Gwilliam

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EVALUATION OF DEVONIAN SHALE POTENTIAL IN PENNSYLVANIA

Morgantown
United States Department of Energy
Technology
Center

GEOLOGIC SCREENING REPORT
FOR
EVALUATION
OF THE
EASTERN GAS SHALES
IN
PENNSYLVANIA

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PREFACE

This report is a geologic screening effort to evaluate areas within Pennsylvania 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.

C.A. Komar
Project Manager
Eastern Gas Shales

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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, 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 Pennsylvania. Geologic data and interpretations are summarized, and areas where the accumulation of gas may be large enough to justify commercial production are outlined. 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

Richly organic black shales of the Devonian clastic sequence are regarded as hydrocarbon source beds. In Pennsylvania, the major black shale formations are, in ascending order: the Marcellus, Rhinestreet, and Dunkirk, with lesser black shales being the Burket, Geneseo, Middlesex, and Pipe Creek.

The amount of organic matter deposited, the type of organic matter, and the extent of conversion of organic matter to hydrocarbon are all critical factors that must be assessed before the search for hydrocarbons begins. An organic carbon content of 0.5 percent by weight is a minimal value established for hydrocarbon generation. Most of what is considered to be black shales exceed this value. Organic types have been classified as derived from either marine, terrestrial, or mixed sources. Terrestrial-attributed organics are essentially only gas producing, whereas marine types generate both oil and gas. Devonian shales in Pennsylvania contain predominantly terrestrial and mixed types of organic matter. Thermal maturity, as measured by vitrinite reflectance, increases from northwest to the east and southeast, indicating increased depths of burial. For the individual black shale facies, levels of maturation of contained carbon in the northwest vary from shallow formations, Dunkirk and Rhinestreet being immature, to the deeper, more mature Marcellus Formation. In the central and east-central parts of Pennsylvania, deposited organic matter in all black shale facies can be considered mature.

In addition to being organically rich, most black shales need to be fractured before commercial production can be expected. Fracture systems can be related to structural movement and to the effects of glacial offloading. Principal areas where fracturing has occurred seem related to basement faulting and late and post Paleozoic overthrusting in the central Allegheny Plateau Province and along the Allegheny Front. Fractures believed to result from post glacial offloading occur along the shoreline of Lake Erie. Stress ratios are indexed numerically to indicate the concentration or extent of natural fractures in an area. Index data for Pennsylvania are so scant that only broad generalizations can be made.

Exploratory drilling should be directed to testing Devonian Shale strata that contain maximum organic richness and have undergone sufficient thermal maturation. Close attention must be directed to determining where fractures have occurred in localized areas of interest. Because most of the hydrocarbons encountered to date in Devonian shale have only minimal volumes, dual completions with other pay horizons should be considered.

Devonian shales most attractive for exploration are the Marcellus, Rhinestreet, and Dunkirk. Counties with optimum conditions for production from the Marcellus are Fayette, Westmoreland, Indiana, and Jefferson. Northwestern Lawrence, Mercer, eastern Crawford, and southeastern Erie Counties are favorable for Rhinestreet exploration. The potential for obtaining production from the Dunkirk shale is best along the shoreline in Erie County.

GEOLOGIC SETTING

The Appalachian basin is a northeast-southwest trending trough which stretches from Maritime Canada to Alabama, and includes all but the southeasternmost corner of Pennsylvania. A shale, Devonian in age, underlies approximately 250,000 square miles in the eastern United States, of which 160,000 square miles are located within the Appalachian basin (fig. 1, Schrider, et al., 1977). During the Paleozoic Era, the region was downwarped and filled with sediments. On at least three occasions during Paleozoic time, the region bordering the east flank of the basin was uplifted to form mountain ranges which shed clastic sediments westward into the basin. The latter two of these three orogenic (mountain making) events are of particular interest in the history of the Devonian shales. The first of the two began in Middle Devonian time; this episode was named the Acadian orogeny. The second of the two important orogenies that affected the

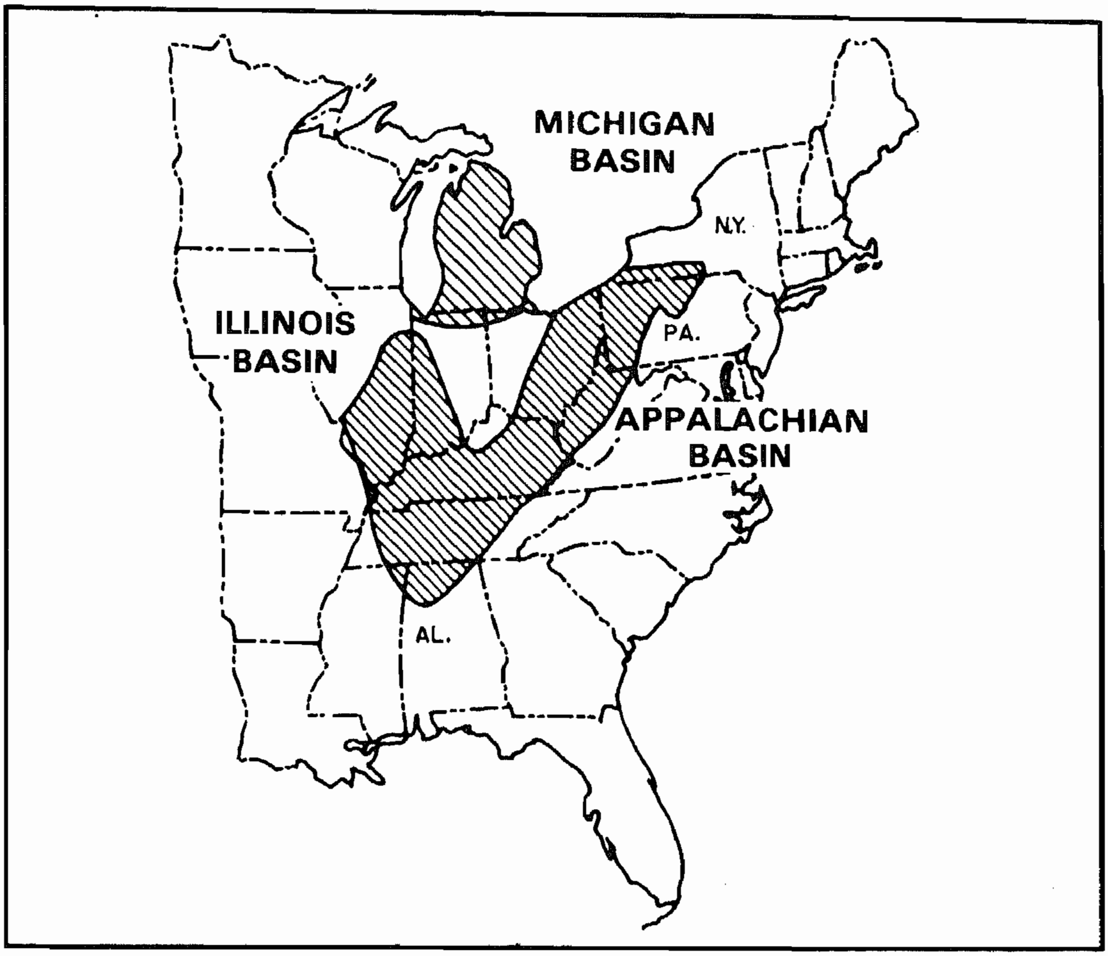

Figure 1. Eastern gas shales area of the gas bearing Devonian and Mississippian shale deposits. After Schrider, et al. (1977).

Devonian Shale was the Appalachian orogeny, which occurred near the close of the Permian Period.

The Acadian uplift was centered in the New England states and the Maritime provinces of Canada. In this orogeny, material eroded from the eastern highlands was deposited westward in a slowly subsiding Appalachian basin. The materials deposited were lithified later to form the sandstones, siltstones, and shales of the Devonian clastic sequence. As the Acadian highlands began to be uplifted and clastics were being spread into the basin, an order of deposition was quickly established, with red beds being deposited in the east closest to the clastic source, by sands farther west, silts westward beyond that, and, in the deepest part of the basin, very fine organic debris and clays. This then became the progressive westward development of the Catskill Delta throughout Devonian time (fig. 2).

Concurrent with the Appalachian orogeny, the entire Appalachian region, including what had been the Appalachian basin, was uplifted. The mountains now exposed in the area are the results of this last uplift and of subsequent erosion.

During the Appalachian orogeny, the eastern flank of the Appalachian basin was intensely folded, faulted, overthrust and intruded by igneous masses. In general the area can be characterized by 2 broadly delineated physiographic provinces: 1) the Allegheny Plateau Province, an autochthanous foreland block lying to the west which has relatively little deformed strata, and 2) the folded and thrust Appalachian Mountains allochthanous block lying to the east, characterized by highly thrust-faulted strata. The Allegheny Plateau Province in Pennsylvania is characterized by a series of gently folded anticlines. Lying within this province is the little deformed Devonian shales, and it is here that the search for Devonian shale gas has taken place to date.

STRATIGRAPHY

MIDDLE DEVONIAN ROCKS

The total interval of the Devonian Shale from the Mississippian-Devonian boundary to the base of the Marcellus Shale Member of the Hamilton Group (top of the Middle Devonian Onondaga Limestone) thickens to the southeast from approximately 1,500 feet in the northwest corner of the state by the Lake Erie shoreline to greater than 8,000 feet along portions of the Allegheny Front (fig. 4). In figure 5, stratigraphic units in western Pennsylvania are correlated with stratigraphic sections in New York and Ohio, clarifying stratigraphic terminology. (Stratigraphic terminology in Pennsylvania can be complex and confusing, especially in instances where New York nomenclature is mixed with Pennsylvania nomenclature and where drillers' terms have been interjected.)

Piotrowski and Harper (1979) separated the Devonian sequence into sandstone and shale facies. The sandstones in the Upper Devonian Series, even though they are proven hydrocarbon reservoirs, are not considered here since these sands do not constitute an unconventional source of gas. (The interested reader should refer to Piotrowski and Harper (1979) for a detailed explanation of these sand zones.) The Devonian-shale sequence consists of brownish-black, organic-rich shale and greenish-gray, organic-poor shale or mudstone (Provo, 1977). Of less importance are some limestones, in particular

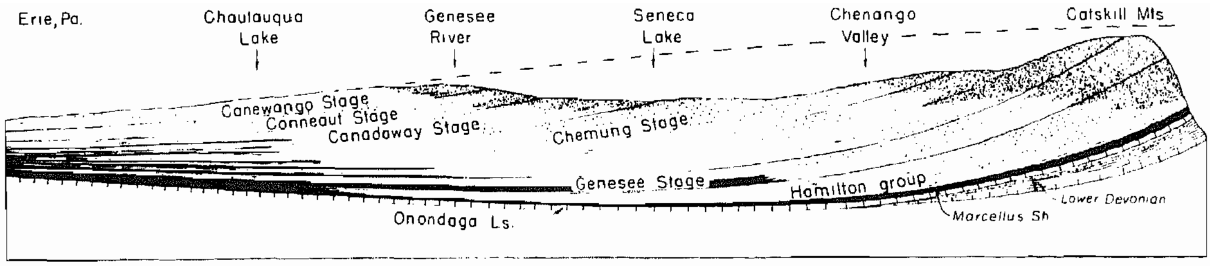

Figure 2. Cross section of the Catskill delta from the Hudson Valley to Erie, Pennsylvania. From Dunbar and Waage (1969).

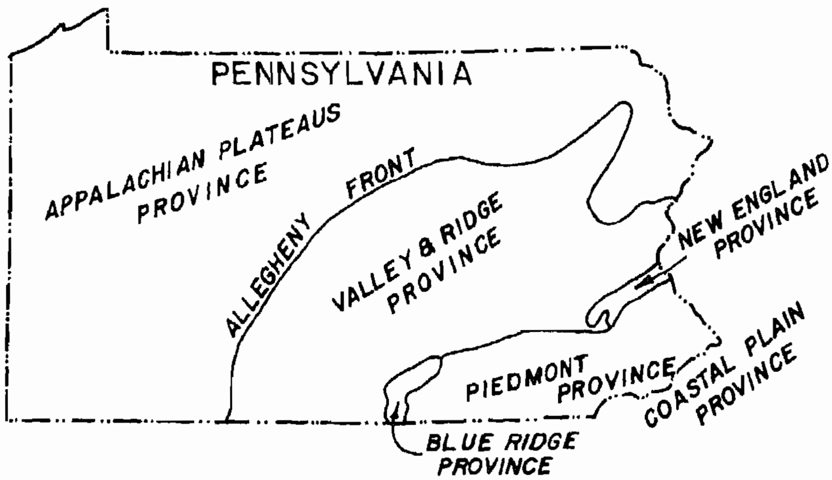

Figure 3. Map showing physiographic provinces present in Pennsylvania.

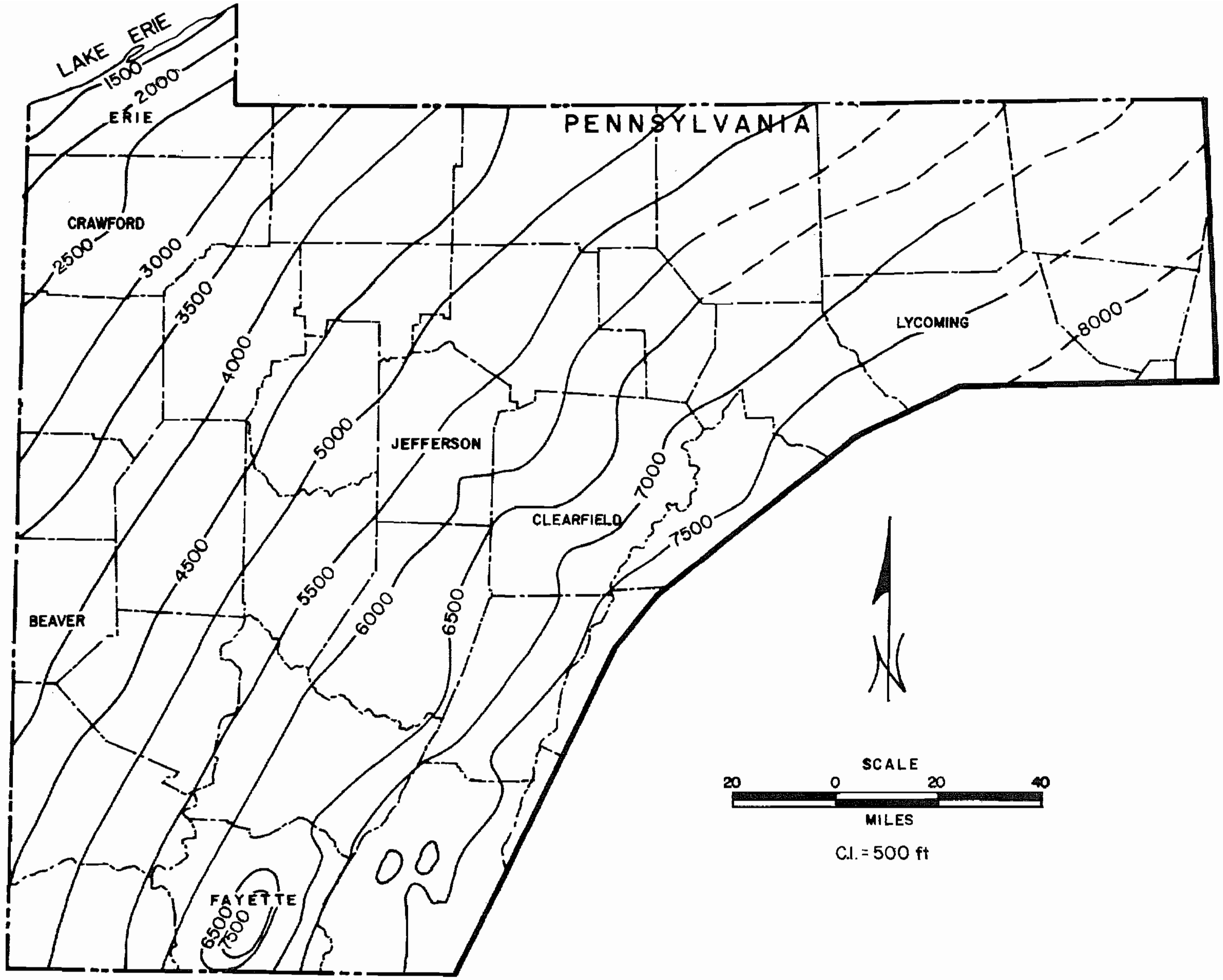

Figure 4. Isopach map of the interval from top of Devonian series to base of the Marcellus Formation.

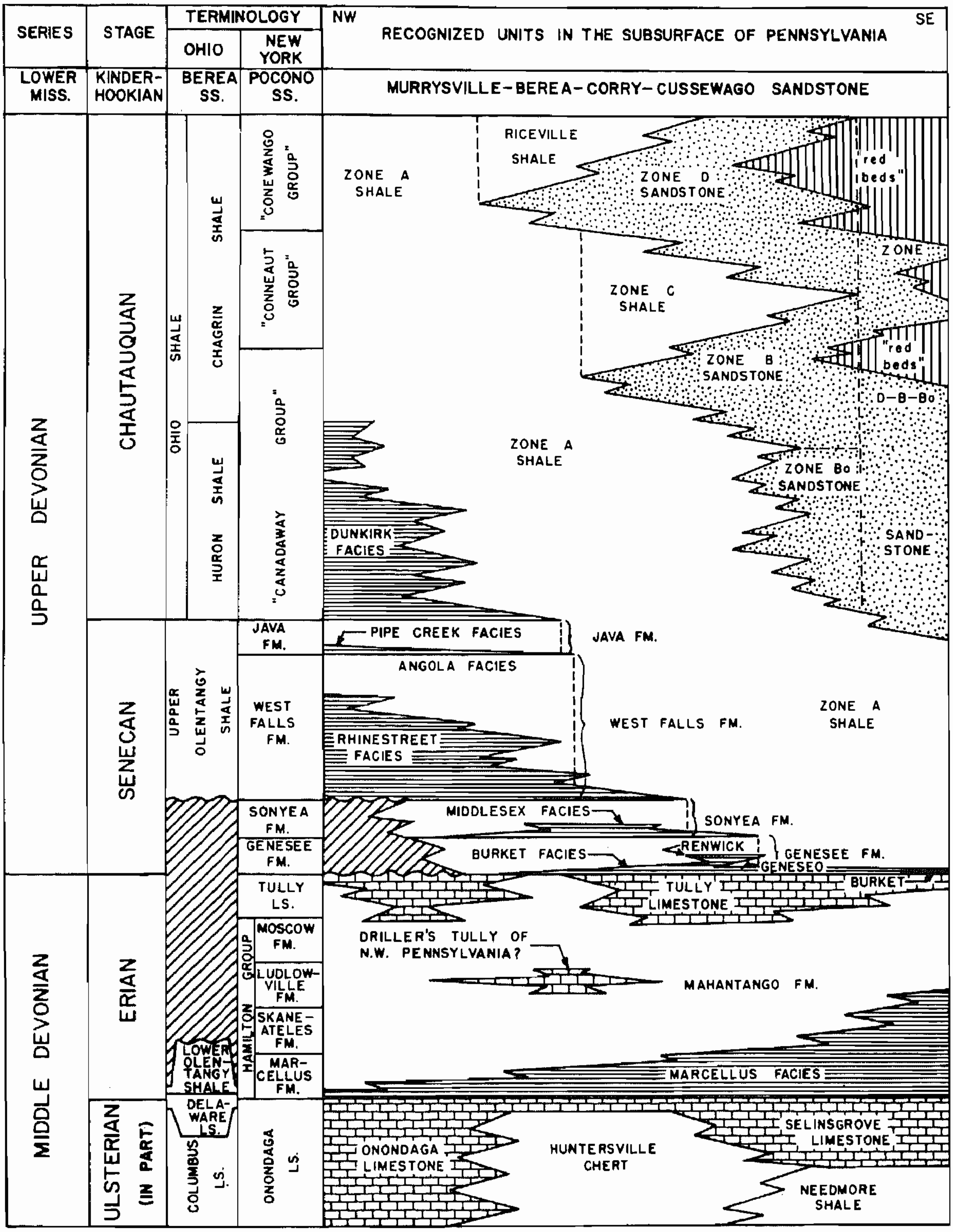

Figure 5. Schematic illustration of Upper and Middle Devonian stratigraphic units in the subsurface of western Pennsylvania and correlation with New York and Ohio stratigraphic sections. In part, after Oliver, et al. (1969) and Patchen (1977).

the Tully Limestone as well as the Middle Devonian Sandstone and red beds of the Upper Devonian series.

Hamilton Group

In Pennsylvania, two formations comprise the (basal) Hamilton Group of the Middle Devonian shale sequence: The Marcellus Formation and the superjacent Mahantango Formation. The Marcellus contains a black radioactive shale facies, which is present everywhere within the Allegheny Plateau Province of Pennsylvania, ranging in thickness from less than 25 feet in northwest Pennsylvania to 250 feet along the Allegheny Front (fig. 6). The Mahantango throughout most of the state is a thick gray-green shale that contains interbedded siltstones and limestones. Total thickness for the Hamilton Group ranges from less than 200 feet in northwestern Pennsylvania to over 1,800 feet along the north-central portion of the Allegheny Front.

Tully Limestone

The Tully Limestone or limestones that occupy a stratigraphic position similar to the Tully Limestone have been used as stratigraphic markers. The top of the Tully has been placed at the base of the Upper Devonian sequence (fig. 7).

UPPER DEVONIAN ROCKS

Genesee Formation

Immediately overlying the Tully Limestone is the Genesee Formation of Lower Upper Devonian age. Like the formations underlying it, the Genesee displays maximum development along the Allegheny Front and thins dramatically to the northwest. Within this predominantly gray-green shale lies the black organic-rich Burket facies. Although commonly only 25 feet thick throughout much of the study area, the Burket can be followed laterally for great distances (fig. 8); only in the northwest corner of Pennsylvania does it pinch out. In the central part of the Allegheny Plateau, it gradually thickens and becomes divided into the Renwick and Genesee shales. Maximum thickness of the radioactive units of the Genesee is attained in the northeastern area adjacent to the Allegheny Front. To this point, as with overlying formations, the source of clastics has been from the southeast with the sequence thinning toward the northwest. The greater development of organic shale in the north-central area suggests to Piotrowski and Harper (1979) that, at least for this short period of time, the soruce for the Burket-Renwick-Genesee rocks was from the northeast.

Sonyea Formation

The Sonyea Formation, as do the previous mentioned formations, thickens to the southeast and pinches out to the northwest. A thin basal organic black shale facies, the Middlesex, can be mapped over short distances, but grades laterally to the east into gray-green shale. As gradation occurs, the Sonyea and the underlying Genesee become indistinguishable lithologically (plate 1).

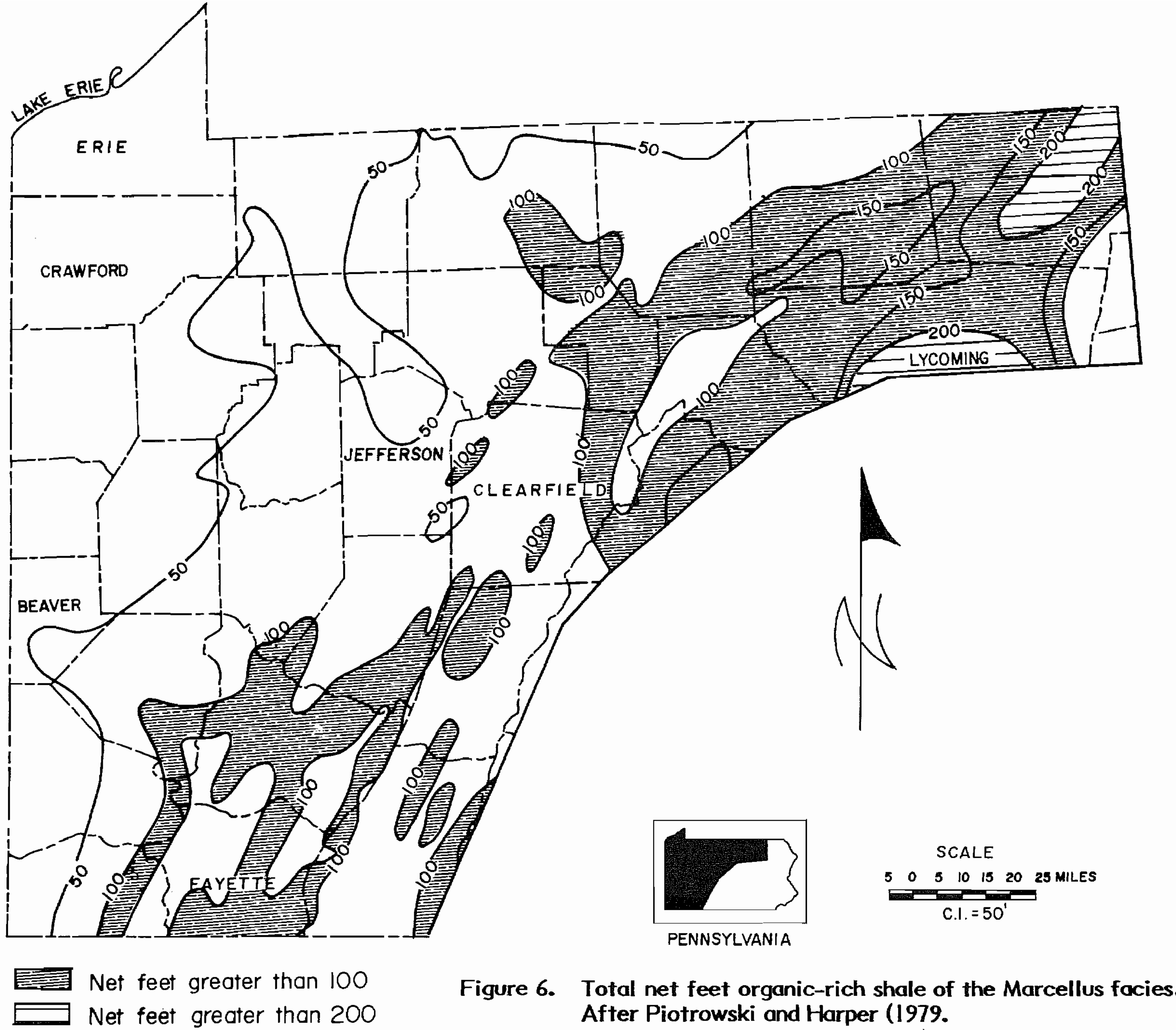

Figure 6. Total net feet organic-rich shale of the Marcellus facies. After Piotrowski and Harper (1979.

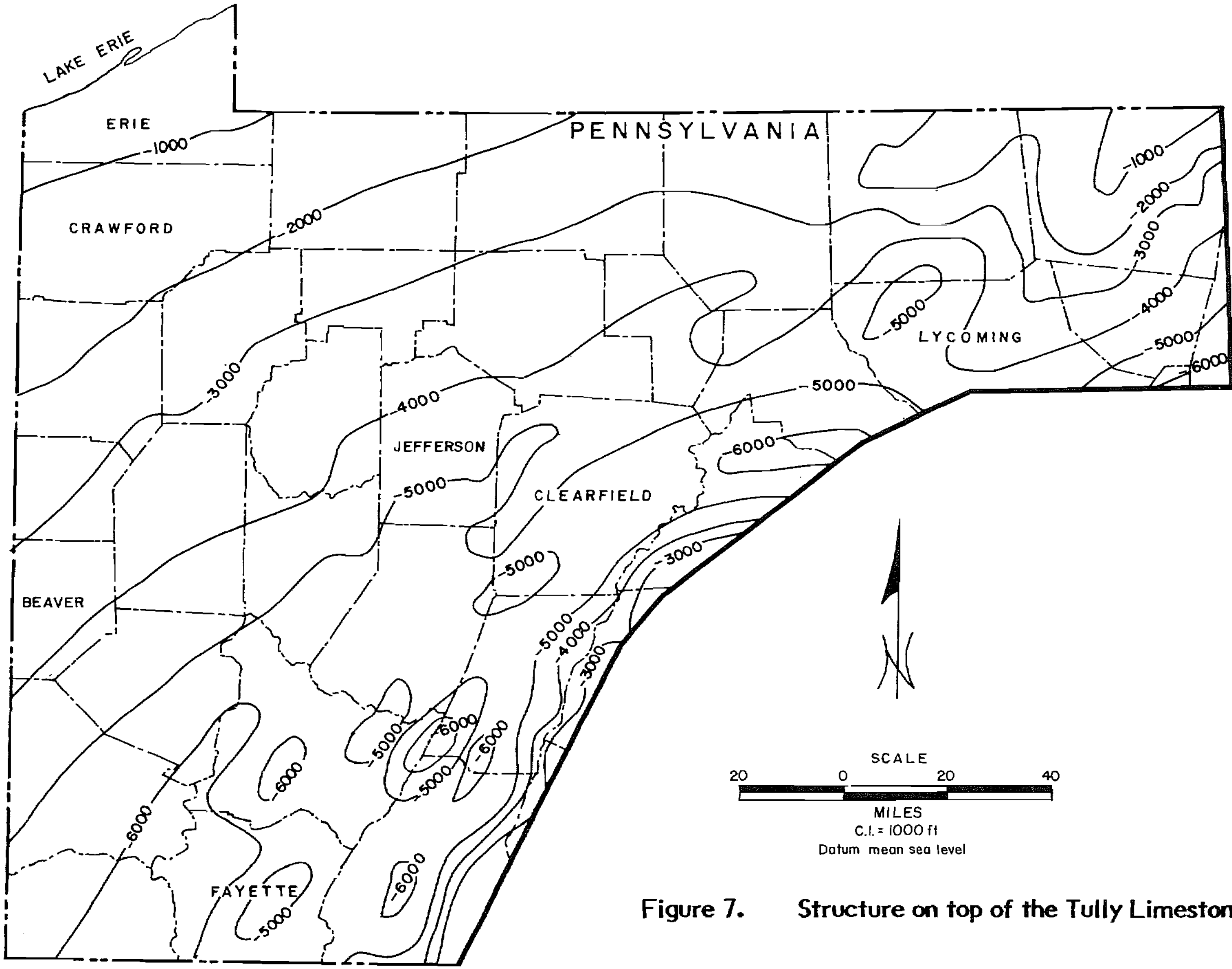

Figure 7. Structure on top of the Tully Limestone.

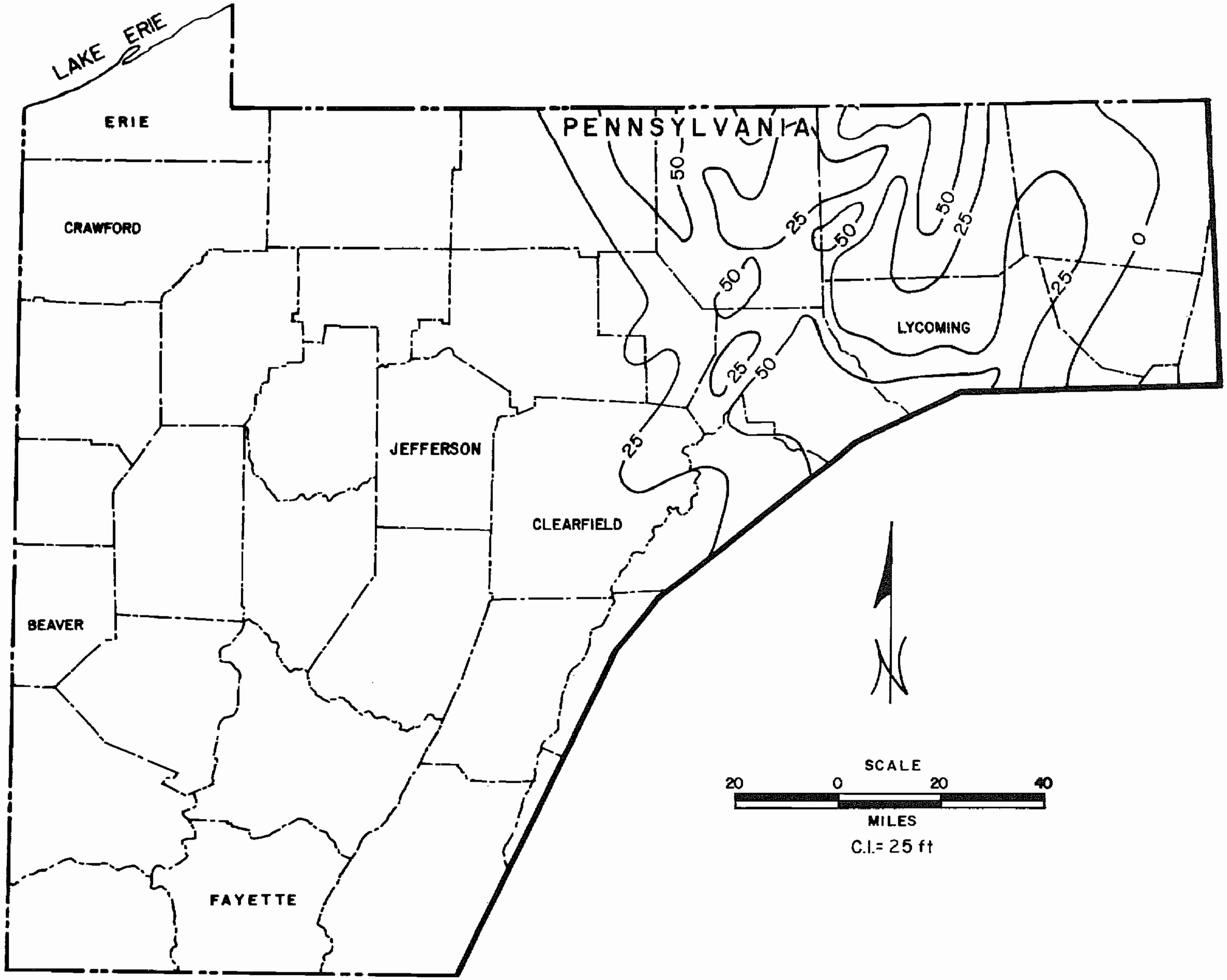

Figure 8. Isopach map of Burket-Geneseo-Renwick radioactive shale facies. After Piotrowski and Harper (1979).

West Falls Formation

A massive radioactive black shale overlies the Sonyea in northwestern Pennsylvania. This shale, the Rhinestreet, along with the overlying, organic-poor Angola Shale, make up the West Falls Formation, which is approximately 1,000 feet thick in the central part of the Allegheny Plateau. To the east, lateral gradation into the eastern clastics is such that lithologic boundaries can no longer be defined. The massive organic Rhinestreet facies thins to the southeast, losing its characteristic radioactive signature, and can no longer be traced (fig. 9). The Angola facies thickens to the southeast, where it becomes indistinguishable from the southeast thinning organic-rich facies of the Rhinestreet.

Java Formation

The Java Formation is observed in northwestern Pennsylvania where its lower boundary is the radioactive Pipe Creek Shale, and its upper boundary is the base of the massive radioactive Dunkirk Shale of the Canadaway Group. The Java thickens to the southeast, but as the overlying Canadaway and underlying West Falls become organically lean, lithologic boundaries become unidentifiable.

Dunkirk Formation

The Dunkirk Shale forms the base of the Canadaway Group. Thickest accumulations of this organic-rich radioactive member occur in the northwest corner of the state (fig. 10). To the southeast, the shale becomes increasingly organic poor to the point where it is undefinable lithologically. Laterally, the Dunkirk grades to sandstone and red bed facies. The Southwales Shale Member of the Perrysburg Formation overlies the Dunkirk.

Black Shale Facies

To generate hydrocarbons, an organic-rich source must be present. Three major shale facies, which have recorded either production or shows, are considered organic-rich: the Middle Devonian Marcellus Shale of the Hamilton Group, the Upper Devonian Rhinestreet Member of the West Falls Formation, and the Upper Devonian Dunkirk Member of the Perrysburg Formation in the Canadaway Group. (Initial shale studies used 20 API units above a shale baseline on a gamma-ray log to indicate an organic-rich shale based on a high radioactive response.)

The radioactive Marcellus of the Hamilton Group is commonly less than 25 feet thick in northwestern Pennsylvania and 150 to 250 feet along the Allegheny Front (fig. 6). The total net thickness of the Upper Devonian shales varies from 1,500 fet along Lake Erie to 4,000 feet along the eastern boundary of the study area. Within this area are the Rhinestreet and Dunkirk facies of which the organic-rich shales attain thicknesses of greater than 250 feet in northwest Pennsylvania and thin to less than 50 feet in the central portion of the Allegheny Plateau area (fig. 11).

Other organic-rich shales, in ascending order, are the Burket Member of the Harrell Formation, and equivalent of the Genesee Formation, the Middlesex Member of the

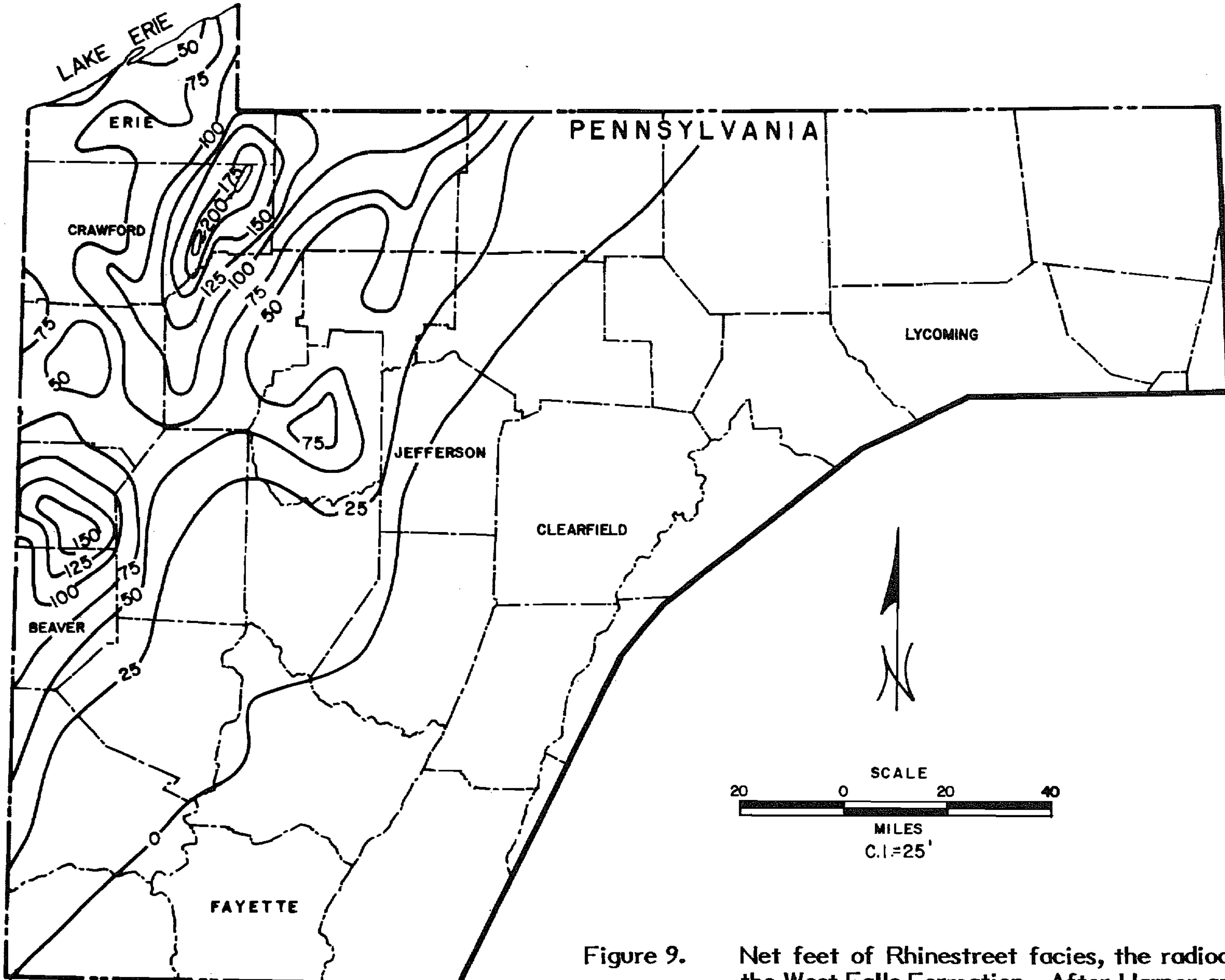

Figure 9. Net feet of Rhinestreet facies, the radioactive unit in the West Falls Formation. After Harper and Piotrowski (1979).

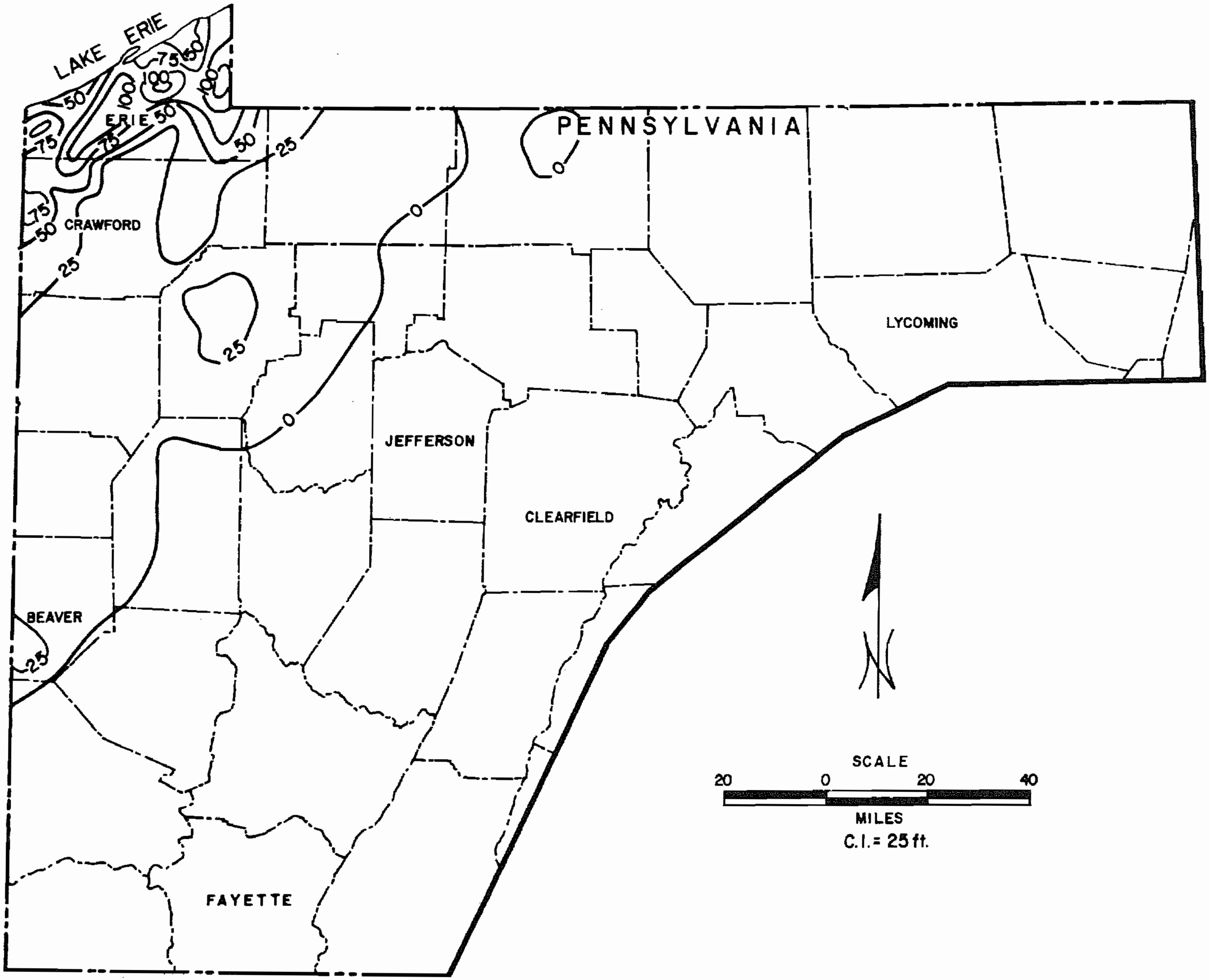

Figure 10. Net feet of Dunkirk facies, the radioactive unit in the Canadaway Group. After Piotrowski and Harper (1979).

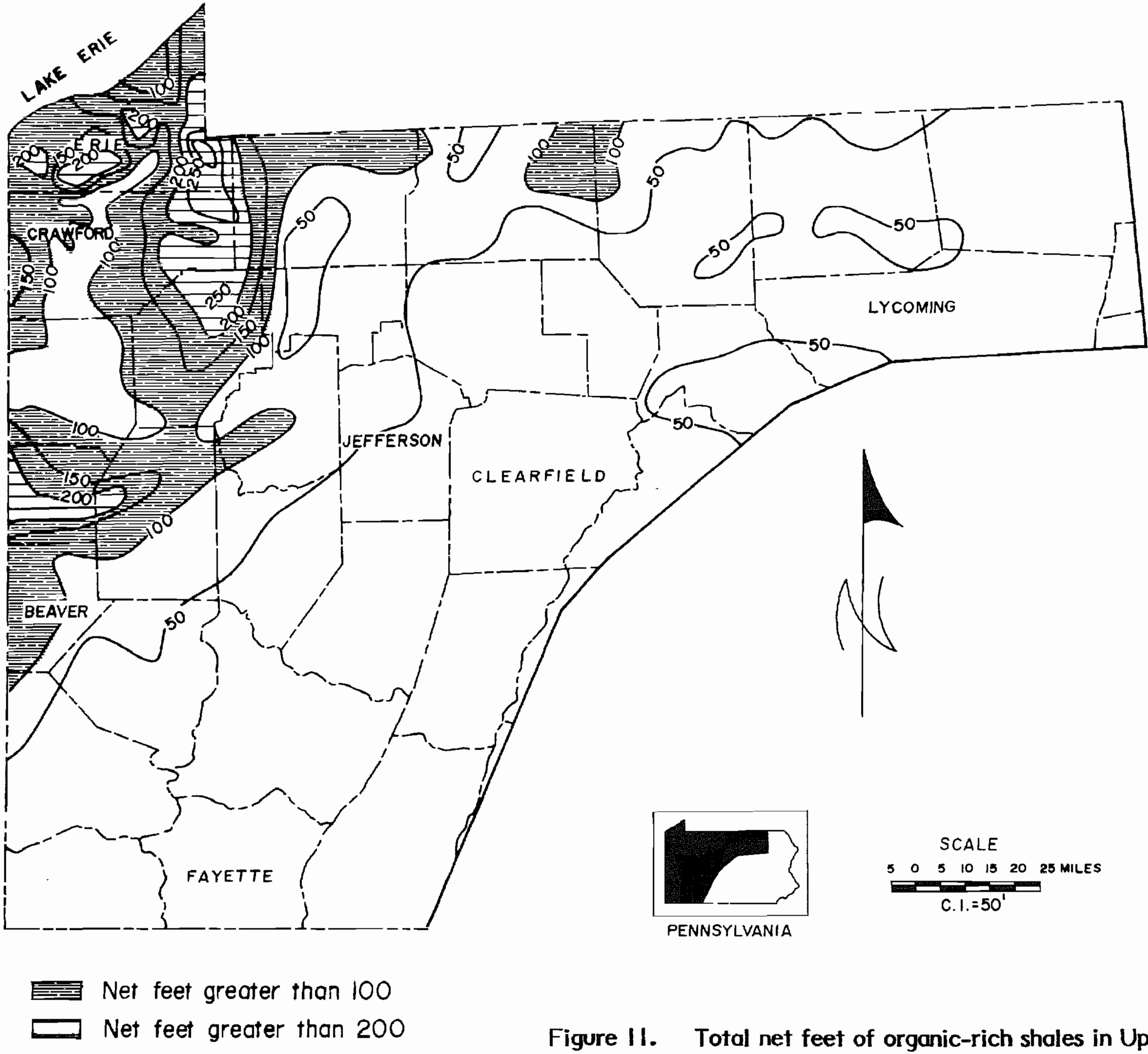

Figure 11. Total net feet of organic-rich shales in Upper Devonian strata. Primarily Dunkirk and Rhinestreet.

Sonyea Formation, and the Pipe Creek Member of the Java Formation. Because these members rarely are thicker than 75 feet, their potential as a hydrocarbon source and reservoir appears limited. However, they are, in many instances, widespread and could be used as marker beds to define lithologic boundaries in underlying and overlying formations. Furthermore, even marginally economic production from these thin beds might be commingled or coproduced with gas from higher yielding, thicker pays.

The internal stratigraphic relationships of the Devonian shale units are shown in the panel diagram (plate 1). The Marcellus is the dominant unit in the central and eastern part of the Allegheny Plateau province. The Rhinestreet becomes dominant to the northwest as the Marcellus thins. The Dunkirk attains its maximum organic-rich character in the northwest (fig. 2).

STRUCTURE

The Appalachian basin, in which large volumes of Devonian shale occur, extends northeast-southwest from New York to Alabama. The Pennsylvania segment of the basin is bounded to the west by the Cincinnati Arch, in western Ohio. The eastern limit of the Appalachian basin is under the Piedmont in extreme western Pennsylvania. Cambrian seas deposited large sections of carbonates in a depression that developed on the Precambrian surface. Crustal instability caused movement upwards of the landmass to the east resulting in the Taconic orogeny of Late Ordovician time which filled the basin with great quantities of clastic material. Again, in Middle Devonian time, new uplift, accompanying the Acadian orogeny, deposited masses of marine and terrestrial materials in the same subsiding basin. It was from this orogeny that the great clastic wedge named the Catskill delta was built. A continuing orogeny, throughout the late Paleozoic, culminated in the Appalachian orogeny which occurred near the close of the Paleozoic.

Within Pennsylvania two distinct physiographic provinces occur: The Valley and Ridge, and the Allegheny Plateau (fig. 3), the Allegheny Front forming the boundary between the two. The Valley and Ridge Province is characterized by strongly folded and faulted rocks resulting from thrust faults generated by the Appalachian orogeny. Beyond the Allegheny Front, the effect of these thrusts is less noticeable at the surface. The bulk of exploration for hydrocarbon has been conducted in the Allegheny Plateau area for two basic reasons: (1) rocks within the Valley and Ridge Province have been thought to be metamorphosed (changed) to such a degree that hydrocarbons are not present, and (2) the present day lack of precise geologic knowledge concerning structure in the Valley and Ridge makes it a very high risk, high cost prospect precluding easy exploration for the smaller operators. Figure 12 is a map showing depths from the surface to the top of the Onondaga Limestone, that is, the base of the Devonian Shale sequence.

Though not within the scope of this report, it should be noted that the folds and faults are a series of thrusts which have miles of displacement originating from the southeast (Harris and Milici, 1977). These thrust sheets have ramped or slid along on the top of nonrigid formations and buried younger rocks; by drilling through the older rocks, an untapped Devonian shale resource may be discovered.

More importantly, one of the results of this tectonic action was to impose a strain on rocks so as to fracture them; such fractures are important in the production of

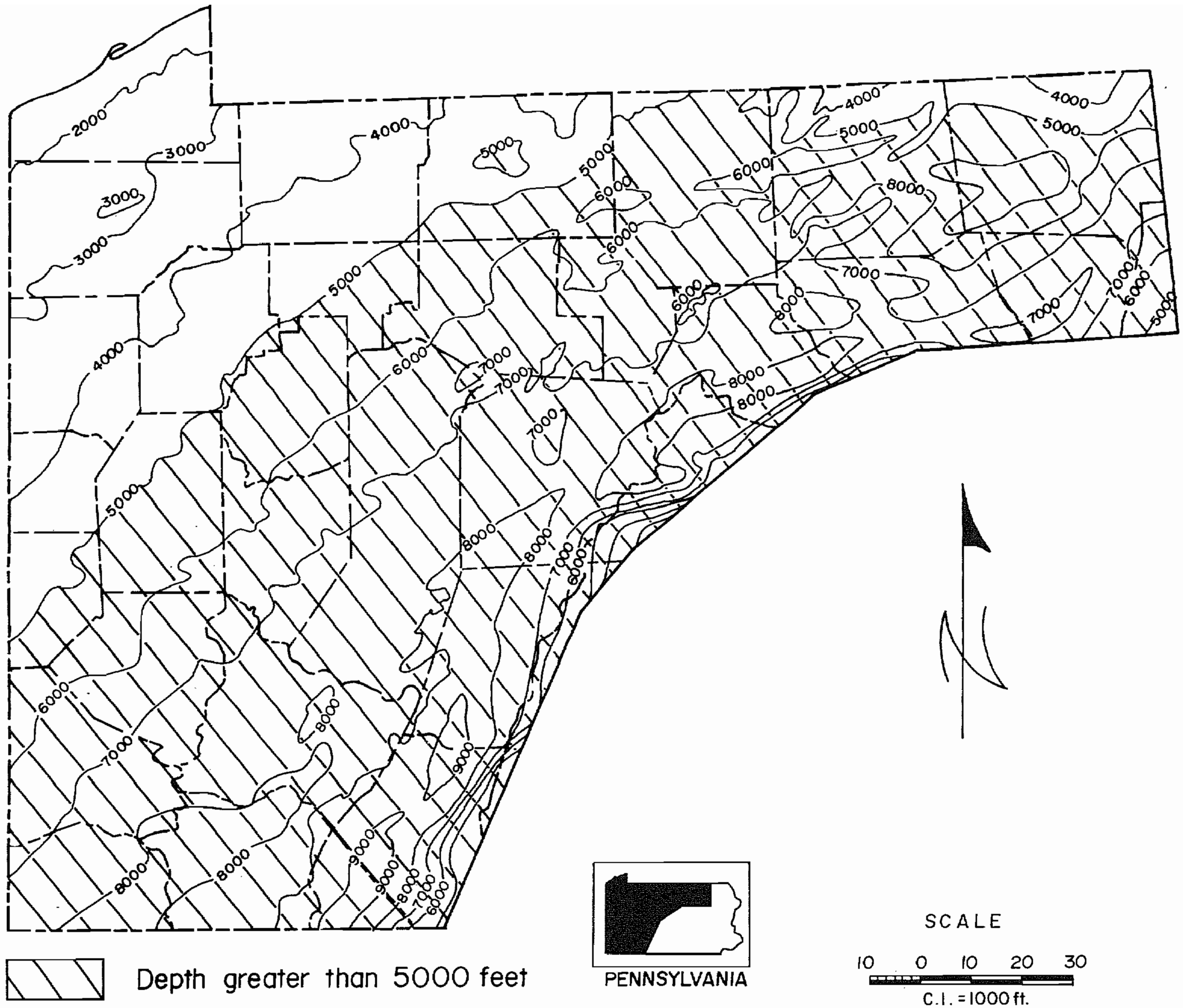

Figure 12. Average drilling depth from the ground surface to the top of the Onondaga Limestone at the base of the Devonian-Shale sequence.

hydrocarbon. An additional fracture-producing mechamism may have been generated by glacial offloading. Fractures occurred as glacial ice was removed and the overloaded rocks readjusted by isostacy. Fractures produced by offloading occur in northwestern Pennsylvania along the Lake Erie shoreline where the base of the shale is commonly less than 1,000 feet below sea level. Exploration in Pennsylvania would have to be limited to the Lake Erie shore area since 800 feet is the depth limit for this type of fracturing (Tarr, 1980).

GEOCHEMISTRY

Evaluation of potential oil and gas sources requires consideration of the amount of organic matter originally deposited in the rock at that location, the relative proportions of different types of organic matter and the original capacity of each for gas generation, and the degree of conversion of the organic matter to hydrocarbon (Claypool, et al., 1978). The amount of organic matter depends on conditions of deposition, rates of accumulation, proximity to sediment source, and rates of organic productivity. Consideration of the types of organic matter will require consideration of different source provenances for the Devonian shales in the Appalachian basin, as established by Maynard (1978) in carbon isotope studies. Post-depositional diagenesis and eometamorphism caused by heating and depth of burial affects the actual conversion from organic matter to hydrocarbon.

Ronov (1958) has determined that 0.5 percent organic carbon (by weight) is the lowest value of organic carbon that can be present in a shale for it to be classified as a source rock. Claypool and Stone (1979) and Zielinski at Mound Facility have determined organic carbon contents for numerous samples of the Devonian Shale from various locations throughout the Appalachian basin. Mean values for the Marcellus, Rhinestreet, and Dunkirk Shales in Pennsylvania have been tabulated and plotted on figures 13, 14, and 15.

The lower value of 0.5 percent organic carbon has been exceeded significantly for all organic-rich facies in Pennsylvania. There appears to be a positive correlation between areas of shows and/or production with areas of increasing organic carbon content. Therefore, these maps may be useful in establishing a trend in which to conduct future investigative work.

The type of organic matter present in the shale, whether marine or terrestrially derived, is important in gas generation because terrestrial carbon appears to yield more methane than marine-derived carbon (Maynard 1978). A relationship based upon values for the ratio of C^{13} to C^{12} (carbon 13 and carbon 12) for Devonian shales is -25 to -26 for shales with terrestrially derived carbon, and -27 to -31 for shales with marine derived carbon. Figure 16 and table 1 show C^{13} variations and the relationship with terrestrial organic matter being controlled by the dominant highlands to the east and northeast, while farther west, away from the source, more negative C^{12} values indicate a shale with a much higher concentration of marine organic derived matter.

Work by Potter, et al., (1980) has led to three conclusions. The source of the Devonian organic matter was from the Acadian orogenic highland, which is indicated by C^{13} to C^{12} ratios showing increasing negative values from east to west within given stratigraphic intervals suggesting a marine organic influence in the west part of the basin.

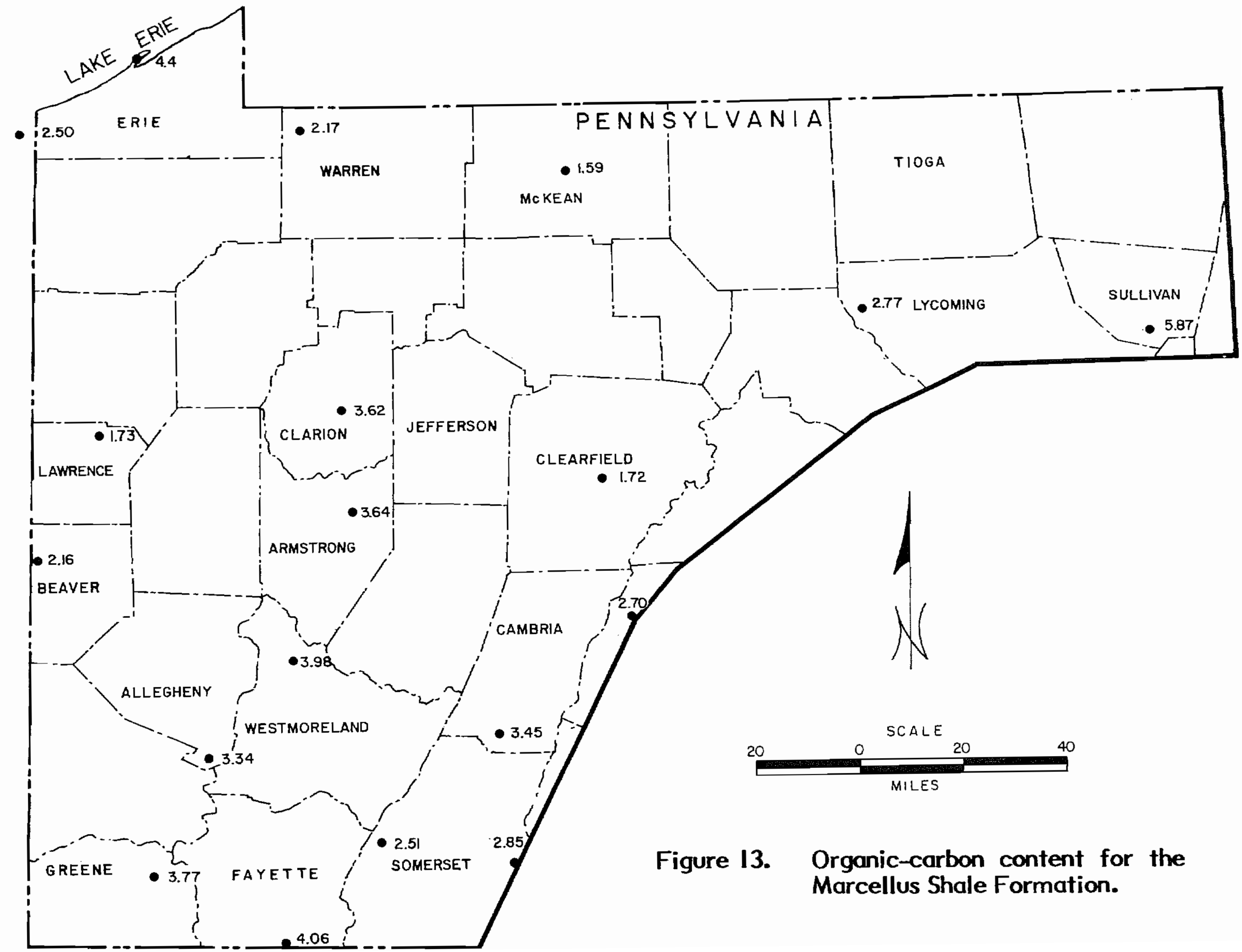

Figure 13. Organic-carbon content for the Marcellus Shale Formation.

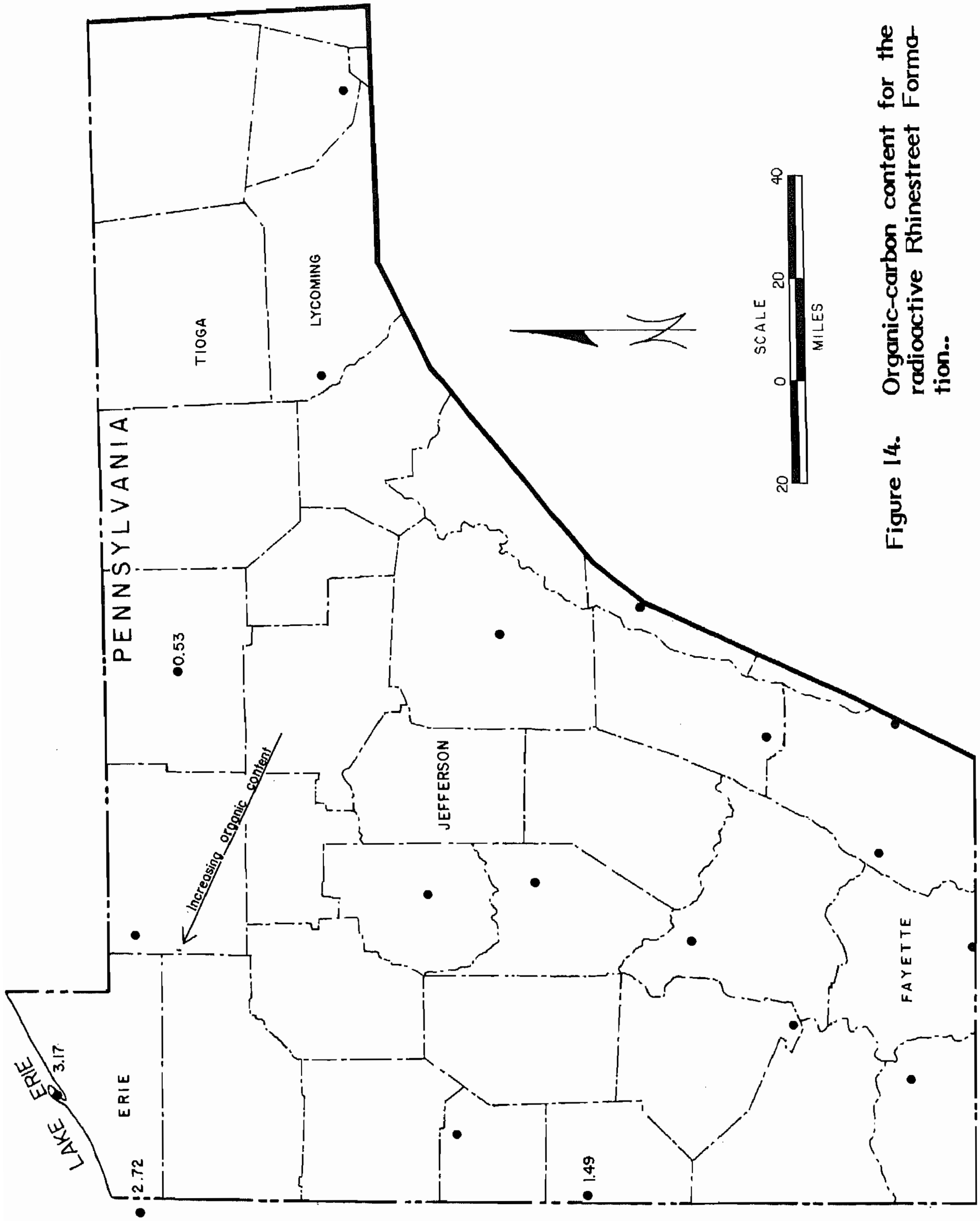

Figure 14. Organic-carbon content for the radioactive Rhinestreet Formation.

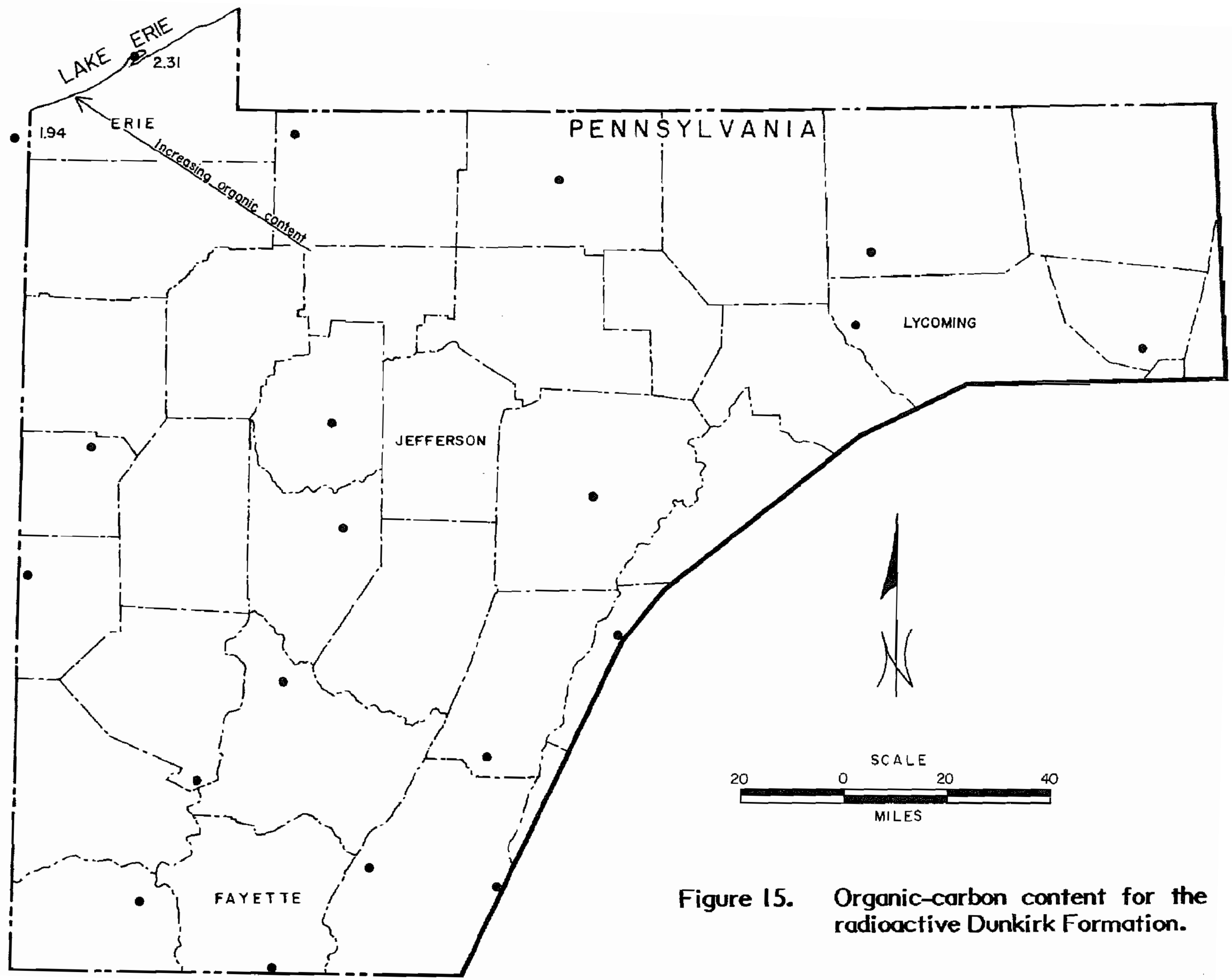

Figure 15. Organic-carbon content for the radioactive Dunkirk Formation.

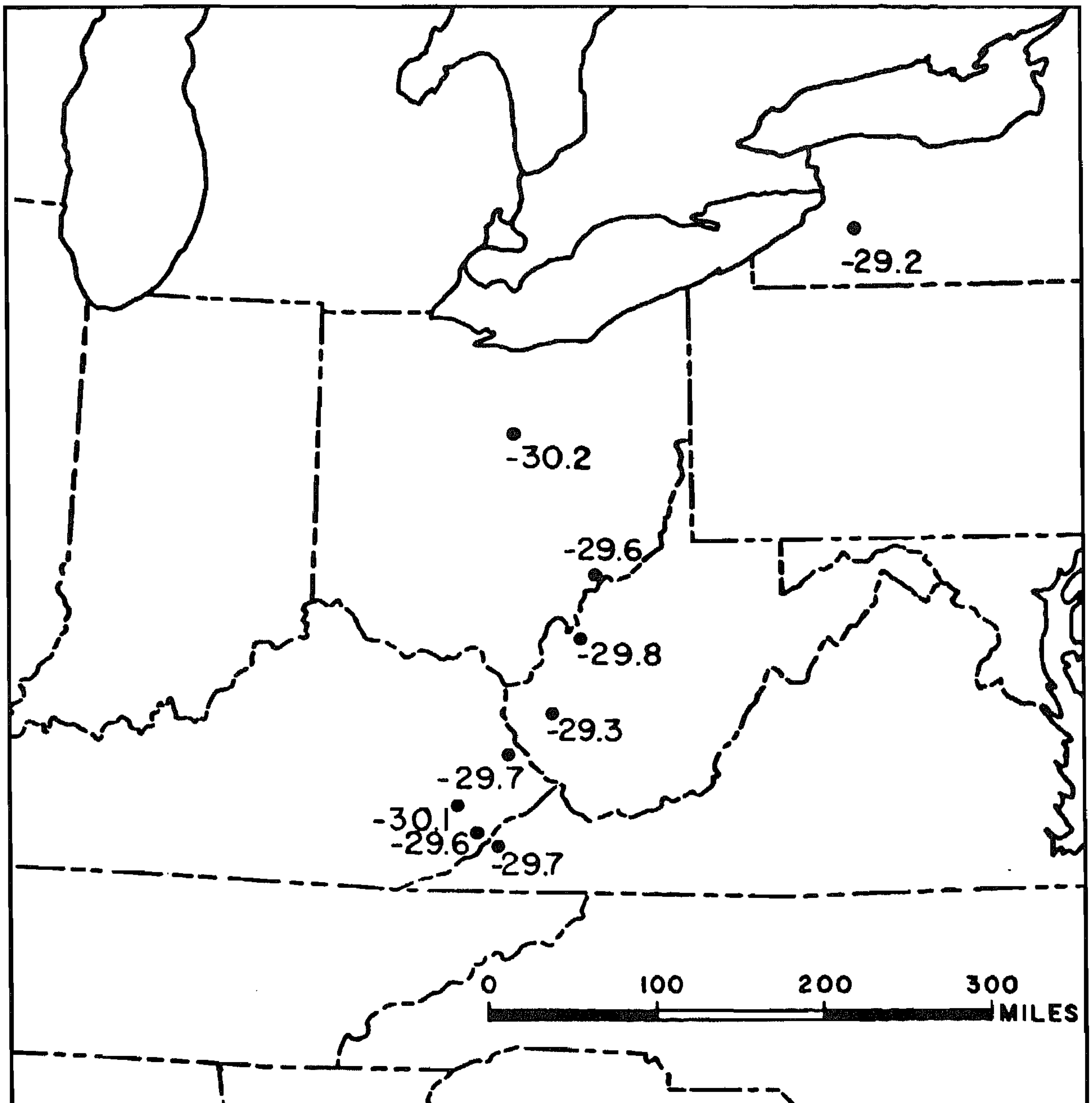

Figure 16. Distribution of carbon isotopes in the Lower Huron Member of the Ohio Shale equivalent to the Dunkirk Shale of New York. After Maynard (1978).

Table 1. Stratal variations in carbon isotopes (After Maynard, 1978)

Stratagraphic unit	Average C^{13}	Number of samples
Appalachian basin		
Marine samples		
Sunbury	-30.3	4
Bedford	-27.7	5
Cleveland	-28.8	25
Chagrin-Three Lick Bed	-27.3	12
upper Huron	-29.3	6
middle Huron	-28.9	12
lower Huron (Dunkirk)	-29.7	31
Java		
Hanover (Upper Olentangy)	-29.4	4
Pipe Creek	-29.1	1
West Falls		
Angola	-27.2	1
Rhinestreet	-29.7	7
Nonmarine samples		
Catskill Shale, Giboa, New York	-24.8	1
Wood fragment, Olentangy Shale, Ohio	-25.6	1
Wood fragment, Huron Shale, Kentucky	-26.8	1
Illinois basin		
Grassy Creek	-29.8	10
Swetland Creek	-29.8	7
Blocher	-30.3	2

Organic content decreases from west to east. Marine organic Devonian shales are the best sources for both oil and gas, while terrestrial sources develop only gas.

C^{13} to C^{12} ratio studies have not been performed on formations below the Dunkirk; therefore, the boundaries between a terrestrial source and a marine source are not known. Potter, et al. (1980) also conclude that the amount of carbon and thermal maturity are the most important factors to be considered in hydrocarbon exploration.

Assuming hydrocarbons are capable of being formed, the extent of thermal maturation must be assessed. Thermal maturity is a function of intensity and duration of postdepositional heating, or load metamorphism, due to the maximum depth of burial (Claypool, et al., 1978). In the Appalachian basin, thermal maturity increases from west to east. Methods that can be used to determine maturity are conodont (fossil) color alteration, methane-carbon isotope ratios, and vitrinite reflectance and thermal alteration index (TAI).

Harris (1978) has done a study on conodont alteration in which she concludes that, as metamorphism progresses, the color of conodonts changes from brown to black during incipient metamorphism (50-300°C), to gray-white and clear as thermal metamorphism (300-500°C) continues. A color alteration index (CAI) has been established from which isograd (lines of equal metamorphism) maps can be constructed (figs. 17 and 18). CAI values range from 1 to 5, 5 representing the greatest color alteration caused by increasing temperatures with depth and pressure. In the Appalachian Plateau Province, the CAI is between 1.5 and 3.0 for the Devonian shale sequence, indicating temperature at a maximum burial to be between 50 and 200°C. Figure 19 shows the placement of the CAI and isograd with respect to oil and gas production in the Silurian-Devonian rocks of the Appalachian basin. Beyond the limits of these isograds, the likelihood of finding commercial quantities of hydrocarbons is remote since this area is below the oil or gas floor limit (fig. 20). (Harris' work deals with conodonts in Paleozoic limestones, but is applicable to conodonts in shale as well.)

The carbon isotope ratio of methane in natural gas, which indicates the degree of conversion of organic matter to hydrocarbon, has been computed by Claypool, et al. (1978) for the Devonian shales (fig. 21). Claypool, et al. (1978) have also shown the relationship between the degree of conversion of organic matter to gas, and chemical and isotopic composition of gas, in the Devonian rocks of the Appalachian basin. Figures 22 and 23 show that, for the Appalachian Plateaus Province, conversion to gas has been almost 50 percent completed. A progression westward across the basin shows the conversion to gas being less complete. (Also, Harris shows decreasing CAI values, indicating lower levels of maturation.) Thus we see a correlation between CAI values and the extent of hydrocarbon generation.

Vitrinite reflectance probably provides the best means of determining thermal maturity in shales (Potter, et al., 1980). Vitrinite is an organic, coal-like mineral, which has a vitreous (shiny) surface. A certain amount of light, when focused upon a vitrinite sample, will be reflected. The percentage of reflected light is measured and directly relates to the maturity of the sample. The more reflectance the sample exhibits, the more metamorphism it has undergone. Figure 20 shows the relationship that exists between vitrinite reflectance, and hydrocarbon generation. Early generation of oil occurs at about 0.5 for vitrinite reflectance and extends to 1.4. A wet gas or condensate zone exists between 1.4 and 2.0; beyond 2.0, only dry gas exists. Figure 24 illustrates plotted indices of reflection for the Appalachian basin. An eastern limit gas and oil line has been

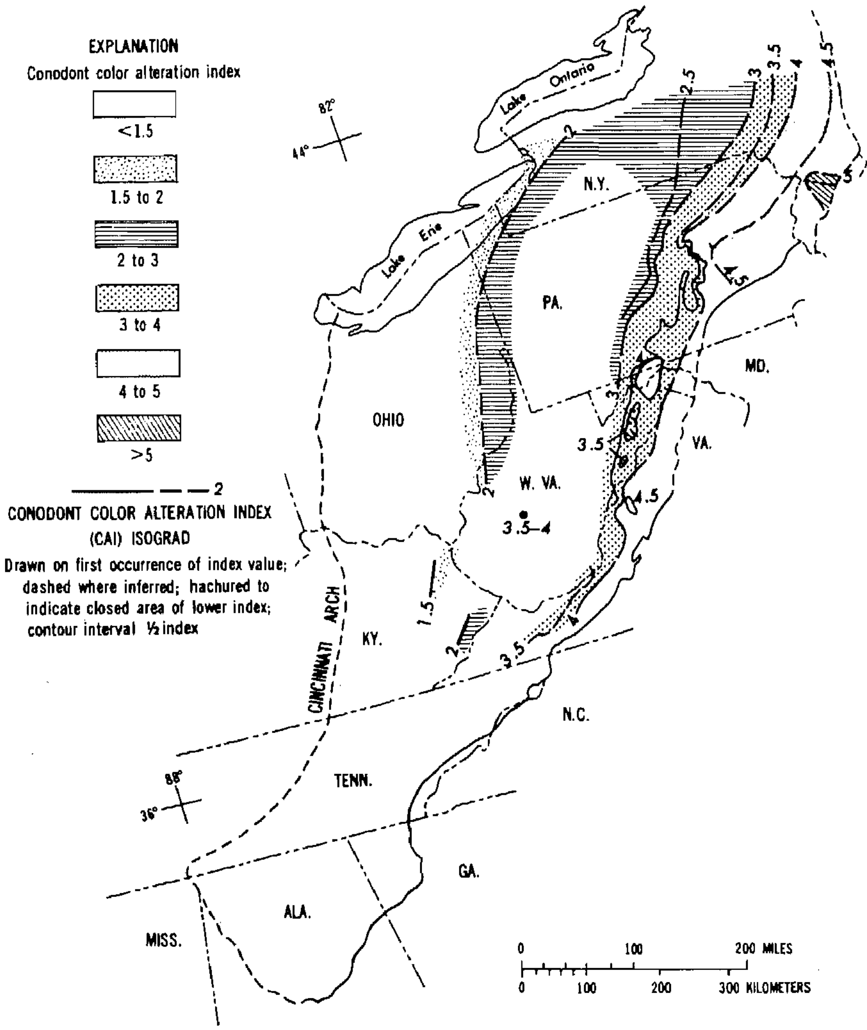

Figure 17. Conodont color alteration isograd map for Silurian through Middle Devonian limestones in the Appalachian basin. After Harris (1977).

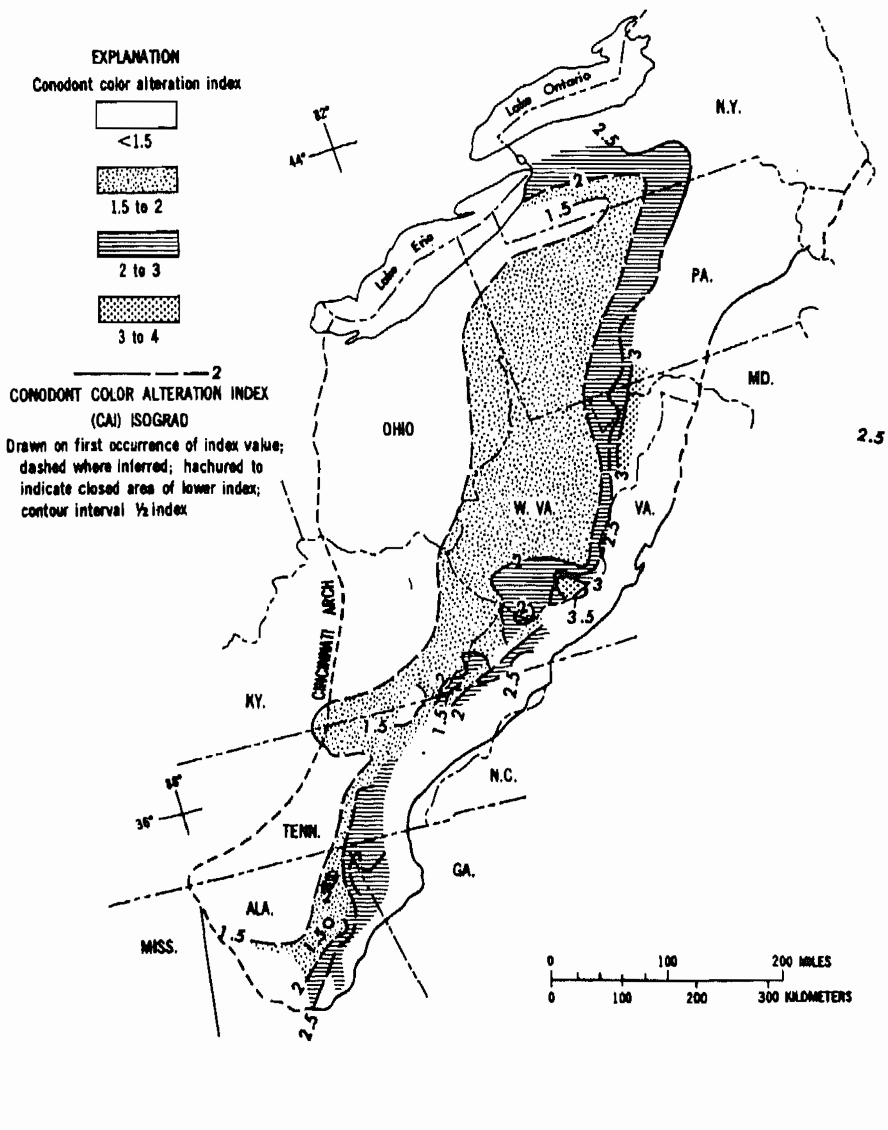

Figure 18. Conodont color alteration isograd map for Upper Devonian through Mississippian carbonate rocks in the Appalachian basin. Sample localities are shown in Harris, et al. (1977).

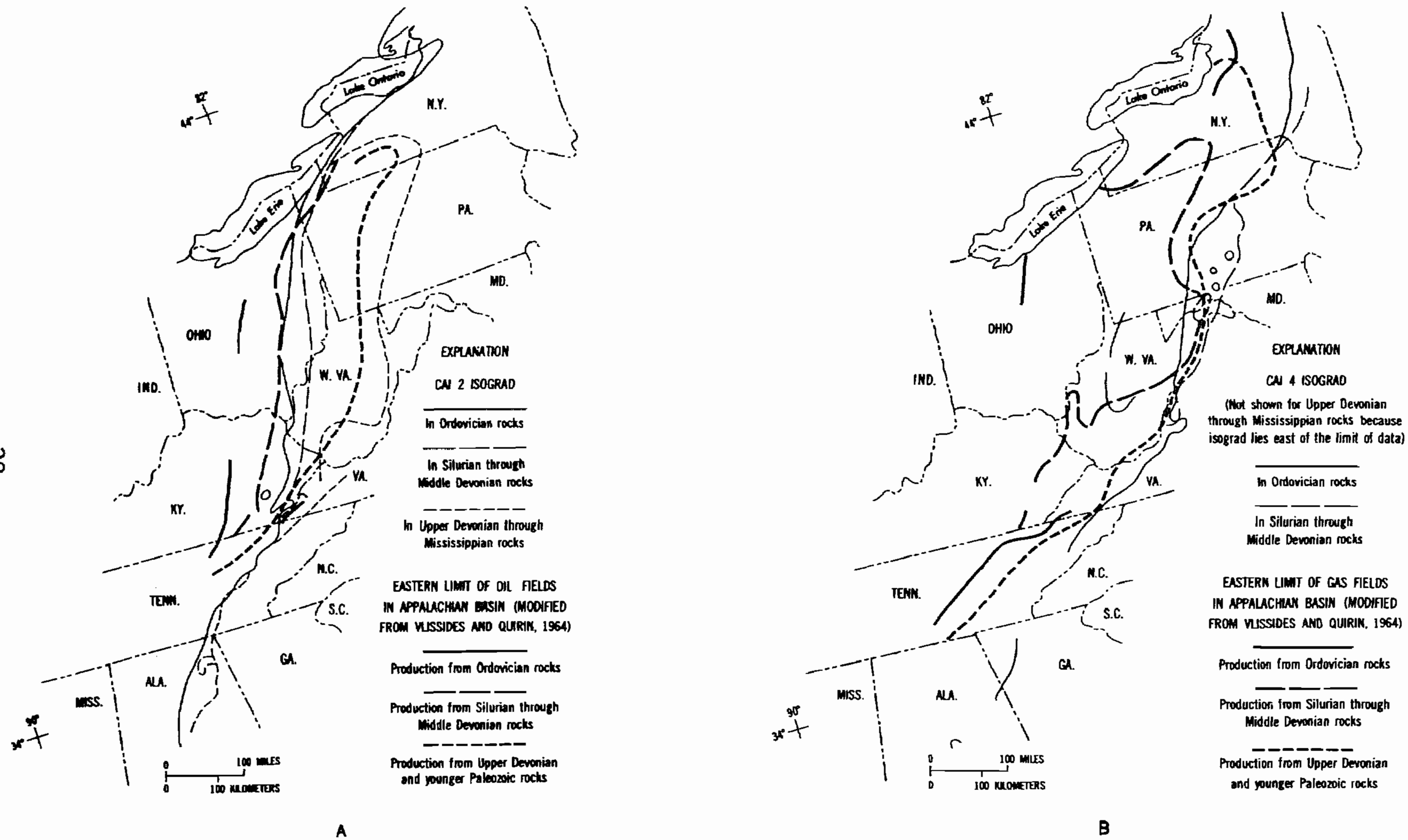

Figure 19. Maps showing the eastern limit of oil (A) and gas (B) production for three stratigraphic intervals in the Appalachian basin. After Harris (1977).

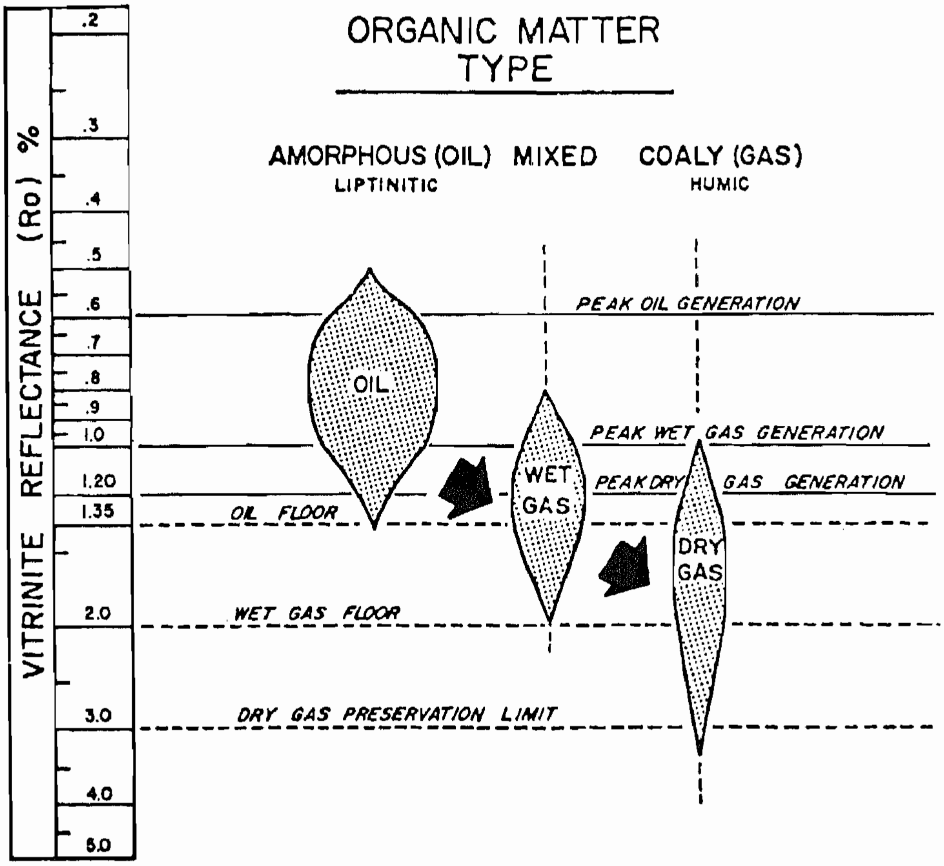

Figure 20. Correlation of various maturation indices and zones of petroleum generation and destruction. After Dow (1977).

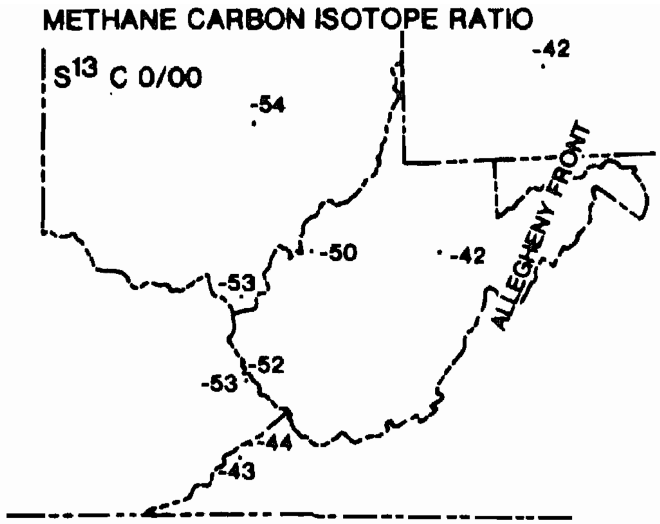

Figure 21. Carbon isotope ratio of methane in natural gas from Devonian rocks of the Appalachian basin. After Claypool, et al. (1978).

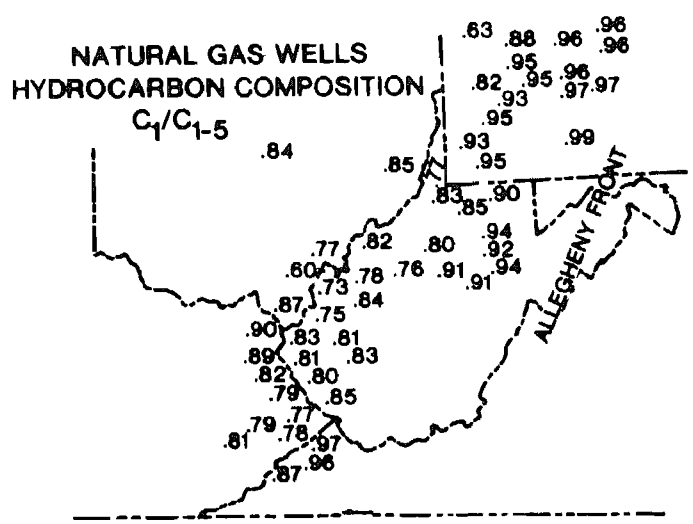

Figure 22. Hydrocarbon composition of natural gas wells producing from Devonian rocks in the Appalachian basin. After Claypool, et al. (1978).

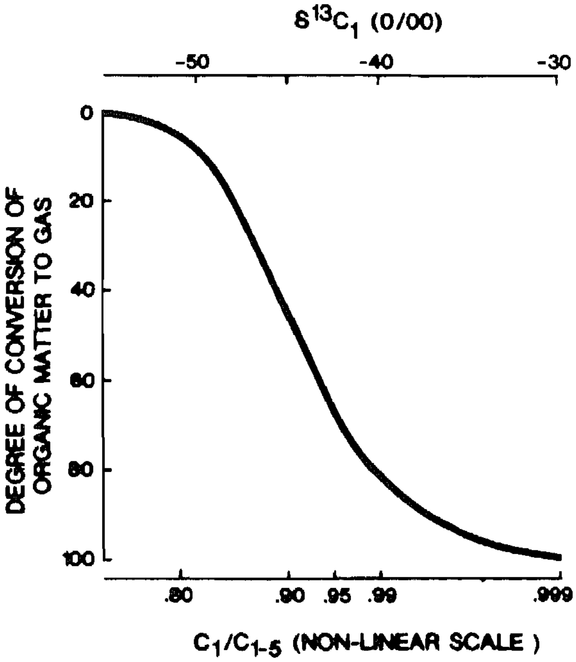

Figure 23. Relationship between degree of conversion of organic matter to gas, and chemical and isotopic composition of gas in Devonian rocks of the Appalachian basin. After Claypool, et al. (1978).

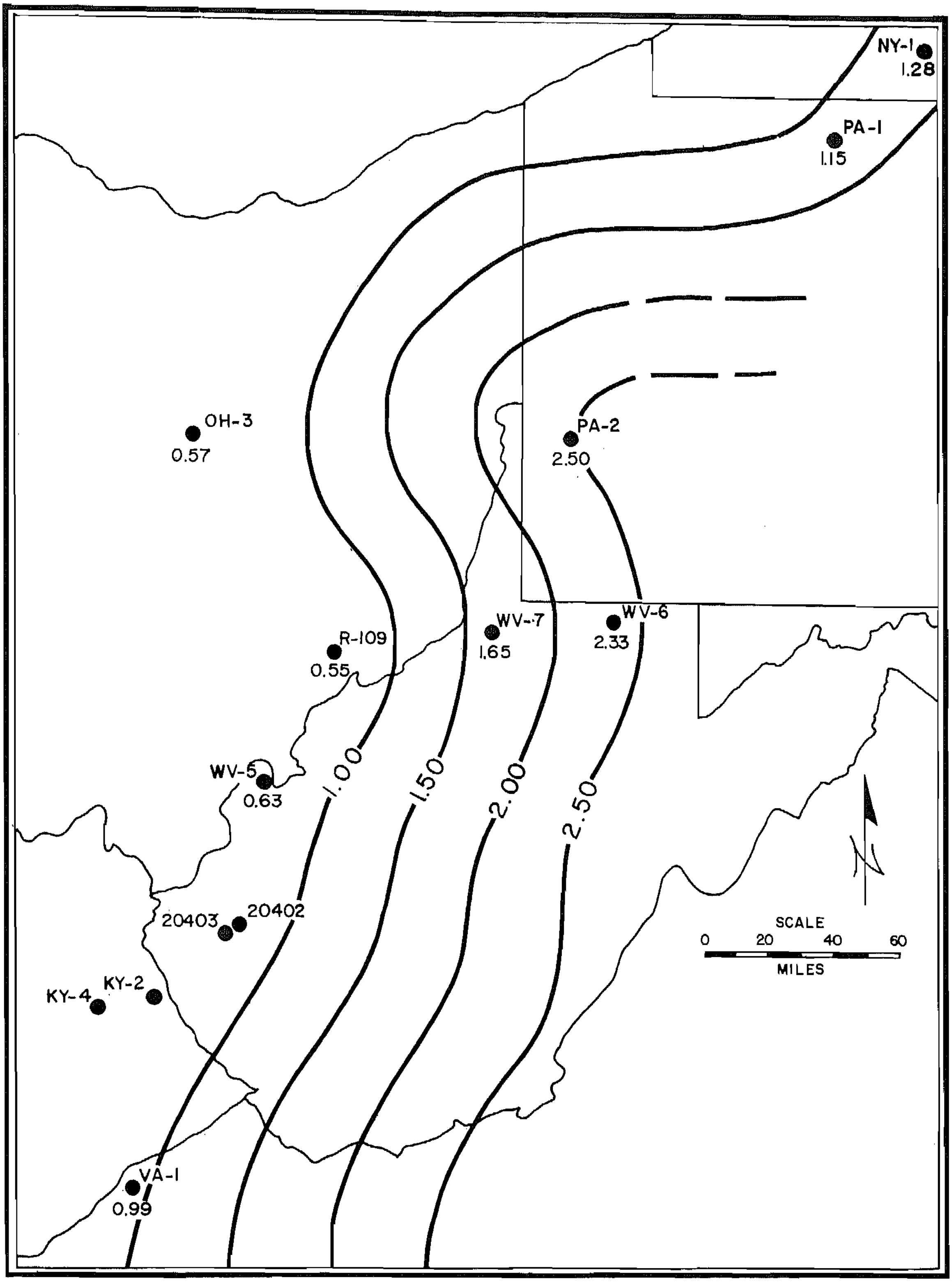

Figure 24. Distribution of vitrinite reflectance for the Devonian shales in Ohio, Pennsylvania, and West Virginia. SAI after Mound Facility (1980).

placed on the map. This limit, which is based upon conodont studies, puts the area for exploration, either gas or oil, within defined limits. Anything east of the gas limit should contain no hydrocarbons as they have either migrated or been literally "cooked" and subsequently destroyed. The range of reflectance values from Pennsylvania and adjacent West Virginia wells indicates that oil, wet gas, and dry gas should occur in the Devonian Shale.

Paleocurrent studies (fig. 25) suggest that, as predicted, the source of clastics was indeed from the east with terrestrially deposited sediments grading westward into marine sediments.

Most data submitted to date have little regard for specific formations. Most values reported are mean values from samples taken throughout the entire Devonian section. Zielinski in his continuing work at the Mound Facility has shown that vitrinite reflectance values increase with depth for each individual well, which accords to theoretical concepts. Organic carbon contents also change from formation to formation in each well, and it is likely that gas analyses would follow suit. These mean values serve only as a very broad guide. The need for "strata specific" data exists and is critical for future understanding of the Devonian Shale basin.

FRACTURE AND PRODUCIBILITY INDICATORS

Characteristically, the Devonian shales have very low porosity and extremely low permeability. Porosity can be classified as either primary or secondary, primary being the pore volume of the rock, which in shale accounts for only 0.4 to 4.0 percent of the total rock volume. Secondary porosity is that attributed to fractures, joints, and bedding planes (Schrider, et al., 1977). Even though some organic-rich shales show good zones of porosity, little if any natural flow is attributed to the primary porosity; good natural flows are associated with fractured zones in the Devonian Shale. Permeability is a measure of a rock's capacity to transmit a fluid through its pores. Therefore, because of their extremely low pore space and low permeability, it is difficult to extract hydrocarbons from source rocks. (There are a number of techniques presently being tested to increase permeability by connecting as many gas-filled fractures as possible and thus increase the flows and reserves of the well.)

Stress Ratios

Traditionally, stress ratios (ratio of minimum in situ compressive stress to vertical overburden stress) have been utilized as a measure of the ease with which a hydraulic fracture can be induced in a particular formation. Stress-ratio values generally range from 0.3 to 1.0. Studies now being conducted will aid in the determination of regional stress-ratio relationships for the Appalachian basin. To date, favorable productive trends have been found to correlate with stress-ratio values between 0.3 and 0.5. Implications are that an area with a high fracture density exists where the tensional relief is horizontal and at a maximum. Production could result by strategically locating a well bore where stress ratios indicate optimum fracture density (Komar, et al., 1979). Areas with stress-ratio values of 0.6 to 0.8 have low fracture density or limited reservoir capacity, whereas values of 0.9 or greater usually indicate an absence of any reservoir capacity. While few values are given for Pennsylvania, the stress-ratio factor in other parts of the Appalachian basin is a promising indication of fracture density and consequent gas production,

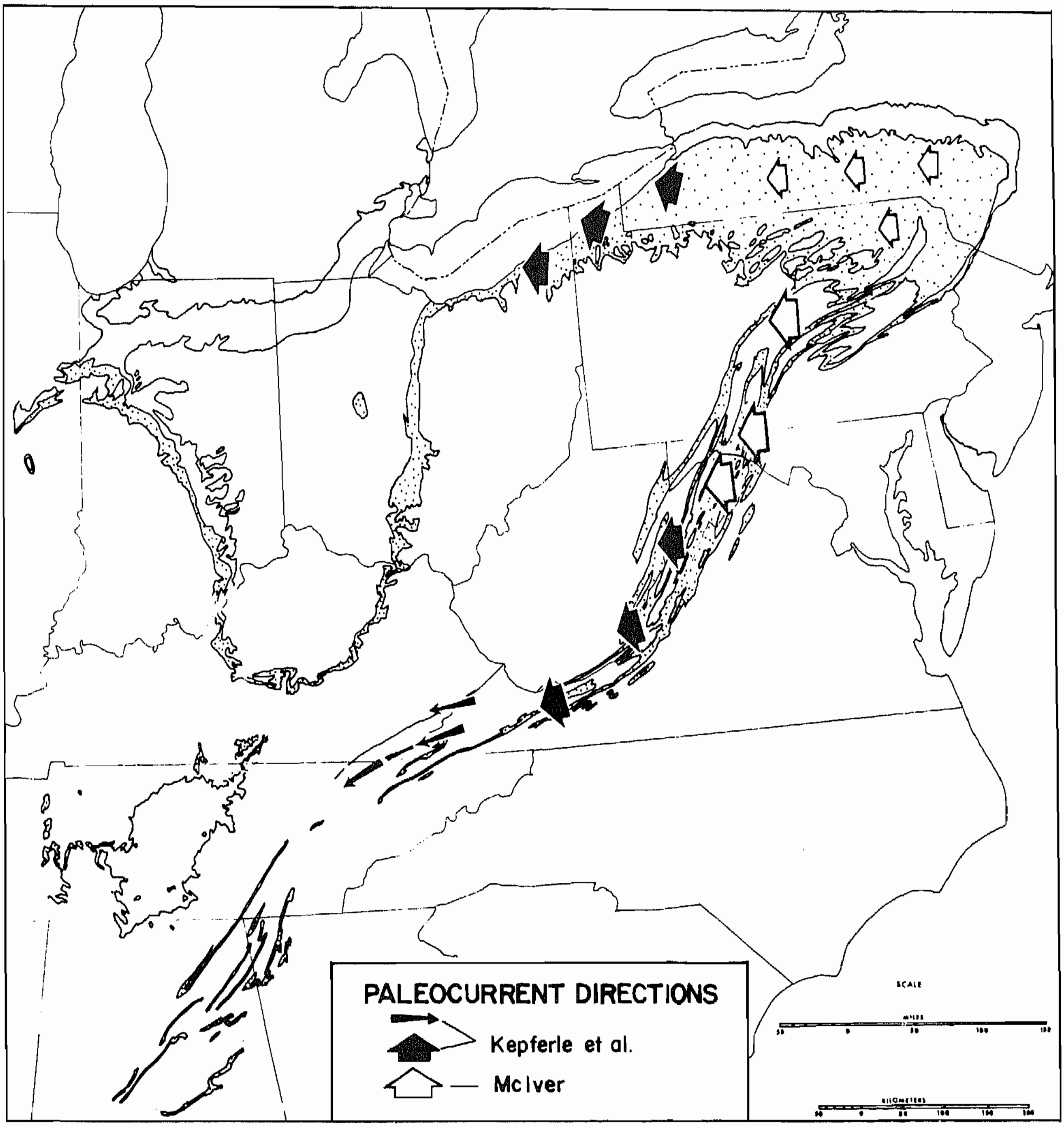

Figure 25. Map of Appalachian basin showing Upper (stippled) and Middle Devonian outcrop belt and summary of Devonian paleocurrents. After Kepferle, et al. (1977).

and should be considered when a target area is delineated. Figure 26 shows the various stress ratios determined for the Appalachian basin to date.

Log Indicators

To evaluate the Devonian shale, a correlation was established between organic-rich black shale facies, gas shows and/or production, and radioactive intense levels as seen on gamma-ray logs. This led to the 20 API unit method, which establishes a baseline on what is considered nonradioactive organic-poor shale. Another parallel index line is positioned 20 API units greater to the right of the baseline, thus representing a radioactive shale threshold. THe 20 API line then became the boundary between organic-poor and organic-rich shales. Actually, the uranium content of the shale is being measured. The only relationship between organic content and radioactive richness (uranium content) seems to be that both are formed under reducing (poor oxygen) marine environments. Subsequent studies show a negative correlation between the uranium and organic content; therefore, radioactivity will not necessarily be an effective indicator of organic carbon content (Zielinski and Nance, 1979, p. iii). Because uranium and organic-rich shales form under reducing or anaerobic (low oxygen) conditions, lack of radioactive response would indicate conditions were inadequate for deposition of both uranium and organic material. Without proper organic content, no hydrocrabons will be produced.

As has been discussed, organic material greater than 0.5 percent by weight or 1.7 percent by rock volume is needed to start the maturation process. Schmoker (1979 and 1980) has undertaken work to define organic facies through calculation from bulk density readings from wire-line logs. The results (fig. 27) indicate that a favorable relationship exists between density logs and volume-percent organic content. (The relationships were derived by comparing measurements from cores with bulk density readings.) Only in northwestern Pennsylvania is the method applicable. The study used a gamma ray to determine potential zones for calculation. The Dunkirk and Rhinestreet black shale facies thin to the southeast and the gamma ray loses its radioactive character. The Marcellus, However, thickens to the southeast. If the undivided massive black shale facies were mapped, possibly a more useful map could be constructed. Zielinski (1980) states that: "While bulk density is a general indicator of organic carbon content, changes in the matrix density of the shale can lead to significant variations in the bulk density of the shales. Such changes occur more frequently in the shales from the eastern Appalachian basin wells." Therefore, additional work is needed to extend this method deeper into the basin.

GAS PRODUCTION

Historical

The best published material on the history of shale gas production in Pennsylvania is found in articles by Piotrowski and Harper (1979, pp 1-6). Regarding the Devonian shale, Piotrowski and Harper wrote:

> The first well in the United States drilled specifically for natural gas produced from Devonian shales in 1821 38 years prior to the drilling of the historical Drake oil well. This shale gas well was drilled in Fredonia, Chautauqua County, New York, and produced enough gas to provide street lighting for the town. With that discovery, drilling commenced along the south

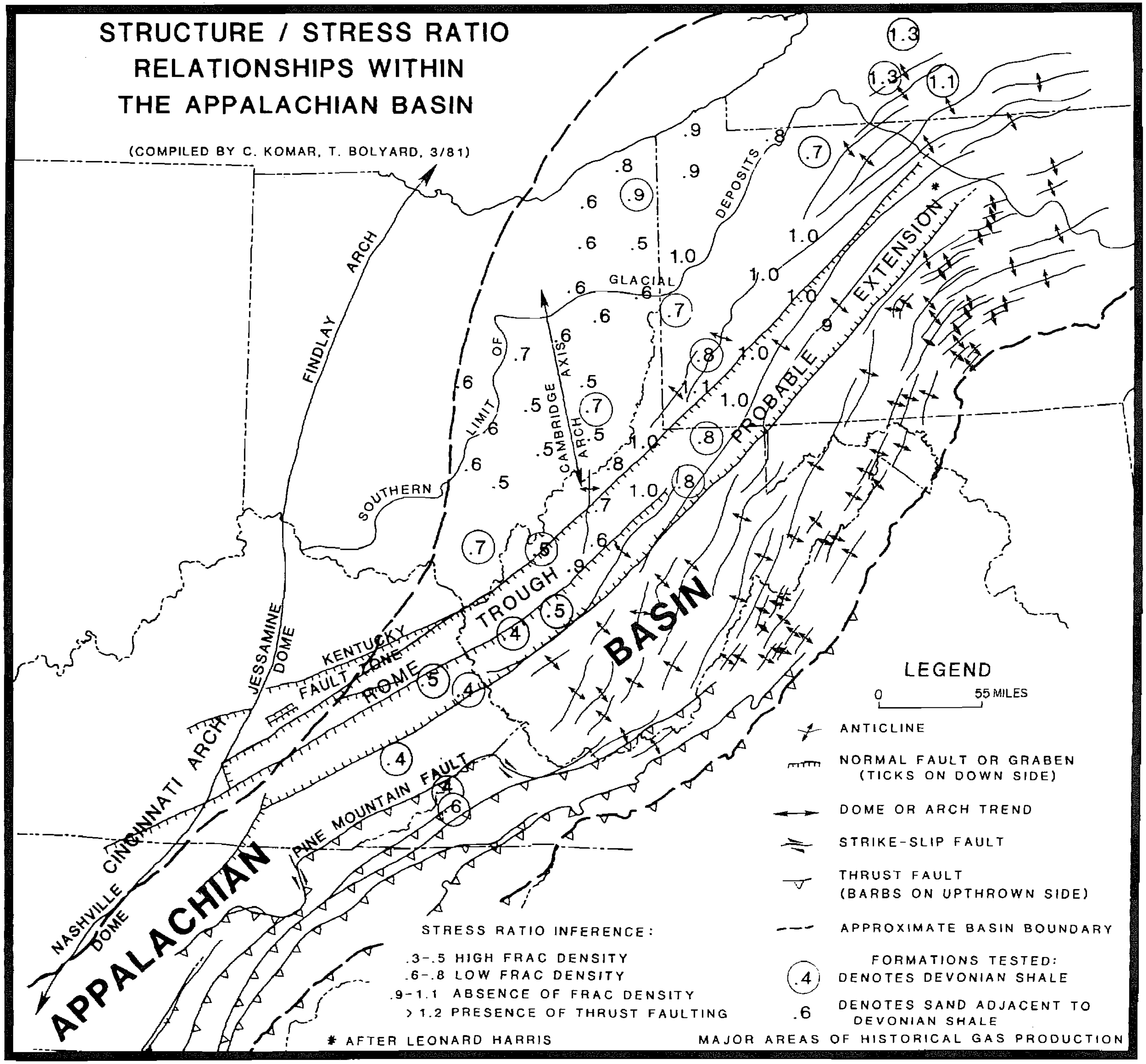

Figure 26. Areal variation of stress ratio, central Appalachian area. After Komar and Bolyard (1979).

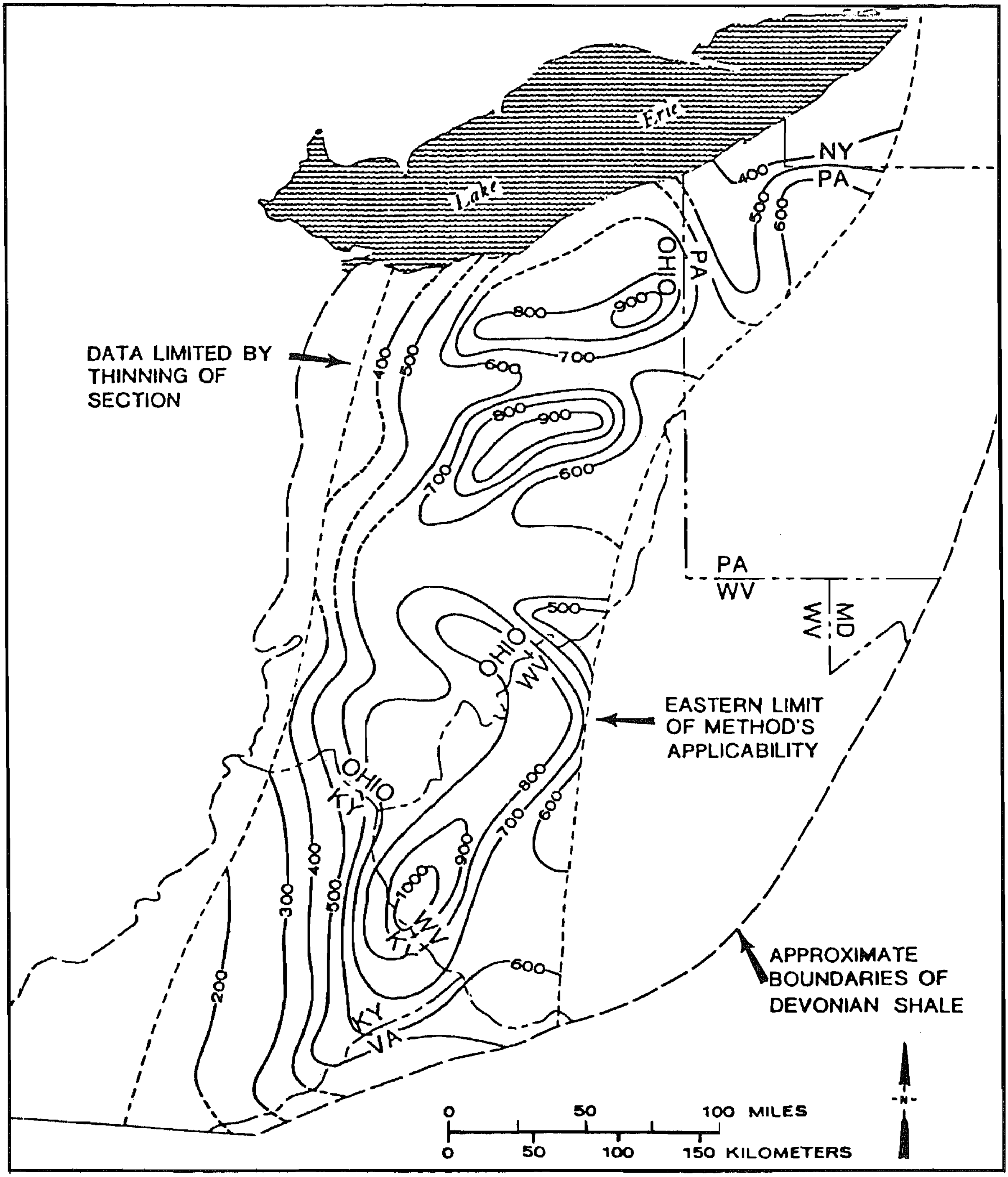

Figure 27. Thickness of organic-rich Devonian shale facies with organic-rich defined as an organic content of 2 percent or more by volume. After Schmoker (1978).

shore of Lake Erie from Dunkirk, Chautauqua County, New York, to Sandusky, Erie County, Ohio. The gas produced from the shales was a valuable commodity available at shallow depths. The low pressure wells had relatively small open flow rates but long life spans. Drilling in the area continued throughout the 1800's and into the early 1900's, but the discovery of high flow rates from Upper Devonian sandstone reservoirs quickly put a damper on shale gas activity. There is very little information on these early shale gas wells other than some descriptive data.

In Pennsylvania the Lake Erie shale gas trend is represented by three fields, North East, Erie, and Girard (fig. 28). These fields were discovered between 1860 and 1880, and although initial production from the discovery wells was small, the fields are still productive. Ashley and Robinson (1922) reported that the wells in these fields were drilled to an average depth of 1,000 feet and had highly variable rock pressures and gas volumes. They also noted that the North East field produced small quantities of oil as well as gas. Some gas was usually encountered during water well drilling. In 1928, Frank Warner of Cranesville, Erie County, drilled a water well on his property to a depth of 36 feet and encountered enough gas for domestic use.

Some data are also available for 20 wells drilled in the Girard field in 1941 by the Ohio Oil Company (now Marathon Oil Company). These wells, located in Springfield Township, Erie County, Pennsylvania, and Conneaut Township, Ashtabula County, Ohio, had open flow rates ranging from a low of 116,000 cubic feet of gas per day to a high of 4,168,000 cubic feet of gas per day. None of the wells produced from a depth greater than 800 feet. Between 1941 and 1961 drilling for shale gas was virtually at a standstill in Pennsylvania. Only two wells are known to have discovered gas in the Upper Devonian shale in the 1960's. The Carter #1 well in Conneaut Township, Crawford County (fig. 28) was originally drilled as a test of the Medina Group (Lower Silurian) and completed as dry in that zone in June, 1961. It was plugged back to 400 feet so the farmer could use the gas encountered in the shale. Leon Matezak drilled a well on his property in 1964 that produced gas from a 350 foot thick zone in the shale. The open flow was gauged at 15,000 cubic feet per day with a rock pressure of 22 pounds.

Current

Regarding recent activity, Piotrowski and Harper wrote:

With the onset of energy shortages and the subsequent increase in natural gas prices, interest has been renewed in the Devonian shales and their potential natural gas resources. Since 1975, 11 wells have been reported in Pennsylvania that produced or had the potential to produce from black organic-rich Devonian shale (fig. 28). The first such well, the Metropolitan Industry #1, in Darlington Township, Beaver County, was originally drilled as a test of the Medina Group (Lower Silurian) by Quaker State Oil Refining Corporation. No gas was encountered in the Medina, and the well was plugged back to 4,550 feet to test the Devonian Rhinestreet shale facies. There was no natural production from the shale, but after hydraulic fracturing the well initially produced 150,000 cubic feet of gas per day with a rock pressure of

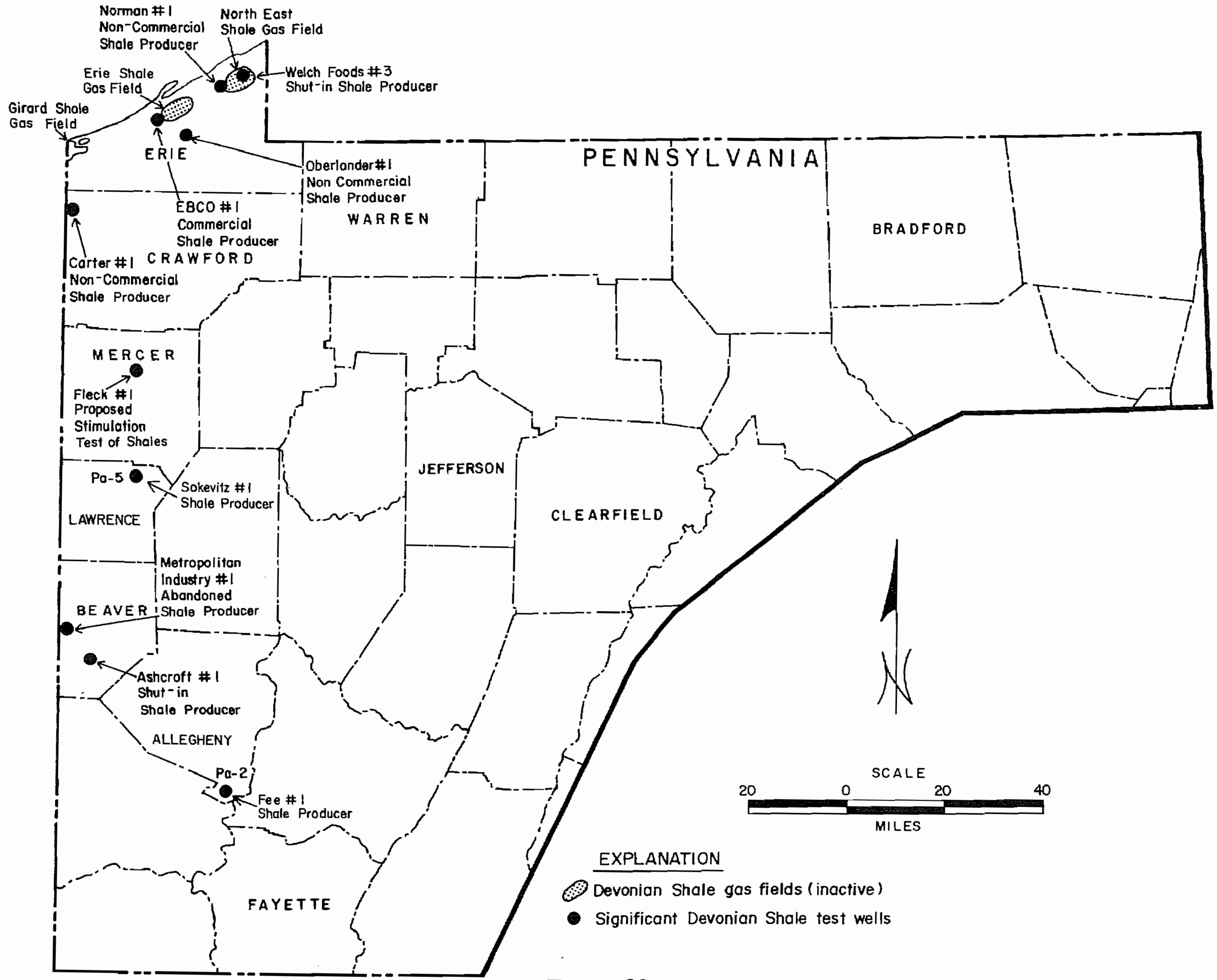

Figure 28. Locations of significant shale gas wells and fields in Pennsylvania. After Piotrowski and Harper (1979).

1150 pounds. This flow did not last long, however, as the gas blew down after only 30 days of production. When it was shut in, the well would again build up pressure, but when opened it would quickly blow down to nothing. Piotrowski (1978) postulated that there was little natural porosity in the shale and that the gas had accumulated in fractures induced by stimulation. However, the fractures apparently were not extensive enough to constitute an adequate reservoir for commercial production of gas and the well was eventually plugged and abandoned.

In April, 1975, Frank Norman of Harbor Creek, Erie County, completed a well on his property at a depth of 875 feet in the Devonian shale. The well produced naturally at an open flow rate of 20,000 cubic feet of gas per day from three zones at 150, 400, and 700 feet; enough gas to insure an adequate domestic supply. In December, 1975, St. Joe Petroleum Corporation completed the Ashcroft #1 well in Greene Township, Beaver County. As with the nearby Metropolitan Industry well, the Ashcroft well was originally drilled as a test of a deeper formation (the Lower Silurian Medina Group). But was plugged back to test the Devonian Rhinestreet shale. Again there was no natural production, and after hydraulic fracturing there was no sustained flow. The gas was there, but with the present state of stimulation and recovery techniques it could not be produced economically. This well is currently shut in.

Nicholas Konzel of Erie, Erie County, drilled a well on his property to a depth of 900 feet. The well was completed in May, 1976, in the Upper Devonian Dunkirk shale facies with a sustained natural flow of 5,000 cubic feet of gas per day, sufficient for domestic use. In September, 1976, Moody and Associates completed the Welch Foods #3 well in the area of the old North East field as a 900 feet deep Devonian shale test. A natural open flow rate of 12,000 cubic feet of gas per day was encountered; after foam fracturing the flow rate was 150,000 cubic feet per day with 80 pounds rock pressure. Piotrowski (1978; also Piotrowski, and others, 1978) reported that a sibilation log run in the well indicated the presence of natural fractures, both in the black shale and the associated gray shale. After a month of testing the flow rate was reported to have decreased to 3,500 cubic feet per day. The well is currently shut in.

Henry Oberlander of Erie, Erie County, completed a shale gas well on his property in April, 1977, at a depth of 800 feet. The well had an initial potential of 4,000 cubic feet of gas per day natural production and is being used for domestic purposes. In September, 1977, Michael Tarasovitch completed a well on his property in North East Township, Erie County, that encountered gas in the shales less than 600 feet deep. The initial open flow was gauged at 3,000 cubic feet per day with a rock pressure of 36 pounds. In November, 1977, the General Electric #3 well was completed in Lawrence Park Township, just outside the city of Erie, Erie County. The well was originally drilled to the Medina Group (Lower Silurian) but was plugged back to 1,450 feet and completed as a shale gas well for the EBCO (Erie Burial Case Company) plant in the city of Erie. This well was drilled to a total depth of 901 feet and had significant shows from three horizons. At 381 feet, an open flow rate of 1,300,000 cubic feet of gas per day was gauged. A second show at 533 feet was gauged at 1,700,000 cubic feet per day, and a third show at 731 feet had a flow rate of 1,300,000 cubic feet per day. After completion of drilling operations, the well was shut in for five days and tested again. This time the natural gas flow was measured at 975,000 cubic feet per day. Sibilation and temperature logs run in nearby wells indicate a system of natural fractures serve as the reservoir in the area; this would account for the large amounts of gas gauged. Although the actual potential of the well is uncertain, the well is producing enough gas to provide an adequate supply for the needs of the Erie Burial Case Company. Samples of the drill cuttings from the three zones of production were analyzed at the Pennsylvania Geological Survey's research laboratory in Harrisburg by John Barnes of the Survey's Mineral Resources Division. The analysis shows that the mineralogy of the shale was consistent at all three horizons, containing abundant illite and quartz, and less abundant though significant kaolinite, chlorite, feldspar and an illitic mixed-layered clay which is significantly expandable. The presence of these expandable clay minerals is important to the design of the stimulation procedures. These expandable clay minerals could result in closed fractures or even a caved-in hole if hydraulic fracturing using fresh water-based fluids were applied.

In March, 1978, the U.S. Department of Energy sponsored a massive foam fracture treatment of the Peoples Natural Gas #1 Fleck well in Sandy Creek Township, Mercer County. The well had originally been drilled as a basement test but was plugged back to 5,200 feet to test the Devonian Rhinestreet shale. Unfortunately, a mechanical failure occurred during stimulation, and the well was plugged and abandoned. In May, 1978, the Wayne Corporation completed a shale well in Millcreek Township, Erie County. The well was originally permitted to test the Medina Group (Lower Silurian) but several shows were encountered between 15 feet and 1,247 feet and drilling was halted at 1,465 feet. After the well was shut for 10 days, it was tested and gauged at 363,000 cubic feet of gas per day natural production, an amount sufficient for commercial production.

Future

In Pennsylvania, stress ratio values for measuring the extent of fracturing have been mapped at only fourteen locations (fig. 26). Since fourteen values are less than representative, gross structural features need to be studied in order to project areas where fracturing might be expected.

Figures 29 (Wagner, 1976), 30 (Wagner and Lytle, 1976), and 31 (Harris, 1978) show the structural complexity of the subsurface in Pennsylvania. Note the coincidental occurrence of growth faults suggested by Wagner and the Rome trough of Harris. Although speculative, these sizable structures, if they exist, would represent zones of weakness that could have been reactivated during recurrent periods of tectonic activity. Thus, associated fractures in the Devonian shales could be expected.

Fractured shales could be expected to occur in front of thrust faults in the Valley and Ridge Province in Pennsylvania. This relationship would be counterpart to the case in the Big Sandy gas field in front of the Pine Mountain Fault in southeastern Kentucky. Production from the Devonian Shale at Big Sandy appears related at least in part to extensive fracturing.

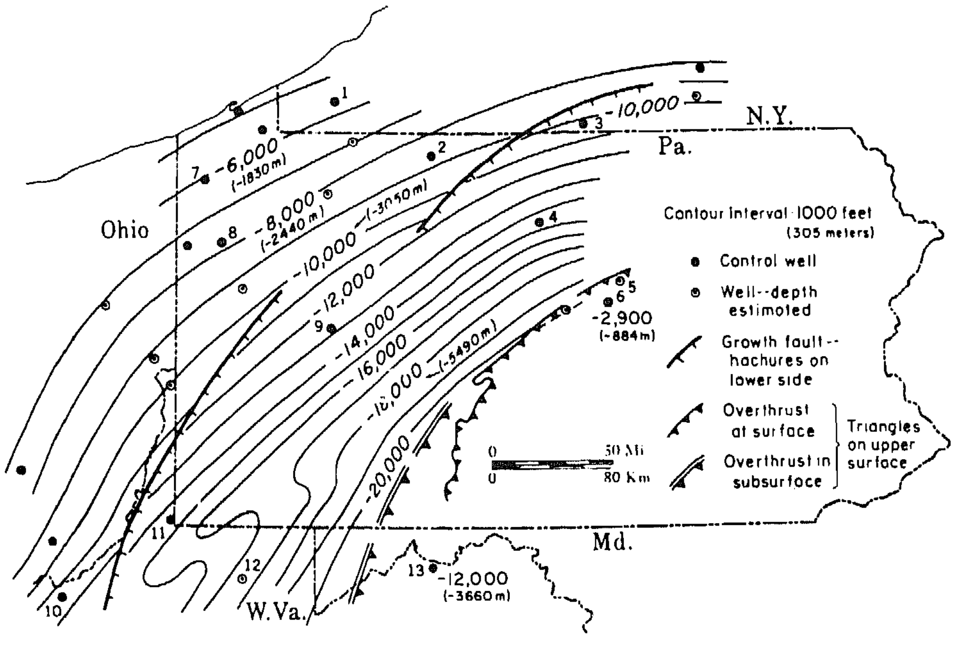

Figure 29. Structure contours on Cambrian gamma-ray correlation line showing growth faults in western Pennsylvania and overthrusts in central Pennsylvania. After Wagner (1976).

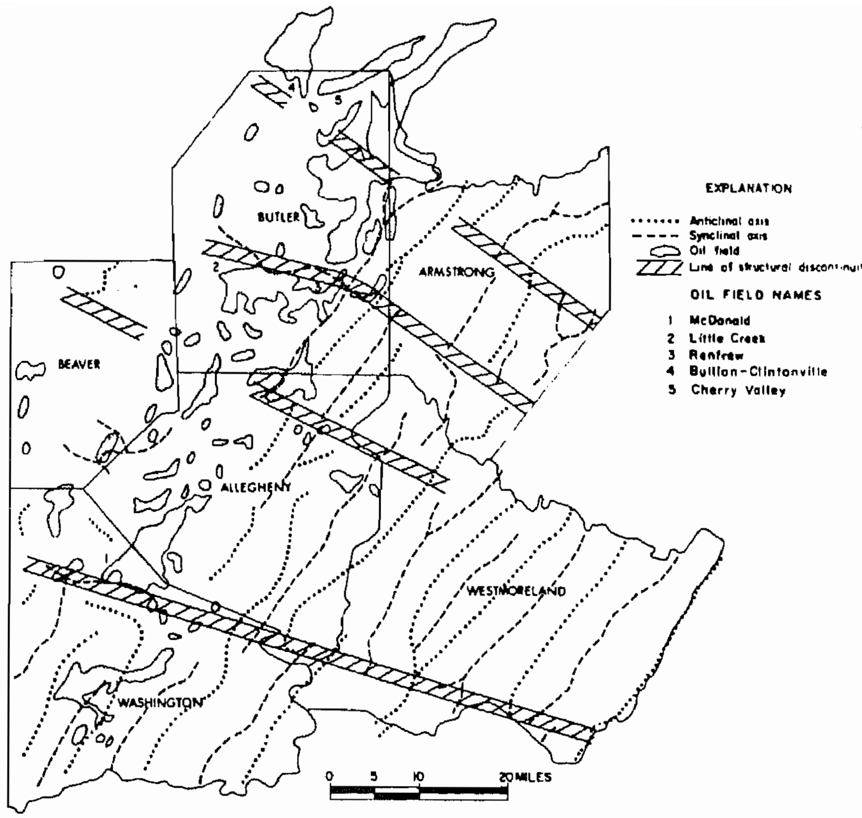

Figure 30. Relationship of the major structures and lines of structural discontinuity to the oil fields in the Greater Pittsburgh Region. After Wagner and Lytle (1976).

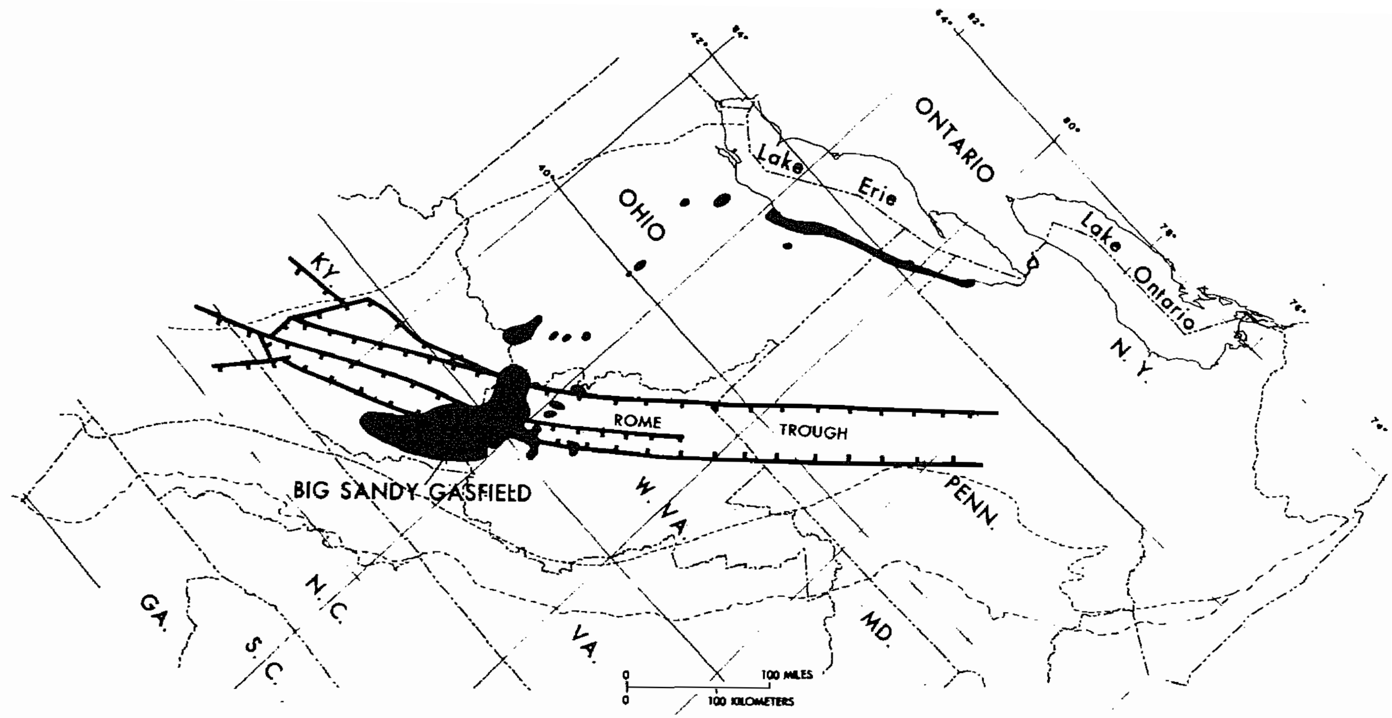

Figure 31. Map showing relation of Rome trough to Big Sandy gas field. After Harris (1978).

Rebound from glacial loading seems to have caused abundant subsurface fracturing along the Lake Erie shoreline. However with maturation indices suggesting immature to barely mature levels, speculation suggests that this shallow fracture system may be connected to deep-seated fractures. As deep-seated fractures tapped deeper source beds, gas could have migrated into the fractured Devonian Shale. Though highly speculative, it might prove interesting to compare analysis of gas from the Devonian Shale with that from deeper pays.

Figure 32 (Harper and Piotrowski, 1980) locates areas of shows and production from Devonian shales. Figures 33 and 35 show indicator relationships in the Marcellus, Rhinestreet, and Dunkirk Shales.

Figure 33 represents the Middle Devonian Shale sequence, which includes the Marcellus. Vitrinite reflectances best represent maturation history. Analysis of the organic carbon content values for the Marcellus shows an organic-rich narrow band running from Fayette north to Jefferson, and turning east to Lycoming County. Areas that extend east into Lycoming, even though organic rich, should theoretically not produce. Areas west of the gas limit line should produce gas with potential for some wet gas between the 1.4 and 2.0 vitrinite contours. The Marcellus thins to the west becoming less mature and generally less organic. An exception is found in the Monsanto Research Corporation Pennsylvania DER/Presque Isle State Park No. 1 well in Erie County in which high organic content in the Devonian Shale occurred. Although rocks in the area are highly fractured, the Marcellus is thin thus limiting the source potential for hydrocarbons. Vitrinite reflectance indicates that the shale is immature to slightly mature. Therefore Marcellus would not be expected to be productive in the northwest corner of Pennsylvania. Best areas for potential in the Marcellus exist in Fayette, Westmoreland, Indiana, and Jefferson Counties where areas of optimum maturation and highest organic carbon values coincide.

Vitrinite reflectance in the Rhinestreet (fig. 34) indicate that, within areas of adequate organic carbon content, stages of generation of petroleum should range from early formation of oil in the northwest corner of the state to oil and wet gas where the Rhinestreet loses its organic richness. Fracture systems developed in the basement possibly extend upward into the Rhinestreet facies. Cored samples from the Pennsylvania No. 2 well indicate that fractures do occur in the shale. Counties which have optimum organic carbon content and maturation levels for the Rhinestreet are northwest Lawrence, Mercer, eastern Crawford, and southeastern Erie.

The extent of the organic-rich Dunkirk Formation is illustrated in figures 15 and 35. Note that only two map control points appear, one being in Erie County, Pennsylvania, the other in northeasternmost Ohio. Lateral changes in the Dunkirk and relationships with other formations are shown in the panel diagram (plate 1). As shown in the vitrinite reflectance map (fig. 24) and the eastern oil and gas limits map (fig. 19), the richest area of Dunkirk is in the northwest corner of the state. Areas to the east and southeast become less rich. Vitrinite reflectances for the Dunkirk indicate that the kerogen borders between immaturity and maturity. Therefore, gas and early generated oil could possibly be present. Some oil has been reported from the Dunkirk. The shale becomes increasingly more mature to the east; however, the organic carbon content becomes less. Dunkirk exploration should progress along the Lake Erie shoreline with close attention being paid to high organic carbon contents and especially fracture systems.

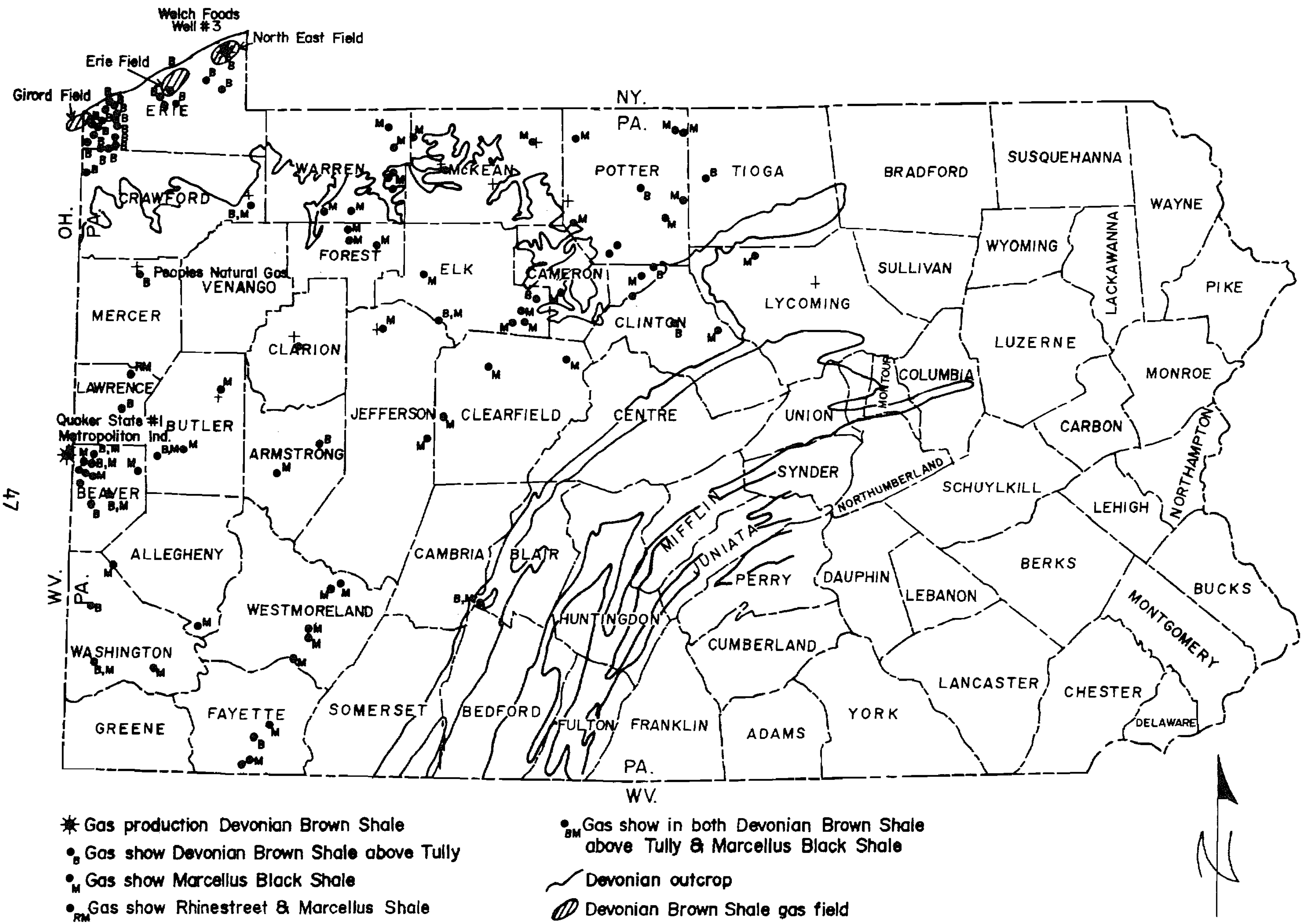

Figure 32. Gas production and show map for Devonian organic-rich shales. After Piotrowski and Harper (1980).

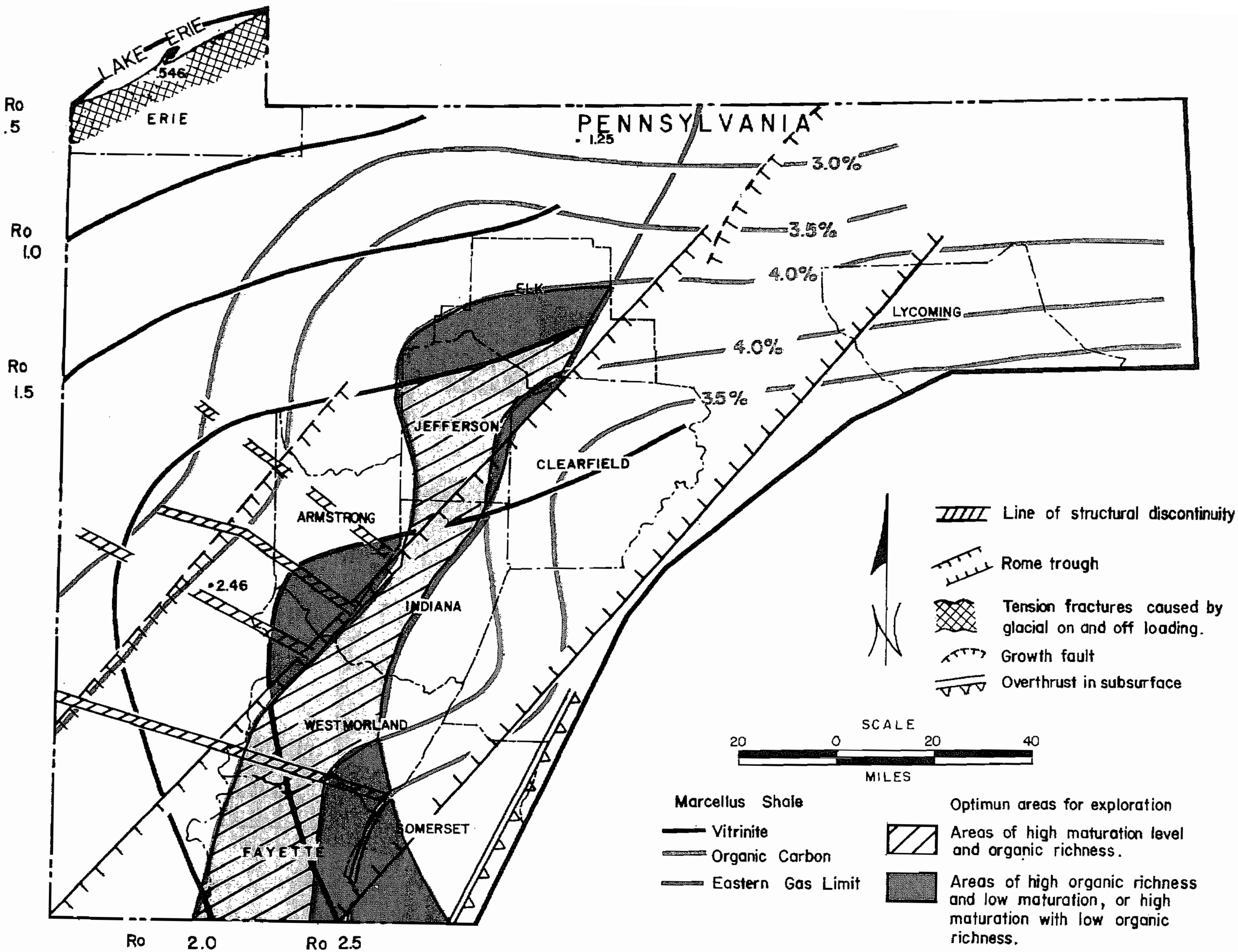

Figure 33. Map showing extent of hydrocarbon indicators in the Marcellus Shale.

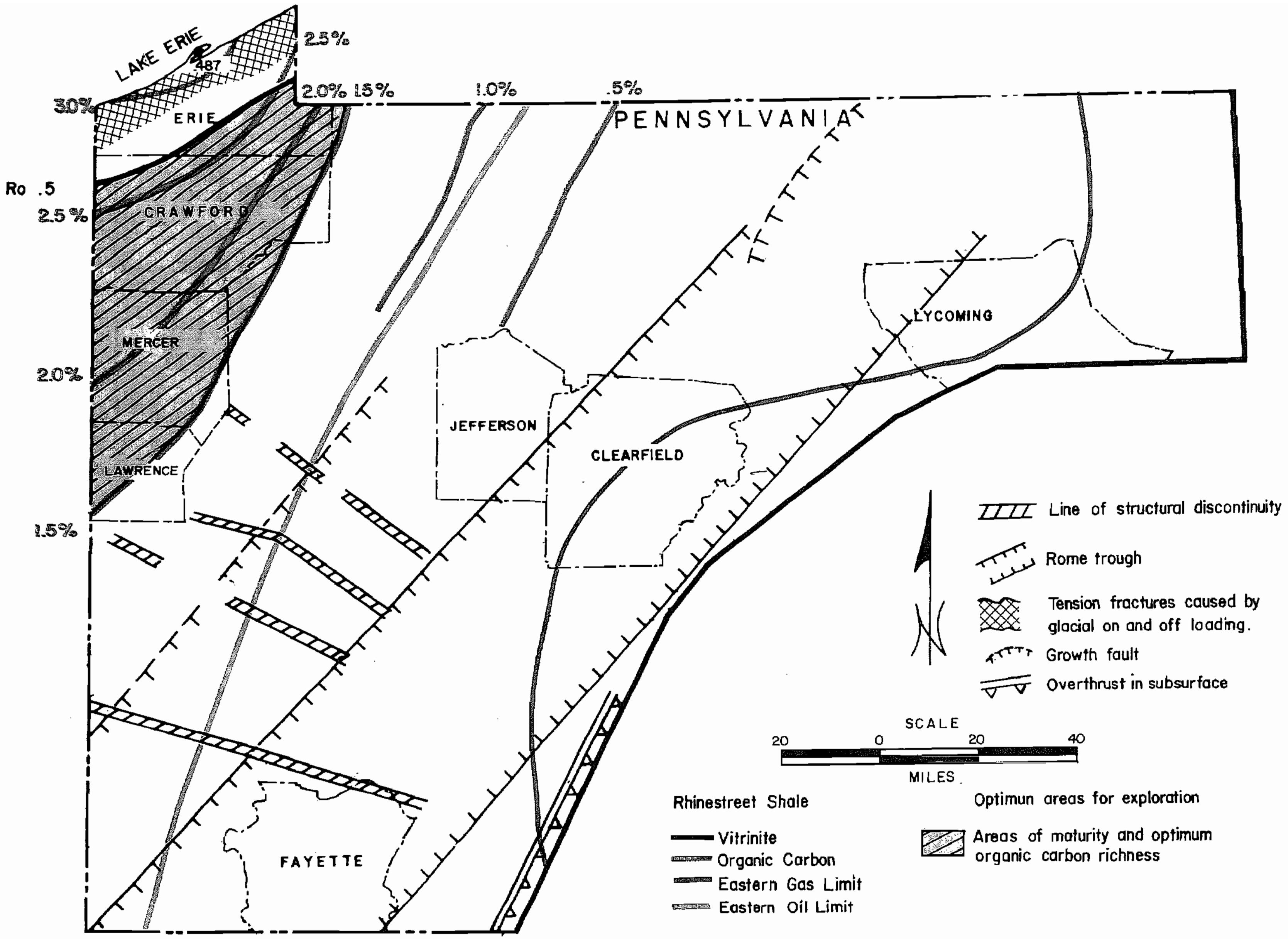

Figure 34. Map showing extent of hydrocarbon indicators in the Rhinestreet Shale.

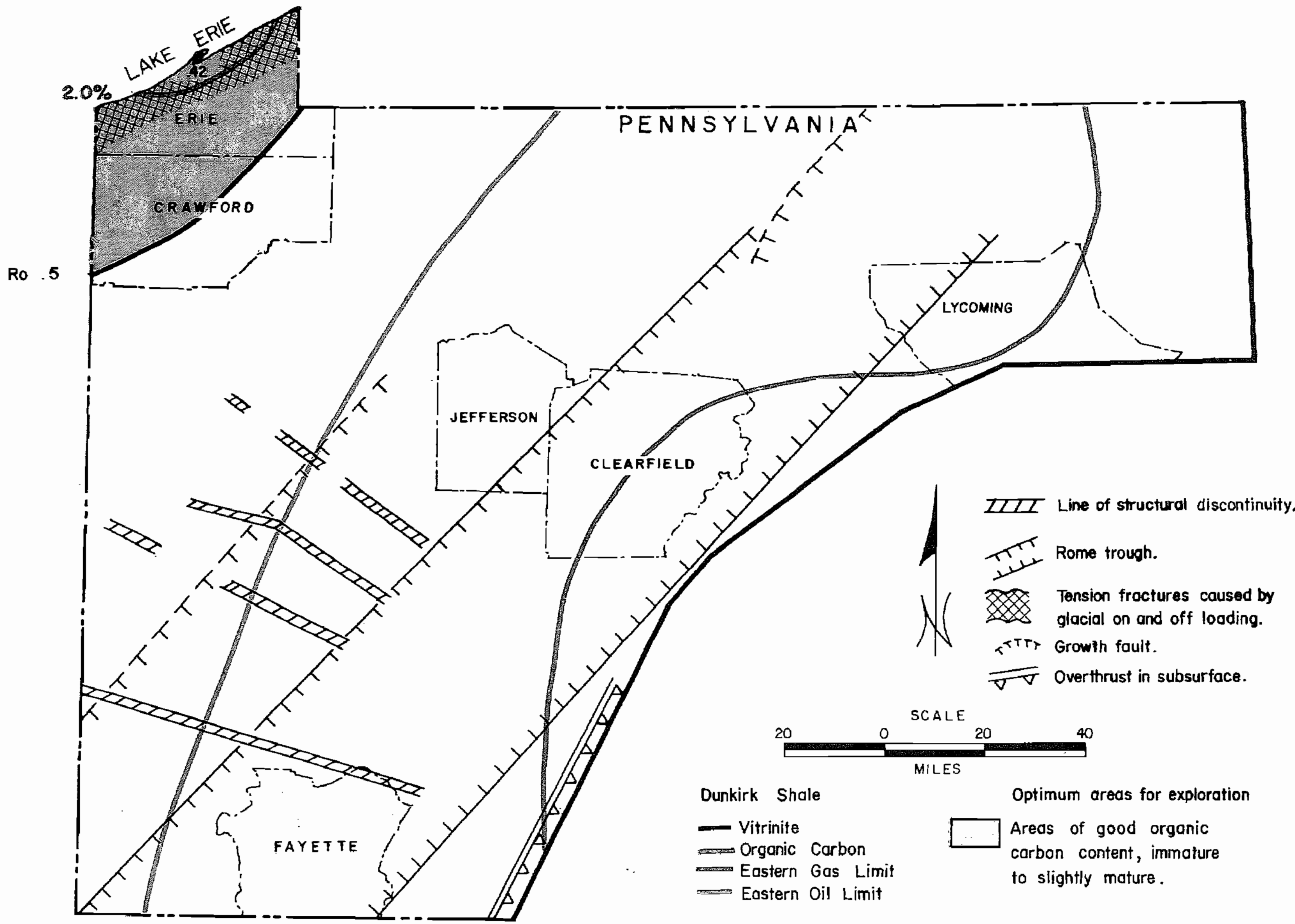

Figure 35. Map showing extent of hydrocarbon indicators in the Dunkirk Shale.

Counties in which favorable production could be expected are summarized, from figures 33-35, in table 2. The selection of optimum areas has been based on current data and thinking.

Table 2. Favorable areas in Pennsylvania for Devonian Shale production

County	Formation	Potential	Range of Subsealevel Depth to Base of Formation
Armstrong	Marcellus	Fair	4500-6000
Crawford	Rhinestreet	Good	900-1200
	Dunkirk	Fair-Good	400-1200
Elk	Marcellus	Poor-Good	3200-5200
Erie	Dunkirk	Good	0- 500
Fayette	Marcellus	Good-Fair	5000-6500
Indiana	Marcellus	Good-Poor	5500-6500
Jefferson	Marcellus	Good-Fair	4400-5700
Lawrence	Rhinestreet	Good-Fair	2200-3500
Mercer	Rhinestreet	Good-Fair	1600-3000
Somerset	Marcellus	Poor-Fair	2500-7000
Westmoreland	Marcellus	Good-Poor	5500-7000

Dual Completion

The potential exists in Pennsylvania for making completions in both primary-target formations and the Devonian Shale. West of the Allegheny Front, there is a potential for dually completing wells in the Marcellus Shale and the Huntersville Chert or Oriskany Sandstone. In northwestern Pennsylvania, the Silurian Medina Sandstones and the Dunkirk offer dual completion prospects.

Recently, on September 5, 1980, Peoples Natural Gas dually completed the Sokovitz No. I well, Lawrence County, Pennsylvania, in the Marcellus and Rhinestreet Shale for a combined gas flow of 133 Mcf per day. In Allegheny County, Combustion Engineering completed the Fee No. 01 well in the Marcellus at 7,330 feet and the Burket Shale at 7,020 feet for a total of 95 Mcf per day. Later perforations and stimulations were made at shallower depths in the Benson, Alexander, and Grit for an additional flow of 225 Mcf per day.

The possible benefits from multiple completions include higher producing rate and faster payout (Allen and Roberts, 1978). Tarr (1980) discusses the methods and considerations in attempting any type of multiple completion and has outlined trend areas in the basin. Figure 36 indicates where the bulk of activity for dual completions exists within the Appalachian basin. The trend along the Lake Erie shoreline holds the most immediate potential. As has been discussed, glacial offloading apparently has caused considerable fracturing in this area. This area now is being drilled extensively for the Medina sandstones.

The National Petroleum Council, June 1980 meeting, provided a Devonian shale resource assessment. An extract from their proceedings is as follows:

> In the Appalachian basin, considerable variation exists in the gas in place estimates depending on the approach taken. For instance, the Appalachian basin gas in place estimates vary from 225 Tcf (if only the black shales as determined by log data were included) to a total of 1,861 Tcf (if sample thicknesses were used and black and gray shales were both included). Rather than present a single resource estimate for the Appalachian basin, the Task Group decided to present the gas in place estimated determined by the two approaches.

Table 3 summarizes the gas in place reserves for Pennsylvania both from log and sample data. With total shale resources of this magnitude operators should fully evaluate any gas shows, samples, cores, and geophysical logs within the Devonian shales.

Table 3. Devonian Shale resource assessment for Pennsylvania (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	92	29,017	45	853	29,017	414
Gray Shale	5,407	29,017	437	4,646	29,017	376
	Average Depth (Feet)	Total (TCF)	Average (BCF/Sq Mi)	Average Depth (Feet)	Total (TCF)	Average (BCF/Sq Mi)
Total Shale Resource	6,790	482	17	6,790	790	27

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

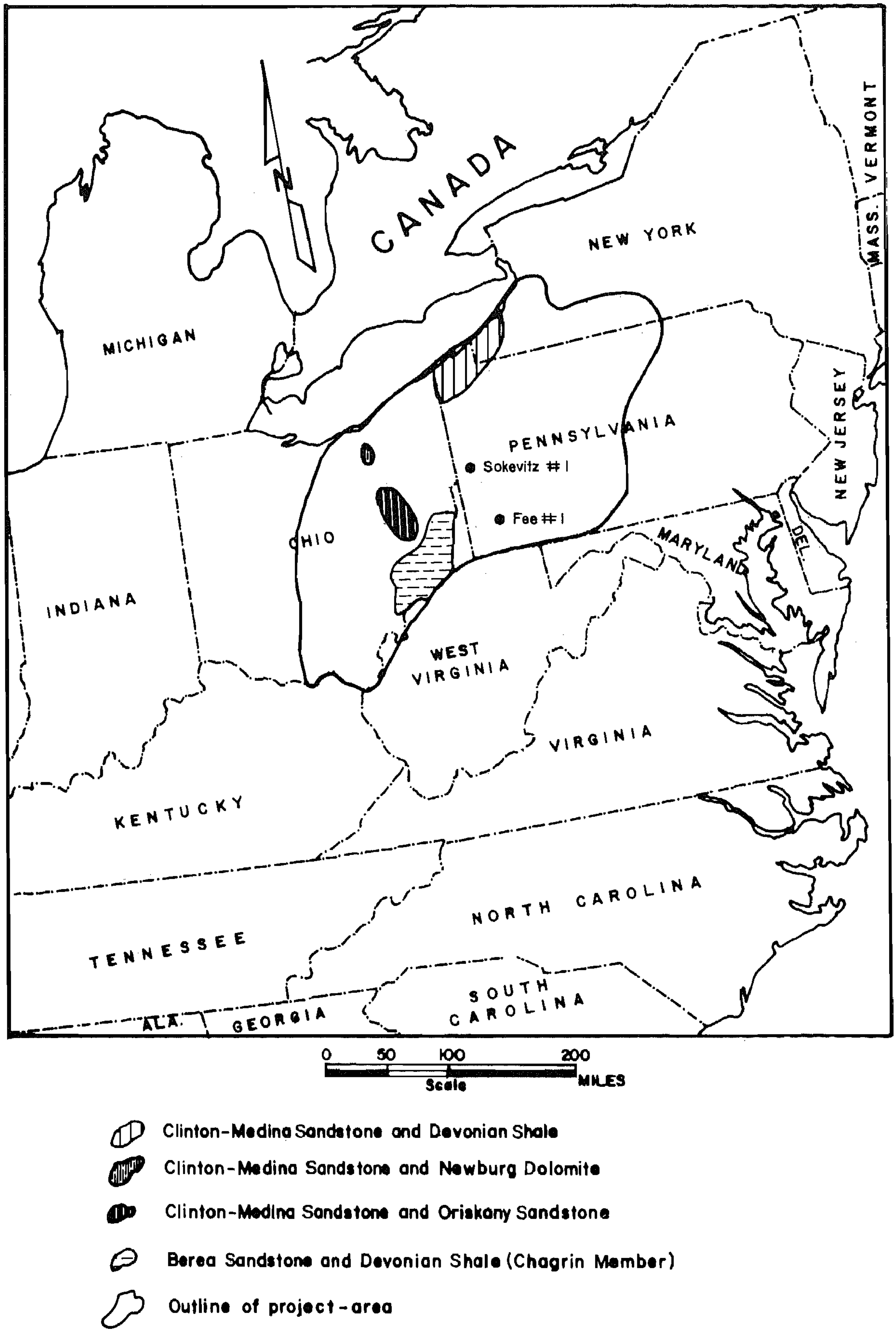

Figure 36. Recent dual completion trends in the northern Appalachian basin. After Tarr (1980).

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APPENDIX
EVALUATION OF DEVONIAN SHALE POTENTIAL IN PENNSYLVANIA

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

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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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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UGR #243

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REMOTE SENSING

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UGR #060

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UGR #S129
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UGR #131

UGR #176

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UGR #062

UGR #S130
Paper EGS-70

WIRELINE LOG STUDIES

UGR #S129
Paper EGS-9

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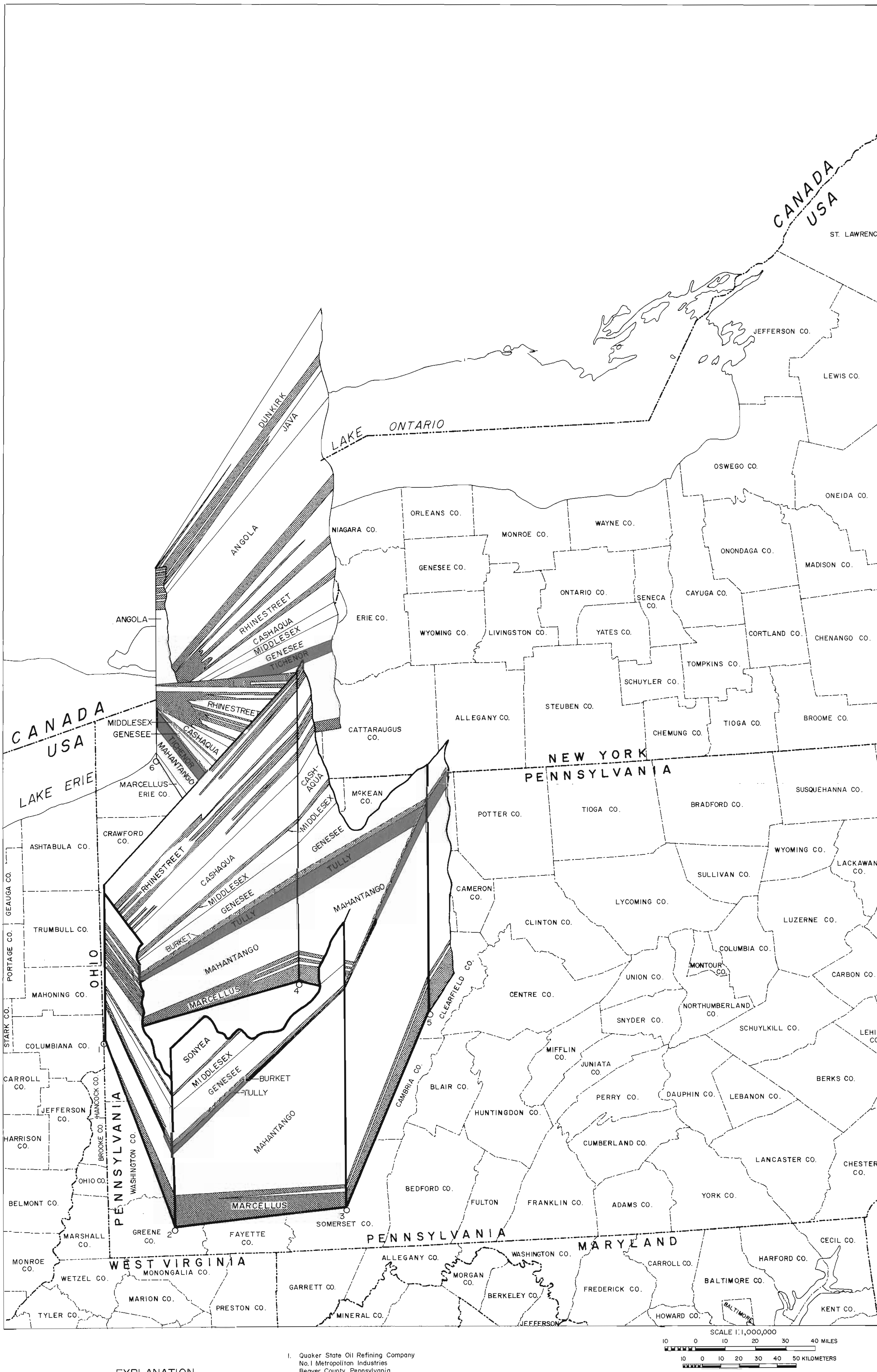

EXPLANATION

○$_2$ Control points
operator
lease name
location

1. Quaker State Oil Refining Company
No. I Metropolitan Industries
Beaver County, Pennsylvania

2. J. A. Fox
No. I George Gordon
Green County, Pennsylvania

3. Shell Oil Company
No. I R.D. Shumaker
Sommerset County, Pennsylvannia

4. Peoples National Gas
No. 6 Peoples National Gas
Clarion County, Pennsylvania

5. Consolidated Gas Supply Corporation
No. WN1011 John M. Chase
Clearfield County, Pennsylvania

6. Monsanto Research Corporation
No. I Presque Isle State Park
Erie County, Pennsylvania

VERTICAL SCALE

Feet: 300, 150, 0

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 DEVONIAN SHALES IN WESTERN PENNSYLVANIA AND WESTERN NEW YORK

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 I