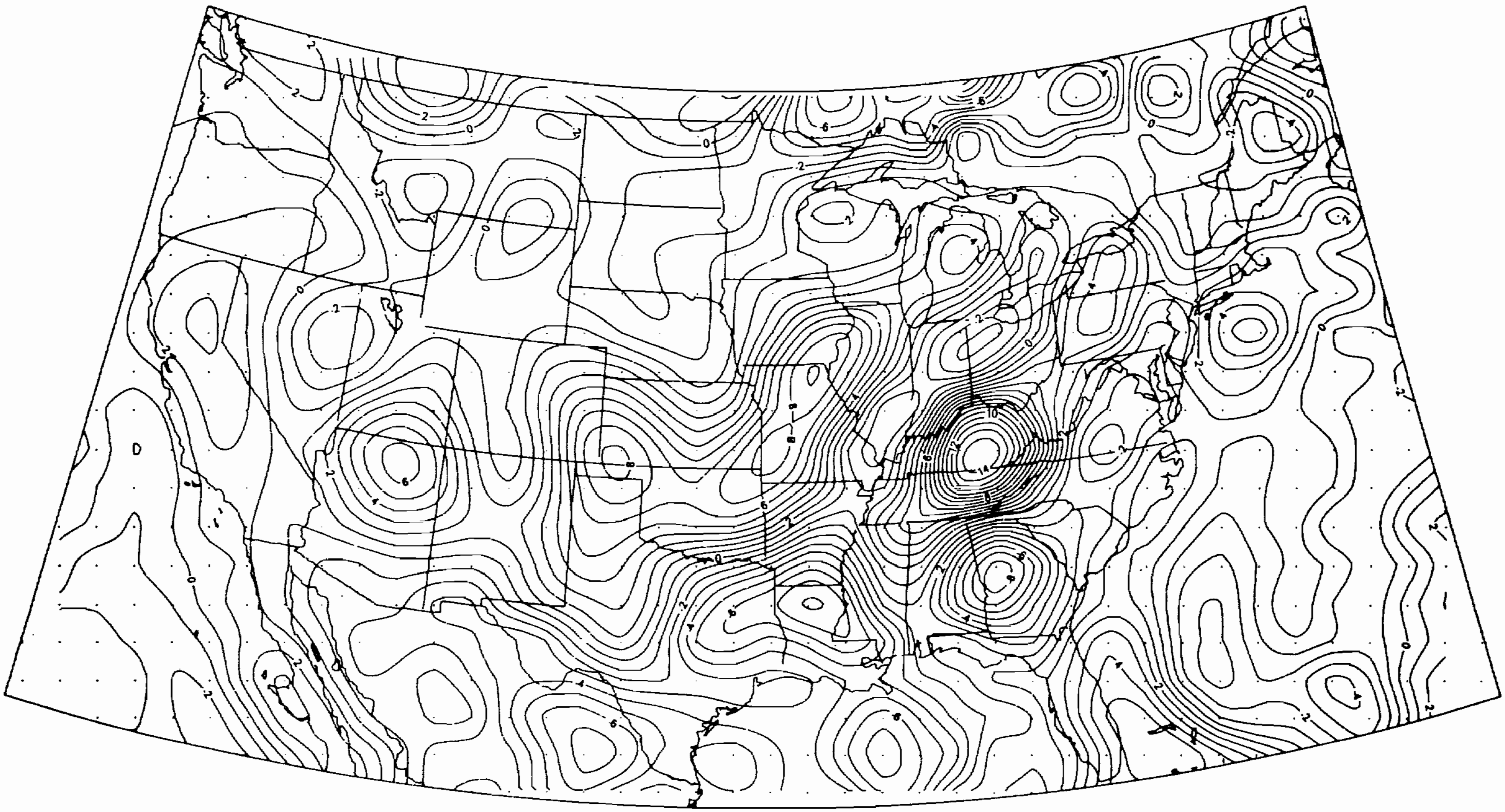


Figure 11. Satellite derived equivalent bulk-magnetization map of the United States. Assumes a constant magnetic crust thickness of 40 kilometers. Units are EMU/CC x 10^4. After Langel (1980).

feet of closure (McFarlan, 1950). At the south end of the Paint Creek Uplift in southeastern Magoffin County, there occurs an apparent contradiction between structural and isopach contours. Isopach contours of the total shale interval trend fairly uninterruptedly north-south. The strike of structure contours on top of the shale sequence changes from approximately northeast-southwest to approximately east-west around an indicated southeast plunging nose (Fulton, 1979). While isopach contours maintain a north-south trend, they become closer spaced east of western Magoffin County, suggesting that a north-south hinge line is present along the eastern side of the Paint Creek Uplift (Fulton, 1979, and Dillman and Ettensohn, 1980).

Rockcastle Uplift

The Rockcastle Uplift is described by McFarlan (1950), quoting Jillson, as a closed anticline about 30 miles long by 10 miles wide in Laurel, Clay and Owsley Counties, Kentucky. On a regional basis, the uplift appears to lie approximately along a crescent-shaped regional gravity trend extending from northeastern Indiana, through western Ohio, and into McCreary and Owsley Counties, Kentucky (McGuire and Howell, 1963). McFarlan, quoting Jillson, additionally indicates that no faulting is involved and that structure is more pronounced in the Mississippian age "Big Lime" (Greenbrier) than in the Pennsylvanian.

To the northeast, the Rockcastle Uplift appears to terminate against a north-south trending structural hinge line which extends from Lewis County to eastern Bell County, Kentucky (Dillman in Blackburn, 1980). The hinge line in Kentucky might be a southward extension of an imprecisely delineated north-south trending hinge line in Ohio (Owens, 1967, and Spindletop Research Center, 1963).

Kentucky River Fault System

The Kentucky River Fault System forms the northern border of the Rome trough. Both the fault system and the trough fit into the 38th parallel lineament (Heyl, 1972, and Shumaker, et al., 1966), and both show evidence of Precambrian to post-Pennsylvanian structural movement (Harris, 1978). In central Kentucky, evidence for the fault system is exposed at the surface; farther east, such evidence has been uncovered by exploratory drilling and geophysics.

Irvine-Paint Creek Fault System

South of and parallel to the Kentucky River Fault System lies the Irvine-Paint Creek Fault System with an approximately counterpart history and description. Both systems, in eastern Kentucky, are characterized by small grabens with subsidiary faults and folds. Likewise, both systems seem to have right lateral wrench phenomena associated with them. In all cases, fractured Chattanooga Shale, and gas-producing potential, might be expected in association with faults, especially those having histories of reactivation.

Warfield Fault

A first glance at a regional structure map suggests that the Warfield Fault forms the southern edge of the Rome trough. However, detailed investigation indicates this is not the case. Rather, the southern edge of the Rome trough appears to be formed by an unnamed basement fault approximately parallel to and north of the Warfield Fault. This Cambrian age basement fault, shown on plate 1, seems to have several thousand feet of throw. A passive structure, the Warfield anticline, lies between the south edge of the Rome trough and the Warfield Fault (Lee, 1980).

The approximately east-west aligned Warfield Fault, Warfield anticline, and southern edge of the Rome trough are transected by a north-south trending strike-slip fault that has disturbed the Mississippian Newman Limestone (fig. 10). The Chattanooga Shale in the area is contorted and faulted and presumably is well suited for yielding natural gas. The intersecting anomalies and contorted shales are located on the north edge of the Big Sandy gas field.

Pine Mountain-Emery River Thrust Fault

The 125-mile-long Pine Mountain Thrust Fault in southeasternmost Kentucky is terminated by two transverse tear faults, Jacksboro on the southwest and Russell Fork on the northeast. Dominant fracture orientations are N10E and N30W in the area of the Pine Mountain Thrust (Raymond, 1979). The shale in the area appears to be source rock and could prove productive.

Southwest of Pine Mountain, the same rationale could be applied to the Emery River Fault in Tennessee. Gas shows in the Chattanooga Shale may be associated with fractures related to the fault system as discussed elsewhere in this report.

GEOCHEMISTRY

As organic matter accumulates and becomes buried, it undergoes changes that, under the right conditions, lead to the generation of oil and gas. Initially, at very shallow depths, the buried organic matter undergoes biochemical (bacterial) decomposition. As time passes, the organic matter is buried deeper, with accompanying increases in temperatures; biochemical decomposition diminishes or ceases, while thermochemical decomposition increases. The extent of hydrocarbon generation from the organic matter depends on three basic interrelated geochemical factors: (1) concentration of organic content, (2) type of original organic material, and (3) thermal evolution or maturation of the material.

Organic Carbon Content

For shales to serve as source rocks for hydrocarbons, their minimum average organic carbon content should be about 0.5 percent by weight, though some place the lower limit at 1.0 percent. Generally, the range is about 2.0 percent (Tissot and Welte, 1978, p. 430). Table 1 indicates the organic carbon contents of Chattanooga Shale samples from wells in and near eastern Kentucky/Tennessee (fig. 12). The data are from the Mound Facility.

The five highest average organic carbon recordings from Appalachian basin wells are presented in table 2; all wells from which samples were taken are located in the western part of the basin. Matthews, et al. (1980) reported maximum carbon contents from scattered eastern Kentucky outcrop samples, as shown in table 3. The same authors also

Table I.Organic content of Chattanooga Shale samples from key wells. Data from Mound Facility Quarterly Status Reports.

Well	County	Organic carbon content (weight percent)		
		Maximum (rich)	Minimum (lean)	Average
KY-2 Columbia Gas Transmission Corp., Columbia Gas No. 20336	Martin	7.75	0.09	2.04
KY-4 Ashland Oil CO. R.S. Skaggs-Kelley Unit No. 3	Johnson	6.98	0.17	2.91
OH-6 Mitchell Energy Corp. Carpenter No. 1-5	Gallia	11.79	0.20	3.83
WV-5 Reel Drilling Co. K/K Farm No. 3	Mason	6.74	0.02	1.33
VA-1 Columbia Gas Transmission Corp., Penn Virginia Corp. Farm No. 20338	Wise	5.66	0.18	1.96

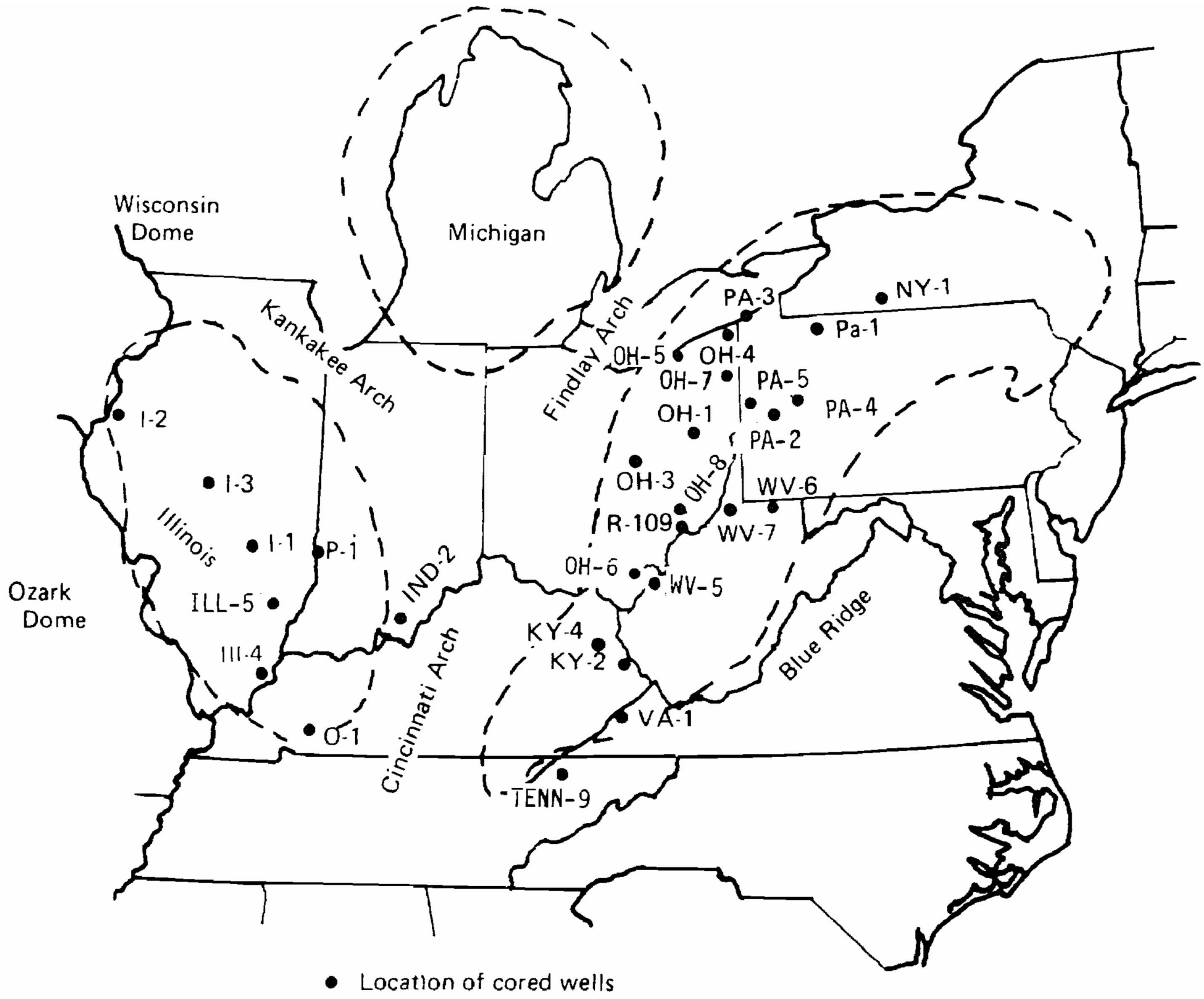


Figure 12. Index map showing locations of METC study wells in and near eastern Kentucky/Tennessee.

Table 2. **Wells with highest organic carbon content. After Zielinski and Moteff (1980).**

Well	County	Organic carbon content (weight percent)
KY-4 Ashland Oil Co. R.S. Skaggs-Kelley Unit No. 3	Johnson	2.91
OH-3 Thurlow Weed and Associates Louise Buckholt No. 1	Knox	2.23
OH-4 Monsanto Research Corp. Bessemer and Lake Erie Railroad Co. No. 3	Ashtabula	2.23
PA-3 Monsanto Research Corp. Pennsylvania DER Presque Isle State Park No. 1	Erie	2.12
KY-2 Columbia Gas Transmission Corp. Columbia Gas No. 20336	Martin	2.04

Table 3. **Organic carbon content of outcrop samples. After Matthews, et al. (1980).**

Member	Maximum organic carbon content (weight percent)
Cleveland	18.0
lower Huron	19.7
Sunbury (Lower Mississippian	19.7
Chattanooga (southern Kentucky)	14.1

report an average carbon content of 11.5 percent for all black shale units in Kentucky. (Samplings were taken from some of the richest black shale units.) Though sampling and analytical methods may vary from one investigating facility to another, the results indicate that the black shale intervals in the Chattanooga Shale in eastern Kentucky contain adequate amounts of organic carbon to make them precursors to hydrocarbons.

Type of Organic Material

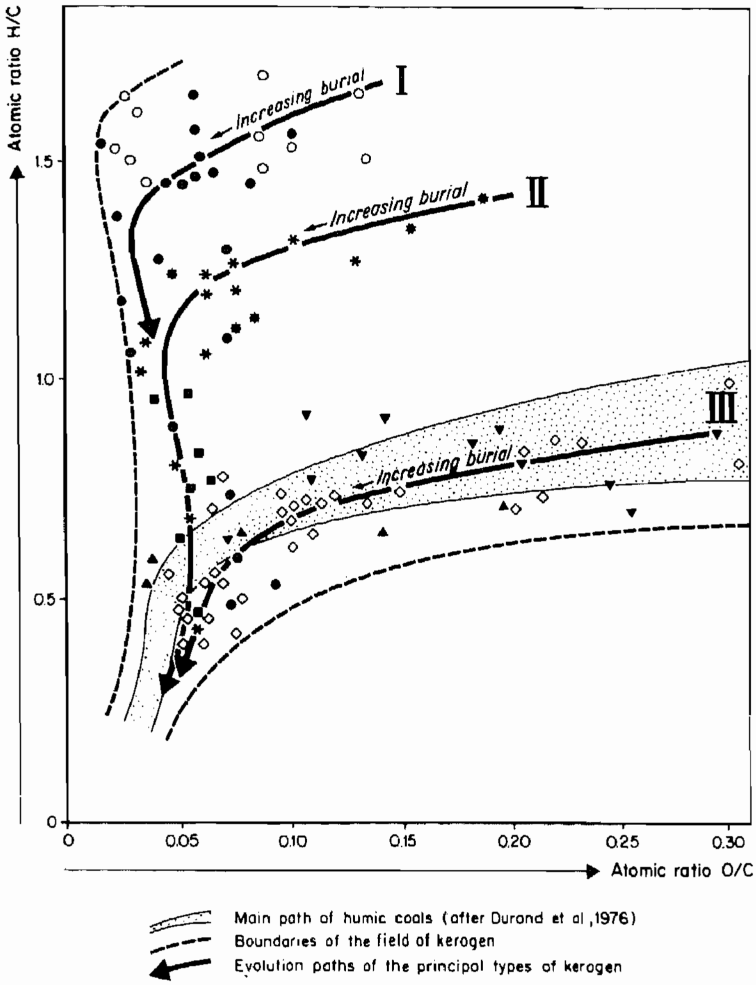
Kerogen, that portion of organic matter in sedimentary rocks that is insoluble in organic solvents (Dow, 1977), can be classified into two types: humic and sapropelic. Humic organic matter is derived principally from plant tissue, especially that resistant to rotting. Commonly, humic material is terrestrial in origin and deposited in swamps which are low oxygen reducing environments and, as a rule, is a source of natural gas. Sapropelic material is composed principally of fatty material, such as plant spores, and generally is regarded as marine or lacustrine in origin. Sapropelic material is a source for oil and gas rather than gas alone. There are few purely sapropelic or humic kerogens; instead, there are gradations between the two caused by variable contributions between continental and marine-derived organic matter. This intermediate kerogen (Type II) is usually more marine based (Tissot and Welte, 1978, p. 144) and is a source of oil and gas.

As kerogen is heated, volatile products such as water and carbon dioxide are driven off. Decreasing amounts of hydrogen and oxygen are left behind. Graphs can be constructed showing diminishing ratios of residual atomic hydrogen to carbon (H/C) and oxygen to carbon (O/C). As volatiles are driven off, H/C and O/C ratios diminish. Analyses of kerogen from well cuttings or laboratory samples display a unique evolution or maturation path (fig. 13). The paths indicate whether a particular kerogen is largely humic (III), largerly sapropelic (I), or intermediate (II) (Hunt, 1979, p. 340). The paths also indicate the degree of maturation of kerogen, which, in turn, provides insight into the extent and type of hydrocarbon generation. The relative location of the sample points plotted on the curve indicate the degree of maturation.

Figure 14 is an H/C versus O/C cross plot of kerogens taken from numerous samples of the Chattanooga Shale at various depths in the KY-4 well in Johnson County, Kentucky. Figure 15 shows cross plots of average atomic H/C versus atomic O/C values for all samples from the KY-4 well in Johnson County, Kentucky, as well as all samples from the KY-2 probe in Martin County, Kentucky. Additionally, average atomic H/C versus O/C values are plotted from other wells in nearby parts of adjoining states. The bias is toward Type II kerogen (Tissot and Welte, 1978, p. 448).

Thermal Maturation

Kerogens from Devonian and younger sedimentary rocks contain plant remains (macerals) that can be identified and classified, and their physical properties studied. Of the macerals, vitrinite, a plant-derived form of coal found in about 80 percent of all shales and sandstones, appears to be the most abundant. Each type of maceral reflects light at a particular value (reflectance). As kerogen and contained vitrinite undergo linearly increasing temperature, maturation proceeds and reflectance increases exponentially. The maturation changes are irreversible; thus, the extent to which hydrocarbon may have been generated can be indexed to a maturation scale based on vitrinite reflectance.



Type	Age and /or formation	Basin, country	
I	Green River shales (Paleocene - Eocene)	Uinta, Utah, U.S.A	●
	Algal kerogens (Botryococcus, etc...) - Various oil shales		○
II	Lower Toarcian shales	Paris, France; W. Germany	✱
	Silurian shales	Sahara, Algeria and Libya	■
	Various oil shales		✸
III	Upper Cretaceous	Douala, Cameroon	◇
	Lower Mannville shales	Alberta, Canada	▲
	Lower Mannville shales (Mc Iver, 1967)	Alberta, Canada	▼

Figure 13. Diagram showing maturation paths of kerogens from various formations. After Tissot and Welte (1978).

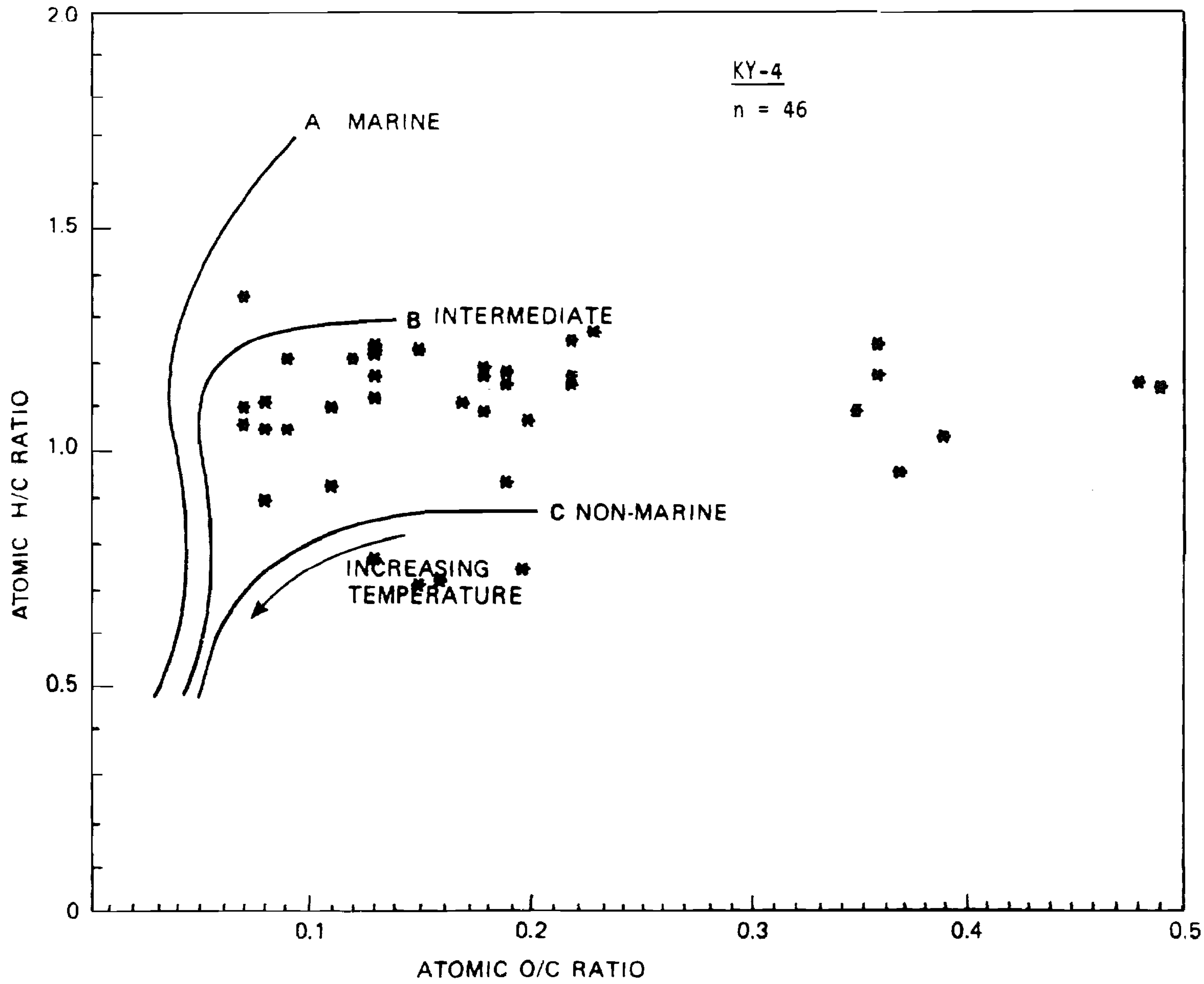


Figure 14. H/C-O/C cross plot of kerogen from METC KY-4 well in Johnson County, Kentucky. From Mound Facility (1980).

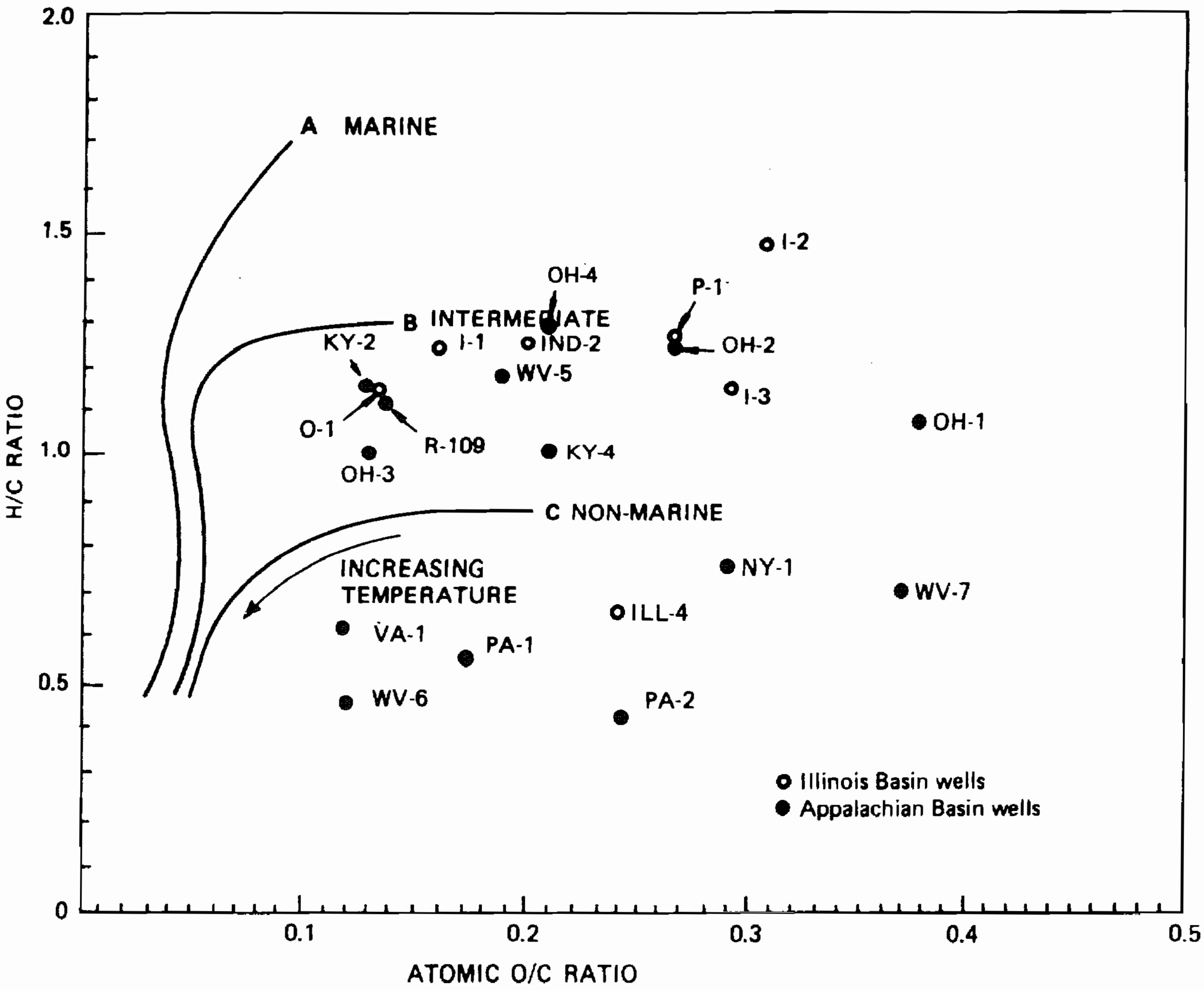


Figure 15. Cross plots showing average H/C-O/C values of kerogens from METC wells in and near eastern Kentucky/Tennessee. From Mound Facility (1980).

Vitrinite reflectance usually is measured on samples immersed in oil, and the value of reflectance from individual kerogen fragments in the sample is reported as R_o. Empirically determined ranges of R_o for hydrocarbon generation are:

R_o(percent)	Hydrocarbon	Comment
0.45	Oil	Lowest known value for oil generation
0.6	Oil	Peak value of oil generation
0.8 to 1.0	Oil	Oil and wet gas generation
1.3	Oil	End of oil generation
2.0	Condensate	End of condensate generation
1.3 to 3.0	Gas	Range for larger gas fields
3.5	Methane	End of methane generation

Another maturation indicator is color change in conodonts, kerogen, or both. (Color-change analysis is a relatively inexpensive and rapid means of determining the extent of maturation; however, a degree of subjectivity is involved which, perhaps, lessens accuracy.) As temperatures increase and maturation occurs, conodonts undergo color changes that have been indexed and correlated with vitrinite reflectance. As with vitrinite reflectance, kerogen color alterations have been indexed to degrees of maturation. Based on extensive sampling experience, the index is:

Kerogen color	Stage	Type hydrocarbon
Yellow-orange	1+	Nil, very slight alteration
Orange	2	Oil or wet gas
Brown	3	Oil or wet gas
Dark brown	4	Dry gas or barren
Black	5	Dry gas or barren

Thermal alteration indices and vitrinite reflectances, along with expected hydrocarbon maturation products, are shown in figure 16. Thermal alteration indices based on kerogen color alteration were established on samples from Kentucky wells in Martin and Johnson Counties, as were average vitrinite reflectance values. Table 4 compares these samples with samples from other nearby wells.

Thermal maturity also can be estimated by measuring the volume of gas (in cubic feet) given off by a cubic foot of shale. Differences in gas content from the same shale unit between well sites appears to be controlled by thermal maturity. Offgas volumes and percent carbon content from specific shale strata have been tabulated for the KY-2 well and the VA-1 well (table 5). Shales in the VA-1 well are regarded as thermally mature, which might suggest that KY-2 shales are immature by comparison.

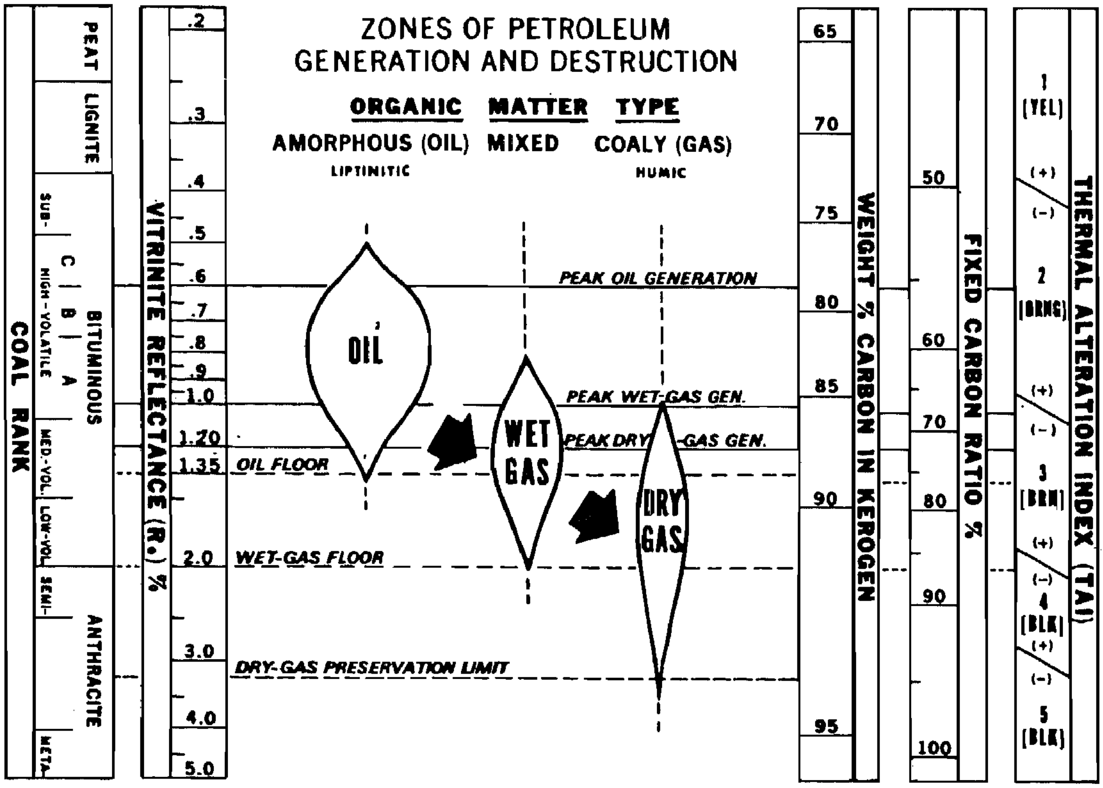


Figure 16. Diagram showing hydrocarbon generation windows indexed to vitrinite reflectance and thermal alteration index. After Dow (1977).

Table 4. Comparison of reflectance and thermal alteration indices of samples from key wells. Data from Mound Facility Quarterly Reports.

Well	County	Average R_o	Thermal Alteration index	Condition
KY-2	Martin	0.52	1+ to 2	Immature to moderately mature
KY-4	Johnson	0.57	1+ to 2	
OH-6	Gallia	N.A.	2- to 2	Moderately mature
WV-5	Mason	0.64	2- to 2+	
VA-1	Wise	1.02	2+	Mature

Table 5. Comparison of offgas and organic carbon content from Chattanooga Shale units in KY-2 and VA-1 wells. After Zielinski (1981).

Unit	Gas volume (cubic feet of gas per cubic foot of shale)		Organic carbon content (weight percent)	
	KY-2	VA-1	KY-2	VA-1
Cleveland	21.6	70.7	4.77	4.76
Chagrin	1.6	6.2	0.61	0.33
upper Huron	5.7	-	2.81	-
Chagrin-Chemung	5.9	59.0	0.96	1.03
lower Huron	14.9	90.3	2.96	2.66
upper Olentangy	10.3	-	1.00	-
Pipe Creek	9.3	-	3.57	-
lower Olentangy	8.7	-	0.87	-
Rhinestreet	20.4	-	2.10	-

FRACTURE AND PRODUCIBILITY INDICATORS

Given the structural features in eastern Kentucky, a variety of related fractures in the Devonian shale can be expected. For example, north of the Kentucky River Fault System, along the Waverly Arch, fracture densities in the Devonian shale should be high, since the arch underwent post-Devonian structural movements (Dever, et al., 1977).

Certain type deformations yield predictable fracture configurations, which, in turn, respond best to particular stimulation techniques (Overby, 1976; Komar, 1978; and Komar, et al., 1980). One is an area of low-angle thrust, such as the Pine Mountain (fig. 17) or Emery or Chattanooga thrust (Harris and Milici, 1977). (Here, however, the Devonian Shale may be an unattractive target because of inadequate thicknesses.) Fractures also could result from rejuvenation along deep-seated basement faults (fig. 18). This would seem to be the case along and within the Rome trough and would relate to the Kentucky River, Irvine-Paint Creek, and Warfield Faults. The Rome trough, including both bordering and contained faults, have histories of movement from Precambrian through Mississippian or Pennsylvanian time (Sutton, 1953, and Harris and Milici, 1977).

Fracture patterns around the Paint Creek Uplift are less easily predicted, since the structural form and origin of the uplift are less easily categorized than the Rome trough or Pine Mountain Thrust system. The uplift appears, however, to have had a history of periodic uplift from Devonian through Cretaceous time (Hudnall and Browning, 1924).

The Rockcastle Uplift appears related to a major gravity anomaly extending at least across Laurel, Clay, Leslie, and Perry Counties, Kentucky. Reports of movement and fracturing of Devonian shale along the uplift are not known. However, in view of post-Devonian involvement of other structures in eastern Kentucky, the Rockcastle Uplift likely underwent uplift or other movement.

East-west alignments of Devonian shale isopach contours along the northeast edge of the Rockcastle Uplift may reflect similarly oriented faulting (Fulton, 1979). Fractured, and possibly productive, Devonian shale might be encountered along such faults, if they exist, as well as in the area of fault intersections with the uplift. (The Devonian shale is productive at Burning Springs, Wood County, West Virginia on the Burning Springs anticline.)

Low stress ratios have been related to areas of high tensional relief where maximum natural fracturing should occur. Stress ratios have been indexed so that a value near 0.43 is most favorable whereas a value of 0.7 marks the borderline between favorable and less favorable areas. Komar and Bolyard, figure 19, show a regional, minimum stress-ratio zone extending across eastern Kentucky. Extension of the zone northeastward includes favorable areas of Devonian shale gas production in Pennsylvania, Ohio, and West Virginia.

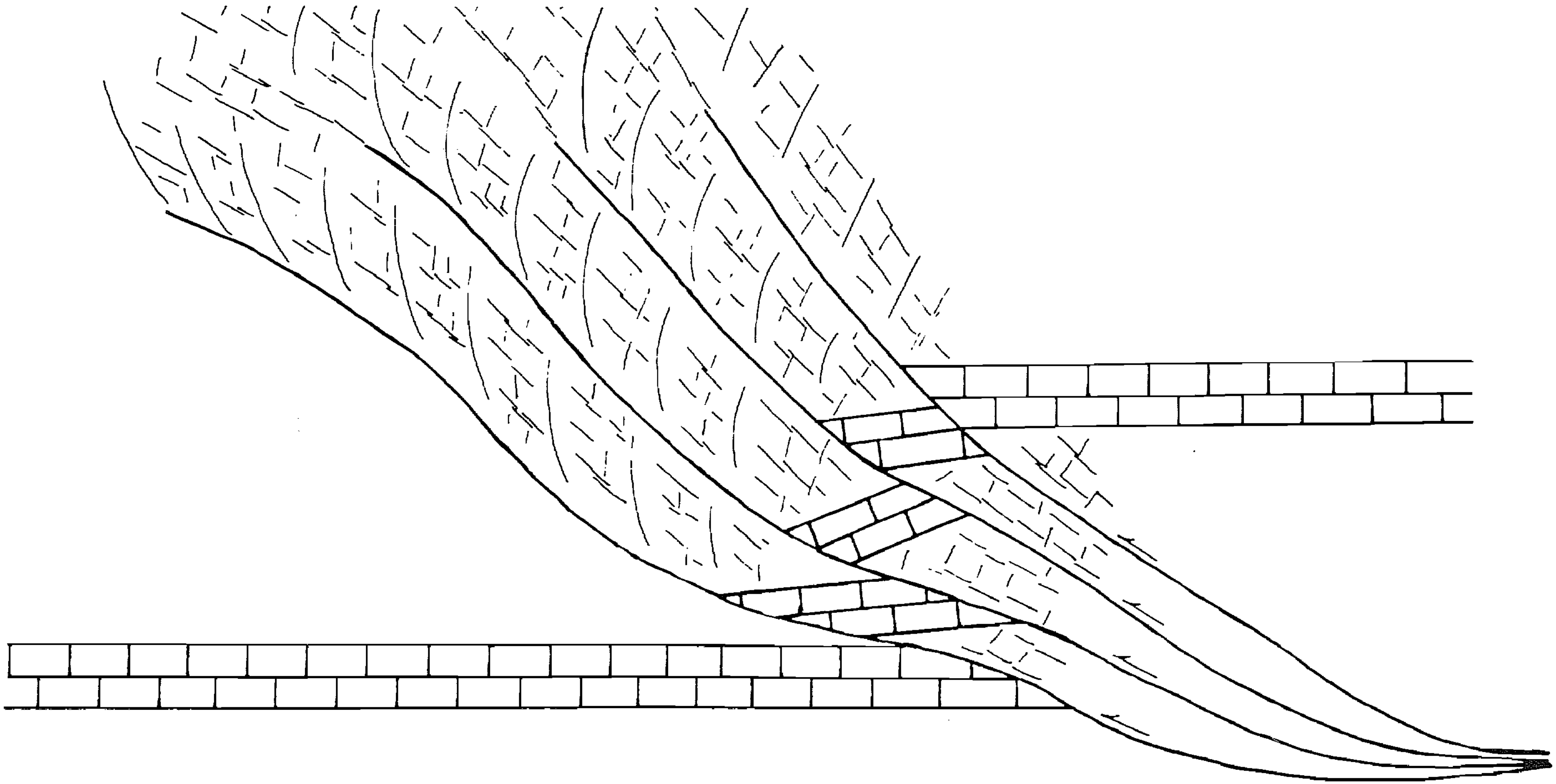


Figure 17. Fractures generated by low-angle thrust faulting during the Appalachian orogeny. After Overbey (1976).

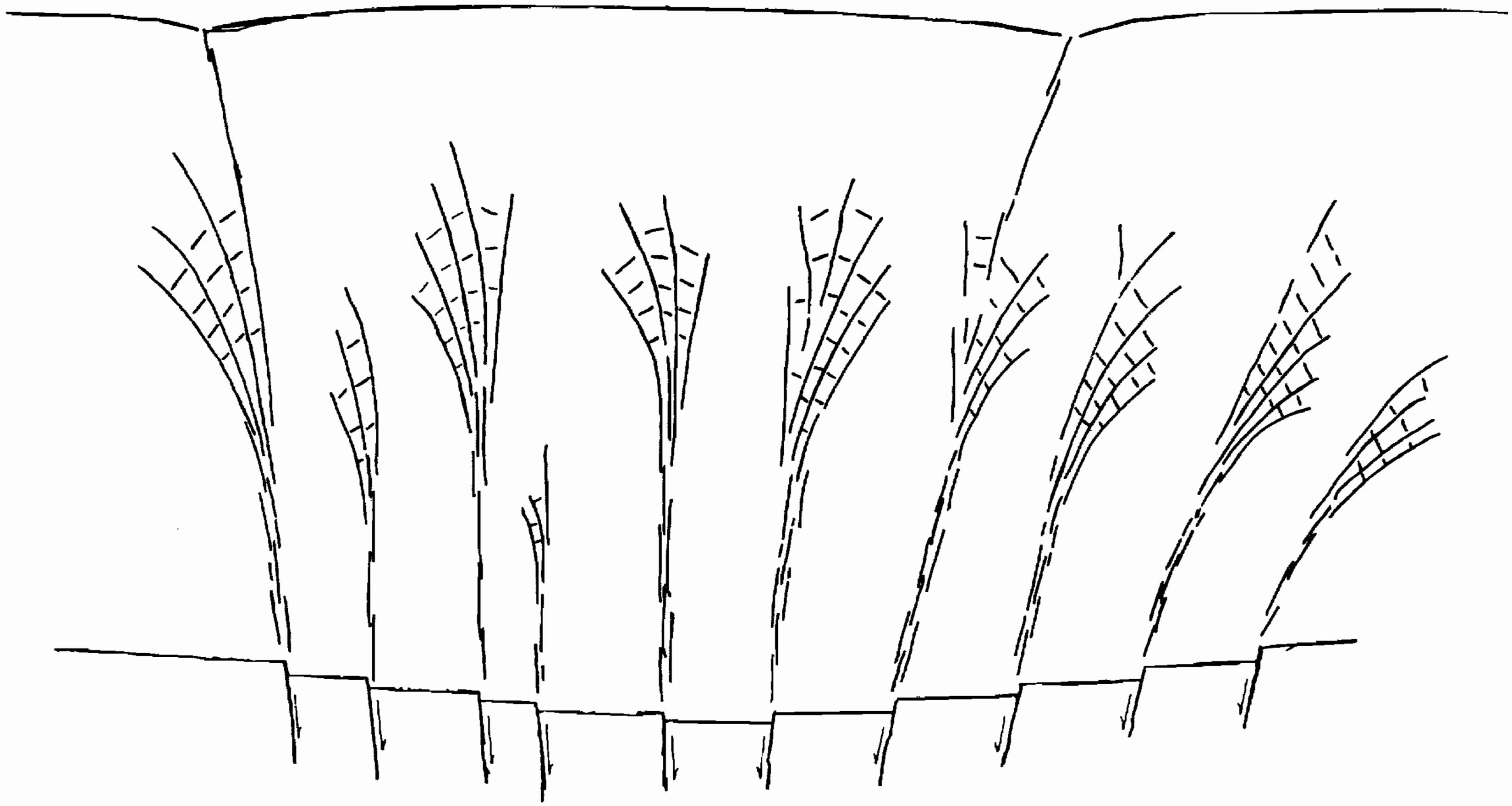
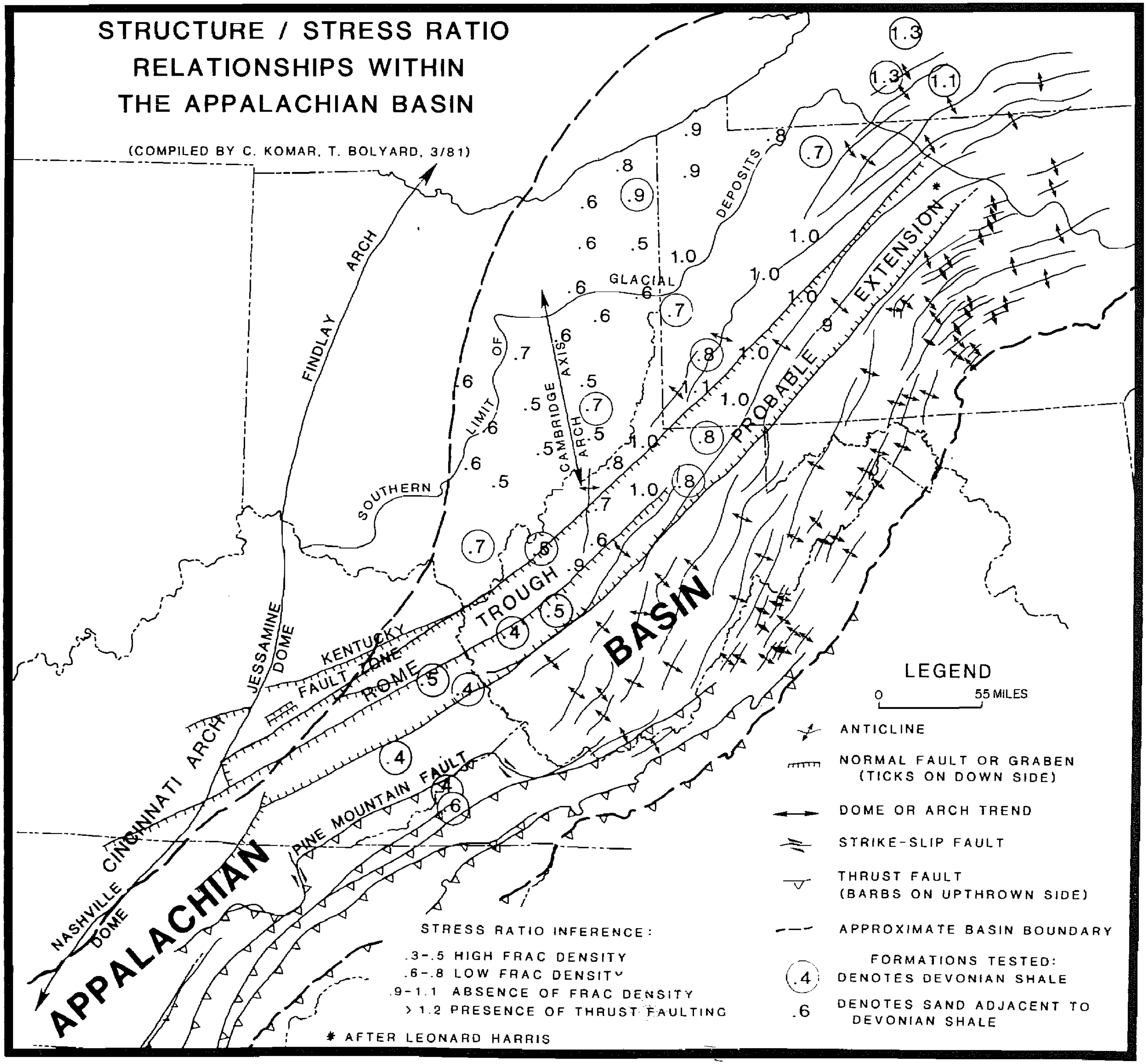


Figure 18. Fractures generated by deep seated basement faulting propagated upward into Devonian shales. After Overbey (1976).


STRUCTURE / STRESS RATIO
RELATIONSHIPS WITHIN
THE APPALACHIAN BASIN
(COMPILED BY C. KOMAR, T. BOLYARD, 3/81)
APPALACHIAN
BASIN
PROBABLE EXTENSION
TROUGH
ROME
KENTUCKY FAULT ZONE
PINE MOUNTAIN FAULT
CINCINNATI ARCH
NASHVILLE DOME
JESSAMINE DOME
FINDLAY ARCH
SOUTHERN LIMIT OF GLACIAL DEPOSITS
CAMBRIDGE ARCH AXIS
LEGEND
0 55 MILES
ANTICLINE
NORMAL FAULT OR GRABEN (TICKS ON DOWN SIDE)
DOME OR ARCH TREND
STRIKE-SLIP FAULT
THRUST FAULT (BARBS ON UPTHROWN SIDE)
APPROXIMATE BASIN BOUNDARY
FORMATIONS TESTED:
.4 DENOTES DEVONIAN SHALE
.6 DENOTES SAND ADJACENT TO DEVONIAN SHALE
STRESS RATIO INFERENCE:
.3-.5 HIGH FRAC DENSITY
.6-.8 LOW FRAC DENSITY
.9-1.1 ABSENCE OF FRAC DENSITY
> 1.2 PRESENCE OF THRUST FAULTING
* AFTER LEONARD HARRIS

GAS PRODUCTION

Historical

The Big Sandy gas field, with the Rome trough cutting across its northern portion, lies in an approximately triangular area between Perry, Martin, and Pike Counties, Kentucky. The field has been studied intensely and many descriptive articles have been published. (See Hunter and Young, 1953; Harris, de Witt, and Colton, 1978; de Wys and Shumaker, 1978; and Shumaker, 1978.) Exploitable gas accumulation in the field is controlled by primary pore space being connected through joints, faults, fractures, and bedding planes (Harris and Colton, 1978).

Though Big Sandy is by far the largest Devonian shale gas tield in the Appalachian basin, other areas have been productive (Wilson and Sutton, 1976). Nearly all of the fields (table 6) fall proximate to, if not atop, a major structural anomaly where fracturing in the shale might be expected. (If any oil has been produced from the shale it has been in minimal quantities compared to gas.)

In Buchanan County, Virginia, adjoining Pike County, Kentucky, natural gas has been produced from black shale in the shear zone beneath the Pine Mountain Thrust. Total shale thickness is reported as 1,000 to 1,500 feet (Young, 1957).

Current

Wells in the Devonian Shale are being completed in the Cutshin area in southeastern Leslie County, Kentucky (Petroleum Information, 1980a). This new producing area appears to be a southwestward extension of the Big Sandy field, with gas production from the shale at approximately 3,900 to 4,300 feet, commingled with that from the shallower Mississippian Greenbrier and underlying Siluro-Devonian "Corniferous" Limestones.

In eastern Tennessee, recent drilling has indicated production from the Chattanooga Shale in the approximate centers of both Scott and Morgan Counties (Petroleum Information, 1980b), which are close to faults or fault-related fractures off the Pine Mountain-Emery River Fault System. In Scott County, initial gas production was reported as 10 thousand cubic feet (Mcf) per day from 1,700 to 1,745 feet. In Morgan County, gas from 39 feet of the shale at about 2,255 feet has been commingled with gas from the Monteagle and Fort Payne with no formation-specific flows indicated.

Drilling reports from eastern Coffee County, Tennessee, show commingled production from the Chattanooga Shale and the Trenton. Test information suggests that little more than local use for the gas might be expected.

Table 6. **Location and year of discovery of eastern Kentucky Chattanooga Shale gas fields. After Wilson and Sutton (1976).**

County	Portion of county	Field	Year of discovery
Bell	northern	Stoney Fork	1952
Boyd	northern	Ashland	1918
Boyd	central	Mavity	1967
Clay	northwestern	Burning Springs	1898
Clay	northwestern	Little Goose	1967
Johnson	southwestern	Swamp Ranch	1928
Johnson/Lawrence		Redbush	1932
Lawrence	southern	Cordell	1917
Magoffin	central	Salyersville	1931
Morgan	southwestern	Grassy Creek	1921
Morgan	central	Index	1926

Future

The Big Sandy area lying approximately between Pine Mountain and the Warfield Fault is an obvious one for continuing effort (fig. 20) because of the probable presence of fractures in the Devonian shale related to major structural anomalies, which are associated closely with gas production. (Drilling depths to the base of the Devonian shale are shown in figure 21 (National Petroleum Council, 1980).) In addition, in large parts of eastern Kentucky, production is obtained from pays above and immediately beneath the Devonian shale--respectively, the "Corniferous" and Greenbrier Formations. Chattanooga as a piggy-back addition to these objectives should therefore be considered.

The most favorable zone (transposed onto figure 20) in eastern Kentucky appears to be southeast of the 0.7 index line, which runs through western Boyd, northwestern Magoffin, northwestern Clay, and central Whitley Counties. Within this area, optimal chances for fracturing (and hydrocarbon potential) probably lie within the Rome trough, along the Warfield Fault, Paint Creek Uplift, and the Lewis-Bell County hinge line. Smaller areas related to local structural anomalies should also be considered. In Tennessee, the area northeast of the Emery River Fault System appears favorable based on structural and related fracture considerations.

Figures 3 through 5 are a series of maps showing the areal extent of the various black shale facies, and equivalents, in the study area. Figure 19 shows favorable stress ratio parameters throughout eastern Kentucky; plate 1 shows the general structural configuration of the region, and figure 22 shows the location of natural gas pipelines in the northeastern U.S. The favorable area, shown in figure 20, includes all or parts of 23 counties in eastern Kentucky and a minimum of 6 counties in Tennessee. Wells penetrating the Devonian sequence in this area should be evaluated for shale gas potential, either as a primary target or as a dual completion possibility. Reserve estimates generated by the National Petroleum Council (1980) provide a state-of-the-art calculation of reserves in-place for eastern Kentucky (table 7) and Tennessee (table 8).

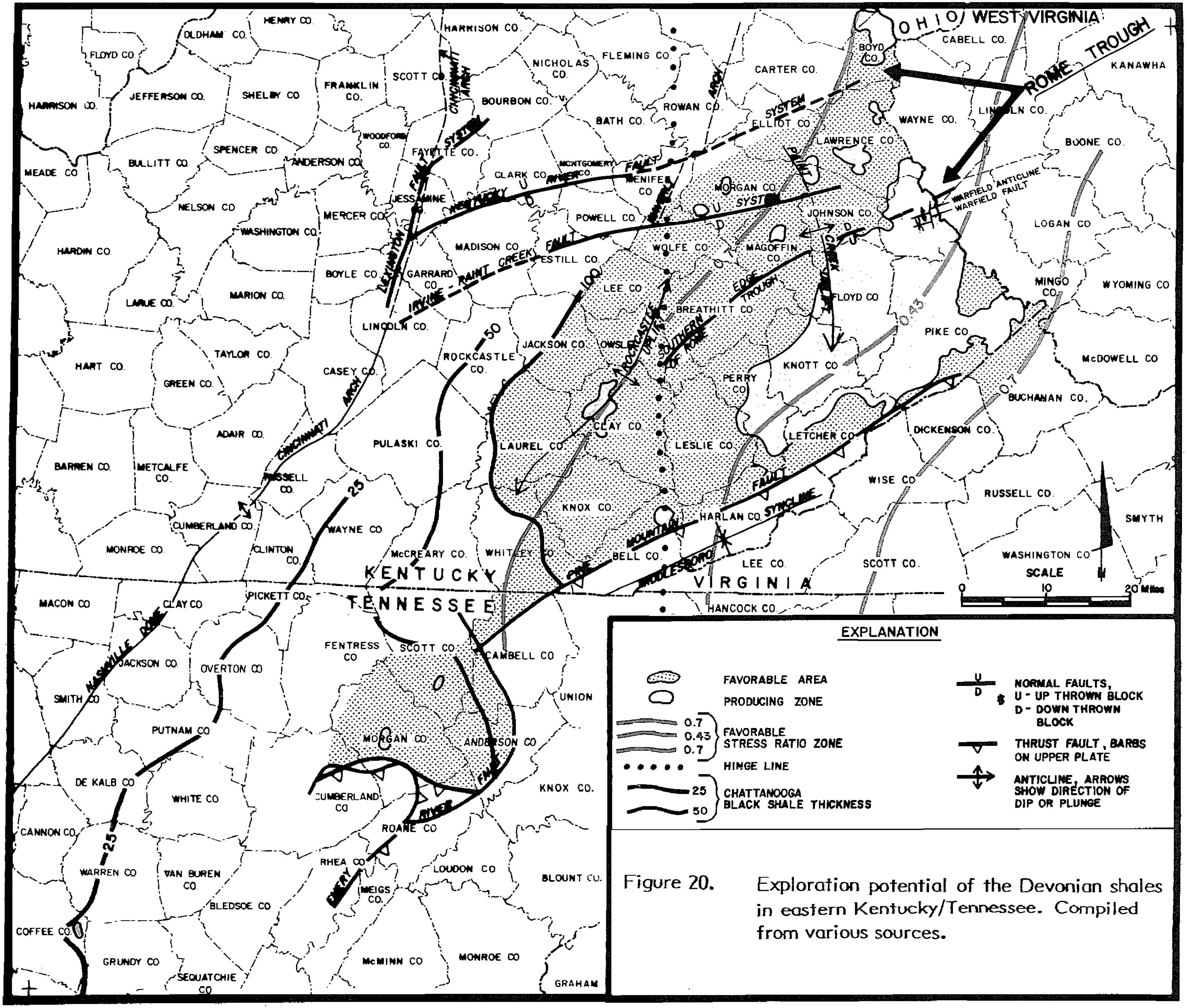


Figure 20. Exploration potential of the Devonian shales in eastern Kentucky/Tennessee. Compiled from various sources.

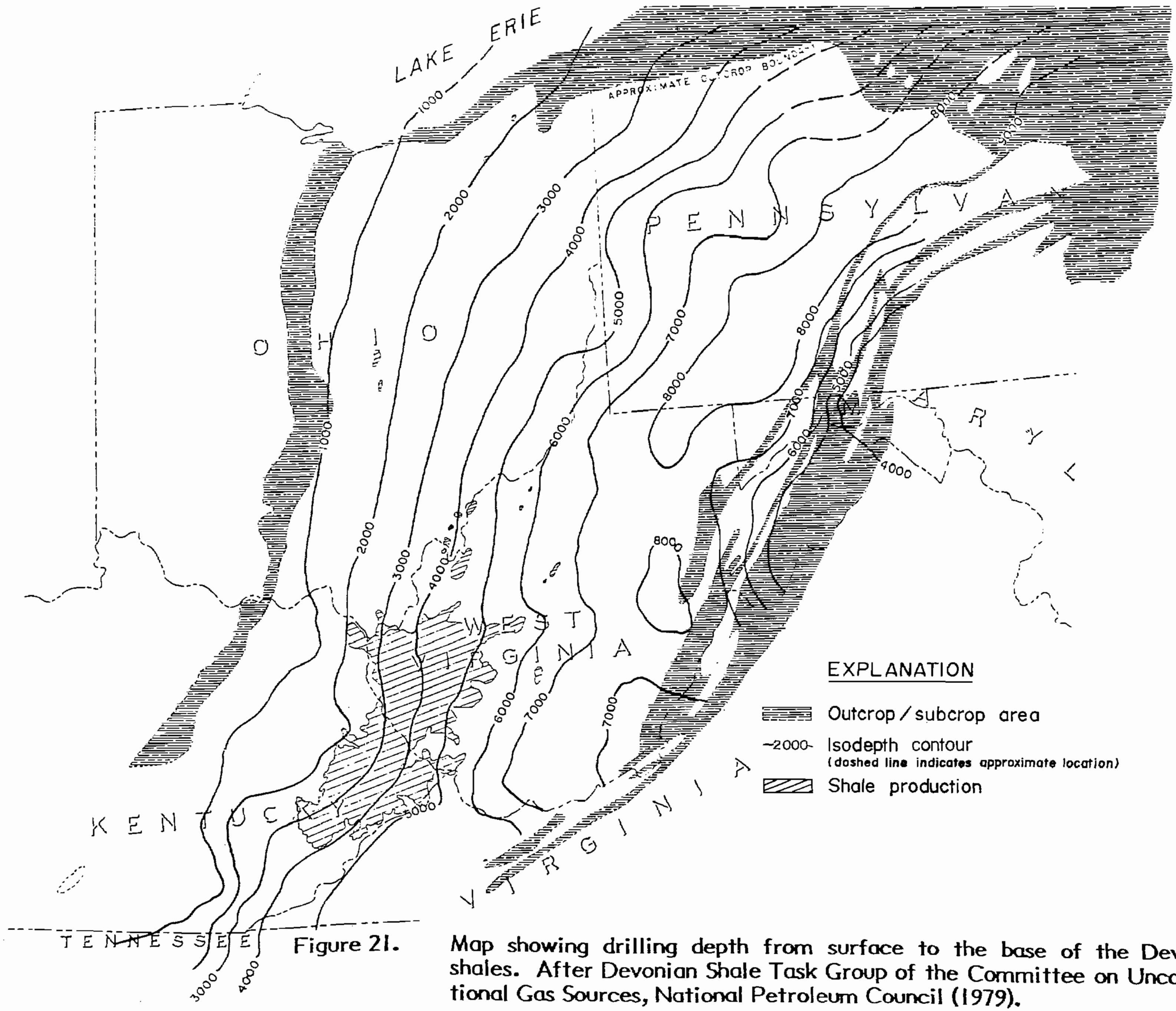


Figure 21. Map showing drilling depth from surface to the base of the Devonian shales. After Devonian Shale Task Group of the Committee on Unconventional Gas Sources, National Petroleum Council (1979).

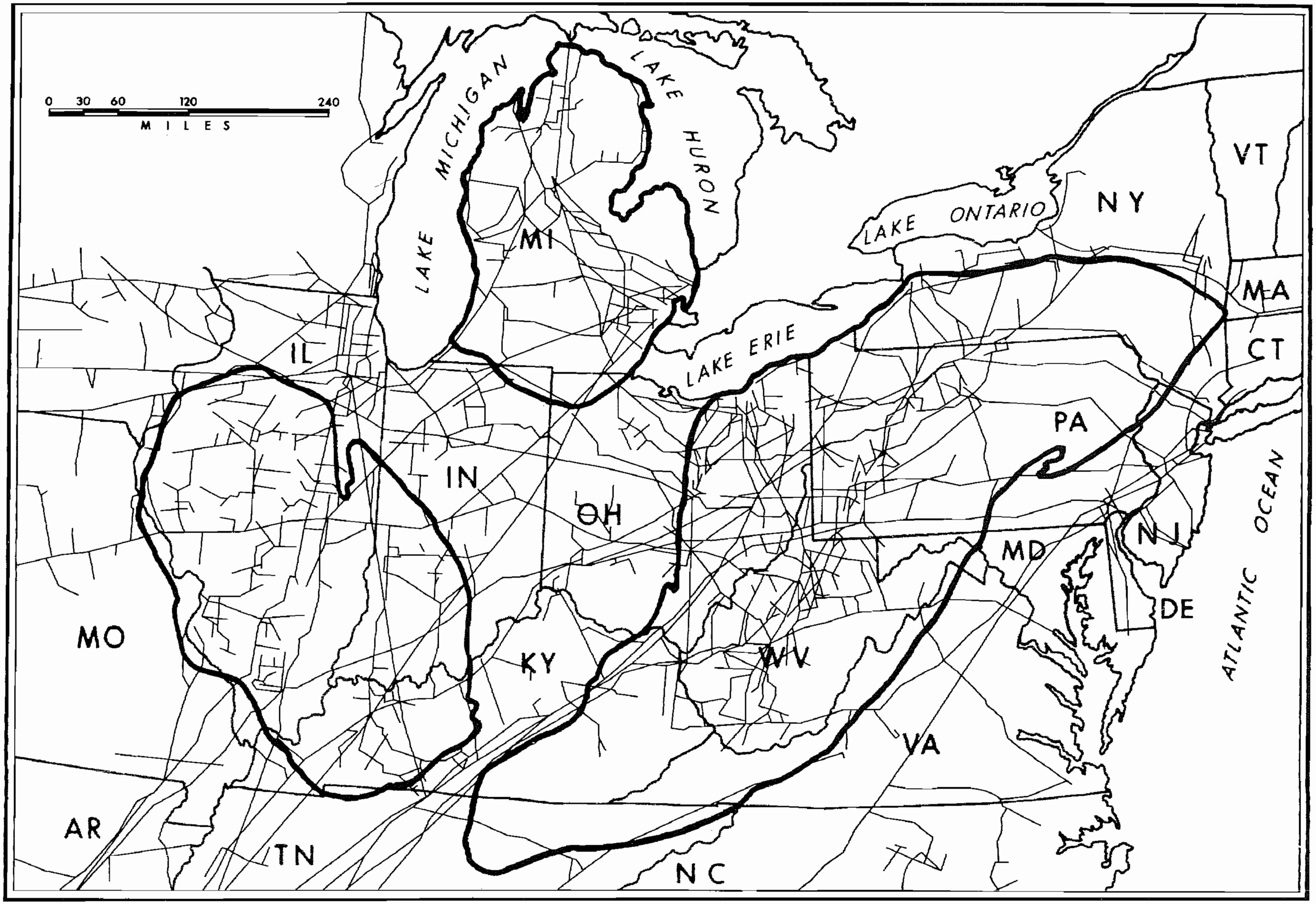


Figure 22. Natural gas pipeline map, northeastern United States. After Oil and Gas Journal.

Table 7. **Devonian Shale resource assessment for eastern Kentucky (after National Petroleum Council, 1980).**

	LOG DATA			SAMPLE DATA		
	Average Thickness (Feet)	Land Area* (Sq Mi)	Total (TCF)	Average Thickness (Feet)	Land Area* (Sq Mi)	Total (TCF)
Black Shale	200	12,829	43	249	12,829	53
Gray Shale	134	12,829	5	92	12,829	3
	Average Depth (Feet)	Total (TCF)	Average (BCF/Sq Mi)	Average Depth (Feet)	Total (TCF)	Average (BCF/Sq Mi)
Total Shale Resource	1,885	48	4	1,885	56	4

Table 8. **Devonian Shale resource assessment for Tennessee (after National Petroleum Council, 1980).**

	LOG DATA			SAMPLE DATA		
	Average Thickness (Feet)	Land Area* (Sq Mi)	Total (TCF)	Average Thickness (Feet)	Land Area* (Sq Mi)	Total (TCF)
Black Shale	48	2,338	2	78	2,338	3
Gray Shale	30	2,338	0.2	0	2,338	0
	Average Depth (Feet)	Total (TCF)	Average (BCF/Sq Mi)	Average Depth (Feet)	Total (TCF)	Average (BCF/Sq Mi)
Total Shale Resource	1,395	2	1	1,395	3	12

*Land area encompasses that portion considered as having Devonian Shale potential, and does not necessarily represent the total area of the state.

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APPENDIX

EVALUATION OF DEVONIAN SHALE POTENTIAL IN KENTUCKY

(Includes Documents, Logs, and Maps in the UGR Information File Concerning Kentucky)

This Appendix is cross-referenced by subtopic. UGR File Accession List Numbers are indicated for each entry. The first time a particular entry appears, the complete reference is given. Subsequent references to that entry are only indicated by the UGR File Accession List Number.

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UGR #451

UGR #508

GROUND WATER

UGR #S130
Paper EGS-74

UGR #S223
Paper EGS-37

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LINEAMENTS

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MINERS SYSTEM

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MODELING, DEPOSITION

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PINE MOUNTAIN OVERTHRUST

UGR #S130
Paper EGS-99

UGR #S223
Paper EGS-36

REMOTE SENSING

UGR #S008
Paper VII

UGR #497

ROME TROUGH

UGR #S130
Paper EGS-60

SCINTILLOMETER

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SEDIMENTOLOGY

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STATISTICAL ANALYSIS

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APPENDIX
EVALUATION OF DEVONIAN SHALE POTENTIAL IN THE APPALACHIAN BASIN

(Includes Documents, Logs, and Maps in the UGR Information File Concerning the Appalachian Basin)

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WIRELINE LOG STUDIES

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Paper EGS-9

APPENDIX

EVALUATION OF
DEVONIAN SHALE POTENTIAL
IN
TENNESSEE

(Includes Documents, Logs, and Maps in the UGR Information File Concerning Tennessee)

This Appendix is cross-referenced by subtopic. UGR File Accession List Numbers are indicated for each entry. The first time a particular entry appears, the complete reference is given. Subsequent references to that entry are only indicated by the UGR File Accession List Number.

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UGR #448

UGR #449

UGR #491

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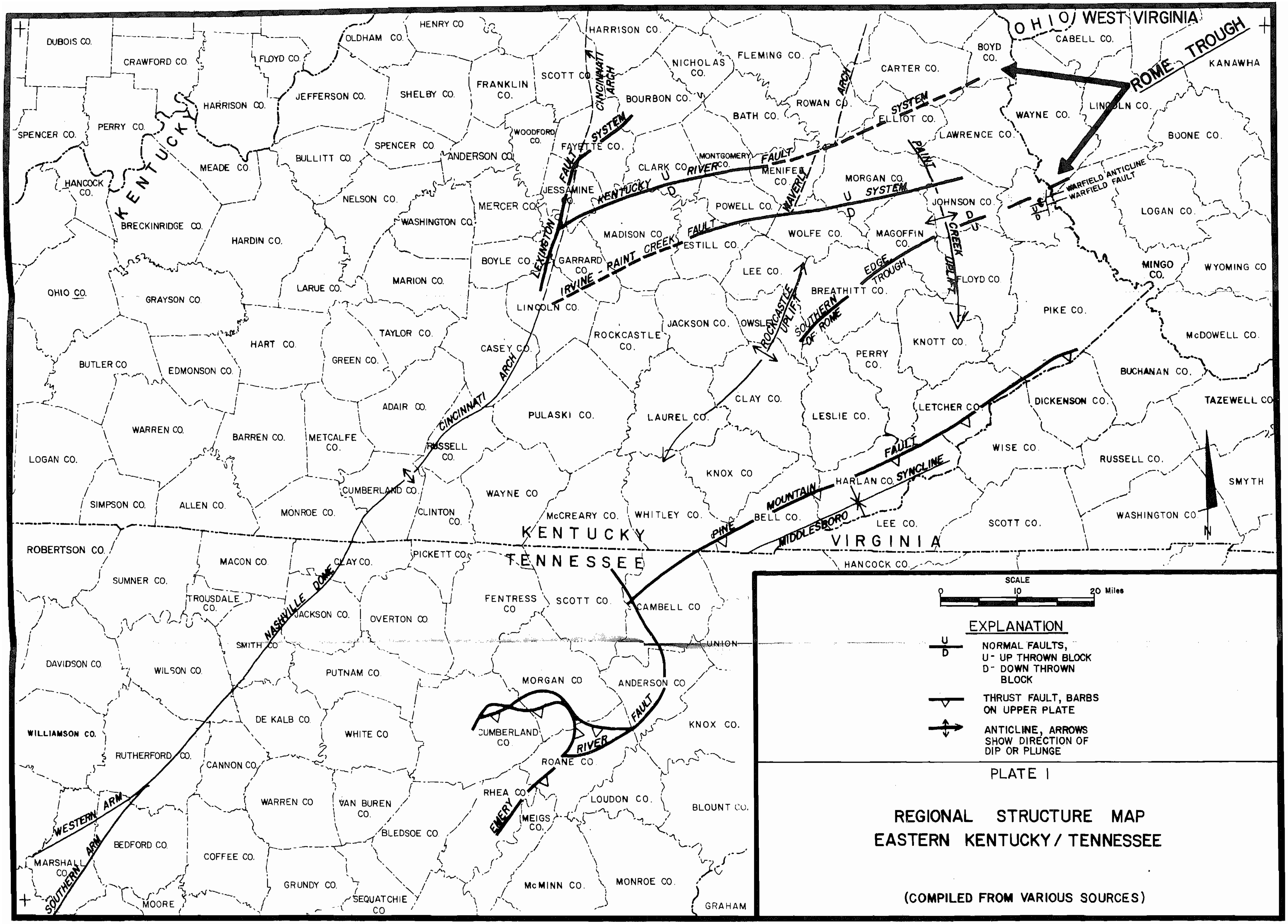
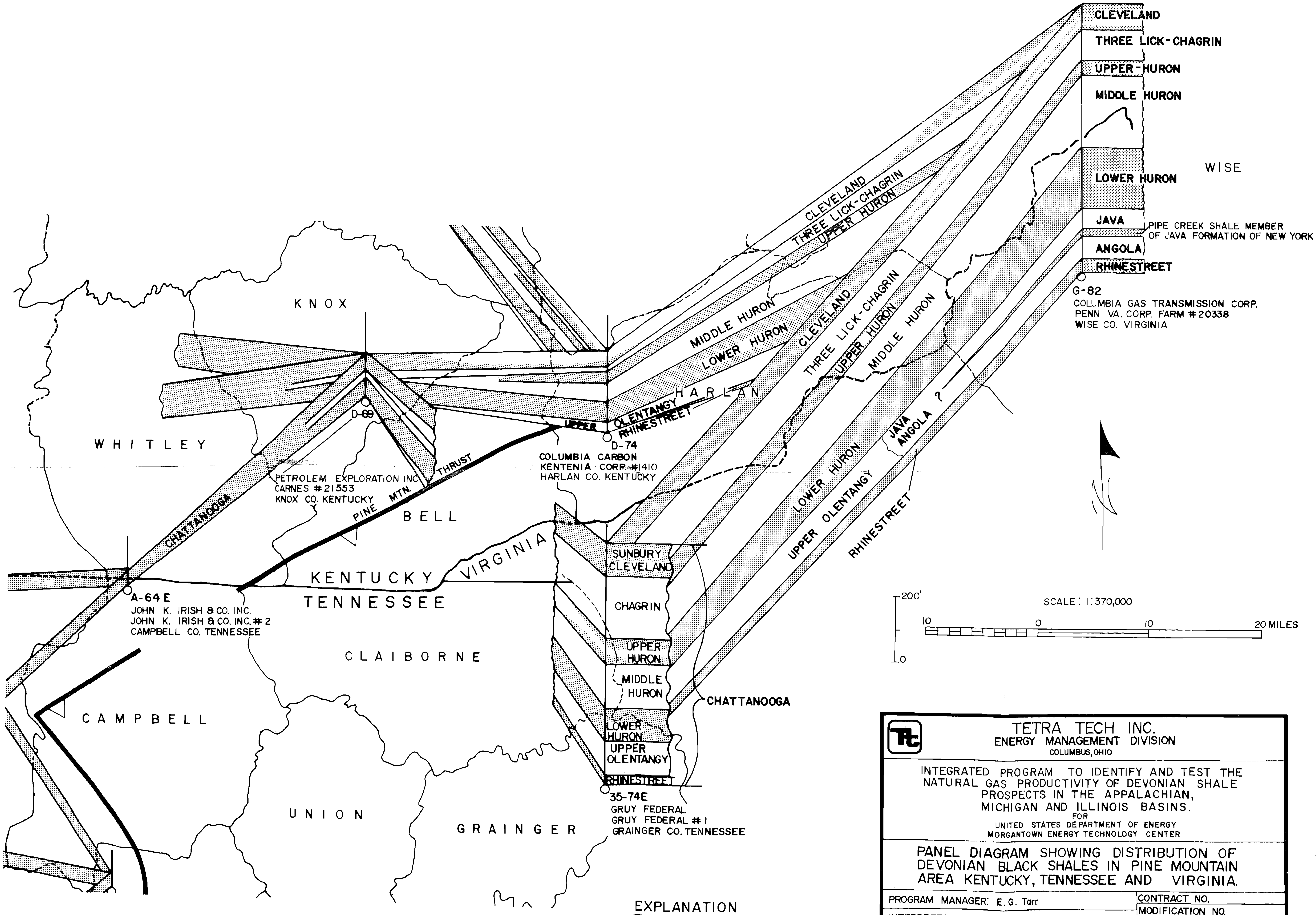


PLATE I

REGIONAL STRUCTURE MAP
EASTERN KENTUCKY / TENNESSEE

(COMPILED FROM VARIOUS SOURCES)



TETRA TECH INC.
ENERGY MANAGEMENT DIVISION
COLUMBUS, OHIO

INTEGRATED PROGRAM TO IDENTIFY AND TEST THE NATURAL GAS PRODUCTIVITY OF DEVONIAN SHALE PROSPECTS IN THE APPALACHIAN, MICHIGAN AND ILLINOIS BASINS.
FOR
UNITED STATES DEPARTMENT OF ENERGY
MORGANTOWN ENERGY TECHNOLOGY CENTER

PANEL DIAGRAM SHOWING DISTRIBUTION OF DEVONIAN BLACK SHALES IN PINE MOUNTAIN AREA KENTUCKY, TENNESSEE AND VIRGINIA.

PROGRAM MANAGER: E. G. Tarr	CONTRACT NO.
INTERPRETATION BY: T. J. SAINEY	MODIFICATION NO.
DATE: January, 1981 DRAWN BY: L. Y. Clements	REVISED: DATE / INITIAL
CONTOUR INT: DATUM:	DWG. NO.

PLATE 2