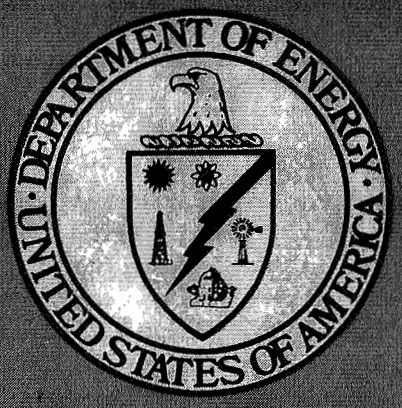

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EVALUATION OF THE DEVONIAN SHALE PROSPECTS IN THE EASTERN UNITED STATES

Final Report

By
Richard A. Struble

Work Performed Under Contract No. AC21-82MC19143

For
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Tetra Tech, Inc.
Columbus, Ohio

TECHNICAL INFORMATION CENTER
UNITED STATES DEPARTMENT OF ENERGY

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INTRODUCTION

The fundamental need for a study of the natural gas resource entrapped in the Devonian shales of the eastern United States became apparent in the United States in the late 1960's. It was during this period that mineral economists were becoming aware that the natural gas reserves in the United States were declining and that the country was fast approaching the point when demand for hydrocarbon energy would exceed domestic production.

Two events of far-reaching importance occurred in the decade of the 70's and brought into focus for the American public the critical nature of the energy situation in the country and the need for new innovative energy programs to reverse the worsening energy dilemma. The first occurred when the complacent energy-dependent society of the United States received a severe jolt because of the Arab oil embargo imposed in 1973. For the first time since World War II Americans were not only unable to get all the gasoline they wanted but additionally were forced to wait in long lines at the gas pumps to purchase gasoline. Americans finally began to realize the strategic disadvantage of a country dependent upon outside sources for energy supplies. A few years later, in 1976 and 1977, a second event occurred which reinforced the first. The industrial northeastern part of the nation was enveloped by a blanket of severe cold weather. Gas transmission companies were unable to furnish utility companies with the requisite quantities of natural gas demanded by industrial, commercial, and residential users. To cope with the situation, industrial plants were shut down, workers laid off, schools closed, and residential users were asked to turn down thermostats well below comfort levels. Most people recognized the crisis proportion of the energy situation, but still some believed the shortages were contrived by the oil and gas companies in order to get a higher price for oil and gas.

To meet the problem of the declining natural gas reserves and to lessen the United States' dependency on foreign oil sources, the United States Energy Research and Development Agency (now the United States Department of Energy) initiated a program to support research and development of natural gas from unconventional sources. The unconventional sources to be evaluated were (1) oil shales, (2) western tight sands, (3) methane from coal beds and (4) geopressured reservoirs in the Gulf Coast.

Natural gas has been produced from Devonian shales in the Appalachian, Michigan and Illinois basins for more than 160 years. One of the earliest reports of Devonian shale gas production was from a well completed in 1821 near Fredonia, Chautauqua County, New York. Production followed in Ohio and West Virginia in the 1860's. Development of gas production in the Big Sandy Field of Kentucky, the largest Devonian black shale field in the Appalachian basin, began in 1914. Historically, the character of the shale production throughout the eastern United States has been low-volume, low-pressure, and low rate of decline with many wells having production histories exceeding 50 years. Because of these producing characteristics, the gas was used primarily for domestic purposes or by small industries, hence the majority of the Devonian shale gas produced in the eastern United States was never considered a part of the United States energy reserve as it never reached commercial markets.

Gas-producing Devonian shales underlie an area of approximately 275,000 square miles in the Appalachian, Michigan and Illinois basins. Original estimates of the volume of natural gas contained in the matrix and fractures of the eastern United States Devonian shales range from between 277 and 900 trillion cubic feet (Tcf) for the total gas-in-place, and from 10 to 520 trillion cubic feet for the economically recoverable shale gas (USDOE, 1980). The United States Geological Survey's estimate of the eastern shales resource is 500 to 600 trillion cubic feet (NAS, 1976). Battelle Laboratory, Mound Laboratory, and selected laboratories estimated the shale resource at 2,400 trillion cubic feet based upon data analyses of Devonian shale cores (MERC/SP-77/3, 1977).

In 1976, the United States Energy Research and Development Agency, Morgantown Energy Technology Center, initiated a major project, The Eastern Gas Shales Project, to develop this potential natural gas resource (MERC/SP-77/3, 1977).

One major objective of the Eastern Gas Shales Project was to demonstrate to oil and gas operators that, with newly-developed exploration and production techniques, natural gas in commercial quantities could be produced from the Devonian shale in the eastern United States. Another objective of the project was to identify the areas within the eastern United States Devonian basins offering the greatest potential for production of natural gas. To accomplish these tasks, it was evident that a major research effort was needed in the areas of resource assessment and shale characterization. Investigators from state geological surveys, universities, federal agencies and analytical laboratories, private research organizations and industry conducted field and laboratory investigations, developed and analyzed data and reported the results of investigation in published maps and reports having wide distribution or at seminars directed toward recovery of natural gas from unconventional gas reservoirs.

After a year or two of resource evaluation and shale characterization work, it became evident that some phases of the total research program were going to produce valuable exploration tools for the development of the eastern United States Devonian shale resource. The identical situation existed in the area of production-stimulation design and research. Important findings from the research were that the black, kerogen-rich, radioactive shales were the source rocks for the natural gas and that the type of organic material, the percent of organic carbon and thermal maturation were important parameters in the generation of the gas resource. Research and production history indicated that secondary porosity in the form of natural fractures or siltstone stringers in the shale were necessary for commercial production from the shale at current market prices. Stimulation designs using various fluids, water, foam, gasses, and explosives have been tested. The results obtained in some wells show promise, but other wells respond poorly to treatment so that the data are being re-analyzed and re-evaluated.

At this point in the research, the exploration phase of the project has reached the state of the art where the most favorable areas for natural gas exploration can be identified using the exploration parameters established by the Eastern Gas Shales Project investigators. These exploration parameters--thickness of source beds, type of organic matter, percent organic carbon, thermal maturation, and the presence of secondary porosity--have been the basis for evaluating the character of the shale and identifying the areas within the Appalachian, Michigan and Illinois basins having the greatest potential for commercial production of natural gas. The above parameters have been used in identifying the most potential exploration areas in New York, Pennsylvania, West Virginia, Ohio, Eastern Kentucky/Tennessee, the Michigan basin, and the Illinois basin. The parameters were also the basis for selecting site-specific areas for Devonian shale drilling sites in the aforementioned states and in the Michigan and Illinois basins.

SUMMARY OF OBJECTIVES

The major objectives of the Eastern Gas Shales Project were: (1) to develop and demonstrate exploration rationales for the identification of areas within the Appalachian, Michigan and Illinois basins which offer the greatest potential for recovery of natural gas in commercial quantities; (2) to develop accurate estimates of gas-in-place and of the economically recoverable resource, and (3) to develop and demonstrate reliable and cost-effective extraction methods (SAI, 1980). To this end, this report is a synopsis of the work of many dedicated professional and technical personnel working with the United States Department of Energy to arrive at the above-stated objectives. Data and conclusions from published and unpublished reports and documents by numerous Eastern Gas Shales Project investigators have been freely used in the compilation of this report and, to the extent possible, reference to the original documents and authors has been cited.

This report is focused primarily on the first two major objectives of the project, the identification of potentially attractive target drilling areas and the accurate estimation of the in-place and economically-producible natural gas resource. Although the accomplishment of these two objectives was dependent upon the efforts of many investigators the data, interpretations, and conclusions from the published Mound Facility Report (Zielinski and McIver, 1982) and the published preliminary report of the United States Geological Survey (Charpentier et al., 1982) offer the most comprehensive compilations of data relative to the distribution and assessment of the natural gas resource and the identification of the most potential target areas for exploration of Devonian Shale gas in the Appalachian basin. Figures 1 and 2, developed by Zielinski and McIver (1982), show the distribution of overall gas source and oil source potential of the Devonian shales of the Appalachian basin. These maps, composites of geochemical parameters (total organic carbon, biofacies type, thermal alteration indexes) and stratigraphic data (thickness), combine source rock quality and thickness to identify areas in the basin with the potential for generating the greatest amounts of natural gas and oil. Due to the low permeability of the shales, much of the formed gas that was generated remained trapped within the shales so the areas of greatest overall source potential also identify the most favorable areas for exploration activity. The occurrence of primary or secondary porosity (i.e., the development of siltstone stringers or natural fractures) in the areas of highest potential would enhance the possibility of commercial production from the Devonian sequence. The gas source potential map (fig. 1, page 4) shows that the Devonian black shale sequence is capable of generating and expelling commercial quantities of gas to internal, contiguous or nearby reservoirs within the Appalachian basin where structural conditions are favorable for migration. The map shows the richest source area and the most favorable prospect area is situated in southeastern Ohio, but that the entire area of eastern Ohio and northwestern West Virginia has excellent gas source potential and would be favorable for natural gas exploration. Other rich gas source and prospect areas are located in southwestern New York, north-central Pennsylvania and in northern Kentucky just west of the common boundary between Ohio, West Virginia and Kentucky. The potential oil source area of the Appalachian basin (fig. 2, page 5) is more restricted in area extent because the generation of liquid hydrocarbons is more stringently controlled by the type of organic matter and a limited range of thermal conditions. Two areas, one centered in southeastern Ohio, but spreading laterally over most of western West Virginia and southwestern Pennsylvania and one located in southwestern New York and north-central Pennsylvania, have the richest oil source potential and, consequently, are the most favorable areas in the basin for exploration of liquid hydrocarbons.

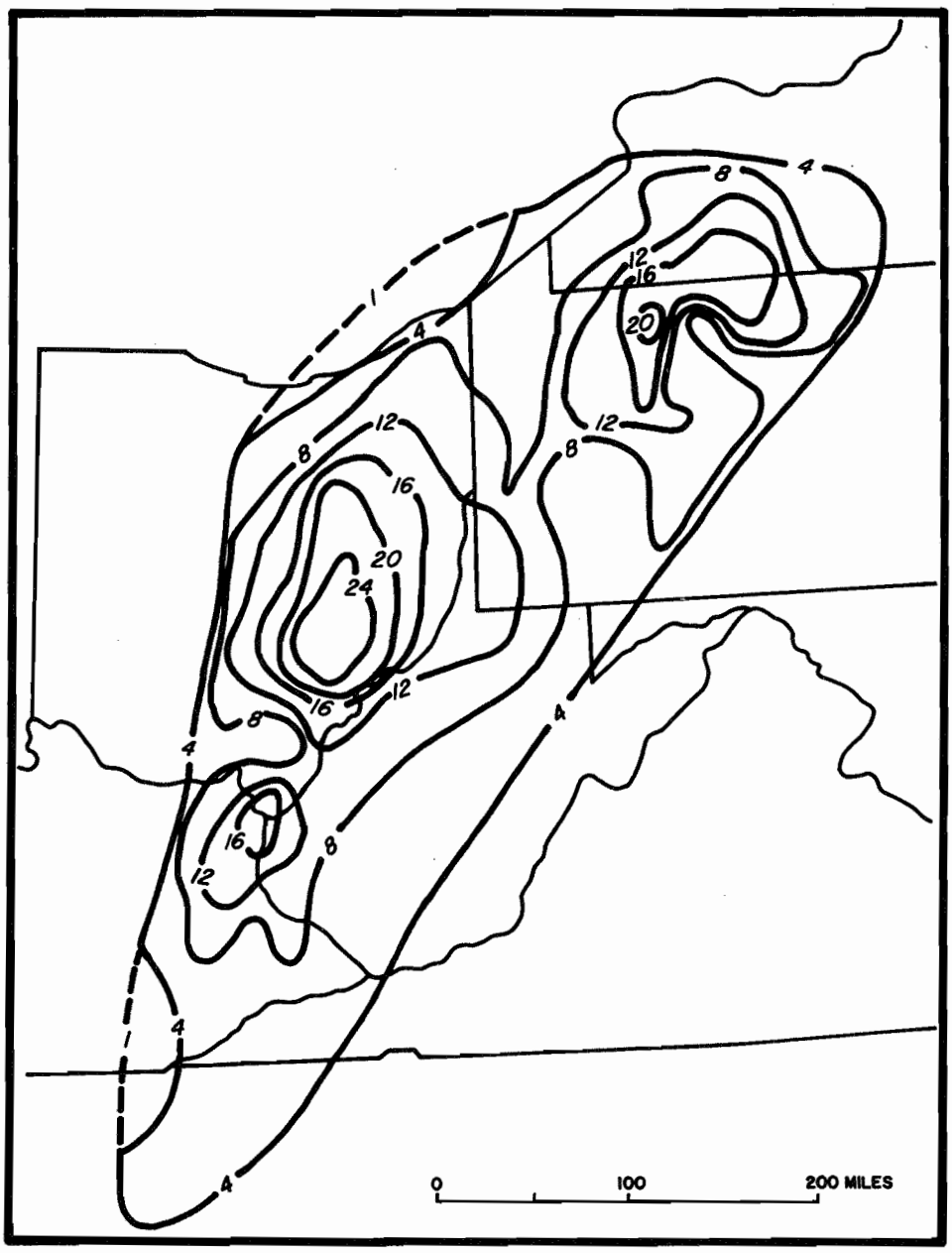


Figure 1. Relative gas potential for Upper Devonian Shales in the Appalachian basin (after Zielinski and McIver, 1982). Contour value x 100 equals relative potential.

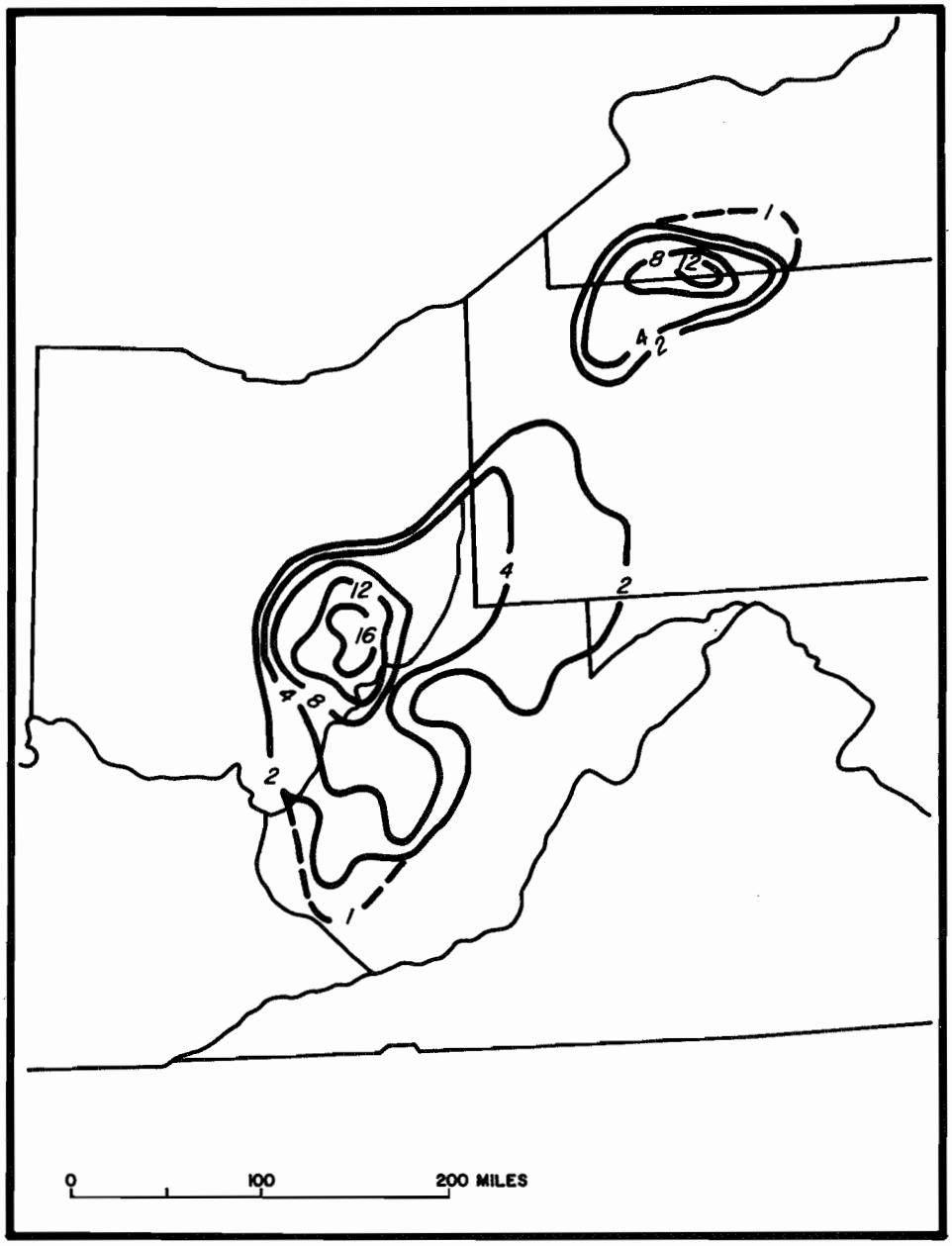
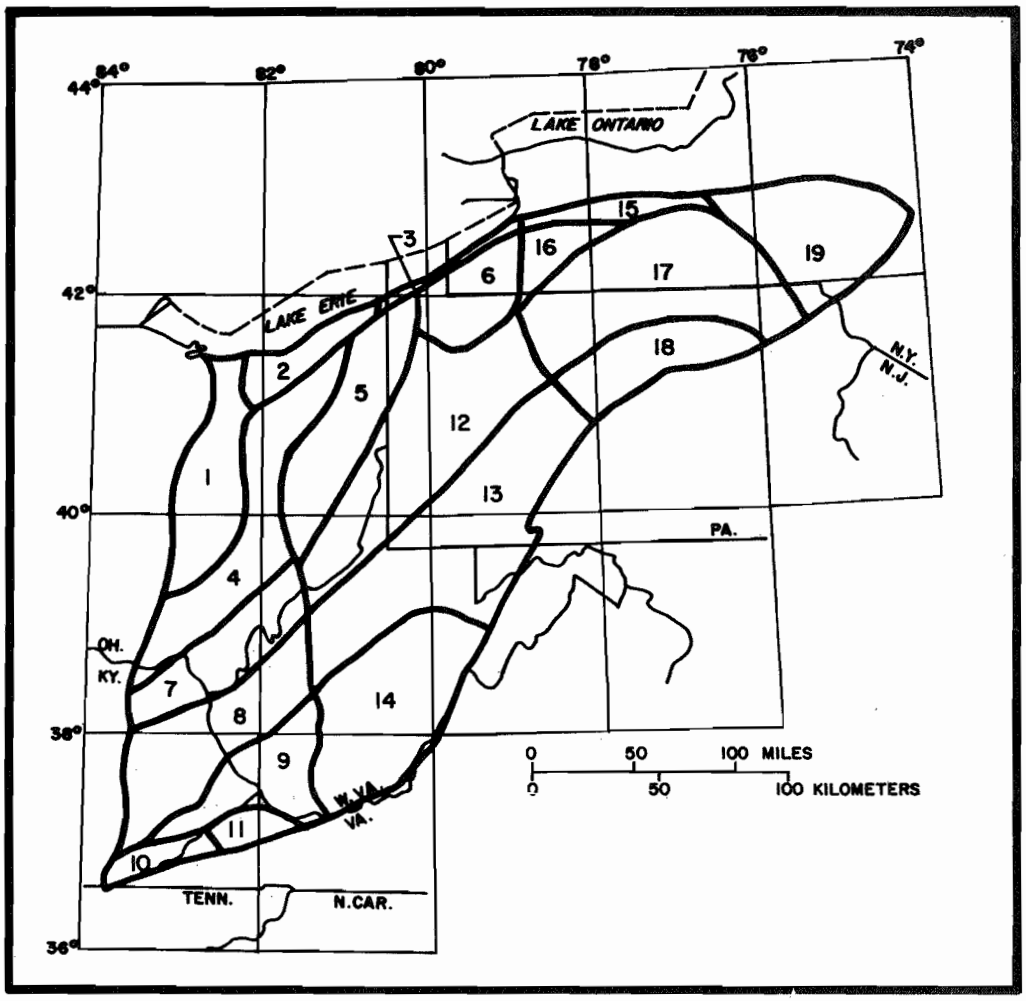


Figure 2. Relative oil potential for Upper Devonian Shales in the Appalachian basin (after Zielinski and McIver, 1982). Contour value x 100 equals relative potential.

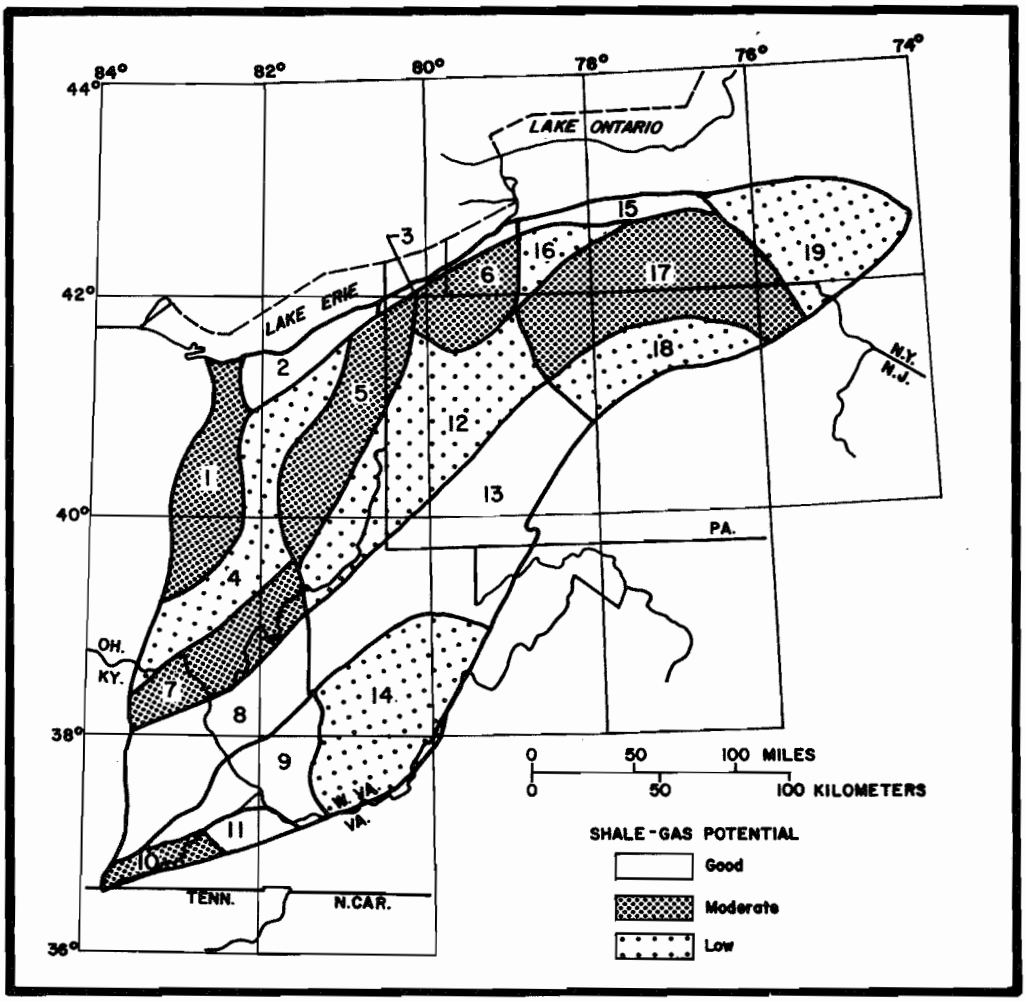
To estimate the unconventional natural gas resource of the Devonian shales in the Appalachian basin, Charpentier et al. (1982) use the "Play Analysis" approach to define the unconventional natural gas resource of the Devonian basin. In their report a play is defined as an areal unit which possesses the necessary favorable geologic and geochemical conditions considered essential for the exploration of natural gas. The geologic and geochemical parameters taken into consideration in defining the play boundaries were the thickness of the black shale, the percent of organic carbon, the thermal maturation of the organic matter and the structural complexity of the area with regard to the development of secondary natural fracture porosity. Historical production of oil or gas, including "shows" from the Devonian shales in play areas, was also a consideration in determining the relative exploration potential of the play areas. Figure 3 is an index map of the 19 play areas which were defined by Charpentier et al. (1982) on the basis of the presence, absence, and quality of the above parameters. In areas of the Appalachian basin where all of the evaluating parameters fall within ranges suitable for generation and accumulation of natural gas, a designation of good relative potential has been assigned. Where a majority of the evaluating parameters fall within favorable ranges and the remaining parameters are close to acceptable standards, a designation of moderate relative potential has been assigned. In areas designated as having poor potential, the ranges of values for the majority of the evaluating parameters do not meet the standards established for classification of the relative gas potential. Play areas 8, 9, 11, and 13, a large contiguous area of the basin covering western Virginia, eastern Kentucky, western and north-central West Virginia and southwestern Pennsylvania, has been designated as an area where the gas potential of the shale is considered good. In these play areas the black shales range in thickness from 400 to 1000 feet, the organic carbon content ranges from 3 to 16 percent by volume, the maturation levels between 1.4 CAI and 3.0 CAI, are within the oil- and gas-generating maturation levels and numerous vertical fractures are present due to moderately to highly complex vertical and horizontal tectonics. Another contiguous area (play areas 2, 3, 15) designated as having good exploration potential extends eastward from central Lake Erie along the south shore through eastern Ohio, Pennsylvania and New York and continues eastward along the Portage escarpment into central New York. In this area the black shales also have adequate thicknesses, ranging from 300 feet to 1000 feet, the organic carbon content varies from 3 percent to 11 percent, the conodont alteration indexes range from a low of 1.5 in the western play area (2) to 2.5 in the eastern play area (15). This grouping of play areas (2, 3, and 15) is situated where numerous vertical fractures have developed as a result of isostatic rebound following depression from ice loading during the Pleistocene Epoch. An additional basis for the good exploration potential designation for this area is the historical production of domestic and small commercial volumes of shale gas from this locality for over 100 years.

The play areas (1, 5, 6, 7, 10 and 17) shown on figure 4 in the dark stippled pattern have been designated by Carpentier et al. (1982) as having moderate gas exploration potential. As mentioned previously, these areas have limited potential with some of the evaluating criteria being close, but not falling within the ranges established for a designation of good shale-gas potential. In these areas of moderate shale-gas potential the shale thickness varies from 200 feet to over 1000 feet, the organic carbon values range between 3 and 16 percent, the conodont alteration index values range between 1.0 and 3.0, and structural conditions vary from simple to complex. The general thinness of the shales, low organic carbon content values, conodont alteration values of 1.0 and 1.5, the structural simplicity, and lack of Devonian shale production and "shows" are factors which lead to the designations of moderate gas-shale potential for these play areas. The remaining play areas (4, 12, 14, 16, 18 and 19), because of less-than-favorable evaluation parameter values, have been designated as having poor shale-gas potential.



1. North-Central Ohio
2. Western Lake Erie
3. Eastern Lake Erie
4. Plateau Ohio
5. Eastern Ohio
6. Western Penn-York
7. Southern Ohio Valley
8. Western Rome Trough
9. Tug Fork
10. Pine Mountain
11. Plateau Virginia
12. Pittsburg Basin
13. Eastern Rome Trough
14. New River
15. Portage Escarpment
16. Cattaraugus Valley
17. Penn-York Plateau
18. Western Susquehanna
19. Catskill

Figure 3. Index map of natural gas plays in the Appalachian Basin. After Charpentier et al. (1982).



1. North-Central Ohio
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8. Western Rome Trough
9. Tug Fork
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11. Plateau Virginia
12. Pittsburg Basin
13. Eastern Rome Trough
14. New River
15. Portage Escarpment
16. Cattaraugus Valley
17. Penn-York Plateau
18. Western Susquehanna
19. Catskill

Figure 4. Qualitative assessment of production potential from Devonian Shales of the Appalachian basin. After Charpentier et al. (1982).

For a detailed discussion of the evaluation parameters within each individual play area and the basis for the potential designation, the reader is referred to the original report by Charpentier et al. (1982).

Correlation between the two interpretations, the overall gas source potential map, figure 1, page 4, and the shale-gas potential map, figure 4, page 8, is difficult because, even though similar exploration parameters were used in the interpretatons, statistical weighting given to certain parameters by the investigators in the two studies has produced some major differences in the qualification of areas of the basin with regard to shale-gas exploration potential. Except for the area near the common boundary of northern Kentucky, southern Ohio and western West Virginia, which shows high relative potential on the overall gas source map and correlates with the good gas-shale potential designation of play area 8, there is little correlation between the two interpretations with respect to areas of high exploration potential (fig. 5). The area in north-central Pennsylvania and southwestern New York which has high relative gas source potential, figure 1, page 4, is designated as having only moderate shale-gas potential on figure 4, page 8. The most noticeable difference occurs in southeastern Ohio. This large area, considered as the richest gas source and gas shale exploration by Zielinski and McIver (1982), is partitioned into only moderate to low shale-gas potential in the Charpentier et al. (1982) interpretation. Some of the factors accounting for the poor correlation between the two interpretations are the importance given to structural complexity, the organic carbon content, and the thermal history. Overall, the general northwest offset of the northeast-trending high-potential source areas of Zielinski and McIver from the areas designated as having good shale-gas potential by Charpentier et al. is due, for the most part, to a general overall thinning of the black shale sequence. This thinning of the black shales towards the east and southeast is due to the introduction of large volumes of organic-poor turbiditic siltstones and fine-grained sandstones into the basin from the east. The thickness of the organic-rich shales in the Appalachian basin strongly influenced the magnitude of the values of relative source potential as defined and mapped by Zielinski and McIver. The Charpentier et al. (1982) interpretation placed greater emphasis upon the unconventional nature of the reservoir (fracture porosity in shale), so a higher statistical weighting was placed upon structural complexity as it related to the origin, development, and distribution of natural secondary-fracture porosity. Therefore, in their interpretation, the good shale-gas potential area was shifted to the vicinity of the Rome trough where a higher density of natural fractures was anticipated due to the folding and faulting associated with horizontal and vertical tectonics.

The structural element was not ignored by Zielinski and McIver (1982) in their investigation. Although the major thrust of their study was based upon the geochemical approach to locate potential source and exploration areas, they identified and mapped the area within the Appalachian basin which they considered the "most favored area" for exploration based upon structure. Figure 6 is an index map showing this area in relationship to the major structure elements in northern Kentucky and central West Virginia. Figure 7 is an enlargement showing the distribution of the "favored area" in West Virginia. The east prong of the Y-shaped area follows the trend of the Central West Virginia arch and the western prong is a southward projection of the Burning Springs anticline from southern Ohio to connect with the Mann anticline in central West Virginia. The "favored exploration area" has the greatest potential for production from the Hamilton Marcellus Formation. In this area the Marcellus has adequate thickness, good organic carbon content and maturation indexes favorable for the generation of both oil and gas. Within the "favored exploration area" east of the axis of the Central West Virginia arch, many decollement-type folds occur along the trend of the arch. The mode

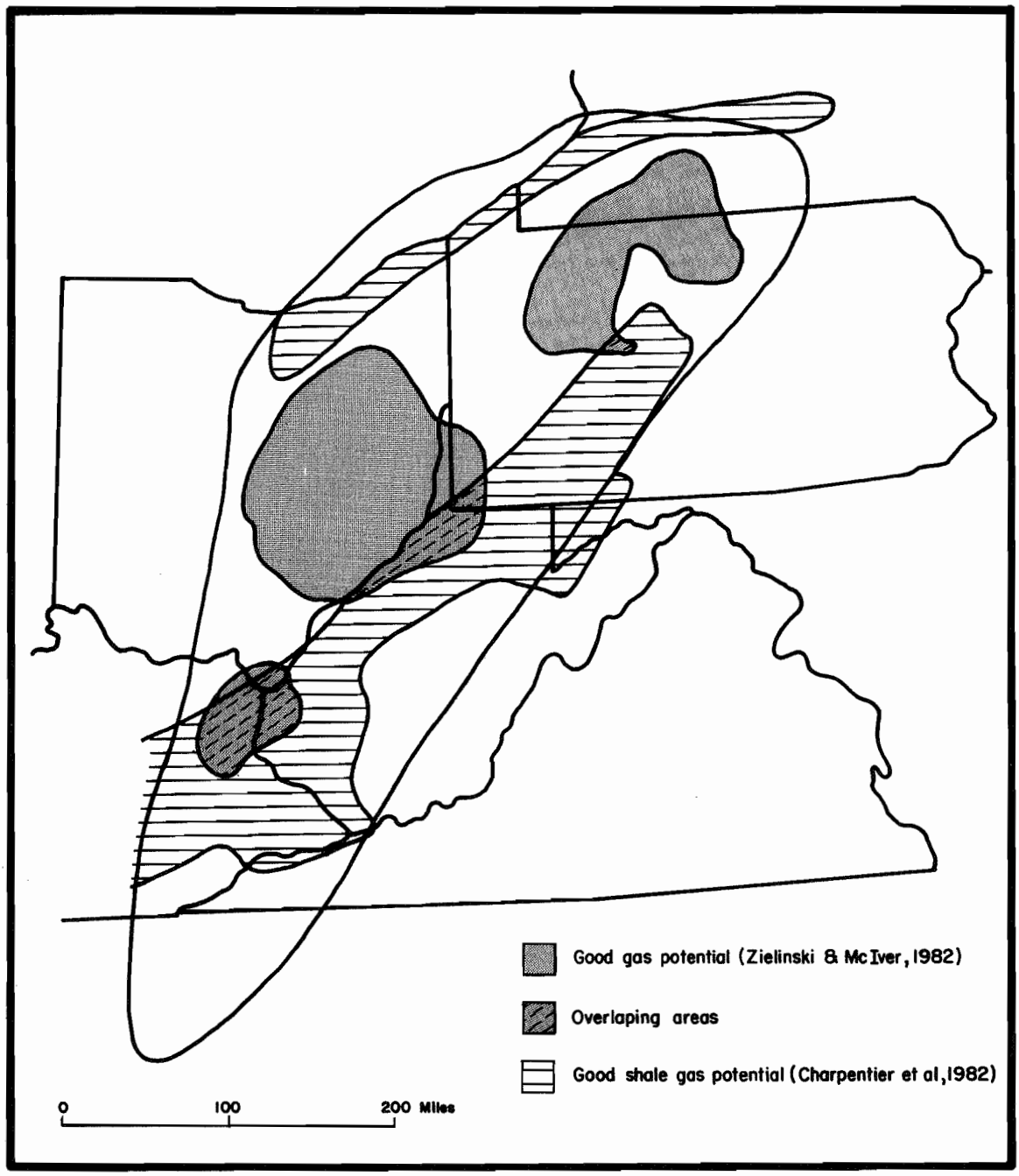


Figure 5 . Comparison of the Zielinski and McIver (1982) and the Charpentier et al. (1982) interpretations of areas with good gas potential.

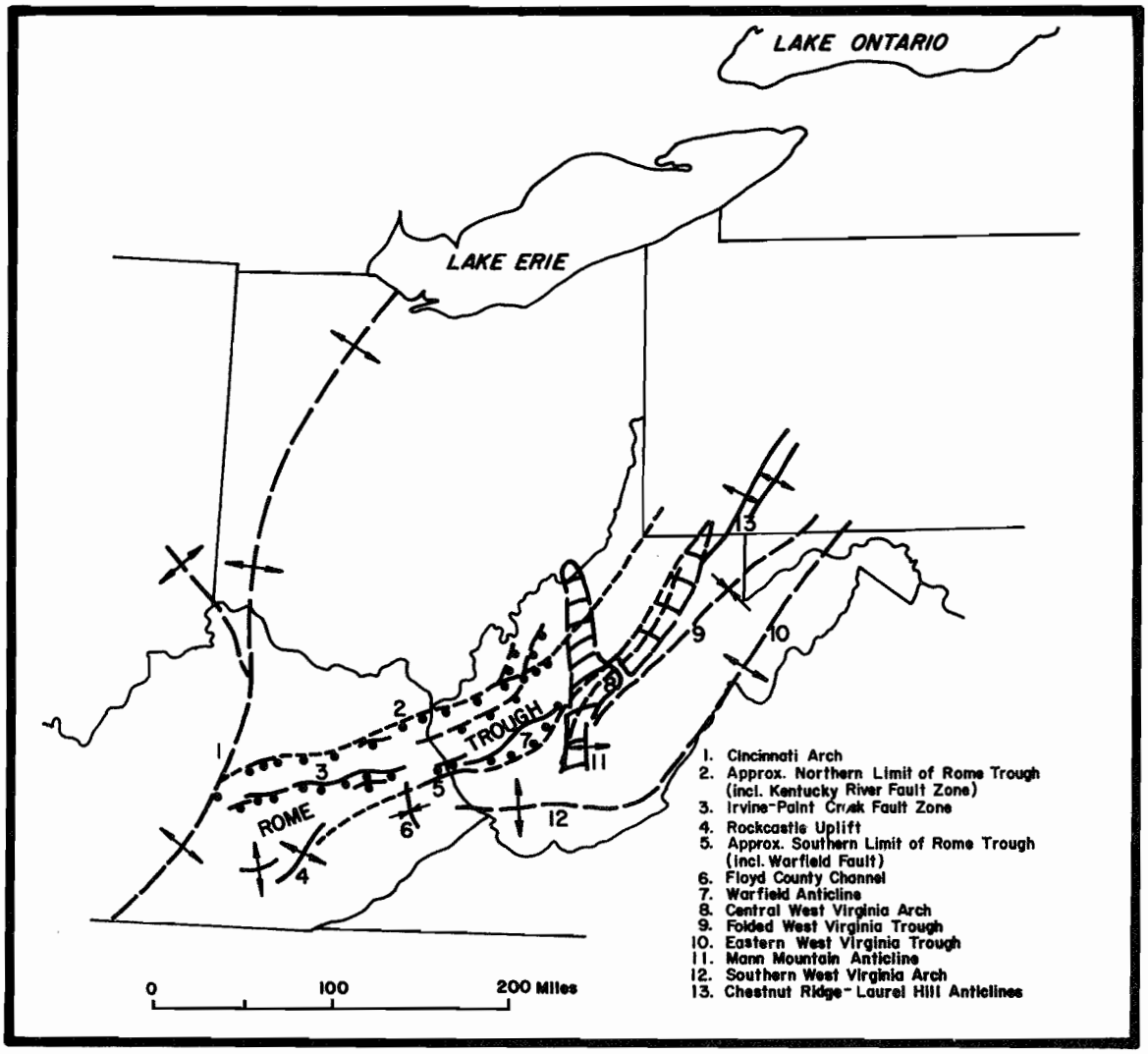


Figure 6. Index map showing location of favored exploration area based upon structure in relationship with structural features in eastern Kentucky and West Virginia. After Zielinski and McIver (1982).

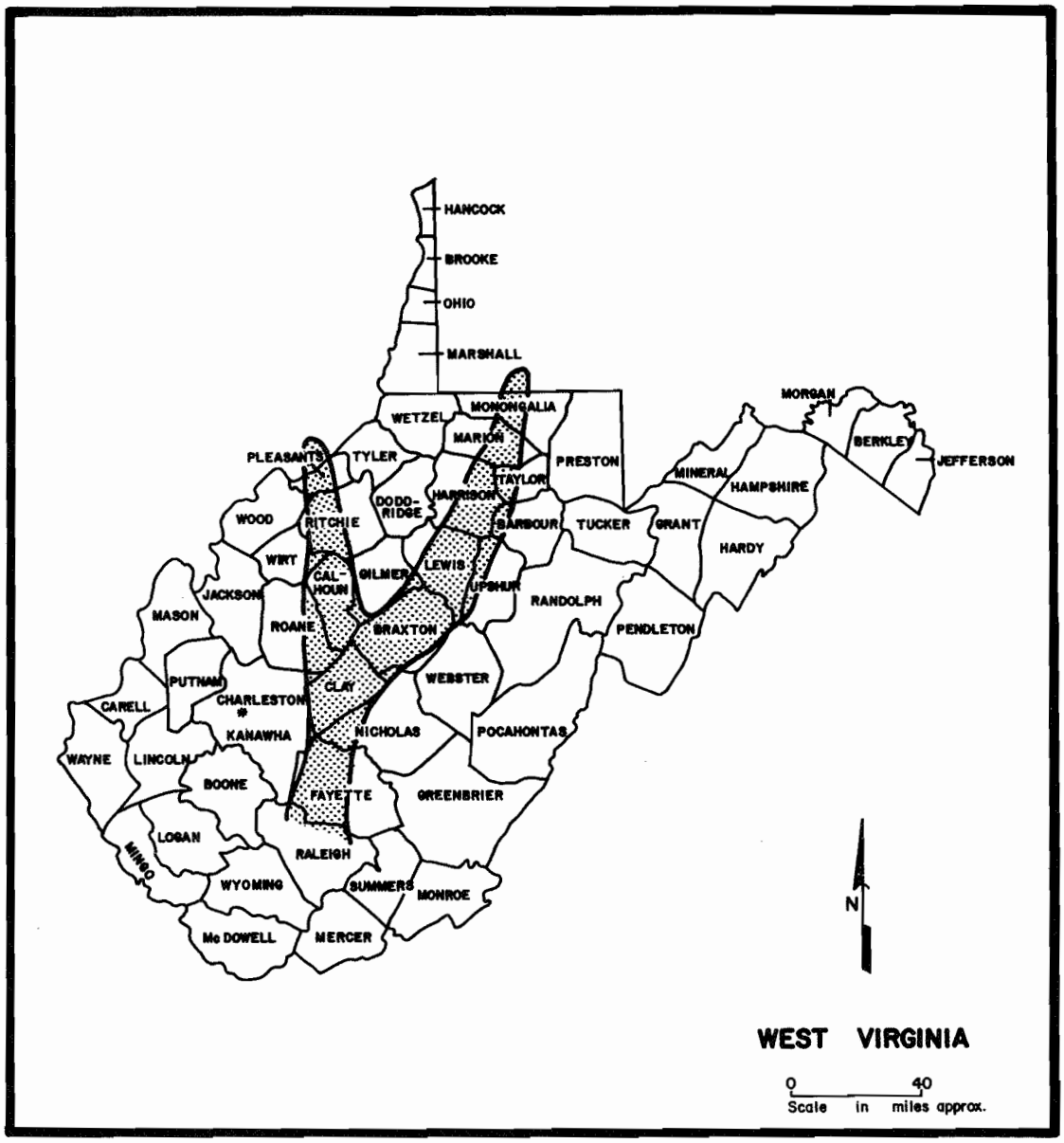


Figure 7. Areal distribution of "favored exploration area" in West Virginia. After Zielinski and McIver (1982).

of the tectonics would indicate thicker-than-normal sections of deformed Devonian Shale could be found in the cores of the anticlinal structures because of shale flow and imbricate faulting in the allochthonous plate. The crests, shoulders, and flanks of the anticlines should be sites for the maximum development of fractures associated with the tectonics and folding. The western prong of the "favored exploration area" marks the western limit of the Silurian Salt (Rodgers, 1963) which is considered by many investigators to be the detachment decollement surface for the Burning Springs anticline. Burning Springs type structures along this trend would also have high potential for secondary fracture porosity along the crests and flanks of the structures. Recently, the western prong has been an active Devonian shale exploration area and the site of recent hydrocarbon discoveries.

The areas designated as having good gas potential on figure 5, page 10, should be considered by explorationists and oil and gas operators as the favorable areas for exploration of natural gas from Devonian shales in the Appalachian basin. In the areas designated as having good shale-gas potential by Charpentier et al. (1982) the black shales have high organic carbon content and adequate thickness, the maturation levels are within the suitable ranges, and structural conditions are favorable for the generating of vertical fractures. Those areas designated by Zielinski and McIver as possessing high gas source capabilities have evaluation parameter values within the ranges considered suitable for the generation and expulsion of natural gas from the shales. Identification of natural fractures within the areas through the use of geophysics, airphoto and satellite imagery interpretations, or structure/stress analyses would enhance the potential for commercial production of natural gas from the Devonian shales.

A discussion of the most favorable areas for natural gas exploration from Devonian shales in the Illinois and Michigan is included within the geochemical section of this report. The areas within these basins which have the greatest potential for commercial production from the Devonian shales are shown on figures 146, 151, pages 254, 261.

A second major objective of the Eastern Gas Shales Project was to develop accurate estimates of the gas-in-place and the economically recoverable resource of natural gas from the Devonian shales in the eastern United States sedimentary basins. To this end, the report of Zielinski and McIver (1982) and Charpentier et al. (1982) provide the most recent and well-documented quantitative estimates of the gas-in-place resource.

At the inception of the Eastern Gas Shale Project investigations the original estimates of volumes of natural gas contained within the fractures and matrix of the Devonian shales in the eastern United States were placed between 277 and 900 trillion cubic feet of gas-in-place from which 10 to 520 trillion cubic feet was considered economically producible with current production techniques (United States Department of Energy, 1980). Another early estimate by the United States Geological Survey (National Academy of Science, 1976) projected the in-place resource at between 500 and 600 trillion cubic feet. Still another report by Science Applications, Inc., based upon off-gassing data from Mound, Battelle and GeoChem Laboratories, estimated the resource at 2,400 trillion cubic feet (United States Department of Energy, 1980).

The geochemical investigations of Zielinski and McIver (1982), which will be discussed in greater detail later in the report, have made possible more accurate estimates of the gas-in-place resource in the Devonian shales of the Appalachian basin. The data base for their study comes from analyses of samples from freshly taken cores from widely spaced wells throughout the northern and central portions of the Appalachian

basin. Included in the data base were the analytical results of controlled off-gassing procedures developed to overcome the limitation of previously used off-gassing techniques used for estimating the volume and composition of gas contained in the core samples. Gas content values calculated from core samples prior to the introduction of the controlled off-gassing program reflected low estimates for gas-in-place because a major volume of the contained gas was lost while the cores were being retrieved from the hole, measured and described. The estimates of the gas-in-place resource calculated from selected controlled off-gassing data were verified by comparison with off-gassing data obtained using a pressure-retaining core barrel. The available controlled off-gassing data combined with analytical data on the character of the kerogen, biofacies type and distribution, and thermal indexes were used by Zielinski and McIver to construct algorithms to derive more accurate estimates of the indigenous gas-in-place throughout the basin. Using the aforementioned algorithms to determine the indigenous gas-in-place for 17 selected stratigraphic intervals within the Devonian sequence and then integrating the data over the entire basin Zielinski and McIver were able to show the distribution of the overall indigenous gas-in-place resource for the Upper Devonian shales in the study areas of the Appalachian basin (fig. 8). The total indigenous gas-in-place estimates derived from the systematic geochemical approach used by Zielinski and McIver is placed at 2579 trillion cubic feet.

The second estimate of the in-place natural gas resource of the Devonian Shale in the Appalachian basin is reported in an unpublished manuscript prepared by the United States Geological Survey (Charpentier et al., 1982). Because the investigators believed that point-source input data into the assessment equation was of limited value, a probabilistic Monte Carlo technique was used in the estimate analysis. The major factors cited for rejecting a deterministic approach and use of point source input data were that the available data were subject to sampling errors and differences in interpretations and the amount of available data was very limited with respect to the size of the assessment area. The Charpentier et al. (1982) assessment formula (fig. 9) breaks the gas resource into three components: (1) the macrofracture gas; (2) the microporosity gas, and (3) the sorbed gas. The probabilistic Monte Carlo procedure utilizes the technique of estimating variations or ranges of potential values for each of the independent variables and entering these values into a framework of probability distribution. Subsequently, each probability distribution is randomly sampled and the assessment formula solved for gas volume. In the Charpentier et al. (1982) study, a high-speed computer permitted the above procedure to be conducted over 1000 times. The determined gas-volume values were used to construct a final empirical probability distribution for the total amount of gas. The framework of the assessment also permitted development of the probability distribution for each category of gas.

Data used to estimate the values for the input probability distribution were derived from published and unpublished reports and maps by the United States Geological Survey, Mound Laboratory Facility, Battelle Columbus Laboratories, and other Eastern Gas Shales Project investigators. A detailed reference to input documents can be found in Charpentier et al. (1982).

The in-place gas content of the Devonian shales was determined for each of the 19 play areas within the Appalachian Basin. The resource, by play areas in trillions of cubic feet, is shown in table 1. The Charpentier et al. (1982) estimate of the in-place natural gas resource of the Devonian shales in the Appalachian basin ranges from between approximately 577 to 1130 trillion cubic feet of gas.

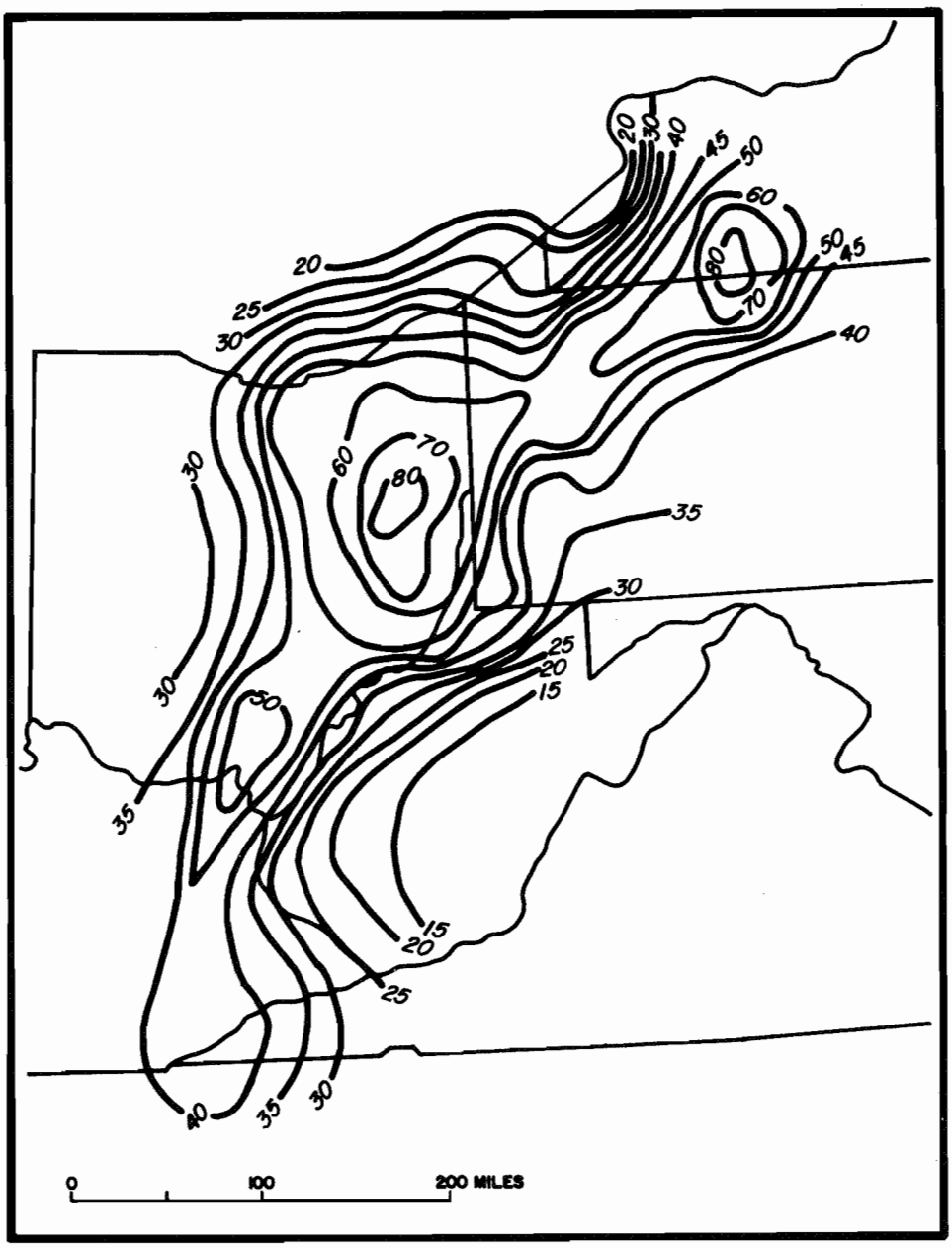
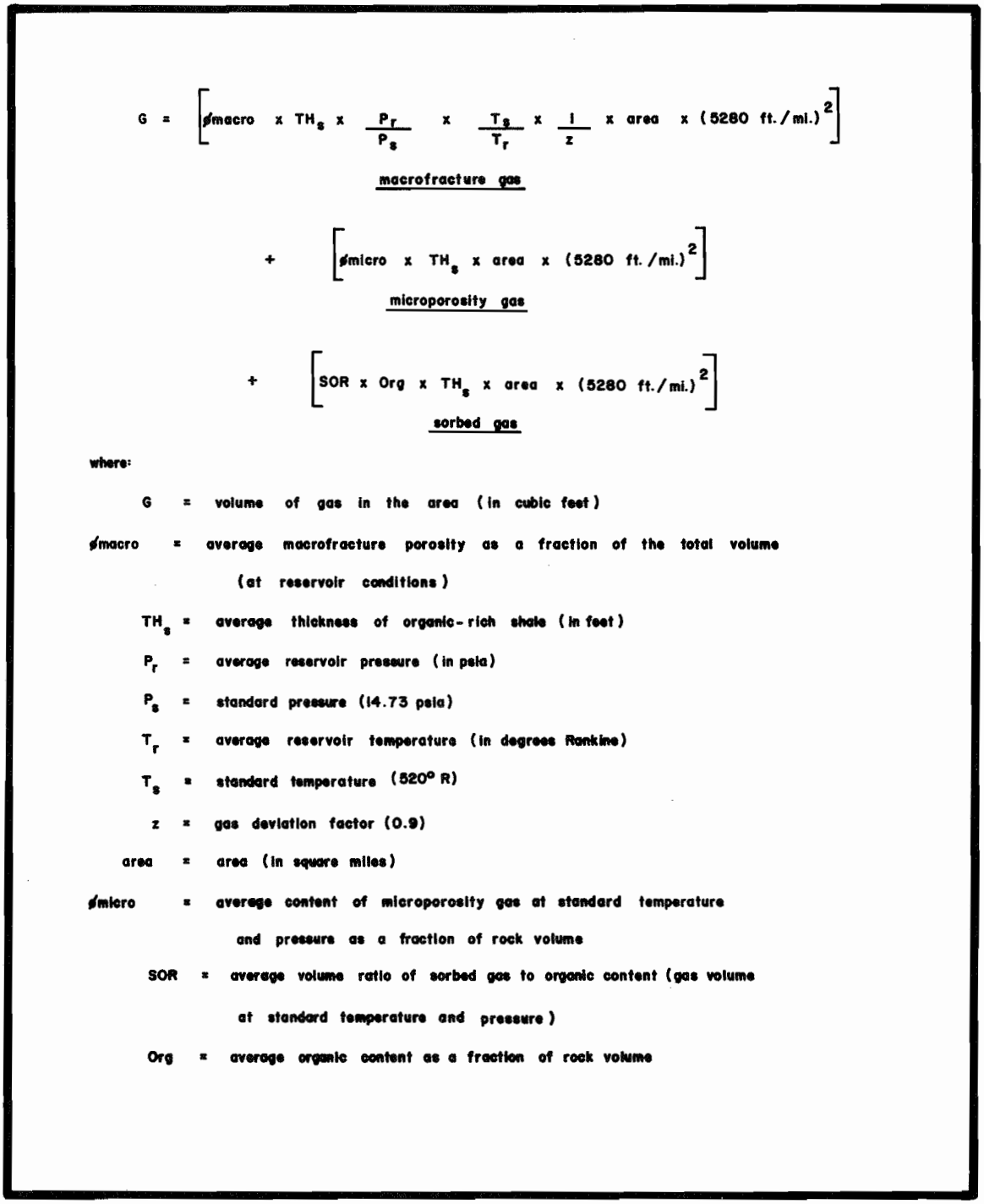


Figure 8. Map showing the total indigenous gas-in-place for the Upper Devonian shales in the Appalachian basin. Contour values in MMCF gas/Acre. After Zielinski and McIver (1982).



$$G = \left[\phi_{macro} \times TH_s \times \frac{P_r}{P_s} \times \frac{T_s}{T_r} \times \frac{1}{z} \times area \times (5280\ ft./mi.)^2\right]$$

macrofracture gas

$$+ \left[\phi_{micro} \times TH_s \times area \times (5280\ ft./mi.)^2\right]$$

microporosity gas

$$+ \left[SOR \times Org \times TH_s \times area \times (5280\ ft./mi.)^2\right]$$

sorbed gas

where:

G = volume of gas in the area (in cubic feet)

ϕ_{macro} = average macrofracture porosity as a fraction of the total volume (at reservoir conditions)

TH_s = average thickness of organic-rich shale (in feet)

P_r = average reservoir pressure (in psia)

P_s = standard pressure (14.73 psia)

T_r = average reservoir temperature (in degrees Rankine)

T_s = standard temperature (520° R)

z = gas deviation factor (0.9)

area = area (in square miles)

ϕ_{micro} = average content of microporosity gas at standard temperature and pressure as a fraction of rock volume

SOR = average volume ratio of sorbed gas to organic content (gas volume at standard temperature and pressure)

Org = average organic content as a fraction of rock volume

Figure 9. Resource assessment equation. Charpentier et al. (1982).

Table 1. **Estimates of in-place natural gas resources in the Devonian shale of the Appalachian basin. After Charpentier et al. (1981).**

	Play	Natural Gas Resources (trillions of cubic feet) low F_{95}[1/]	high F_5[1/]	mean
1.	North-Central Ohio	17.9	34.2	25.9
2.	Western Lake Erie	21.7	31.3	26.5
3.	Eastern Lake Erie	2.1	3.3	2.7
4.	Plateau Ohio	44.4	76.2	59.9
5.	Eastern Ohio	35.2	55.1	44.7
6.	Western Penn-New York	20.4	28.2	24.3
7.	Southern Ohio Valley	19.7	36.2	27.7
8.	Western Rome Trough	38.0	74.0	56.0
9.	Tug Fork	13.7	25.9	19.7
10.	Pine Mountain	10.7	18.7	14.6
11.	Plateau Virginia	3.9	10.2	7.1
12.	Pittsburgh Basin	76.8	129.9	102.1
13.	Eastern Rome Trough	70.7	132.5	100.3
14.	New River	38.5	91.7	63.1
15.	Portage Escarpment	8.5	21.3	14.6
16.	Cattaraugus Valley	10.4	23.2	16.6
17.	Penn-York Plateau	98.1	195.2	146.0
18.	Western Susquehanna	24.1	67.7	44.9
19.	Catskill	22.1	75.8	47.6
	Entire basin	577.1	1130.8	844.2

[1/] F_{95} denotes the 95th fractile; the probability of more than the amount F_{95} is 95 percent. F_5 is defined similarly. Because of dependency between plays, these fractiles (unlike those in many other studies) are additive.

Comparison of the two estimates of gas-in-place by Zielinski and McIver (1982) and Charpentier et al. (1982) shows the probabilistic approach of estimating the resource resulted in a much more conservative value (1130 TCF) than the approach using selected geochemical algorithms (2579 TCF). Comparison of these latest two estimates with other recently reported estimates are shown in table 2.

Table 2. Comparison of estimates of in-place natural gas resources in the Devonian shale of the Appalachian basin (in trillions of cubic feet).

Smith (1978)	206-903
Federal Energy Regulatory	285
Kuuskraa and Meyer (1980)	400-2,000
National Petroleum Council (1980)	225-1861
Zielinski and McIver (1982)	2579
Charpentier et al. (1982)	577-1131 (844 mean)

Which of the estimates, the conservative or the optimistic, is correct or nearest to the actual gas-in-place value will not be known until after a much larger analytical data base can be assembled from throughout the basin. The wide discrepancy in the values is due to (1) the approach taken, (2) the limited amount of data available for the size of the area being studied, and (3) assumptions which have been made in order to project data between control points. Also to be considered are errors inherent in sampling procedures and interpretations by different investigators utilizing different analytical techniques. It would seem probable that the correct estimate of the Devonian shale in-place gas resource lies somewhere between the Zielinski and McIver (1982) figure of 2579 TCF and the Charpentier et al. (1982) figure of 1130 TCF. This conclusion assumes that the gas volume data from off-gassing experiments used by Charpentier et al. (1982) did not account for gas lost during the retrieval, measurement and describing of the core prior to placement in the leak-proof containers. By comparing the results of off-gassing experiments using a core obtained with conventional core barrels and pressure controlled core barrels, investigators have demonstrated that the gas release volume was exponential with time and much more gas has been lost than originally thought.

The assessment of the Devonian shale natural gas resource for the Michigan basin has been estimated at 74 trillion cubic feet of gas (TCF) by the National Petroleum Council (1980). The distribution of the gas between the black and gray shales of the Antrim/Ellsworth Formation is shown in table 3.

Table 3. **Devonian Shale resource assessment for Michigan. After National Petroleum Council (1980).**

LOG DATA

	Average Thickness (Feet)	Land Area* (Sq Mi)	Total (TCF)
Black Shale	93	34,081	53
Gray Shale	218	34,081	21

	Average Depth (feet)	Total (TCF)	Average (BCF/Sq Mi)
Total Shale Resource	1,890	74	2

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

A total of 86 trillion cubic feet of gas (TCF) has been estimated as the natural gas resource available from the Devonian shales in the Illinois basin. The distribution of the Illinois basin resource is shown on table 4.

Table 4. **Devonain Shale resource assessment for the Illinois, Indiana and Kentucky portions of the Illinois basin. After National Petroleum Council (1980).**

	Total Shale		Total Shale Resource	
	Average Thickness (Feet)	Land Area* (Sq Mi)	Total (TCF)	Average (BCF/Sq Mi)
Illinois	213	7,484	28	4
Indiana	141	11,597	28	2
Kentucky	194	9,069	30	3
Grand Total	177	28,150	86	3

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

The economically recoverable gas resource from the Devonian shales in the Appalachian basin have been estimated in three recent investigations by the National Petroleum Council (1980), Pulle and Seskus (1981), and Zielinski and McIver (1982). The National Petroleum Council estimate of the total gas-in-place in the Devonian shale was 225 trillion cubic feet of gas if only the radioactive black shales were considered, or 1861 trillion cubic feet of gas from the combined gray and black shale sequence. They also estimated that 44 percent of the land area in the Appalachian region would not be available for drilling and developing, which reduced the estimate of available gas-in-place to 56 percent of the original total or 125 trillion cubic feet of gas for the black shales and 1040 trillion cubic feet of gas for the total shale sequence. The National Petroleum Council recoverable gas estimates were based upon decline curve analyses derived from a review of existing production data and completion technology from 2741 Devonian shale wells over a 36-county area of Kentucky, West Virginia, Ohio and New York. Although the production decline analysis was conducted over relatively small segments of the total resource area, the average well production data extrapolated over the entire basin was modeled using a single hyperbolic decline equation. Using the aforementioned production decline data in conjunction with current conventional fracturing technology and a 160-acre well spacing, the National Petroleum Council estimated the producible Devonian shale gas in the Appalachian basin to be 37.4 trillion cubic feet of gas. This value indicates a recovery factor of approxiamtely 30 percent of the in-place resource. For a detailed discussion of data base and interpretive techniques used in arriving at this above estimate, please refer to the original report (National Petroleum Council, 1980).

The Science Application Incorporated estimates (Pulle and Seskus, 1981) were obtained in terms of a probability distribution which quantified the inherent uncertainty associated with questionable geological and production data (Pulle and Seskus, 1981). In this study, the basin was partitioned into areas made up of clusters of counties which had similar stratigraphic, geochemical and structural properties. It was assumed that the distribution of production per well or wells within the cluster would be representative of all wells drilled within the boundary of the cluster. Analysis of production from wells throughout the study area indicated that well productivity on a county and regional basis was lognormally distributed and that the total recoverable gas over the entire basin was statistically normally distributed. The final determination of the recoverable resource considered, in conjunction with production data, a well spacing of 160 acres, a success ratio for each cluster area and well-shooting technology as the fracturing mechanism. The properties of the normal distribution indicated a 95 percent probability of the total recoverable resource falling between 17.06 and 23.34 trillion cubic feet of gas. The mean value for the recoverable resource is 20.2 trillion cubic feet of gas. For a detailed discussion of the methods and parameters used in defining the estimate, refer to the original manuscript (Pulle and Seskus, 1981).

A third estimate of the recoverable natural gas resource from the Appalachian basin Devonian shales was made by Zielinski and McIver (1982) from a review of the data and interpretations developed by Pulle and Seskus (1981) in their investigation. A correlation by state of production per area evolved from the review of the data over the 14-county area of Ohio, Kentucky and West Virginia where production data was available. The average production for Kentucky counties was 2.3×10^{-3} TCF/mi^2, for Ohio counties 0.7×10^{-3} TCF/mi^2 and for the West Virginia counties 1.5×10^{-3} TCF/mi^2. Average production rates appeared to be independent of the in-place gas resource. Zielinski and McIver (1982), noting that no attempt was made to qualify the data by production practices, recognized the potential significance of the correlation of the production per area factor in the assessment of the recoverable resource. They also recognized from the

other studies that gas production from shot Devonian gas wells is diffusion-controlled over a long term (over 10 years) and that cumulative production is dependent directly upon the controlling production parameters (matrix porosity, permeability and fractures). Accordingly, if it could not be demonstrated with additional production data that production per area values were consistent for larger sample populations, then a base case value of the recoverable resource could be estimated (Zielinski and McIver, 1982). Based upon available data and the gross assumption that production per area values are dependent upon the controlling production parameters for individual states, Zielinski and McIver (1982) have estimated the recoverable resource for the area encompassing the states of Ohio, West Virginia and Kentucky to range between 30 and 50 trillion cubic feet of gas assuming a well spacing of 160 acres and shot-well completion technology. No data were available for estimates for other states in the Appalachian basin. A comparison of the estimates in the three studies is shown in table 5.

Table 5. Comparison of the estimates from recent studies of the recoverable natural gas resource in the Appalachian basin in trillion cubic feet (TCF).

	Minimum	Maximum	Mean
National Petroleum Council		37.4	
Science Applications Inc. (Pulle and Seskus, 1981)	17.6	23.34	20.20
Monsanto Mound Facility (Zielinski and McIver, 1982)	30.0	50.0	40.0

GEOLOGY OF THE DEVONIAN SHALE NATURAL GAS RESOURCE

REGIONAL SETTING

The in-place natural gas resource from the Devonian shale of the eastern United States has been estimated to be between 277 and 900 trillion cubic feet (Tcf). The Devonian shale reservoir containing this resource underlies an area of approximately 275,000 square miles within the confines of the Appalachian, Michigan and Illinois basins. The regional setting of the three basins within the area of the eastern United States is shown on figure 10. Although deposition in the three basins was not contiguous throughout Devonian time, each of the basins was a site for accumulation of thick deposits of highly organic black muds during Middle and Late Devonian time. The high organic content of the black muds which lithified into the black petroliferous shales is considered to be the source for the matrix gas now trapped in the Devonian shales and sandstones as well as for the free gas found in areas of secondary fracture porosity within the Appalachian basin.

Appalachian Basin

The present form of the Appalachian basin came into existence through the deformation generated by the Alleghenian orogeny at the close of the Paleozoic Period. The basin, elongate and narrow in shape, trends southwestward from southwestern New York through western Pennsylvania, eastern Ohio, West Virginia, western Virginia, east-central Kentucky, east-central Tennessee and terminates just south of the common corner of northwestern Georgia and northeastern Alabama. The Allegheny Structural Front marks the eastern limit of the Appalachian basin. The western boundary is less well-defined but is considered to follow the trend of the Findlay arch in northwestern Ohio and the Cincinnati arch through western Ohio and northern Kentucky. Through southern Kentucky and Tennessee the western boundary follows the trend of the Nashville dome and its northern projection.

From New York southward to northern Alabama, Middle and Upper Devonian rocks underlie an area of approximately 100,000 square miles in the Appalachian basin (Dennison, 1971).

Physiographically the boundaries of the Appalachian basin closely coincide with the boundaries of the Appalachian Plateau Province as designated by Fenneman (1938). The geographic area of the province is shown on figure 11. The province has been subdivided into seven physiographic sections, each categorized on the basis of distinctive topography, structure, surficial material, and drainage patterns. The higher elevations along the eastern margin of the province have been designated the Catskill Mountain, the Allegheny Mountain, and the Cumberland Mountain Sections (fig. 11). The mountain sections occupy approximately 20 percent of the province. The Cumberland Plateau Section and the glaciated and unglaciated Allegheny Plateau Sections encompass the remaining 80 percent of the province. A sharp boundary exists between the glaciated and unglaciated plateau sections in contrast to the non-distinct boundaries found between the other sections of the provinces.

Figure 10. Distribution of gas-bearing Devonian-age shales in the eastern United States.

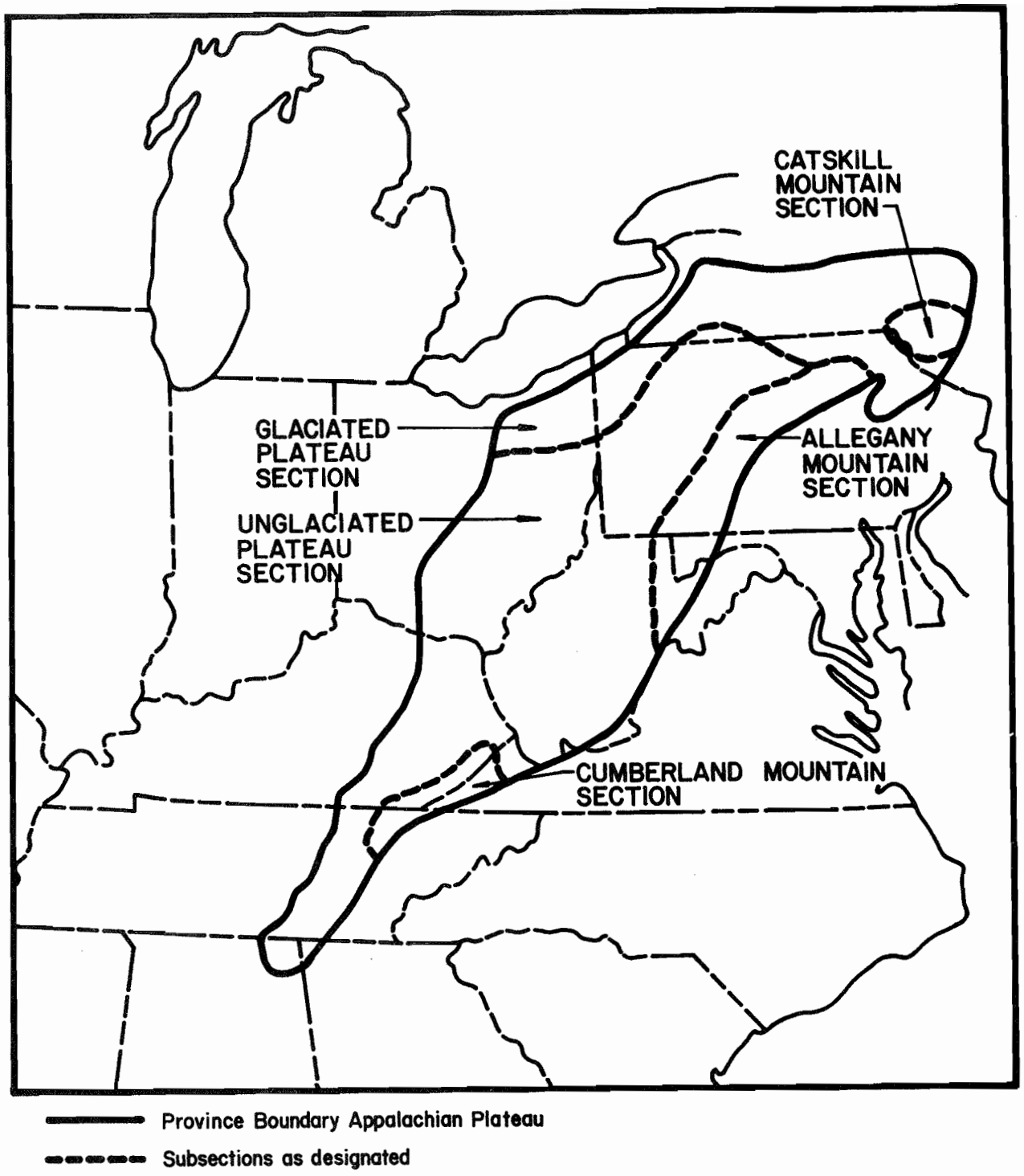


Figure 11. Approximate boundary of the Appalachian Plateau Province. After Fenneman (1938). Mountain Sections and Glaciated Plateau Section shown by dotted lines.

In general, the geographic areas of the plateau sections occur adjacent and west of the mountain sections bearing the same name. Low relief, moderate dissection and a dendritic drainage pattern reflecting the horizontal to slightly dipping nature of the bedrock are characteristic elements of the plateau sections. The dendritic drainage is in sharp contrast to the parallel drainage patterns found in the Ridge and Valley Province, where the rocks are folded into long sinuous anticlines and synclines. The Mohawk Section of the province falls outside of the basin area, and is not shown on figure 11.

Accessibility for exploration of Devonian shale gas within the Appalachian Plateau Province ranges from good along the western side of the province in east central Ohio to poor along the eastern side of the province where relief, steep slopes and tree cover combine to restrict accessibility.

Michigan Basin

The Michigan basin, as described by Cohee (1965), includes the Southern Peninsula, the eastern part of the Northern Peninsula, eastern Wisconsin, northeastern Illinois, northern Indiana, northwestern Ohio and western Ontario. The area of the basin, including those areas covered by Lake Michigan, Lake Huron and Lake St. Clair, is approximately 122,000 square miles. A framework of surrounding basement outcrops and other structural features define the basin (Ells, 1969). The western limit of the basin in central and northwestern Wisconsin is defined by the position of the Wisconsin arch. The Canadian Shield in northern and northeastern Michigan serves as the northern boundary. The Algonquin arch in Ontario and the Findlay arch in northwestern Ohio are the eastward and southeastward limits of the basin. In northern Indiana and northeastern Illinois the southern and southwestern boundaries of the basin are defined by the Kankakee arch (fig. 12).

Physiographically the Michigan basin falls within the boundary of the Great Lakes Section of the Central Lowlands Province as designated by Fenneman (1938). The southern, western and northern boundaries of the section closely align with the structural boundaries of the Michigan Basin. However, the eastern boundary of the section falls far to the east of the eastern structural limit of the basin. The Great Lakes Section is characterized by numerous lakes and features of Pleistocene glaciations, i.e., ground moraine, outwash plains, kettles, kames, and lake plains.

Accessibility for oil and gas exploration within the region should be moderate to good because of low relief and abundance of well-drained soils.

Illinois Basin

The Illinois basin, located in the east-central United States, is elliptical in shape with the major axis trending northwest-southeast. Geographically, the basin is centered in southeastern Illinois and covers most of west central and southern Illinois, the south-

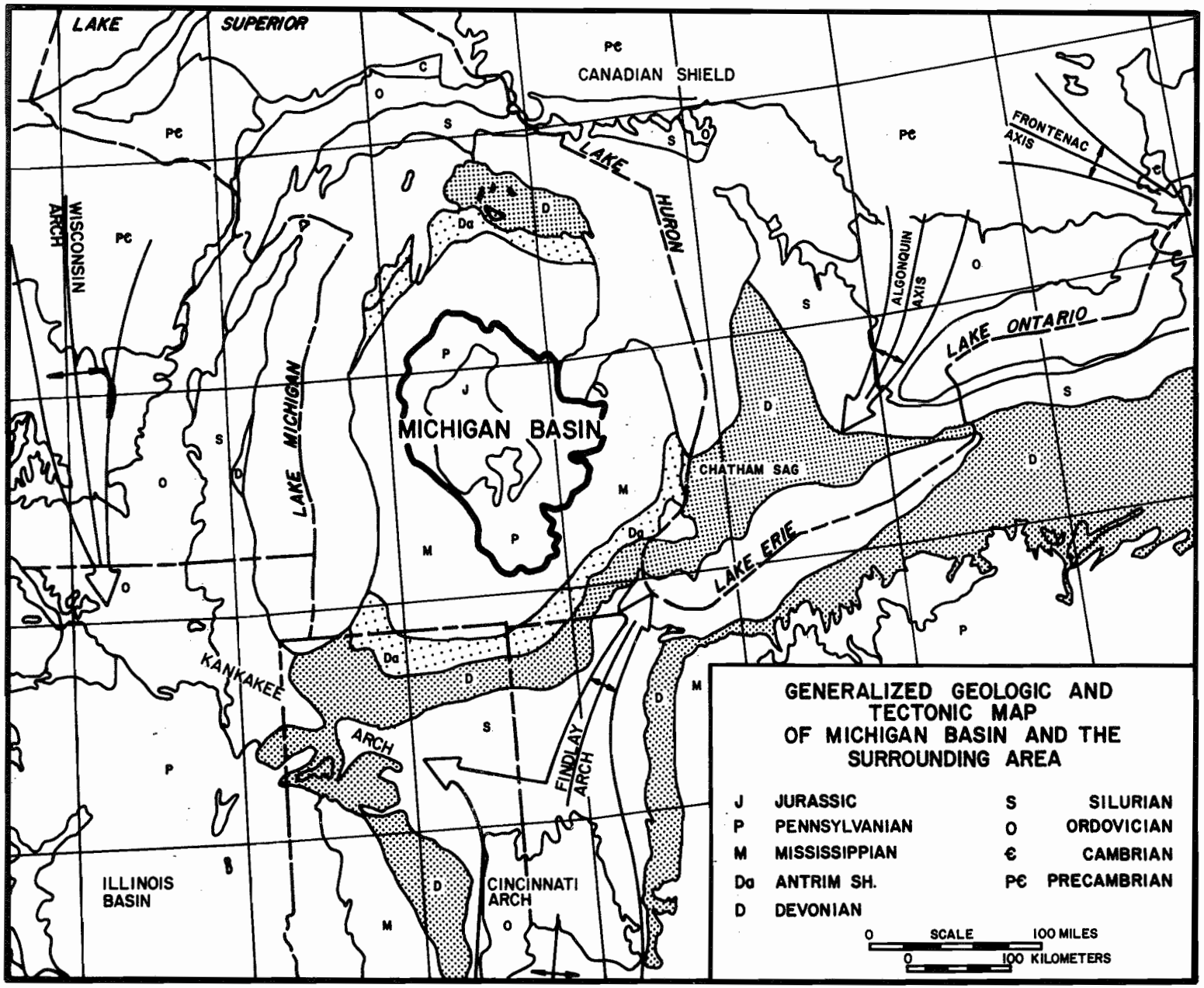


Figure 12. Map showing structural elements which define the Michigan basin. Gardner (1974).

west part of Indiana, and north central Kentucky. The basin is a structural depression surrounded on all sides by a framework of positive structural elements (fig. 13). To the southeast and, east the basin is separated from the Appalachian basin by the Nashville dome and the Cincinnati arch. To the north, separating the basin from the Michigan basin, are the Kanakee arch and the Wisconsin arch. The western and southwestern limits of the basin are defined by the Mississippi arch, the Ozark dome, and the Pascola arch. The area encompassed by the above structural framework is approximately 53,000 square miles.

Physiographically, the Illinois basin is located almost entirely in the Till Plains section of the Central Lowlands Province of Fenneman (1938). Extreme southern Illinois, Indiana, and the Kentucky part of the basin are located in Fenneman's Interior to Low Plateaus Province. The boundary separating the two provinces is shown on figure 13.

The Till Plains section is characterized by landforms and materials of glacial origin. Loess covered ground moraine, end moraine, outwash, kames, and other related glacial features are common throughout this section of the lowlands provinces. In contrast, the low plateaus is moderately dissected by youthful and mature streams into rolling uplands of moderate relief.

Low relief and glacial soils should afford good to excellent accessibility for oil and gas exploration during dry weather in the lowland province. Accessibility should range from good to moderate in the low plateaus region where locally, relief reaches 400 to 500 feet and slopes become steep and tree-covered.

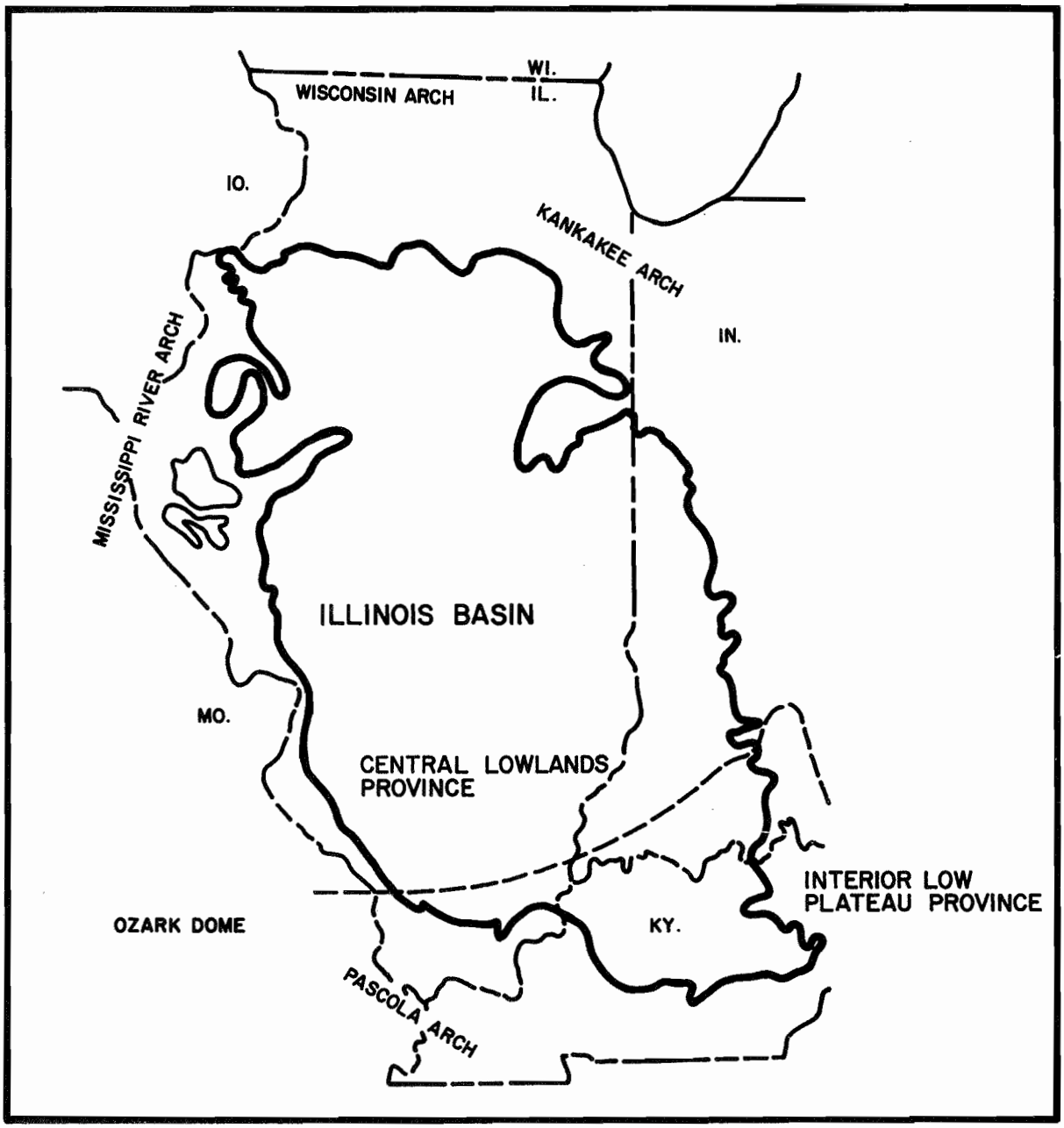


Figure 13 . Generalized Tectonic Map of Illinois Basin and surrounding area. Dashed line is boundary separating physiographic provinces.

STRATIGRAPHY

Introduction

Rocks of Middle and Upper Devonian age are limited in distribution to three basins of deposition in the eastern United States. The Middle and Upper Devonian sequence in the Appalachian basin consists primarily of a westward-thinning wedge of clastic sedimentary rocks. In the Illinois and Michigan basins clastic sediments are restricted mainly to the Upper Devonian. The thickness of this wedge ranges from 11,000 feet in east-central Pennsylvania to less than 50 feet along the margins of the Appalachian, Michigan, and Illinois basins. Lithologically the sequence varies from fine-textured shales, mudstones, and siltstones to coarse-textured sandstones and shales. Thin limestone units and calcareous shales make up a very small part of the Appalachian basin Middle and Upper Devonian sequence. The lithologic and spatial relationships of the strata within the sequence have been interpreted by workers in the Appalachian basin region to represent the different facies within the framework of a prograding delta model of deposition. The finer-textured darker-colored shales and the organic-rich sediments occurring in the Michigan and Illinois basins and along the western and southern margins of the Appalachian basin indicate more normal marine sedimentation around the distal margin of the Catskill delta. The lighter-colored, organic-poor shales, siltstones and mudstones which interfinger from the east into the organic-rich shales are interpreted as delta front and turbidite sediments deposited around the proximate margin of the Catskill delta or shall marine shelf deposits.

The most complete section of Devonian-age rocks exposed at the surface in the United States is located in the northeastern part of the Appalachian basin in the western half of New York. For this reason this area of New York has become the classic reference section for the Middle and Upper Devonian series of North America. The exposures in western New York were the basis for the most serious research or investigations of Devonian-age stratigraphy and sedimentation undertaken in the eastern United States. Over the past 120 years, the exposures in southwestern New York have been studied extensively by many geologists.

The Middle and Upper Devonian stratigraphic sequence in the Michigan basin ranges in thickness from approximately 3500 feet in the center of the basin to approximately 800 feet along the margins. The basal units of the Middle Devonian (Onesquethaw Stage) consist primarily of limestones and dolomites that are correlative with the Onondaga limestone equivalents in the Appalachian and Illinois basins. The Rogers City Formation and the Traverse Group limestones comprise the upper units of the Middle Devonian (Cazenovia, Tioughnioga Stages) in the Michigan basin. The predominately carbonate sequences of the Michigan and Illinois basins grade laterally eastward through alternating limestone and shale sequences into predominately marine shales of the Hamilton Group in Ontario and New York. Black and gray shales, siltstones and limited amounts of sandstone are the dominant lithologies of the Upper Devonian (Finger Lakes, Cohocton, Cassadaga, Bradford Stages) sequences in the Michigan basin. The black shale facies dominates in Ontario and the eastern portion of the Michigan basin and grades westward into the normal marine shale facies of the Ellsworth Formation along the western margin of the basin.

This report, a study of the potential of the Devonian Shales as a source of natural gas, is focused primarily on the Middle and Upper Devonian shale facies of the eastern United States sedimentary basins. The shale facies, a westward thinning wedge which, in the northern Appalachian basin, includes almost the entire Middle and Upper Devonian section from the top of the Onondaga Formation to the top of the Perrysburg Formation of New York. In the Michigan basin the shale facies (Antrim/Ellsworth) is restricted only within the Upper Devonian. The upper part of the Antrim/Ellsworth shale facies in the Michigan basin grades laterally into the sandstone and siltstone of the prograding Catskill delta in the northern Appalachian basin. These correlations and stratigraphic relationships are shown on plate 1.

In the Illinois basin, rocks equivalent to the Middle and Upper Devonian clastic sequence in the northern Appalachian basin range from a feather edge to a maximum thickness of over 700 feet. Marine carbonates which were deposited throughout Middle Devonian time were succeeded by a fine clastic shale facies during the Late Devonian in the Illinois basin.

The basal Middle Devonian unit in Illinois, the Grand Tower Limestone, correlated within the Illinois basin to the Jeffersonville Limestone of Indiana and Kentucky and with the Onondaga Limestone of the northern Appalachian basin. Continuation of the carbonate environment throughout the remainder of the Middle Devonian resulted in the deposition of the Lingle Limestone in Illinois and the North Vernon and Sellersburg Limestones in the Indiana and Kentucky portions of the Illinois basin. The Lingle, North Vernon, Sellersburg sequence is correlative with the predominately fine clastic Hamilton Group in New York and the northern part of the Appalachian basin (plate 1).

The Upper Devonian sequence in the Illinois basin consists chiefly of a black shale sequence designated the New Albany Shale which attains a maximum thickness of approximately 450 feet in southeastern Illinois. The New Albany grades laterally into the shale sequence of the lower part of the Upper Devonian of New York. The upper part of the Illinois basin New Albany Shale is equivalent with the interbedded sandstone and siltstone facies of the prograding Catskill delta of New York and Pennsylvania. Intrabasin and interbasin correlations and stratigraphic relationships are shown on plate 1.

The primary reference sources for the discussion on Middle and Upper Devonian stratigraphy for this report will be the International Symposium on the Devonian System by the Alberta Society of Petroleum Geologists (1967) and the seven screening reports prepared by Tetra Tech, Incorporated, Columbus, Ohio, for the United States Department of Energy on the evaluation of the Devonian shales as a potential natural gas source (Tetra Tech, 1981, DOE/METC 118, 119, 120, 121, 122, 123, 124), as well as from newly generated stratigraphic sections and research conducted by Tetra Tech, Inc. Because of the complex stratigraphic relationships within the Devonian age reference section, there still remains disagreement between workers on correlations within the reference area and correlations from the reference area into surrounding regions. Where necessary to show the basis of correlation used in this report, additional references will be made to the work and interpretations of investigators who have contributed to the understanding and correlation of the rocks of the Devonian-age sequence.

Previous Workers

APPALACHIAN BASIN

Studies of Devonian-age rocks began in the Appalachian basin as early as 1838. The earlier studies from 1838 to 1930 were generalized reconnaissance or detailed investigations of relatively small areas. The Devonian System became established in North America in 1847 through the writings of Verneuil, whose views were made known by Hall's translations (Cooper et al., 1942). In 1851, Hall accepted the Devonian System and the European framework.

The Devonian System has been divided into a threefold arrangement: the lower, middle and upper. The three divisions are unequal, the Upper Devonian outweighing the other two divisions. Because there is some question about the correspondence of the American divisions with the European divisions, the American Devonian has been subdivided into 10 stages with judgment being reserved as to which stages or parts of stages will be placed in the lower, middle and upper divisions (Cooper et al., 1942). The Devonian shale sequence in the New York reference section (top of Onondaga Limestone to the top of the Perrysburg Formation) corresponds with the interval represented by the Cazenovia, Tioughnioga, Taghanic, Finger Lakes, Cohocton and the lower part of the Cassadaga stages. The stages are time intervals spanning several formations, characterized by distinctive faunal assemblages and similar paleoenvironments.

Initial work on the American Devonian System commenced over 140 years ago. These early attempts were concerned primarily with defining major subdivisions within the American section and fitting these subdivisions into the framework of the European System. This early work on the Devonian strata in the New York classic section was undertaken by John Hall and Lander Vanuxem in 1838 and their progress is reported in the annual reports of the New York 3rd and 4th geological districts (Hall, 1839, 1840, 1841; Vanuxem, 1839, 1840). Near the turn of the century, C.S. Prosser (1893, 1897, 1898), James Clarke (1903, 1908), Clarke and Luther (1904), and D.D. Luther (1902, 1903) continued stratigraphic and paleontologic investigations of the Devonian section of New York. The New York section was subject to continued investigations during the years between 1910 and 1950. Major contributions during this period were A.W. Grabau (1917), G.H. Chadwick (1919, 1923, 1924, 1933, 1935), G.A. Cooper (1930,1935), K.E. Caster (1933), and I.V. Fox (1932). Beginning in 1947 the United States Geological Survey undertook a study of the occurrence and origin of petroliferous black shales in the Appalachian basin. Included in this study were the organic-rich Devonian black shales of New York.

In the course of these studies over 400 closely-spaced stratigraphic sections of Upper Devonian rocks were measured and described, and detailed geologic mapping was completed in the outcrop belt of western and central New York. Lithostratigraphic correlations, made possible because of the closely-spaced stratigraphic control and abundance of key stratigraphic marker beds, were instrumental in the interpretation of the complex stratigraphic and facies relationships occurring within the sedimentary framework of the prograding Catskill delta. J.F. Pepper and Wallace de Witt, Jr. (1950, 1951); Pepper, de Witt, and Colton (1956); de Witt and Colton (1958, 1959) made significant contributions to the studies of the Devonian stratigraphy of New York during this period. Between 1960 and 1976, L.V. Rickard (1964, 1975) continued his investiga-

tions and work on the correlation of Devonian stratigraphic units within the state. From 1976 onward, the major contributor to the study of Devonian rocks in New York has been the New York Geological Survey in conjunction with the Eastern Gas Shales Project. These investigations are restricted to the Devonian shales and are part of the larger investigations of Devonian shales throughout the Appalachian basin being undertaken by the United States Department of Energy. Reference to reports describing the results of investigations on New York Devonian-age stratigraphy during this recent period of study and the name of principal investigators and authors can be found in the bibliography of the United States Department of Energy's evaluation of the Devonian Shales of New York (Tetra Tech, 1981, DOE/METC 122).

Although the Middle and Upper Devonian sediments in the Appalachian basin reached maximum thickness in east-central Pennsylvania and rivals the New York section for completeness, it did not receive the attention from workers because it did not have the distinction of being the American standard reference section. Prior to the 1900's significant investigations of the Devonian-age stratigraphy of Pennsylvania were conducted by Sherwood (1878), Stevenson (1878) and Prosser (1892, 1895). The contributions to Devonian paleontology (Williams and Kindle, 1905) included work on the Devonian section in Pennsylvania. Other contributions to the study of Devonian stratigraphy during the period from 1900-1920 included the investigations of Charles Butts (1906), J. Barrell (1913, 1914), and W.A. Ver Weibe (1917). Bradford Willard's contributions to the Devonian stratigraphy of Pennsylvania were enormous during his tenure at the Pennsylvania Geological Survey and during the early years of his professorship at Lehigh University. In the 1930's and 1940's Willard was the principal author of numerous publications and reports on the Devonian stratigraphy of Pennsylvania (Willard, 1933, 1934, 1934a, 1935, 1935a, 1937, 1937a, 1947; Willard and Caster, 1935; Willard, Swartz, and Cleaves, 1939). Recent work on the Devonian stratigraphy of Pennsylvania has been performed in conjunction with the United States Department of Energy's Eastern Gas Shales Project. Comprehensive studies on the characterization, resource potential and the subsurface correlation of the Middle and Upper Devonian Shales of the Appalachian basins included investigations undertaken by the Pennsylvania Geological Survey. Basin-wide stratigraphic and sedimentological investigations which include the area of Pennsylvania have also contributed to a more complete understanding of stratigraphic relationships of the Devonian Shales of Pennsylvania. For a complete listing of Eastern Gas Shales Project contributing authors and publications on the stratigraphy of the Devonian shales in Pennsylvania, refer to the bibliography of the United States Department of Energy's evaluation of the Devonian shale in Pennsylvania (Tetra Tech, 1981, DOE/METC 119).

Some of the earliest investigations specific to Devonian-age stratigraphy and paleontology in Ohio were undertaken in the late 1890's by R.P. Whitfield (1882, 1893). Additional contributions were added by the work of Stauffer (1907, 1907), Claypole (1903) shortly after the turn of the century. Prosser (1912, 1913), Kindle (1912), and Verwiebe (1917) conducted investigations and published reports on Devonian stratigraphy during the period from 1910-1920 while Stewart (1927, 1928, 1938) and Lamborn (1927, 1929) continued investigations through the 1930's. In the 1940's the works fo G.A. Cooper (1941, 1942), Hass (1947) and Stumm (1942) contributed to the understanding of the Devonian sequence in Ohio. Hoover (1960) summarized the present state of knowledge of the Missippian-Devonian shale sequence in Ohio and discussed local and regional correlation and identification problems which are still not resolved. This was followed by a comprehensive subsurface study of the Devonian shales in Ohio and equivalent units in Pennsylvania and New York (Schweitering, 1970). Recent work on the Devonian shale sequence in Ohio is in conjunction with the Eastern Gas Shales Project. For a complete

listing of recent stratigraphic articles and contributing authors, refer to the bibliography of the United States Department of Energy's evaluation of the Devonian Shales in Ohio (Tetra Tech, 1981, DOE/METC 122).

Reports of investigations on Devonian stratigraphic and paleontologic work in the West Virginia portion of the Appalachian basin began to appear around the turn of the century. One of the earliest contributions on Devonian paleontology to include areas of West Virginia was the work of Williams (1905). Prosser (1915) studied the Middle and Upper Devonian stratigraphy of the Romney, West Virginia region, and W.A. Price (1923) reported on the descriptions of stratigraphic units within the Chemung series. The stratigraphic framework of the Devonian System in West Virginia was the subject of reports by P.H. Price (1940) and Woodward (1943). During the period from 1960-1975 the work of Dennison (1961, 1963, 1970, 1971), Dennison and de Witt (1972), and Hasson (1966, 1972, 1974, 1974) contributed to the understanding of the complex Devonian stratigraphy along the Appalachian structural front in the area of Pennsylvania, Maryland, West Virginia and Virginia. Reference to post-1976 stratigraphic investigations of Devonian-age shales in West Virginia in conjunction with the Eastern Gas Shales Project can be found in the bibliography of the United States Department of Energy's evaluation of the Devonian shales in West Virginia (Tetra Tech, 1981, DOE/METC 120).

Throughout the southern Appalachian basin the Chattanooga Shale is classified by most recent workers as Upper Devonian-Lower Mississippian in age, but in northeastern Tennessee the lower part of the formation is still assigned to the Middle Devonian by some workers. The number of investigators who have studied Devonian paleontology and stratigraphy in the southern Appalachian area is large, so the names of only a few major investigators of the Chattanooga stratigraphy will be cited. Some of the earliest attempts to define the age and distributions of the Chattanooga were undertaken by Williams (1905), Ulrick (1911), and Swartz (1927, 1929, 1929). In the Tennessee portions of the basin, the work of Dunbar (1918, 1919, 1920) was primarily concerned with the stratigraphy and correlation of the Devonian units while Swartz (1924) defined the age of the Chattanooga. In the 1950's, Conant (1953, 1953, 1954) and Glover (1955) conducted investigations on the stratigraphy and uranium content of the Chattanooga Shale for the United States Atomic Energy Commission, Conant working in Tennessee and Glover working in Alabama. Later stratigraphic work in Tennessee by Hass (1956), and Conant (1961) addressed the subject of the age and correlations of the Chattanooga and Maury formations. From 1976 to the present a large volume of work on the stratigraphy and corrleation of Devonian-age shales has been conducted in conjunction with the Eastern Gas Shales Project. The titles and names of the principal investigators involved in this recent work are cited in the bibliography of the United States Department of Energy's evaluation of the Devonian shales of Eastern Kentucky and Tennessee (Tetra Tech, 1981, DOE/METC 121).

MICHIGAN BASIN

Some of the earliest reports on the distribution, stratigraphy and paleontology of the Middle and Upper Devonian sequence in the Michigan basin appeared in the early annual reports and subsequent volumes of the Michigan Geological Survey (Winchell, 1861; Lane, 1895; 1901, 1905, 1908). Grabau (1901) discussed the Devonian sequency in the Alpena and Presque Isle regions while Cooper (1906) included a discussion of the Devonian rocks in his study of Bay County. The Antrim Shale was discussed by Sherzer (1913) in his geological

investigation of Wayne County, Michigan and Smith (1914) referred to the formation in his report on the occurrence of oil and gas in Michigan. Stauffer (1916) reported on the age of the Detroit River Formation, Ver Weibe (1927) on the stratigraphy of Alepna County, Michigan.

In the 1930's and 1940's investigations, including studies of the stratigraphy and paleontology of the Devonian sequence, were reported by Newcomb (1930), Bassett (1933), Warthin (1934), Warthin and Cooper (1935), Newman (1936, 1938), Radabaugh (1937), Ehlers and Radabaugh (1938), and Ehlers (1938), Tarbell (1941), Cooper (1941, 1942), Cohee (1944, 1947), Cohee and Underwood (1947) and Kelley (1947, 1949). Contributions to the knowledge of Devonian stratigraphy during the 1950's and 1960's came from the investigations of Landes (1951), Cohee (1951), McGregor (1954), Briggs (1959), and Sandford (1967). Baltrusaitio (1974) reported on the Middle Devonian bentonite of the Michigan basin, Gardner (1974) on the Middle Devonian stratigraphy and depositional environments in the Michigan basin, Koch (1978) on the brachiopod paleoecology, paleogeography and biostratigraphy in the upper Middle Devonian of eastern North America and Ells (1979) has developed a series of interconnecting cross sections extending from the base of the Antrim upward to the base of the Mississippian for the southern peninsula of Michigan.

The Middle and Upper Devonian rocks in the northwestern Ohio portion of the Michigan basin have received a great deal of attention by investigators attempting to establish the age and correlation of the northwestern Ohio units with the units exposed in northern and central Ohio. Winchell (1874) was one of the earliest workers to attempt correlation between central and northern Ohio and across the Findlay arch into northwestern Ohio. Stratigraphic and paleontologic investigations have continued from the time of Winchell to the present in an effort to resolve correlation problems and build a stratigraphic framework which is amenable for both regions. Important contributors to the present understanding of the age and correlation of the Middle and Upper Devonian sequence in Ohio have been Stauffer (1907, 1909, 1916, 1938), Grabau (1917), Lamborn (1927), Steward (1927, 1929, 1930, 1933, 1936, 1940, 1945), Carmen (1936, 1948, 1952, 1960), Ehlers (1951), Hoover (1960) and Sanford (1968).

Geologic investigations of Middle and Upper Devonian rocks of the northern Indiana portion of the Michigan basin have been extensively studied by geologists both from Indiana and Michigan. Reference to important pre-1975 studies are cited in Indiana Geological Survey Bulletins #44 (Lineback, 1970), #45 (Orr, 1971), and #53 (Doheny, Droste and Shaver, 1975). For a complete listing of post-1976 references to the New Albany Shale for the Eastern Gas Shales Project investigations in the Michigan basin, refer to the United States Department of Energy's Evaluation of the Devonian Shales in the Michigan Basin (Tetra Tech, 1981, DOE/METC 123).

ILLINOIS BASIN

Investigations of the Middle Devonian carbonate sequence in the Illinois basin began with the work of Worthen (1866), Weller (1897), and Udden (1899). The stratigraphy and paleontology of this sequence of rocks has been studied extensively from the time of these early investigations to the present. A partial list of workers contributing to the current knowledge of the stratigraphy and intrabasin and interbasin correlations of the units include Ekblaw (1912), Savage (1920, 1921), Weller (1936, 1944), Cooper and Cloud (1938),

Cooper et al. (1942), Warthin and Cooper (1944), Cooper (1944, 1945), Workman (1944), Schwalb (1955), Workman and Gillette (1956), Swann and Workman (1961), Meents and Swann (1965), Collinson et al. (1962,1967), Collinson (1962), Grimmer (1968) and North (1969).

In their report on the Upper Devonian New Albany Shale Group in Illinois, Cluff, Reinbold and Lineback (1981) cite previous stratigraphic investigations and suggested correlations by Campbell (1946), Collinson et al. (1967), Lineback (1968), North (1969), Workman and Gillette (1956). Reference to other recent investigations of the New Albany Shale Group in Illinois in conjunction with the Eastern Gas Shales Project are included in the Department of Energy's Devonian Shale studies of the Illinois basin (Tetra Tech, 1981, DOE/METC 124).

The Middle Devonian system in the Indiana portion of the Illinois basin is composed of carbonates similar in texture and composition to the carbonates in Illinois. This sequence of rocks, ranging from zero feet to over 250 feet in southern and southwestern Indiana have been studied extensively over the years. Results of early findings and investigations on this sequence of rock appeared in the early annual reports of the Indiana Geological Survey (Collett, 1882; Kindle, 1901; Seibenthal, 1901). In a recent investigation of the geology of the Silurian and Devonian System southwest of the Cincinnati arch, Becker (1974) cites previous investigators who have contributed to the understanding of the stratigraphic framework of the Middle Devonian sequence in Indiana. Included as major contributors are Cumings (1922), Sutton and Sutton (1937), Dawson (1941), Murray (1955), Perkins (1963), Orr and Pollock (1968), and Droste and Vitaliano (1973).

In a recent study of the Upper Devonian New Albany Shale in Indiana, Becker (1970) provides a fairly complete bibliography of geological investigations undertaken since the earliest reported account by D.D. Owen (1838). Post-1976 investigations in conjunction with Eastern Gas Shales Project work are cited in the United States Department of Energy's screening report for the Illinois basin (Tetra Tech, 1981, DOE/METC 124).

Geologic studies of the Upper and Middle Devonian rocks of Kentucky ran more or less concurrently with studies in the Illinois and Indiana portions of the Illinois basin. The Middle Devonian carbonate sequence in north central and western Kentucky is very similar in lithology and texture to the Middle Devonian sequences in the Indiana and Illinois portions of the basin. The reports of early investigations on the geology of the Middle Devonian of Kentucky were published in the annual reports of the Kentucky Geological Survey (Owen, 1857; Whitfield, 1875). At the turn of the century the paleontologic investigations of Kindle (1898) and Williams and Kindle (1903) included studies of the Middle Devonian sequence in Kentucky. A partial list of other workers contributing to the current knowledge and framework of the Middle Devonian from the turn of the century to the present includes Butts (1915), Miller (1915), Savage (1930), Freeman (1941), Stumm (1961, 1964), Kessling and Lineback (1967), Collinson et al. (1967), Orr and Pollock (1968), Powell (1970), and Conklin and Conklin (1974).

Girty (1898), Savage and Sutton (1931), Hoskins (1951), Collinson et al. (1967), Bharadway, Tirvari and Venkatachala (1971), and Phillips, Nickals and Andrews (1972) have conducted geologic investigations on the Upper Devonian New Albany Shales of Kentucky. More recent studies on the New Albany Shale of Kentucky in conjunction with the Eastern Gas Shales Project are cited in the bibliography of the United States Department of Energy screening report for the Illinois basin (Tetra Tech, 1981, DOE/METC 124).

Distribution of Black Shale in Individual Basins and Their Interrelationship, Correlation, and Boundaries

Devonian-age shales in the Appalachian basin and their equivalent facies in the Michigan and Illinois basins generally have two basic lithologies, either organic-rich shale facies or the lighter-colored, organic-poor shale or mudstone facies. The dark, organic-rich shales and fissile, black or dark greenish-gray and contain few marine fossils. X-ray analysis and thin section studies show that the dark shales consist primarily of the mineral illite, clay-sized quartz, and organic matter in the form of spore cases such as Tasmanites or as amorphous masses disseminated within the fine particles of clay and quartz (Provo, 1976). Other constituents commonly observed are silt size, angular to elongate quartz grains, pyrite in the form of blebs, spheres, and cubes and dolomite in the form of irregular shaped grains and rhombs, all making up less than 10 to 15 percent of the organic-rich shale. Single grains of chert, plagioclase feldspar, and mica are occasionally observed.

In contrast, much less organic matter along with a corresponding increase in clay minerals and minor constituents (quartz, pyrite, and dolomite) is characteristic of the organic-poor shales and mudstones. Sequences of organic-poor shales are composed of black to medium gray shales, mudstones, siltstones, a few sandstones, and a greater abundance of fossils than occur in the black organic-rich facies.

The two lithographic types are easily distinguished in outcrop sections on the basis of color and lithology.

In the subsurface of the Appalachian, Michigan, and Illinois basins the two facies (lithologies) are recognizable by their characteristic expression on the gamma-ray logs. The black, organic-rich shales are recognized in the subsurface by a typically high radioactive response on gamma ray logs. The high gamma ray readings of geophysical logs is in response to the association of uranium with organic matter in the shales, hence the radioactive black shales are easily identified in the subsurface and can be correlated over wide areas of the Appalachian, Michigan, and Illinois basins.

In the Devonian reference section of New York, the black shale sequence is generally considered as extending from the top of the Onondaga Limestone through the Perrysburg Formation. This sequence of rocks exhibits several cycles of deposition which began with the deposition of black, organic-rich mudstone was followed by the deposition of light-colored organic-poor mud, clays and siltstones. The cyclic nature of the Middle and Upper Devonian strata is very evident in the Appalachian basin but less pronounced in the Illinois and Michigan basins.

The Onondaga Limestone which marks the base of the Devonian shale sequence in the New York reference section has been informally placed in the Onesquethaw Stage and informally assigned to the Middle-Devonian (Oliver et al., 1967). During Onesquethaw time, deposition of the Needmore Shale in the northeastern part of the Appalachian basin signaled the uplift of a source area to the east of the basin and the beginning of Catskill sedimentation. The Needmore Shale is interpreted as pro-delta mud facies which fans outward approximately 120 miles west of a clastic source area located at the approximate

latitude of Baltimore, Maryland (Dennison, 1971). The unit is recognized over eastern and central Pennsylvania, and eastern West Virginia. West and southwest of the limits of the Needmore Shale, the Huntersville Chert of southwestern Pennsylvania, West Virginia, and western Virginia is considered a nonclastic facies equivalent of the Needmore. The Columbus Limestone of eastern Ohio and the Onondaga Limestone of northwestern Pennsylvania and southwestern New York are marine limestone facies equivalent of the Needmore Shale and Huntersville Chert. (Generalized distribution of equivalent Onesquethaw facies in the northern part of the basin can be seen on figure 14.)

The southern part of the Appalachian basin, as now defined, was part of the stable craton during Onesquethaw times and only local areas were receiving sediments. The Frog Mountains sandstone of northwestern Georgia and northern and central Alabama has been assigned to the Onondaga on the basis of the fauna identified in the type section.

The Devonian shale sequence overlies rocks of the Onesquethaw stage throughout much of the northern portion of the Appalachian basin. Along the southern and western margins of the basin, the black shale sequence overlies the rocks of the lower Devonian and Silurian age. Locally in Tennessee and Kentucky the black shales overlie rocks of the Ordovician age. The generalized thickness and distribution of the Devonian shales in the Appalachian basin are shown in figure 15.

The top of the Devonian-age shale sequence in the New York reference area is placed at the top of the Perrysburg Formation. This boundary marks the highest stratigraphic occurrence of distal margin pro-delta sediments in the reference area. Because of the westward progradation of the Catskill delta throughout Middle and Upper Devonian time, the top of the Devonian Shale sequence is diachronous from lower Middle Devonian in the northeastern part of the Appalachian basin (south-central Pennsylvania and western Maryland) to later Upper Devonian-Mississippian along the western and southern margins of the basin. At the New York reference area, the Perrysburg Formation is classified as Middle Upper Devonian (Cassadaga Stage).

The lithologic change upward from the organic-rich distal basin shales of the Harrell and Millboro Formations to the Flysch type turbiditic siltstones, and sandstones of the Braillier Formation (Potter, 1981; Lundegard, 1980) defines the upper limit of the Devonian shale sequence in the outcrop belts of Pennsylvania, Maryland, and West Virginia (lower Upper Devonian-Finger Lakes Stage). Locally, in south central Pennsylvania and western Maryland east of the eastern limit of the Harrell Shale, the Braillier Formation directly overlies the Mahantango Formation and the top of the Devonian Shale sequence is interrupted at the upper boundary of the Marcellus shale (lower Middle Devonian-Cazenovia Stage). In northwestern Pennsylvania the Murrysville sandstone (Lower Mississippian) marks the top of the shale sequence. In the subsurface of Ohio, western Pennsylvania, West Virginia and eastern Kentucky, the base of the Mississippian Berea Sandstone marks the upper boundary of the Devonian-age shales for purposes of the Eastern Gas Shale Project investigations. In the southern portion of the Appalachian basin the top of the Devonian shale sequence is placed at the boundary between the Chattanooga and the Maury shales in east-central Tennessee and northwestern Georgia. The boundary between the Chattanooga Shale and Forty Payne Chert marks the top of the sequence in northeastern Alabama. The general distribution of stratigraphic units overlying the Devonian-age Shale sequence is drawn on figure 16.

In the Michigan basin the Devonian black shale sequence conformably overlies the Squaw-Bay Limestone. In the eastern portion of the Michigan basin the Devonian shale

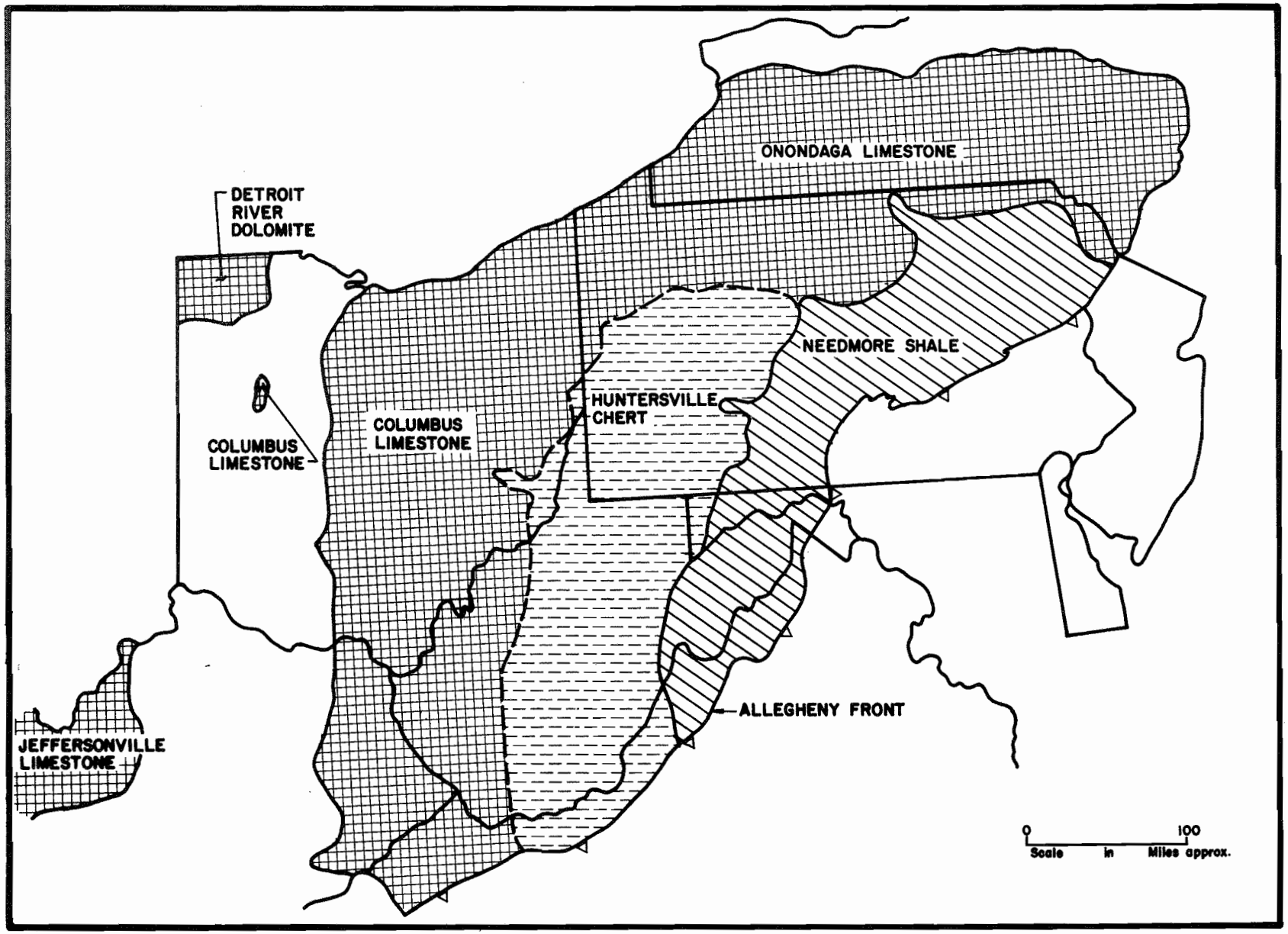


Figure 14. Generalized distribution of equivalent Onesquethaw facies in the northern part of the Appalachian basin.

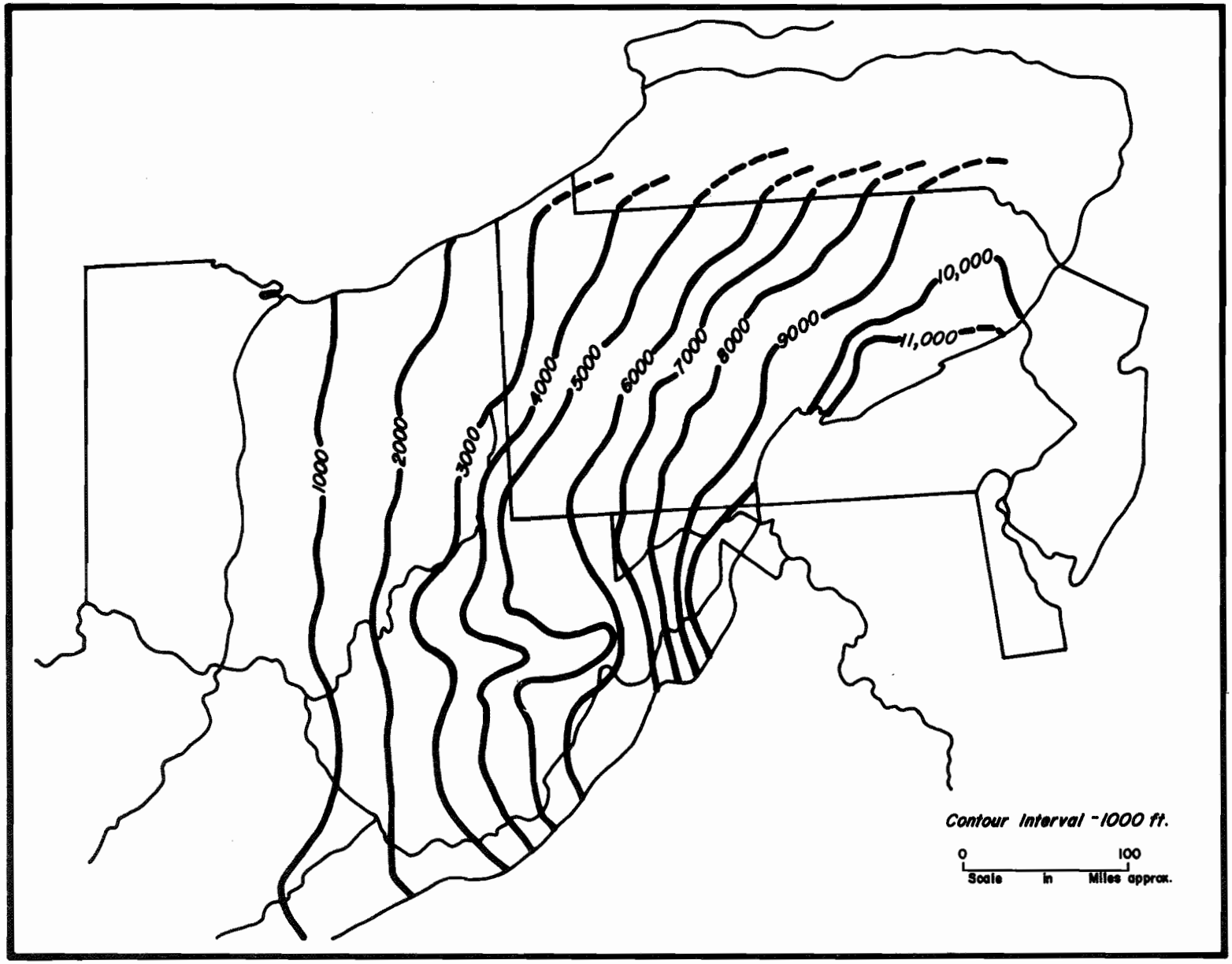


Figure 15 .Generalized thickness and distribution of Devonian shales in the Appalachian basin. Modified from Oliver, et al. (1967).

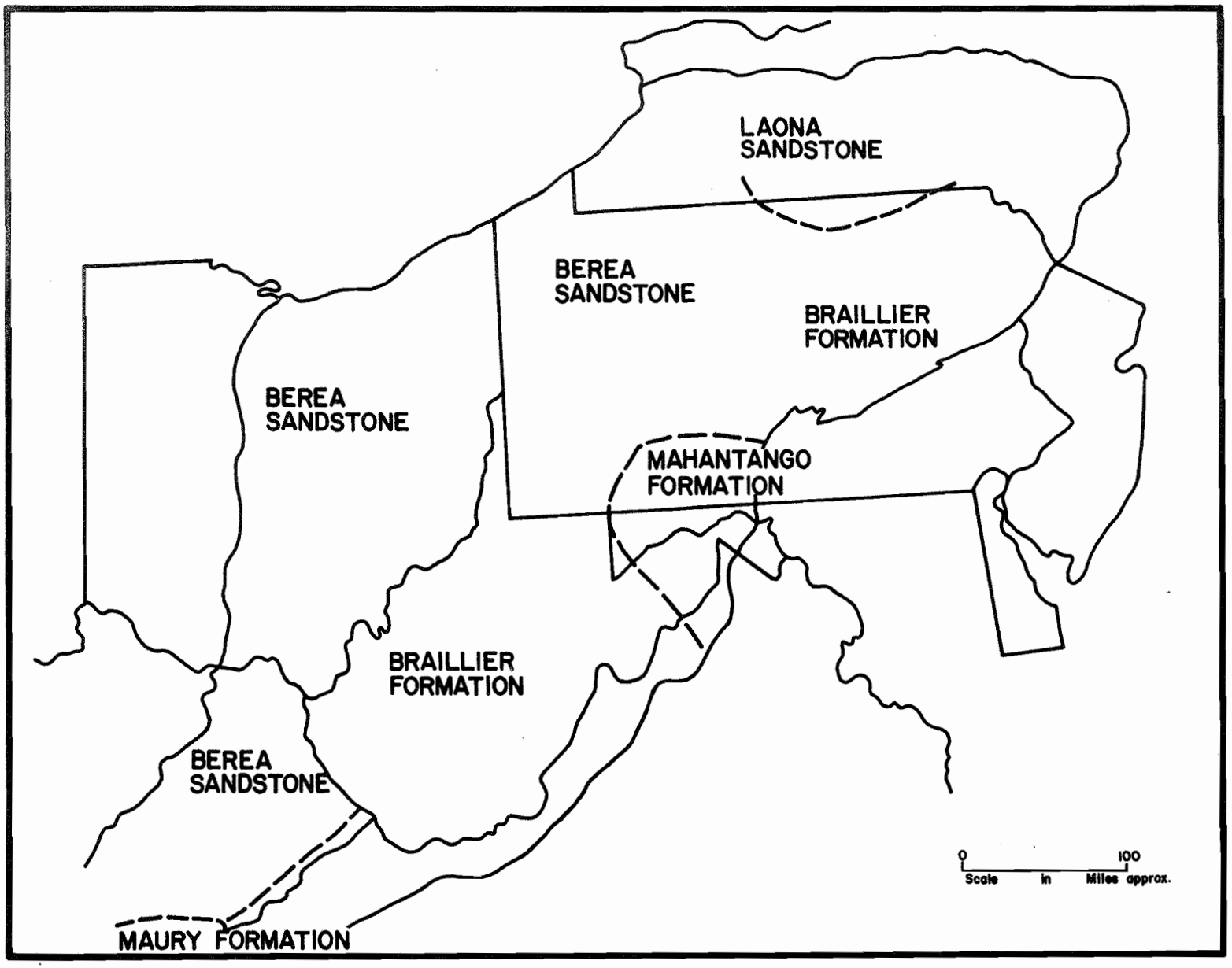


Figure 16. The generalized distribution of stratigraphic units overlying the Devonian-age black shale sequence in the Appalachian basin.

sequence, as defined for Eastern Gas Shale Project purposes, includes the Antrim Shale and the Bedford Shale, with the top of the sequence being marked by the Berea Sandstone. The sequence in the western portion of the Michigan basin is composed of the Antrim and the Ellsworth Shales with the top defined by the overlying Coldwater Shales. The entire Devonian black shale sequence in the Michigan basin is considered Upper Devonian in age. The combined thickness and the distribution of the Bedford/Antrim and the Ellsworth/Antrim Devonian shale sequence in the Michigan basin is shown on figure 17.

The name "New Albany Shale" has been applied to the Devonian shale sequence of the Illinois basin. The New Albany is given formation rank in Indiana and Kentucky, but is assigned group rank in Illinois. The base of the New Albany is the top of the North Vernon Limestone in the Indiana portion of the basin, the Sellersburg Limestone in western Kentucky, and the Lingle Limestone in the Illinois portion of the basin. In Illinois the top of the Devonian shale is defined by the Chouteau Limestone, while the Rockford Limestone marks the top of the sequence in Kentucky and Indiana.

The thickness of the New Albany Shale Group in the Illinois basin ranges from less than 50 feet around the margins of the basins to over 400 feet in northwestern Kentucky, (fig. 18). The age of the New Albany Shale ranges from Middle Devonian to Lower Mississippian. This diachronous age is the same in Ohio where the black shale sequence ranges into the lower Mississippian without discernable physical difference from the Bedford Shale. This Ohio sequence is overlain by the Berea Sandstone deposited as a delta-type sediment whose source was to the north in Canada.

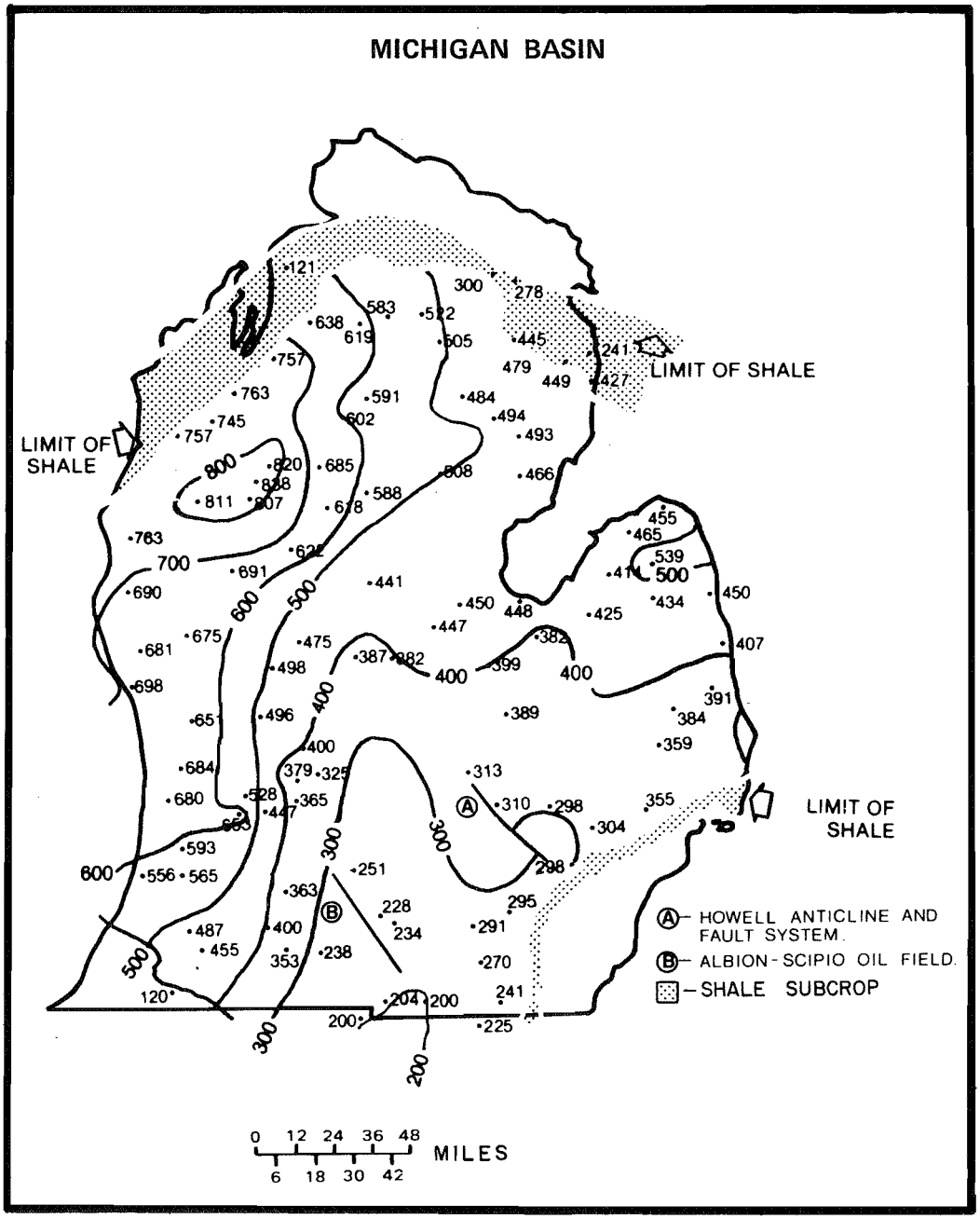


Figure 17. Isopach Map showing combined thickness of Bedford/Antrim or Ellsworth Antrim Shales. Contours in feet. After Mound Facility (1980).

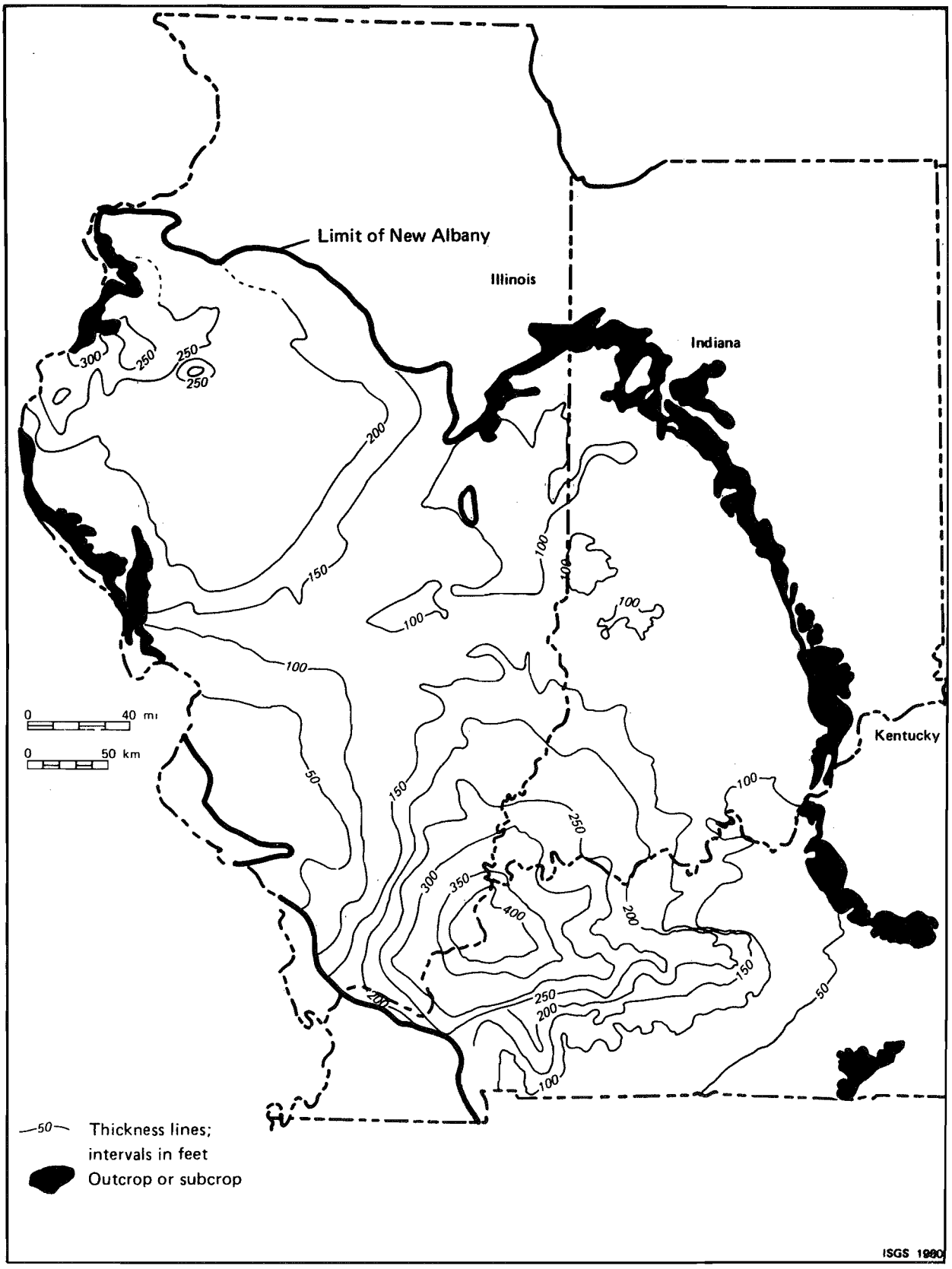


Figure 18. Thickness of the New Albany Shale Group in the Illinois basin. After Reinbold (1978), Bassett and Hasenmueller (1978), and Schwalb and Potter (1978).

Physical Stratigraphy

INTRODUCTION

A major objective of the Eastern Gas Shales Project was to determine the natural gas resource potential of the Devonian-age shales of the eastern United States and to characterize the shales with regard to physical and chemical properties. To meet this objective a detailed stratigraphic analysis was undertaken in order to define the thickness and distribution of the Devonian shales within the depositional basins of the eastern United States. This investigation dealt primarily with the subsurface stratigraphy of the region because outcrop areas of the Devonian-age shales occupy only a small percentage of the total area of distribution. The stratigraphic investigation in the Appalachian basin was a tremendous undertaking because, except for the Big Sandy Field in Kentucky, little interest had been given to the Devonian-age shales as a reservoir for oil and natural gas. In most states few geophysical bore-hole logs covering the Devonian shale interval were available, compared to the number of wells that had been drilled, so only the results of a limited number of subsurface investigations were available prior to 1976. At the surface the stratigraphic relationships of the rocks within the Catskill delta framework have been the subject of investigations for over 100 years. To the present, because of the complex geological structure and complex facies relationships, some disagreement in interpretation and correlation of stratigraphic units still exists between workers studying the sequence in different areas of the province.

The investigations of the Eastern Gas Shales Project have made a significant contribution to the understanding of the Devonian-age stratigraphic and facies relationships. Basin-wide, detailed correlations of highly radioactive shales identified from gamma ray logs were instrumental in tying the subsurface stratigraphy of the depositional basins to equivalent units cropping out at the surface. These data will provide the basis for the resource assessment of natural gas from the Devonian shales in the Appalachian, Michigan and Illinois basins.

The physical stratigraphy will include discussions of the (1) name, data, author, and type area of each stratigraphic unit, (2) dominant lithology and color, (3) thickness and distribution and (4) basinwide and intra-basin correlation of units within the eastern United States depositional basins.

APPALACHIAN BASIN

The scope of the Eastern Gas Shales Project investigations in the Appalachian basin included detailed subsurface stratigraphic investigations in New York, Pennsylvania, West Virginia, Virginia, Ohio, eastern Kentucky and Tennessee. The basin extends southward into northeastern Alabama and northwestern Georgia but, because of the small geographical area, these areas were not given the detailed stratigraphic coverage of the regions to the north.

The subsurface stratigraphic framework of the Appalachian basin, developed by the investigators of the Eastern Gas Shales Project, is a composite of Ohio stratigraphic terminology and the nomenclature used in New York state. In New York the Devonian shale sequence occupies the interval between the top of the Onondaga Limestone and the top of the Perrysburg Formation. Petroliferous black shales which occur within this sequence have been correlated into the subsurface Devonian rock sequences of southwestern New York, northwestern Pennsylvania, eastern Ohio, northwestern West Virginia, eastern Kentucky and Tennessee. The petroliferous Marcellus shales of the Hamilton Group of New York have been identified in the subsurface of Pennsylvania, West Virginia and extreme eastern Ohio. Petroliferous shale members of the Upper Devonian Genesee, Sonyea, West Falls, Java and Perrysburg Formations are also recognized in the above states, but the radioactive shale within the stratigraphic interval of the Perrysburg is designated "Lower" Huron Member in the subsurface of the basin except in New York and Pennsylvania where it is designated the Dunkirk Member of the Perrysburg Formation.

Post-Perrysburg black shale stratigraphic units in the Appalachian basin have been correlated and referenced with the upper Devonian units found in Ohio.

Middle Devonian

New York

Onondaga Limestone. The name Onondaga Limestone was first used by John Hall (1839) to describe the rocks lying between the Oriskany Sandstone and the Seneca Limestone that were exposed in Onondaga County, New York (fig. 19). The Onondaga Limestone as described by J.M. Clarke and J.O. Luther (1905) for the interval between the Oriskany Sandstone and the Marcellus Shale conforms more closely with the usage of Eastern Gas Shales Project stratigraphers. The Onondaga is a medium-to-coarse-crystalline, light-to-medium-gray limestone characterized by an abundance of corals and local occurrence of chert nodules. The formation is widespread over western New York, western Pennsylvania and West Virginia. Onondaga-age rocks form a relatively uniform blanket across the northern part of the Appalachian basin from eastern New York to central Ohio and thin towards the south, where only small patches are known east of the Cincinnati arch in Kentucky, Georgia and Alabama (Oliver et al., 1967). In the outcrop belt of western New York the Onondaga Limestone ranges in thickness from 50 feet to 200 feet. In other areas, the limestone ranges from a feather edge in the southern basin to an average of approximately 100 feet in the central Ohio and western New York portion of the basin.

In Ohio the stratigraphic equivalent of the Onondaga Limestone is the Columbus Limestone, while to the south in Virginia and eastern Kentucky, the Huntersville Chert correlates, and is equivalent, at least in part, to the Onondaga Limestone of New York. To the east in Maryland and eastern Pennsylvania, the Needmore Shale is considered to be the fine-grained clastic facies equivalent of the Onondaga Limestone.

In the Michigan basin the Anderdon Limestone member of the Detroit River Formation in Michigan and the Jeffersonville Limestone of northeastern Indiana are stratigraphic correlatives of the Onondaga. The Jeffersonville Limestone of Indiana and Kentucky and the Grand Tower Limestone of Illinois are the Illinois basin equivalent of the Onondaga.

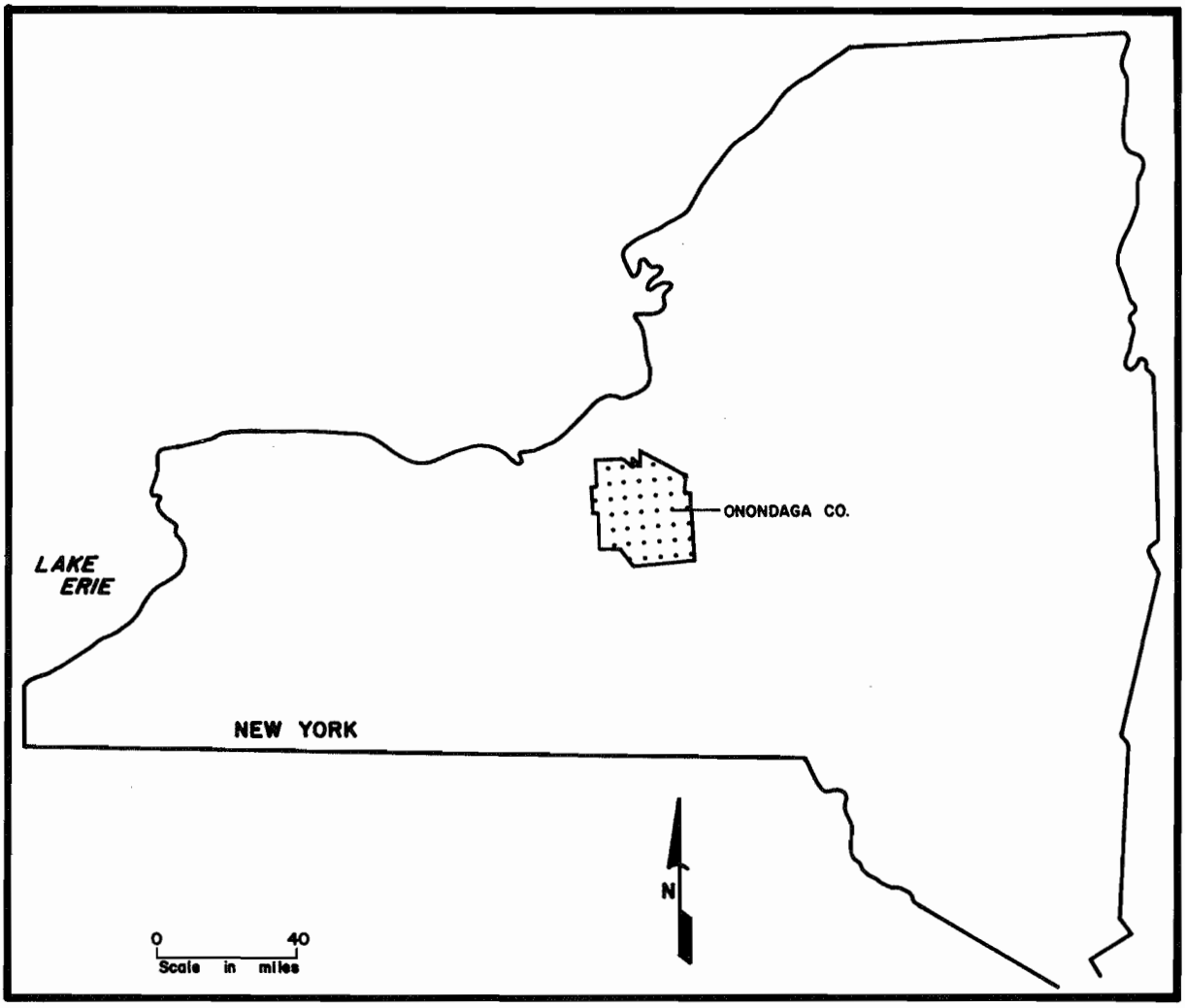


Figure 19. Index map identifying localities referenced in the stratigraphic discussion of the Onondaga Limestone.

The Tioga bentonite occurs near the top of the Onondaga Limestone and is a key stratigraphic time marker recognized in both the Appalachian and Illinois basins.

Hamilton Group. The basal unit of the Devonian-age shale sequence in the classic New York reference section has been designated the Hamilton Group. These rocks of Middle Devonian age are assigned to the Cazenovia and Tioughniaga Stages of the Eastern North American Devonian Classification System (Oliver et al., 1967). The Hamilton group, as defined by Cooper (1930), consists of, in ascending order, the Marcellus Formation, Skaneateles Formation, Ludlowville Formation and Moscow Formation. Figure 20 is an index map identifying localities cited in the discussion of the Hamilton Group.

The name "Hamilton Group" was first used by Vanuxem (1840) for exposures near villages of West Hamilton, Cazenovia, and Pompey Hill, Madison and Onondaga counties, New York. At the type section the group occupied the interval later to be designated Ludlowville Shales. Until 1930, the name Hamilton Group was applied to a variety of time-stratigraphic intervals on the basis of fauna and stratigraphic correlation. On the basis of the fauna, G.A. Cooper (1930) redefined the Hamilton Group by raising the Marcellus to formation rank and included it along with the Skaneateles, Ludlowville and Moscow as a formation within the Hamilton Group.

Along the outcrop belt of the Hamilton Group, which extends east-west across western New York from Lake Erie to Albany County in south central New York, the group thickens eastward from 285 feet in exposures near Lake Erie, to over 1680 feet in the Scholarie Valey. However, the group reaches maximum thickness in Pennsylvania. In western New York, Hamilton Group strata dip toward the southeast at approximately 30 feet per mile. In the Albany County area in eastern New York the dip changes to the southwest at approximately 35 feet per mile.

In the reference area the group rests conformably upon the Onondaga Limestone and is unconformably overlain by the Tully Limestone.

Marcellus Formation. The Marcellus Formation has been assigned to the lower part of the Cazenovia Stage of the Eastern North American Devonian Classification System. Localities cited in the discussion of the Marcellus sequence are identified on figure 21.

The name Marcellus was first proposed by Hall (1839) for rocks exposed in the vicinity of the village of Marcellus in Onondaga County, New York. From 1839 to 1930 the name Marcellus was used by Vanuxem (1841), Hall (1843), Emmons (1846) and Clarke and Luther (1904) to describe slightly different time-stratigraphic rock sequences exposed in the mid-Devonian outcrop belt. Cooper (1930) defined the unit as it is presently used by Eastern Gas Shales Project stratigraphers and by the New York and United States Geological Surveys. In Cooper's definition the Marcellus was given formational rank and assigned along with the Skaneateles, Ludlowville, and Moscow Formations to the Hamilton Group. By definition, the unit included the rocks occurring within the interval from the top of the Onondaga Limestone to the base of the Skaneateles Formation. Cooper subdivided the formation into eight members, all of which are recognized today, in a slightly different framework by the New York Geological Survey in the Onondaga County outcrop area. The stratigraphic relationship of the members of the Marcellus are shown on figure 22. The lowermost member, the Union Spring shale, is black or greenish-gray, fissile shale of the distal basin facies. Directly overlying the Union Springs member is

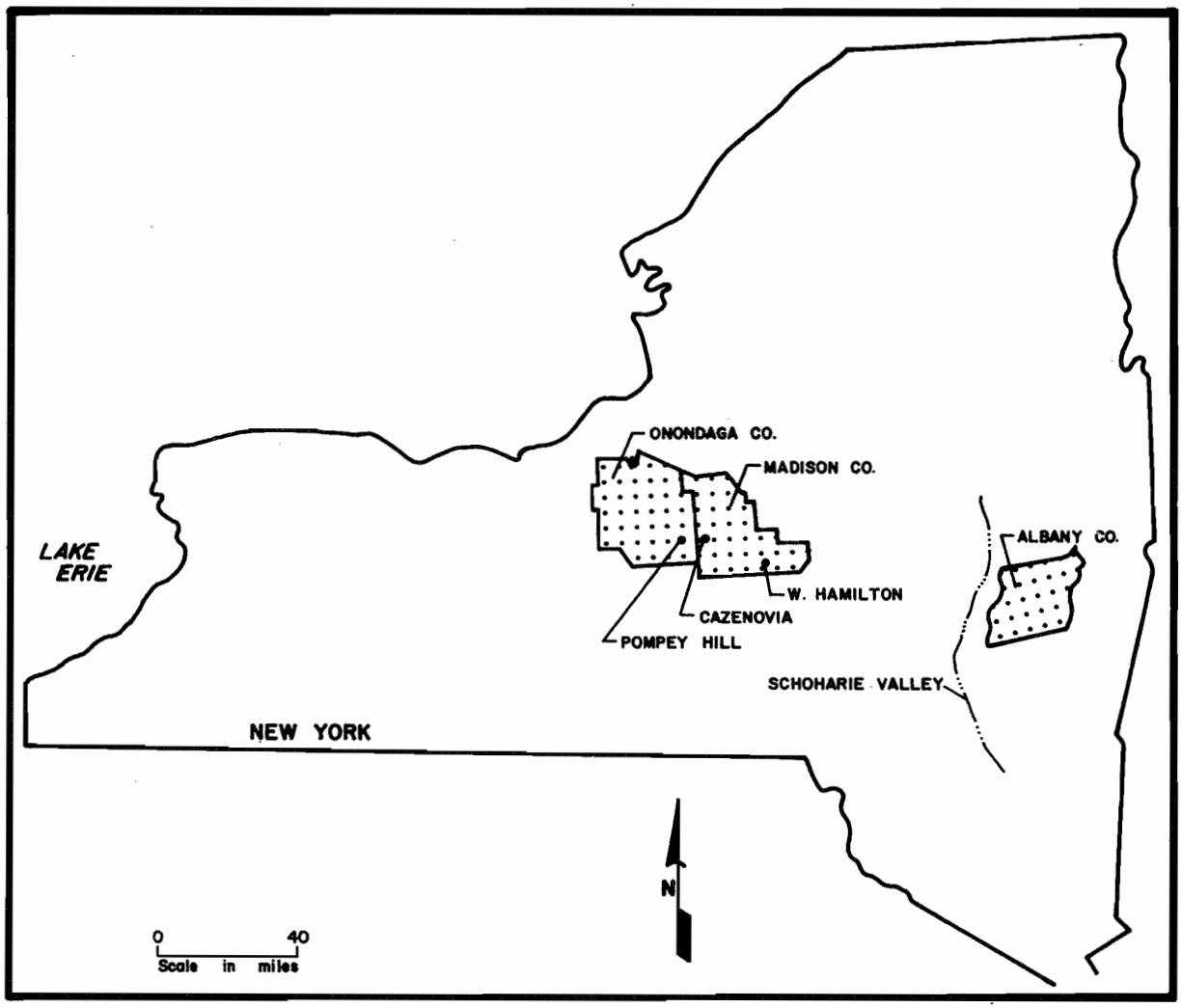


Figure 20 . Index map identifying localities referenced in the stratigraphic discussion of the Hamilton Group.

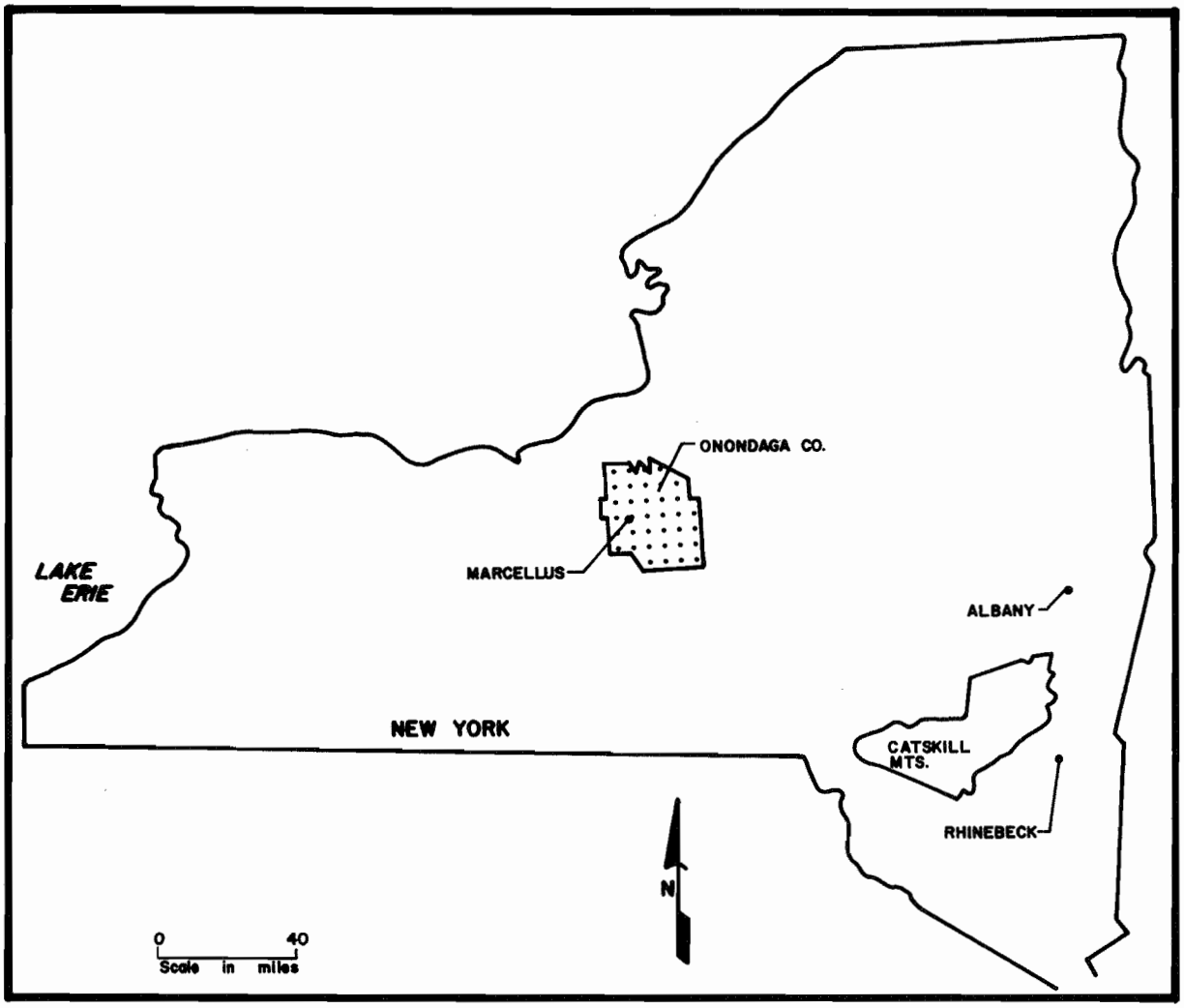


Figure 21. Index map identifying localities referenced in the stratigraphic discussion of the Marcellus Formation.

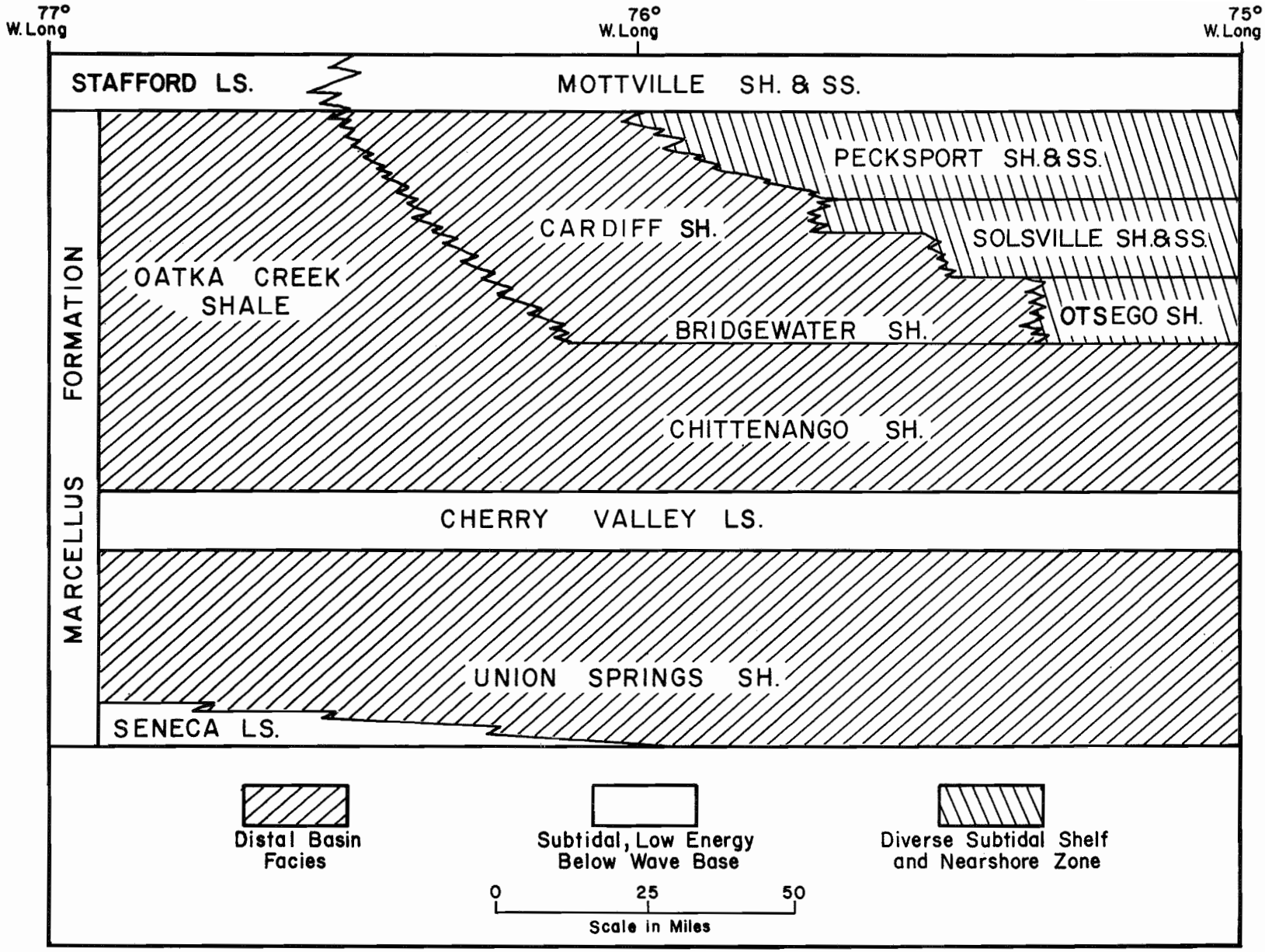


Figure 22. Schematic diagram of stratigraphic framework and facies relationships within the Marcellus Formation. After Rickard (1975).

the Cherry Valley limestone, a thin, argillaceous, fine-crystalline, fossiliferous limestone assigned a subtidal low energy environment of deposition by Rickard (1975). The Chittenango shale, Bridgewater shale and Cardiff shale, all interpreted as distal basin deposits, interfinger to the west with the Oatka shale member. To the east the Bridgewater and Cardiff shales intertongue with the Otsego shale, the Solsville shale and sandstone and the Pecksport shale and sandstone of the diverse subtidal, prodelta, delta front and delta platform facies. Further east near Rhinebeck, south of Catskill, the members above the Cherry Valley intertongue with the Mount Marion shale and sandstone of the same facies.

In the outcrop belt the unit ranges in thickness from approximately 50 feet near Lake Erie to approximately 800 feet in eastern New York 50 miles west of Albany.

The Marcellus has been correlated into the subsurface of central and western New York, northeastern and western Pennsylvania, eastern Ohio and into West Virginia. In the subsurface the unit is recognized by high gamma response on gamma-ray geophysical logs. The Marcellus is composed of black to brown to dark-gray fissile, highly organic shale, very similar lithologically to the black shales of the distal basin facies of the outcrop section. The distribution of the radioactive Marcellus Shale in the Appalachian basin is shown on figure 23. However, the distribution is not shown east of the structural front.

In the subsurface the unit ranges in thickness from a feather edge in eastern and southeastern Ohio to over 250 feet in northwestern Pennsylvania.

The stratigraphic equivalents of the Marcellus Formation in the Appalachian, Michigan and Illinois basins are shown on the correlation chart, plate I. Near the Allegheny Front in Pennsylvania and West Virginia, the Marcellus intertongues and is in part equivalent with the Mahantango Formation. Further to the south in Virginia and eastern Kentucky the Marcellus is equivalent to the lower part of the Millboro Shale. In Ohio, beyond the limit of recognized radioactive shale, the stratigraphic equivalent of the Marcellus occurs within the "Lower" Olentangy Shale sequence.

In the Michigan basin the clastic Marcellus facies is in part equivalent with the Dundee Limestone carbonate sequence.

The Marcellus equivalent in the Illinois basin, also in the shallow marine facies, occurs in the base of the North Vernon Limestone of Indiana, the Grand Tower Limestone of Illinois and the Jeffersonville Limestone of western Kentucky.

Skaneateles Formation. The Skaneateles Formation has been assigned to the upper part of the Cazenovia Stage of the Eastern United States Devonian Classification System. The formation was first named by Vanuxem (1840) for the shale sequence which covers the north end of both sides of Skaneateles Lake (Wilmarth, 1957). Localities cited in the discussion of the Skaneateles Formation are shown on figure 24. Where sandy layers appear in the Skaneateles east of the type sections, Cooper (1930) subdivided the formation into six members. In the Cayuga and Skaneateles Lake regions the formation is composed of soft, dark-gray shale with a basal calcareous layer called the Mottville (Cooper, 1930). Similarly, in the Chenango Valley area, the basal member of the formation is the Mottville Shale and Sandstone. The depositional environment of the Mottville Member is interpreted by Rickard (1975) to be subtidal shelf, near-shore and

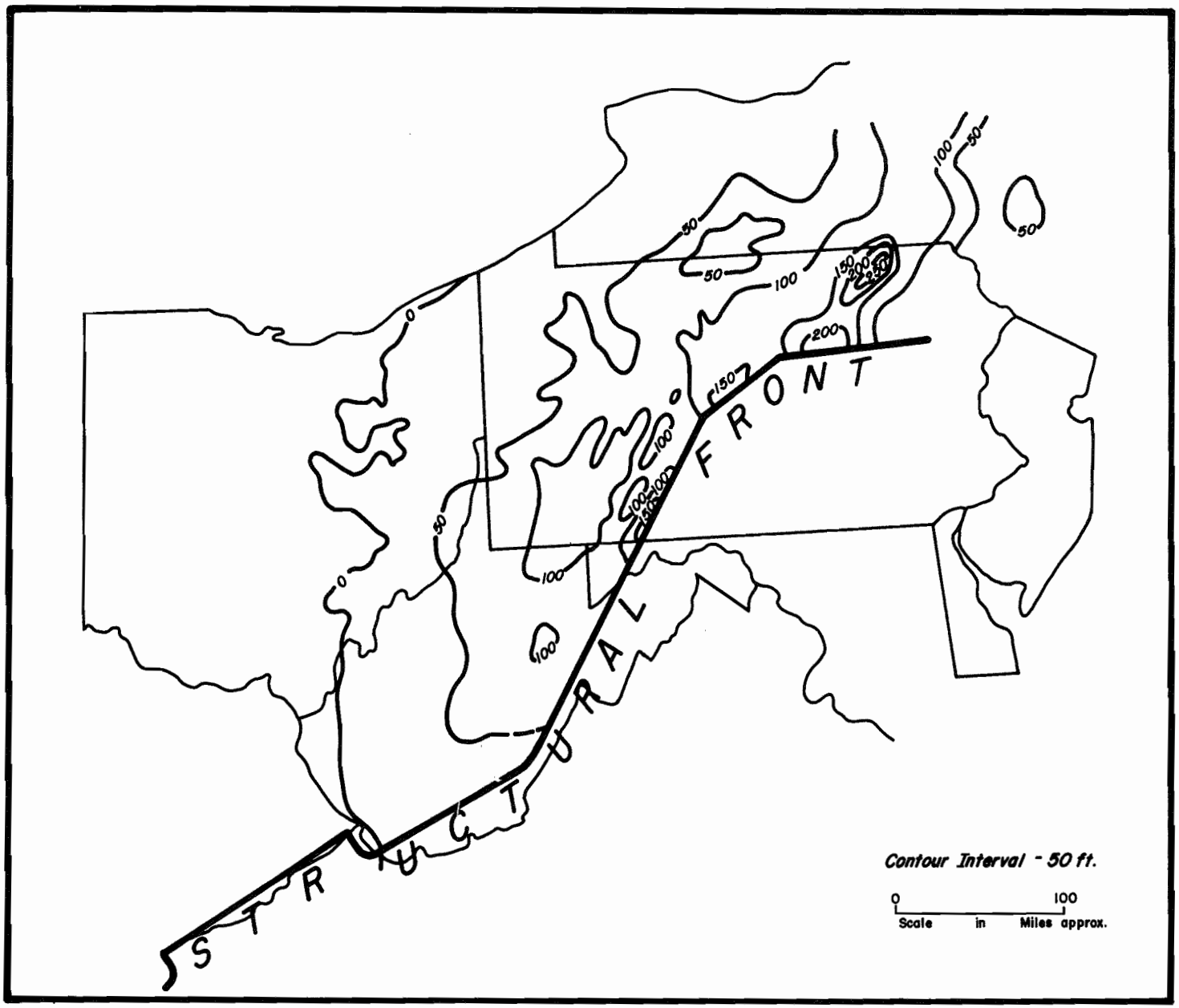


Figure 23. Generalized thickness and distribution of the radioactive Marcellus Shale of the Appalachian basin.

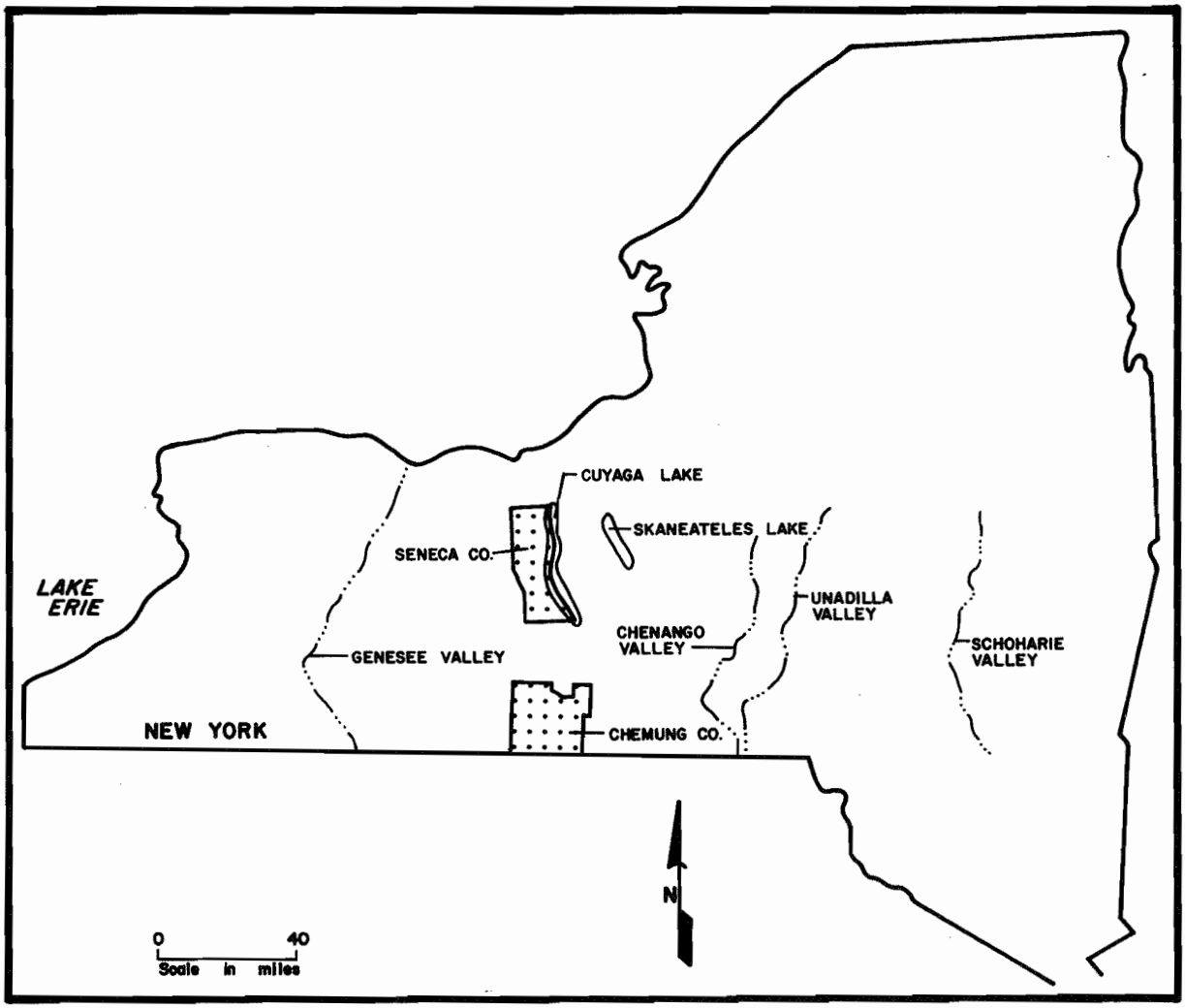


Figure 24. Index map identifying localities discussed in the stratigraphic discussion of the Skaneateles Formation.

delta front facies. To the west in the Genesee Valley region (fig. 24, page 53) the Mottville Member changes facies laterally into shallow marine limtestone and is designated the Stafford Limestone Member. In the western portion of the outcrop area the Levanna Shale Member directly overlies the Stafford and Mottville Members. The Levanna Member is composed of dark-gray to black, fissile shales of the distal basin and is characteristically similar lithologically to the Marcellus. East of the Lake Skaneateles region the Levanna is broken into three units by lighter-colored shales and sandstone tongues of the subtidal, near shore shelf facies. In ascending order the members are designated: the Delphi Shale, the Pompey Shale and Sandstone, and the Butternut Shale. Each member consists of a thin basal black shale of the distal basin facies overlain by a lighter-colored unit of the diverse subtidal shelf facies. Further east beyond the eastern limit of the black shale tongues of the Delphi, Pompey and Butternut in the vicinity of the Schohaire Valley, the diverse subtidal shelf facies of the Skaneateles Formation is equivalent with the lower part of the Panther Mountain Shale and Sandstone. The stratigraphic framework of the Skaneateles in the New York outcrop area is shown on figure 25.

The thickness of the Skaneateles Formation in the New York outcrop belt ranges from 60 feet in the Lake Erie area to over 550 feet in the Unadillia Valley region. In central New York the major black shale facies of the Hamilton Group are represented by the Marcellus Shale and the Levanna Shale Member of the Skaneateles Formation. These black shale units cannot be subdivided on subsurface data, but based upon thickness estimates from well cutting examination, the combined thickness of black shale in the Hamilton Group ranges from 100 feet near Lake Erie to more than 1200 feet in the Chemung and Seneca County region (Kamakaris and Van Tyne, 1980). These thicknesses are not borne out by geophysical log studies which show the maximum combined net black shale thickness in the Hamilton Group to be 180 feet in west-central New York (Van Tyne et al., 1980). The Skaneateles has not been correlated in the subsurface of the Appalachian basin beyond local areas in New York.

The surface and subsurface correlation of the Skaneateles Formation throughout the Appalachian, Michigan and Illinois basins will be discussed in combination with other post-Marcellus formations of the Hamilton Group. In the subsurface this interval consists of the lighter-colored shales and sandstones occurring between the top of the Marcellus and the base of the Tully, where present, or the base of the Genesee Group.

Ludlowville Formation. The Ludlowville Formation occurs within the lower half of the Tioughnioga Stage of the Eastern North American Devonian Classification System. The term "Ludlowville Shale" was first used by Hall (1839) for exposures in the Cayuga Lake region. Localities cited in the discussion of the Ludlowville are identified on figure 26. The sequence Hall designated as Ludlowville overlies the Skaneateles Formation and extended upward from the base of the Centerfield Member to a bed designated "Ecrinal Limestone." Cooper (1930) attempted to define the formation more closely and suggested retaining the name Ludlowville Shale, but he proposed that the reference section be designated for the exposures on Paines Creek at Aurora. Cooper's reference section extended from the base of the Centerfield Member to the base of the Portland Point beds. At the reference section on Paines Creek, Cooper subdivided the Ludlowville, from the base to the top, into the following members: the Centerfield Member, Ledyard Member, Wanakah Member, Tichenor Member, and the Deep Run Member. Goldring (1931) defined the Ludlowville Shale as underlying the Menteth Limestone Member of the Moscow Formation and overlying the Skaneateles Formation, hence the definitions of

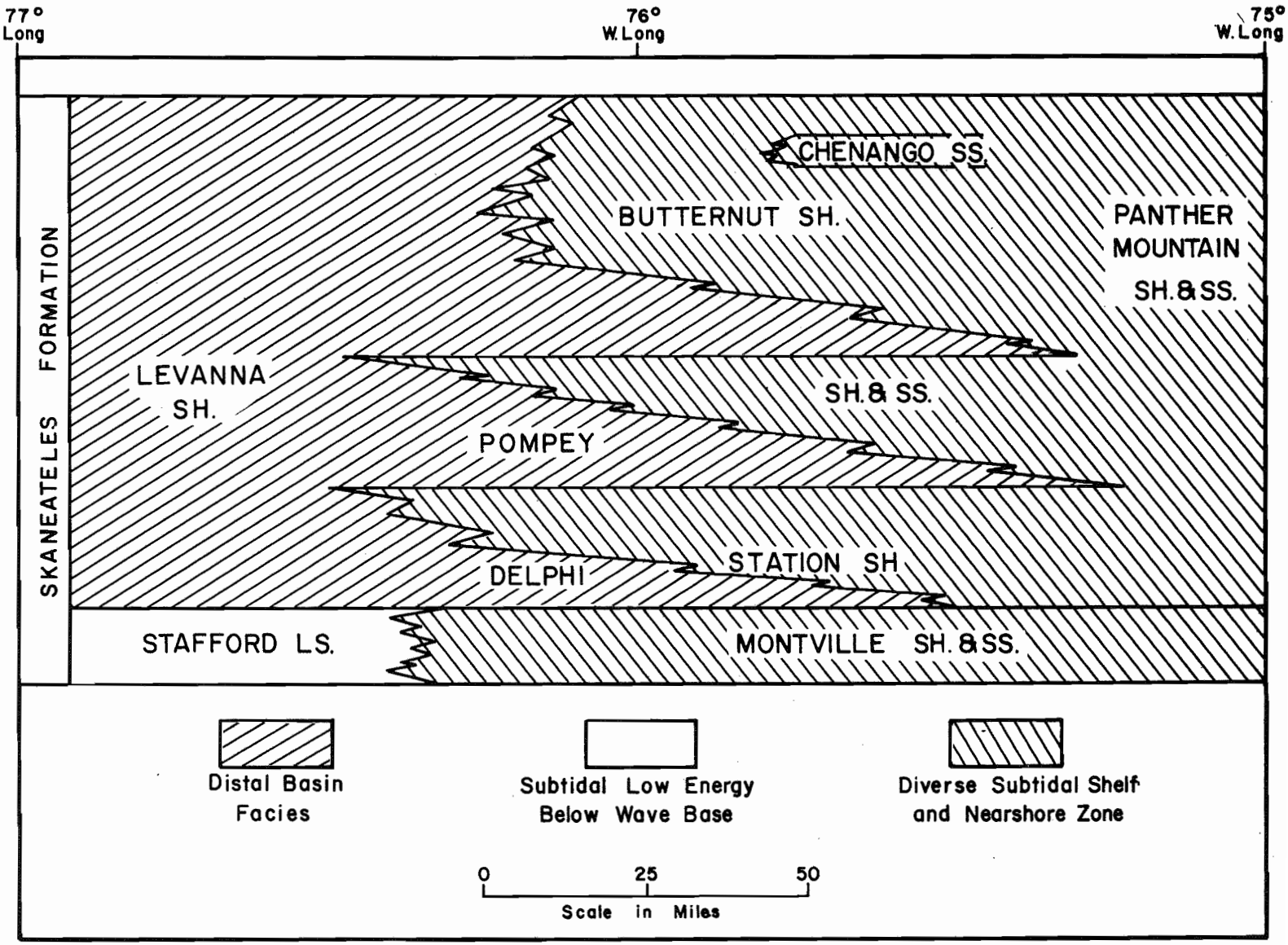


Figure 25. Schematic diagram of stratigraphic framework and facies relationships within the Skaneateles Formation. After Rickard (1975).

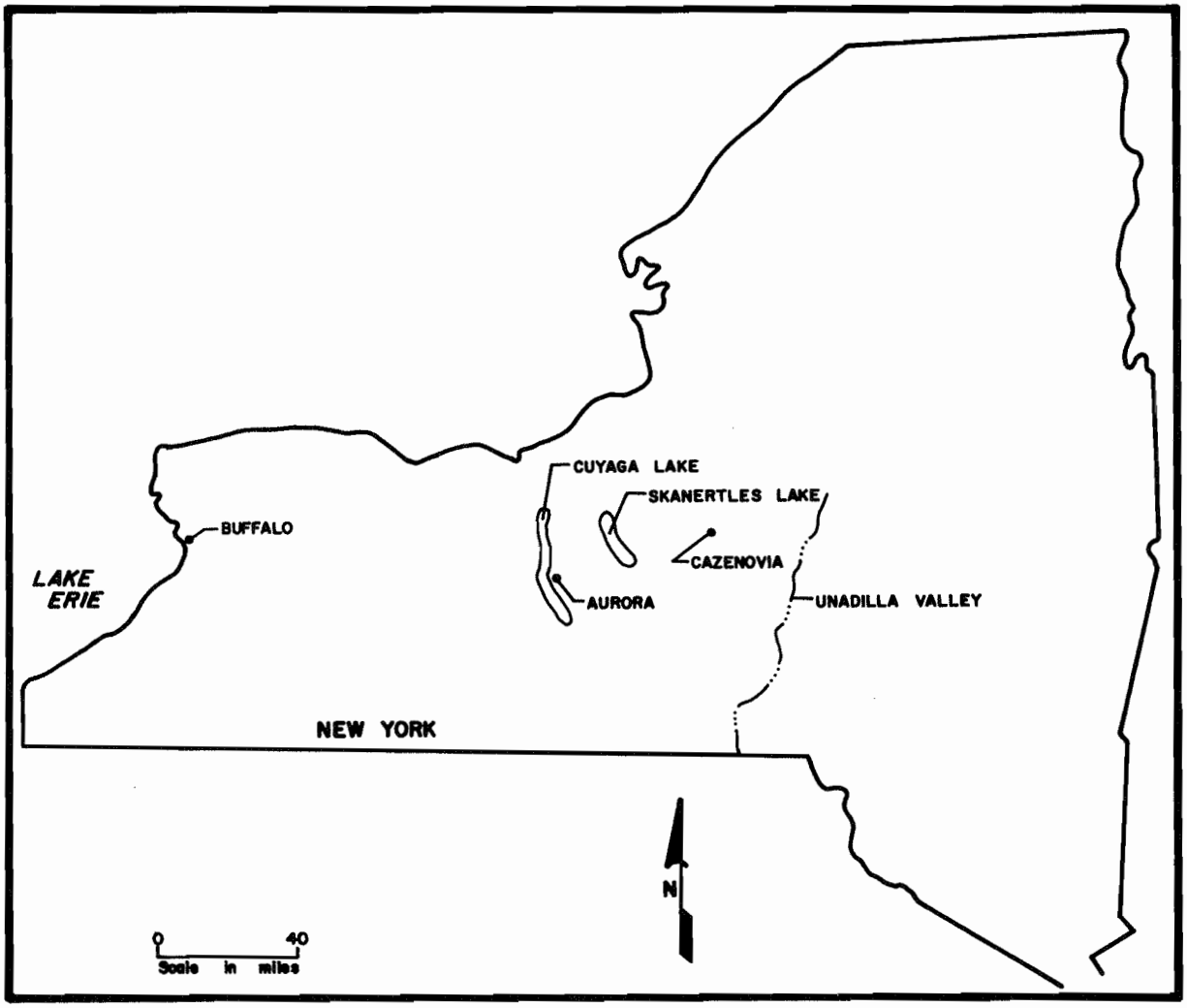


Figure 26 . Index map identifying localities referenced in the stratigraphic discussion of the Ludlowville Formation.

Cooper and Goldring are identical if it is considered that the Menteth Limestone Member is the stratigraphic equivalent of the Portland Point Limestone Member as interpreted by Rickard (1975, plate 3). The definition proposed by Goldring is consistent with the stratigraphic framework established by Eastern Gas Shale Project stratigraphers, and is consistent with the current usage of both the New York State Geological Survey and the United States Geological Survey.

The Centerfield Limetone Member, the basal unit of the Ludlowville, consists of fossiliferous, thin limestone or thin sandy limestone beds. Over its outcrop belt the unit varies in thickness from approximately 4 feet to 10 feet. The Centerfield is interpreted by Rickard (1975) to have been deposited in a subtidal low energy depositional environment. Overlying the Centerfield Member is the Ledyard Shale Member, which is composed of brittle, fissile, black shale (Marcellus type facies) and interpreted by Rickard (1975) as reflecting a distal basin facies. The remaining upper members of the Ludlowville Formation consist of soft, lighter-colored shales and thin limestone marker beds that reflect deposition in the subtidal, low-energy environment of deposition of Rickard (1975). The Tichenor Limestone Member, a thin crinoidal limestone, separates the Wanakah Shale Member below from the overlying Deep Run Shale Member. The Wanakah Shale Member is composed of soft, calcareous light to dark bluish-gray, fossiliferous shale which ranges in thickness over the extent of its outcrop from 5 to 13 feet. The Deep Run Shale Member is brittle, bluish-gray, fissile shale which ranges in thickness from 1 to 55 feet over the outcrop area. The Tichenor Limestone Member has been a key stratigraphic marker bed and an important unit in the understanding of the stratigraphic framework of the Hamilton Group stratigraphy. The unit is thin (1 to 2½ feet), consistent, easily identified and widespread from the shore of the Lake Erie eastward for approximately 100 miles. The fauna, similar to that of the Centerfield Limestone Member, is distinctive for the Tichenor.

In New York the outcrop area of the Ludlowville Formation ranges in thickness from approximately 80 feet in the vicinity of Lake Erie in the Buffalo area to approximately 275 feet in the Unadillia Valley region.

The Ludlowville Formation has not been defined in the subsurface of the Appalachian, Michigan or Illinois basins, hence no subsurface thickness data on the formation is available.

East of Lake Skaneateles, along the outcrop belt, the Ludlowville Formation interfingers with rocks of the diverse subtidal shelf and delta facies. Only the basal Centerfield Limestone Member is persistent east of Lake Skaneateles. In the vicinity of Lake Skaneateles the Ledyard and Wanakah Members correlate with the Otisco and Ivy Point shales of the diverse subtidal shelf facies. The Tichenor Limestone stratigraphic equivalent in the diverse subtidal shelf facies is the Owasco Shale. Eastward from Cazenovia to the Unadillia Valley region the stratigraphic equivalent of the Ludlowville Formation in the diverse subtidal shelf facies correlates with the upper part of the Panther Mountain Shale and Sandstone. The stratigraphic relationships and framework of Ludlowville Formation for the New York outcrop area are shown on figure 27.

Moscow Formation. The Moscow Formation is plaed in the upper part of the Tioughnioga Stage of the Eastern North American Devonian Classification System. The unit was first designated by Hall (1839) to describe the sequence of rock exposed along Little Beards Creek near the village of Leicester (formerly Moscow), Livingston County,

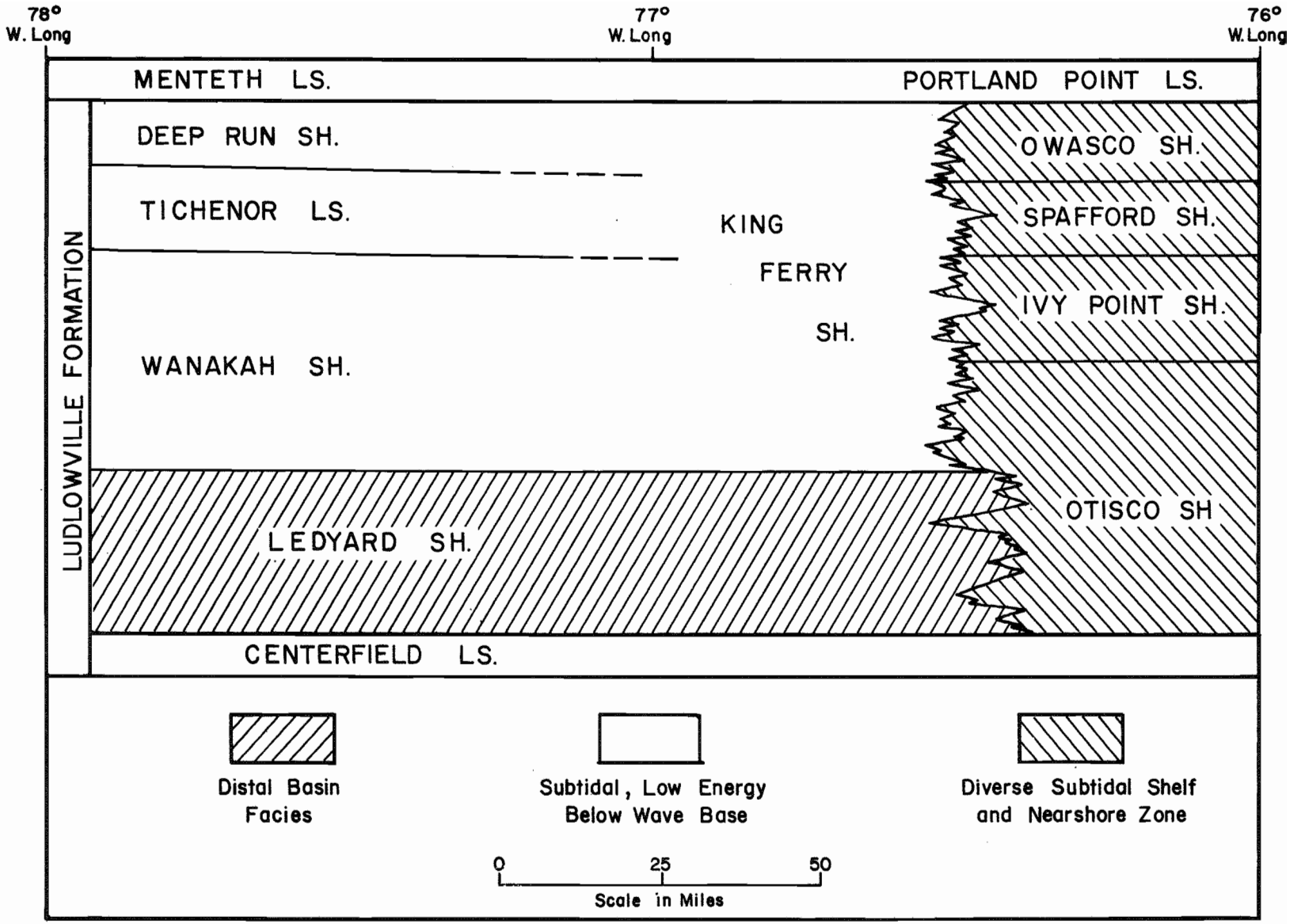


Figure 27 . Schematic diagram of stratigraphic and facies relationships within the Ludlowville Formation. After Rickard (1975).

New York. Localities cited in the stratigraphic discussion of the Moscow Formation are shown in figure 28. Hall limited the base of the Moscow at the base of the "Encrinal" Limestone which he believed to be equal to the "Encrinal" of the Cayuga Lake region at Ludlowville (Wilmarth, 1957). The "Encrinal" at Moscow has now been correlated with the Tichenor Limestone. Cooper (1930) proposed to redefine the Moscow to include the Menteth Limestone and all overlying beds to the base of the Tully Limestone, in the areas where it was present. Cooper retained Hall's type locality even though the formation is not completely exposed. The Moscow Formation at the type section was subdivided from the base upward into the Portland Point Limestone Member, Kashong Shale Member, and the Windom Shale Member. At the type section these units are interpreted to reflect shallow marine deposits of the subtidal low energy facies of Rickard (1975). The Menteth Limestone has the widest lateral distribution and can be correlated eastward into the Portland Point Limestone Member of the Otselic Valley region. The Kashong and Windom Shale Members lose their subtidal low energy characteristics and change facies into diverse subtidal shelf and delta deposits in the Lake Skaneateles (Cayuga County) region. Along the outcrop belt, the eastward equivalent of the Kashong and Windom Shale Members in the diverse subtidal shelf and delta facies is the Cooperstown Shale and Sandstone.

The Portland Point Limestone Member is composed of thin limestone beds and light-colored calcaeous shales. In the Lake Skaneateles area where the Portland Point Member is recognized, the basal limestone bed is called the Menteth Limestone. West of Lake Skaneateles the entire unit is designated the Menteth Limestone. The Portland Point varies in thickness in the outcrop area from a feather edge to a maximum thickness of 8½ feet. The Kashong Member over the extent of its outcrop area ranges in thickness from zero to 85 feet while the Windom Member thickness ranges from 17 to 85 feet in the area of the outcrop.

The Moscow Formation thickens eastward and varies from approximately 60 feet in the Buffalo area of Lake Erie to a maximum of 500 feet in the Schoharie valley region. The stratigraphic relationships and framework of the Moscow Formation in the New York outcrop area are illustrated graphically on figure 29.

Because the upper three formations of the Hamilton Group cannot be defined and correlated in the subsurface, regional correlation of the individual unts was not attempted throughout the Appalachian, Michigan and Illinois basins. However, this sequence of rocks occupies the interval between the top of the Marcellus Formation and the base of the Tully Limestone so that when the Tully is absent, the base of the Genesee Formation becomes the boundary. This latter interval, in effect, as bounded by two radioactive shale units which have been defined in the subsurface, can therefore be widely correlated over the northern Appalachian basin in New York, Ohio, Pennsylvania and West Virginia. South of the outcrop belt in northeastern and south-central Pennsylvania and in West Virginia the stratigraphic equivalent of the Skaneateles-Ludlowville-Moscow interval is the Mahantango Formation. During this time in the Ohio portion of the Appalachian basin, a period of non-deposition and erosion ensued during the post-Marcellus interval of Hamilton Group deposition and hence there are no deposits at this age. In the southern portion of the Appalachian basin in Virginia and eastern Kentucky the Millboro Shale is the time-stratigraphic equivalent of the post-Marcellus Hamilton of the northern Appalachian basin. At the extreme southern end of the Appalachian basin in northwestern Georgia and northeastern Alabama the interval is marked by a period of erosion and nondeposition.

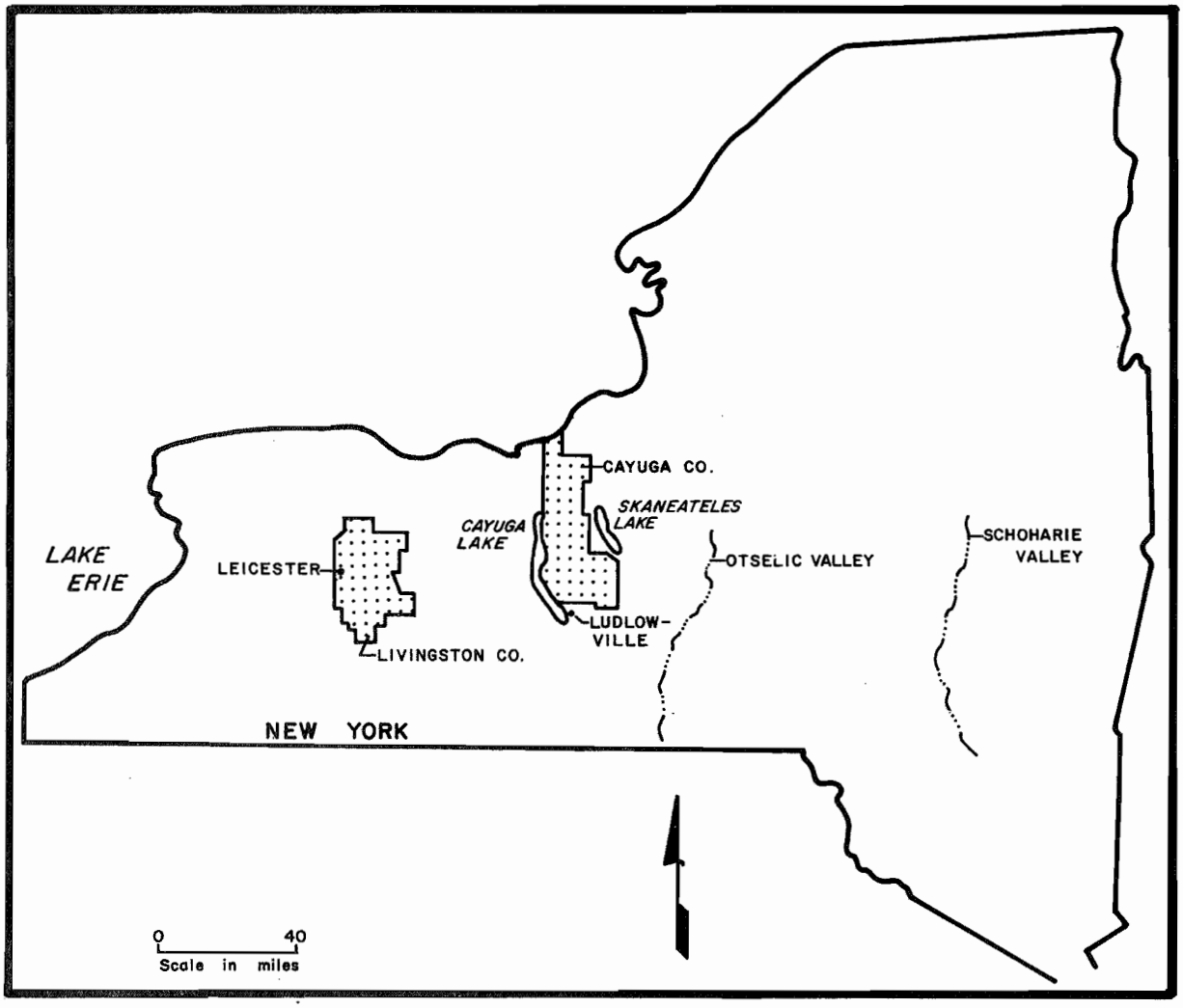


Figure 28. Index map identifying localities referenced in the stratigraphic discussion of the Moscow Formation.

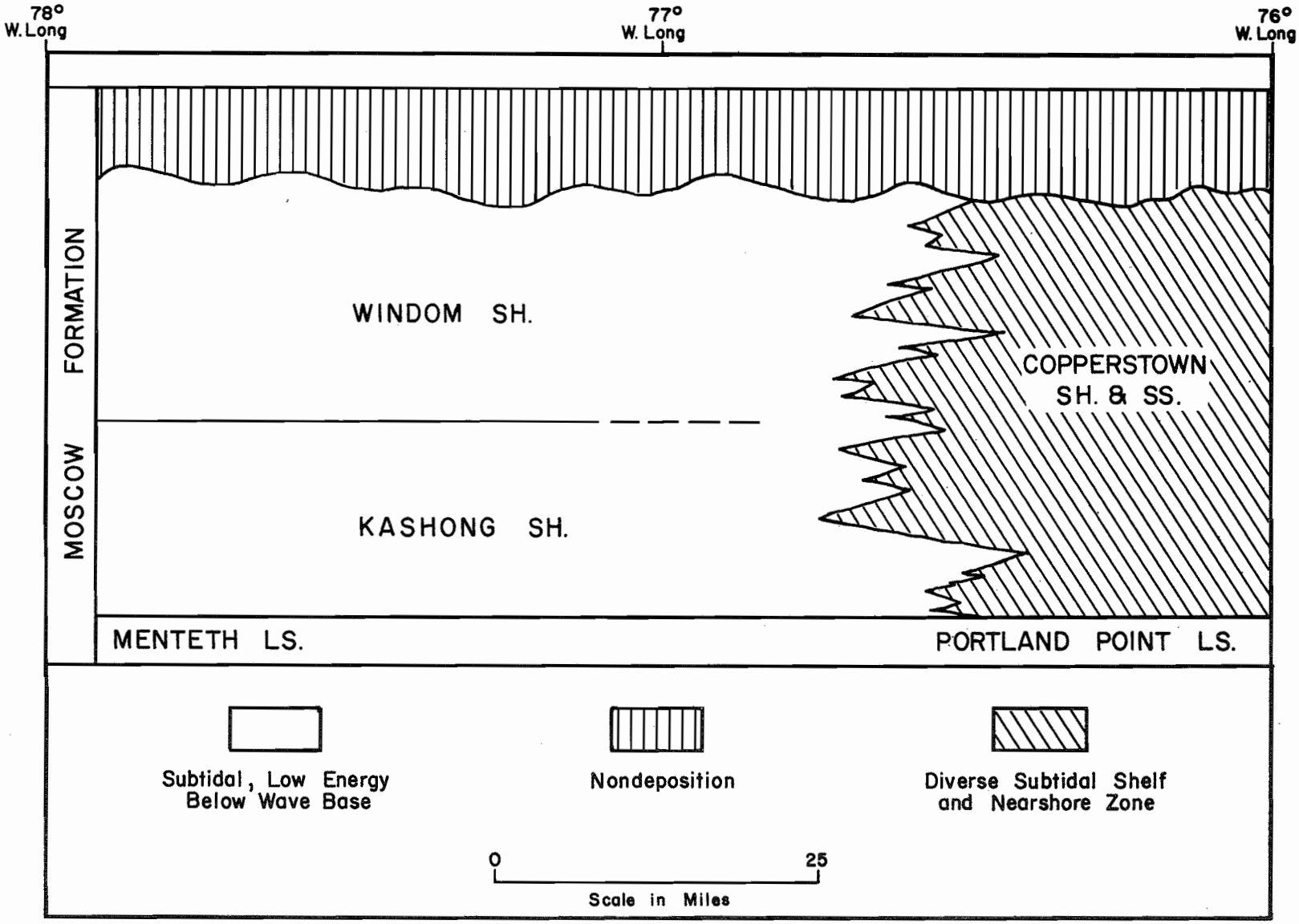


Figure 29. Schematic diagram of the stratigraphic and facies relationships within the Moscow Formation. After Rickard (1975).

In the Michigan basin the Middle Devonian Cazenovia and Tioughnioga interval was a period of shallow marine carbonate deposition. The Hamilton Group time-stratigraphic equivalent in the southern Indiana portion of the Michigan basin is the upper part of the North Vernon Limestone. The lower part of the Traverse Group in Michigan is interpreted to be the time-stratigrahic equivalent of the post-Marcellus, Hamilton beds of New York. In the northwestern Ohio portion of the Michigan basin the Ten Mile Creek Dolomite and the Silicia Formation, which are correlative with parts of the "Lower" Olentangy Shale, may represent time-stratigraphic equivalents of the lower part of the post-Marcellus, Hamilton Group deposits.

In the Illinois basin the post-Marcellus, Hamilton Group time-stratigraphic interval was also a period of shallow marine carbonate deposition. The upper part of the Lingle Limestone in Illinois and the upper part of the North Vernon Limestone of Indiana are interpreted to be equivalent stratigraphically with the post-Marcellus, Hamilton sequence of New York. The Sellersburg Limestone in the Kentucky portion of the Illinois basin is the stratigraphic equivalent of the Lingle and the North Vernon Limestones. Therefore, the upper part of the Sellersburg Limestone is interpreted to be the time-stratigraphic equivalent of the Skaneateles-Ludlowville-Moscow interval in the Illinois basin.

The correlation and stratigraphic relationship of the Hamilton Group equivalents in the three basins is shown by the correlation chart, plate 1.

Tully Limestone. Presently the Tully Limestone is placed in the Taghanic Stage of the Eastern North American Devonian Classification System (Rickard, 1975). The top of the Taghanic Stage marks the boundary between the Middle and Upper Devonian within the framework of the Eastern North American Devonian System. There still remains disagreement among Devonian stratigraphers concerning the position of the Tully within the classification system. In west-central New York the Tully lies upon Middle Devonian Hamilton Group (Moscow Shale) with disconformable contact and underlies with sharp contact the Geneseo Shale which is capped by Upper Devonian Genundewa. Thus, the Tully occupies a position that is either upper Middle Devonian or lower Upper Devonian (Cooper, 1967). The difference in opinion among the stratigraphers working with the New York or Pennsylvanian sections results from: (1) the complex stratigraphy and facies distribution within the Middle and Upper Devonian interval in the outcrop belt, (2) differences in interpretation which evolve from biostratigraphic versus rock-stratigraphic correlations, (3) no index fossils which can be used to date accurately either Middle or Upper Devonian beds, and (4) remaining disagreement on the position of the Middle-Upper Devonian boundary in the standard Devonian sequence in Belgium (Rickard, 1975). Among those who continue to support a Middle Devonian age for the Tully Limestone as advocated by Cooper et al. (1942) and Rickard (1975) are: Cooper (1967), Klapper and Ziegler (1967), Orr and Klapper (1968), Oliver and others (1967, 1969), Orr (1971), and Klapper and others (1971), Heckel (1972). Cooper (1967) and Oliver and others (1967) consider the Tully brachiopods and corals to be Middle Devonian types (Rickard, 1975). Rickard (1975, plate 3) places the positions of the Tully at the top of the Erian Series, considered to be Middle Devonian within the framework of the North American Classification System; however, on plate 3 he questions the position of the Middle-Upper Devonian boundary. The Middle Devonian age for the Tully conforms with the stratigraphic framework established for Eastern Gas Shales Project investigations.

The Tully was first named by Vanuxem (1838) for exposure found at June's quarry and in the adjacent ravine one mile northeast of Tully village, Onondaga County, New York (Cooper and Williams, 1935). Localities cited in the following stratigraphic discussion of the Tully Limestone are shown on figure 30. The Tully Limestone is composed of drab-gray to bluish-gray, very fine crystalline, fossiliferous limestone with planar to wvy silt and fine sand laminae. West from the type section the unit varies in thickness from 8 inches to 30 feet.

In the area of the type section, Cooper and Williams (1935) subdivided the unit into three members, in ascending order the Tinker Falls, Apulia, and West Brook. Beyond the eastern limit of the Tully Limetone in the Chenango Valley region, Cooper and Williams (1935) using faunal evidence, carried the Tully interval into the shale and sandstone facies of the prograding Catskill delta. In the Otsego County area, within the shale and sandstone facies, they subdivided the interval into three members from the base upward, the New Lisbon, Laurens, and West Brook Members. In a more recent, comprehensive study of the Tully Limestone based upon rock stratigraphic correlation techniques, Heckel (1973) subdivided the formation into an upper and lower member. Rickard's (1975) development of the stratigraphic framework for the Devonian of New York followed Heckel's subdivision of the Tully (fig. 31).

The Tully Limestone of west-central New York, in the concept of a rock-stratigraphic unit, extends eastward from the Seneca Lake area for nearly 100 miles before pinching-out in the Chenango Valley area. The eastern limit of this lower member is in the Otselic Valley region. Beyond the eastern limit of the Tully Limestone where it is a subtidal, low energy facies, the unit interfingers with the Gilboa shale and sandstone unit that has been interpreted by Rickard (1975) to reflect deposition within the diverse subtidal shelf and delta environment.

The Tully interval has been traced from the New York area southward in the outcrop along the Allegheny front as far south as Bedford, Pennsylvania. It attains its greatest thickness, 240 feet, in central Pennsylvania. Further south along the front in West Virginia, the Tully equivalent is interpreted to be a calcareous shale called the Tully member of the Harrell Shale by Hanson (1966). The unit has not been identified in Virginia, although the interval is probably present within the Millboro Shale sequence.

Within the subsurface, the Tully has been a key stratigraphic marker south and west of the New York and Pennsylvania outcrop areas, and it appears that the unit can be extended in the subsurface for about 200 miles southwest of the New York outcrop belt into western Pennsylvania, Maryland, West Virginia, Virginia, and extreme southeastern Ohio. In the subsurface the thickness of the formation ranges from a few feet at the depositional or erosional margins, to over 200 feet along the axis of the depositional basin. The distribution and thickness of the Tully in the northern part of the Appalachian basin are shown on figure 32.

In all but extreme eastern Ohio, the Tully interval appears to be represented by a period of nondeposition, but in the eastern part of the state the lower part of the gray Olentangy Shale is correlative with the Tully Limestone facies. In the Kentucky-Tennessee portion of the Appalachian basin, the Tully interval has not been identified but faunal evidence suggests the Tully equivalent at the base of the New Albany-Chattanooga shale sequence.

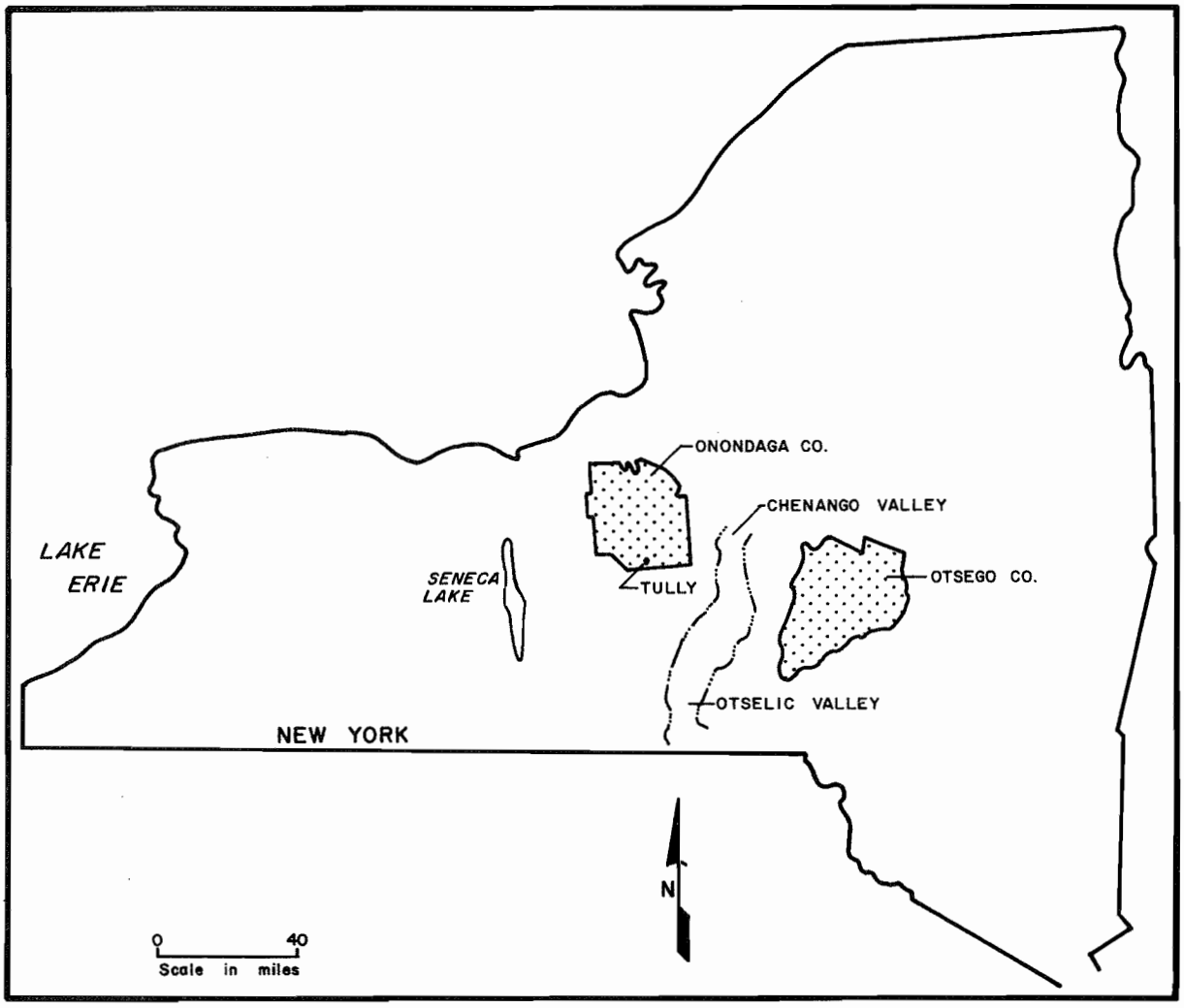


Figure 30 . Index map identifying localities referenced in the stratigraphic discussion of the Tully Limestone.

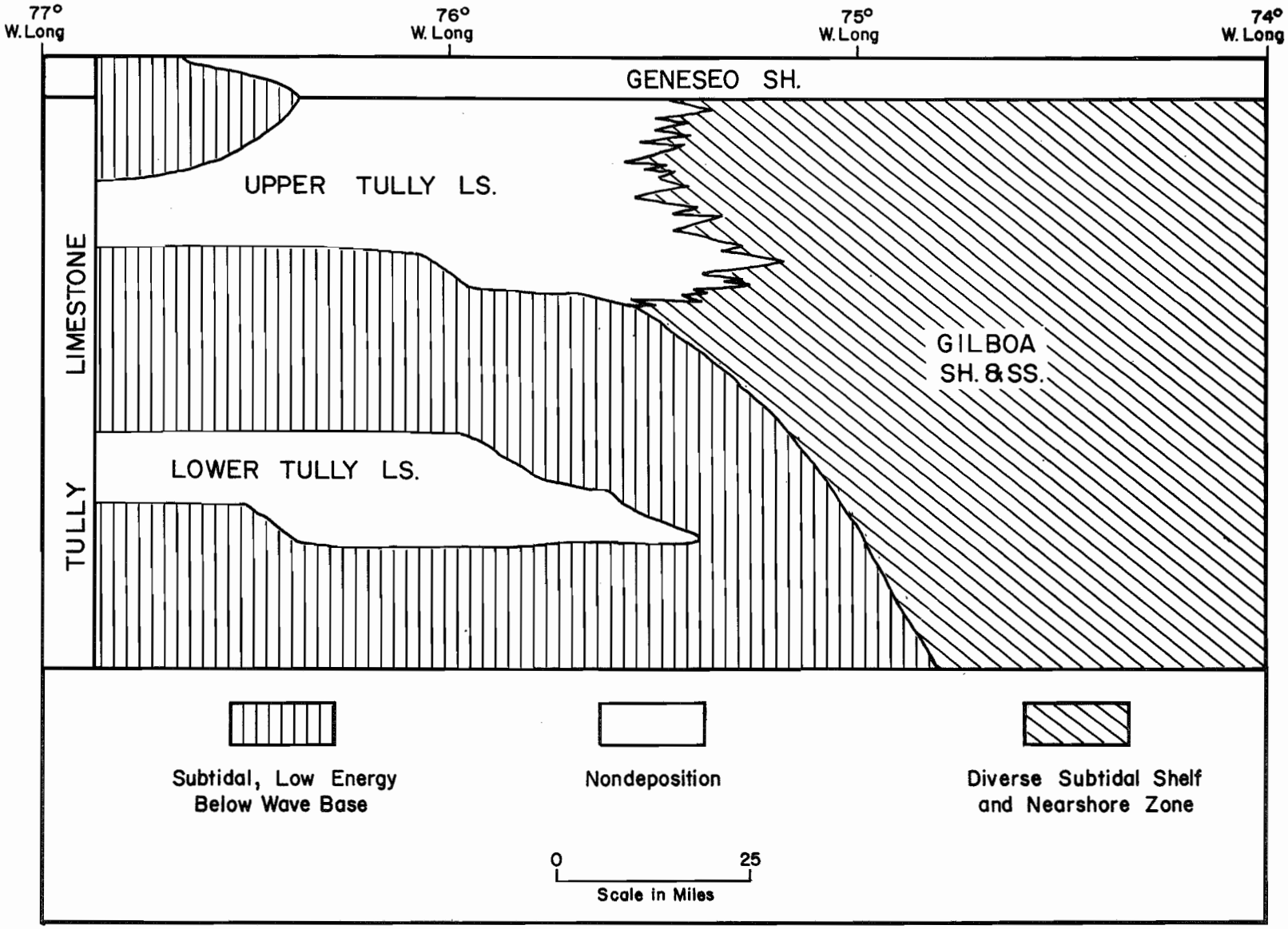


Figure 31. Schematic diagram of stratigraphic and facies relationships within the Tully Limestone. After Rickard (1975).

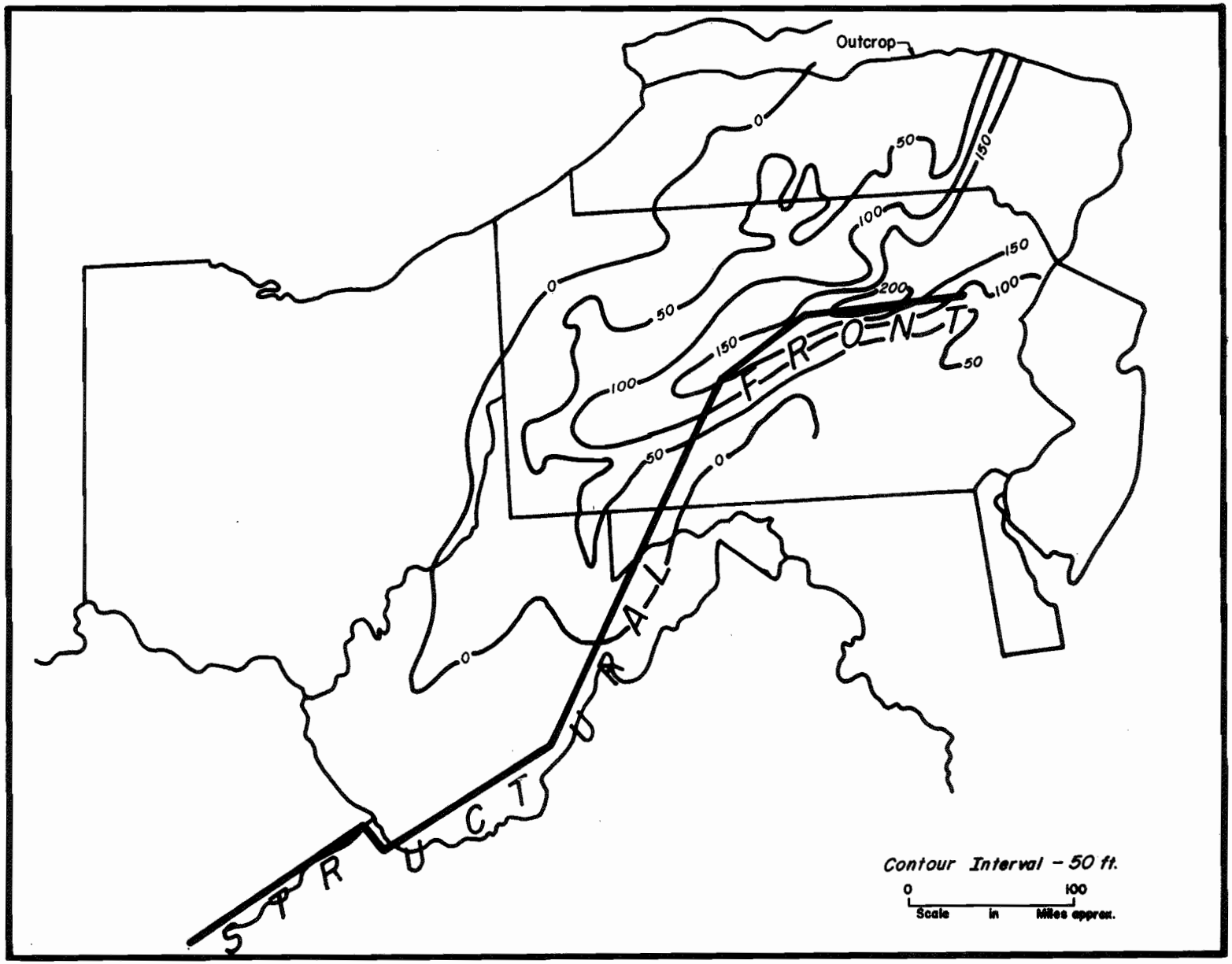


Figure 32 . Generalized thickness and distribution of Tully Limestone. After Heckel (1973).

In the Michigan basin faunal evidence strongly suggests that the Tully Limestone is correlative with the upper part of the Traverse Group.

Although the Tully interval has not been identified in the Illinois basin, it is probably represented in the basal part of the New Albany Shale. The stratigraphic position of the calcareous Blocher Member suggets that it may be the Illinois basin equivalent of the Tully. The stratigraphic relationship of the Tully within the Appalachian, Michigan and Illinois basins is shown by the correlation chart, plate 1.

As pointed out earlier, the subsurface stratigraphic framework adopted for Eastern Gas Shales Project investigations in the Appalachian basin is a composite of New York and Ohio nomenclature. Beyond the limits of the basin where the New York and Ohio units could not be traced or identified, local facies names were incorporated into the stratigraphic framework. The physical stratigraphy of the Middle and Upper Devonian stratigraphic units of Ohio and the names applied to local facies equivalents within the Appalachian basin will be discussed in the following paragraphs. The discussion of the Ohio Middle and Upper Devonian units is summarized from Stewart (1955), Hoover (1960) and Schwietering (1970). For Eastern Gas Shales Project purposes, the Devonian Shale sequence in Ohio was considered to occupy the interval between the Onondaga equivalent limestone at the base and the Berea Sandstone at the top. The local name "Columbus Limestone" comprises the Onondaga interval in Ohio. Localities referenced in the stratigraphic discussion of Ohio are identified on figure 33.

Ohio-Eastern Kentucky

Columbus Limestone (Onondaga). The name "Columbus Limestone" was first applied by Mather (1859) for approximately 140 feet of limestone occurring in the statehouse artesian well in Columbus, Ohio. This sequence of limestone, the Corniferous of Hall (1843), included both the Columbus and Delaware Limestones as known today. Newberry (1873) subdivided the unit into two divisions, as upper the Sandusky Limestone, and as lower the Columbus Limestone. From the time of these early investigations until the mid-1950's, many stratigraphic and paleontologic investigations of the Middle Devonian sequence in Ohio have contributed to the knowledge of the age, correlation and stratigraphic framework of the Columbus Limestone. Contributions during this period were made by Orton (1878), Whitfield (1880), Prosser (1905), Swartz (1907), Stauffer (1909), Westgate (1926), Wells (1947) and Stewart (1955). In the outcrop belt in Franklin and Delaware Counties, Ohio, the Columbus Limestone reaches a thickness of approximately 105 feet. Northward along the central Ohio outcrop belt the unit thins to approximately 60 feet in quarries at Sandusky, Marblehead and Kelly's Island. The Columbus disconformably overlies the Bass Islands Group and the contact is marked by a one-foot conglomeratic layer with Bass Island pebbles enclosed in a matrix of Columbus Limestone. The upper contact is marked by a bone bed 3 to 14 inches thick. In the outcrop belt the unit can be separated into two distinct lithologic facies. The lower part of the unit is massive, brown dolomitic limestone containing only a few poorly-preserved fossils. The upper facies, typically a thick-bedded massive light-gray, fossiliferous limestone, contains chert both as nodules and discontinuous lenses. In the subsurface the Columbus Limestone is included within the "Big Lime Formation" of the drillers. Because the upper and lower contacts of the Columbus are indistinct on geophysical logs, no attempt has been made to show the distribution and thickness of the unit in the subsurface of eastern Ohio. From sample investigations in the South Birmingham Pool area of Erie

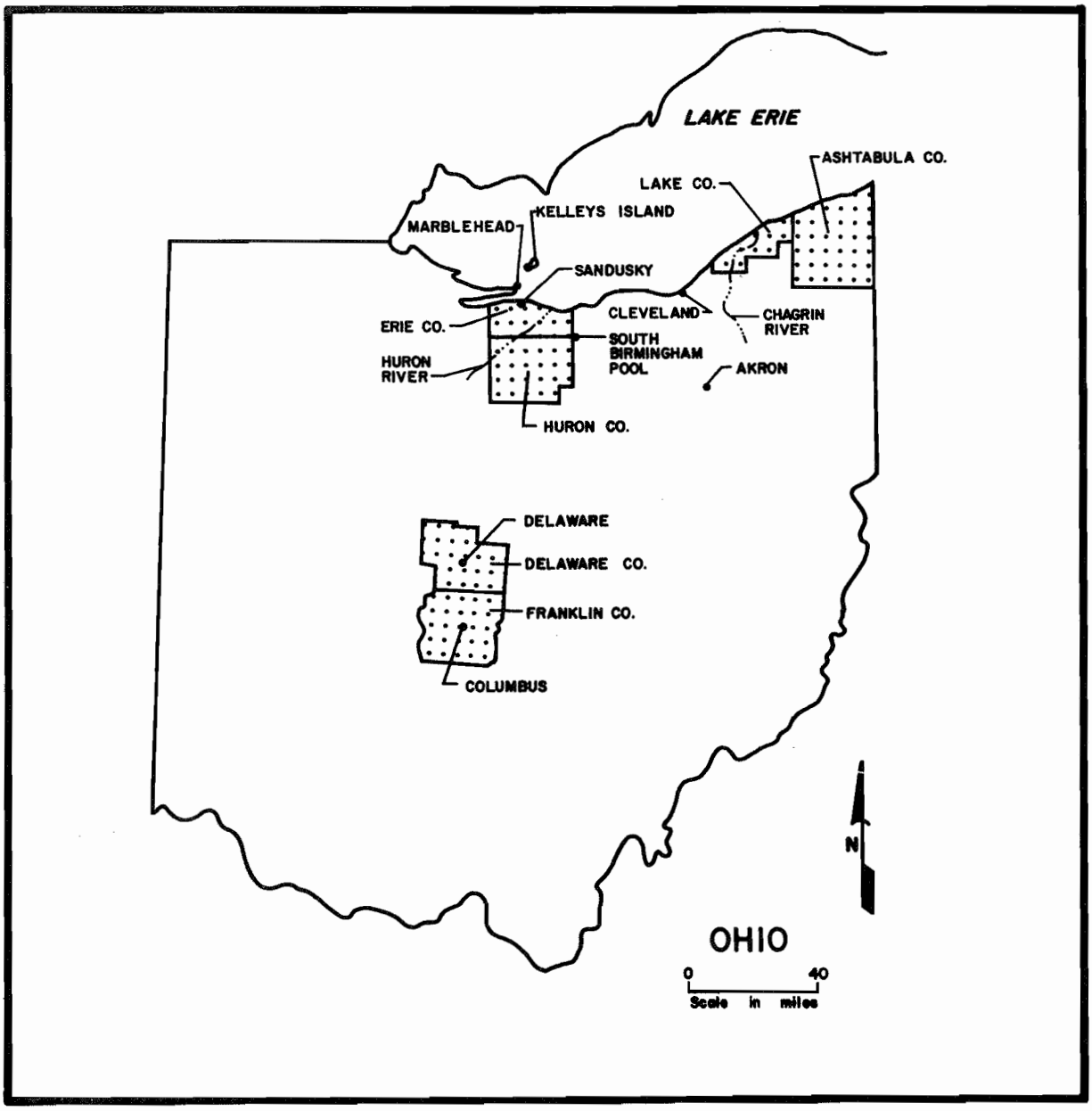


Figure 33. Index map identifying localities referenced in the discussion of the Middle and Upper Devonian stratigraphic units in Ohio.

and Lorain Counties, Ohio, Janssens (1968) reports a thickness of 175 feet for the combined Columbus Limestone and Detroit River Group. The Columbus Limestone is currently assigned to the Onesquethaw Stage of the New York reference section and correlated with the Detroit River Group of northwestern Ohio, the Anderdon Limestone and Detroit River Formation in the Michigan basin, the Jeffersonville and Grand Tower Limestone in the Illinois basin and the Onondaga Formation and Huntersville Chert in the Appalachian basin.

Delaware Limestone (Onondaga). The upper unit of the Onondaga sequence in Ohio is the Delaware Limestone. Winchell (1874) was the first to use the name Delaware for the upper part of the Corniferous in central and northern Ohio. Orton (1878) first used the term Delaware in a formational sense for the upper 32 feet of blue limestone exposed near Delaware, Ohio to replace the name Sandusky Limestone which had been proposed earlier by Newberry (1874). The stratigraphic and paleontoligic work previously mentioned in the discussion of the Columbus Limestone contributed equally to the understanding of the stratigrahic and age relationships of the Delaware Limestone in Ohio. The Delaware is typically a blue, argillaceous limestone which weathers brown at the surface. The unit, which is commonly more thinly bedded than the Columbus, is interbedded with thin beds of brown shale and chert. Fossils are abundant locally. Because the contact between the Delaware and Columbus Limestones is indistinct on geophysical logs throughout eastern Ohio, the subsurface thickness of the unit has not been mapped by Eastern Gas Shales Project investigators in Ohio. There still remains some disagreement among investigators about the age and correlation of the Delaware Limestone. From surface data the unit has been assigned by Stewart (1955) to the Cazenovia Stage of the New York reference section and correlated with the Dundee Limestone of northwestern Ohio and Michigan, the lower part of the Traverse Formation of Indiana and the Marcellus Shale of New York. In the subsurface the Eastern Gas Shales Project investigators have combined the Columbus and Delaware Limestone and correlated the sequence with the Onondaga Formation in the Appalachian basin, the Detroit River Group in the Michigan basin, and the Grand Tower and Jeffersonville Limestones of the Illinois basins (plate 1).

Olentangy Shale. The name Olentangy Shale was first applied by Winchell (1874) for exposures of bluish to greenish shale which lies directly beneath the Huron Shale along the banks of the Olentangy River valley in Delaware County, Ohio. Excellent histories of the development of the nomenclature and problems of age classification and correlation can be found in the works of Hoover (1960) and Schwietering (1970). Cooper and others (1942) and Oliver and others (1967) subdivided the Olentangy Shale into two prts, the lower, Middle Devonian and the upper, Upper Devonian in age. Tillman (1970), on the basis of the ostracod fauna from the Olentangy, was able to subdivide the unit into an upper and lower part and assigned a Middle Devonian age to the lower and an Upper Devonian age to the upper unit. In the subsurface investigations of Lowden (1965), Tillman (1970) and Schwietering (1970) two subdivisions are evident from examinations of gamma-ray neutron logs, well cuttings and outcrop sections. The upper unit is considered Upper Devonian and correlated with the Java and West Falls Groups of New York and the lower unit has been assigned a Middle Devonian age and correlated in part with the Hamilton Group of New York (Schwietering, 1970). Eastern Gas Shales Project investigators have followed the stratigraphic framework of Tillman (1970) and Schwietering (1970) and separated the Olentangy Shale into a "Lower" Olentangy Member (Middle Devonian) and an "Upper" Olentangy Member separated by a well-defined unconformity.

The "Lower" Olentangy Member in the outcrop section in central Ohio is composed of bluish-gray to greenish-gray shale interbedded with thin, compact blue limestone layers. Small pyrite concretions and nodules are common in the "Lower" Olentangy Member and the unit reaches a thickness of approximately 50 feet along the outcrop belt in north-central Ohio. The character of the shale in the subsurface changes from gray to dark gray and black shale with interbeds of thin limestones and a basal black, carbonaceous highly radioactive shale. The subsurface facies ranges in thickness between 150 and 200 feet along the Ohio-Pennsylvania border. Equivalent rocks in eastern Pennsylvania and south-central New York attain a thickness of greater than 2000 feet (fig. 34). The "Lower" Olentangy Member rests conformably upon the Middle Devonian Limestone units and correlates with the Mahantango and Marcellus Formations of West Virginia and Pennsylvania. In southeastern Pennsylvania and northeastern West Virginia the Mahantango intertongues with the Millboro Shale of Virginia and eastern Kentucky, while further east the Mahantango equivalents intertongue with the redbed lithofacies of the Catskill Formation of New York and the Hampshire Formation of West Virginia.

Pennsylvania-West Virginia

The stratigraphic framework and nomenclature for rocks of Hamilton age in Pennsylvania have undergone an evolution for over 95 years beginning with the work of White (1883) and continuing through the recent classification proposed by Faill and others (1978). This evolution in the stratigraphic nomenclature is shown on figure 35 and discussed in detail by Faill and others (1978, p. 4-8). Where the units of the Hamilton Group of New York have been traced into Pennsylvania, the New York terminology, which has been previously discussed, has been retained. In central and south-central Pennsylvania where the New York units are not recognized, a host of local stratigraphic names have been proposed for the Hamilton equivalent lithofacies by investigators working in the region. The following discussion of the post-Onondaga Middle and Upper Devonian units within the stratigraphic framework adopted by Eastern Gas Shale Project stratigraphers is summarized from Faill and others (1978), Ellison (1965), Willard (1935) and Butts (1940). Localities referenced in the stratigraphic discussion of Pennsylvania are shown on figure 36.

Mahantango Formation. In areas of Pennsylvania where the formations of the Hamilton Group of New York cannot be recognized, the currently accepted post-Onondaga Middle Devonian stratigraphic framework consists of the Marcellus and the Mahantango formations. The placement of the Tully is still in question, but Faill and others (1978) place the Tully in the Middle Devonian as a member of the Mahantango Formation. Eastern Gas Shale Project stratigraphers consider the subsurface Mahantango formation to occupy the interval between the Marcellus Formation and the Tully Limestone and where the Tully is absent between the Marcelus and the Geneseo Shale. The name Mahantango was proposed by Willard (1935) for the sequence exposed along West Mahantango Creek, Snyder County, Pennsylvania. In central Pennsylvania the Mahantango is composed of shales, siltstones, silty mudstones, sandstones and conglomerates. A thin calcareous interval at the top is considered to be the Tully (Faill and others, 1978). The formation is made up of a series of upward coarsening lithic units which begin generally with claystone or shale and grade upward into fine to coarse-grained fossiliferous sandstones. The contacts between cycles are sharp, consisting of abrupt changes from

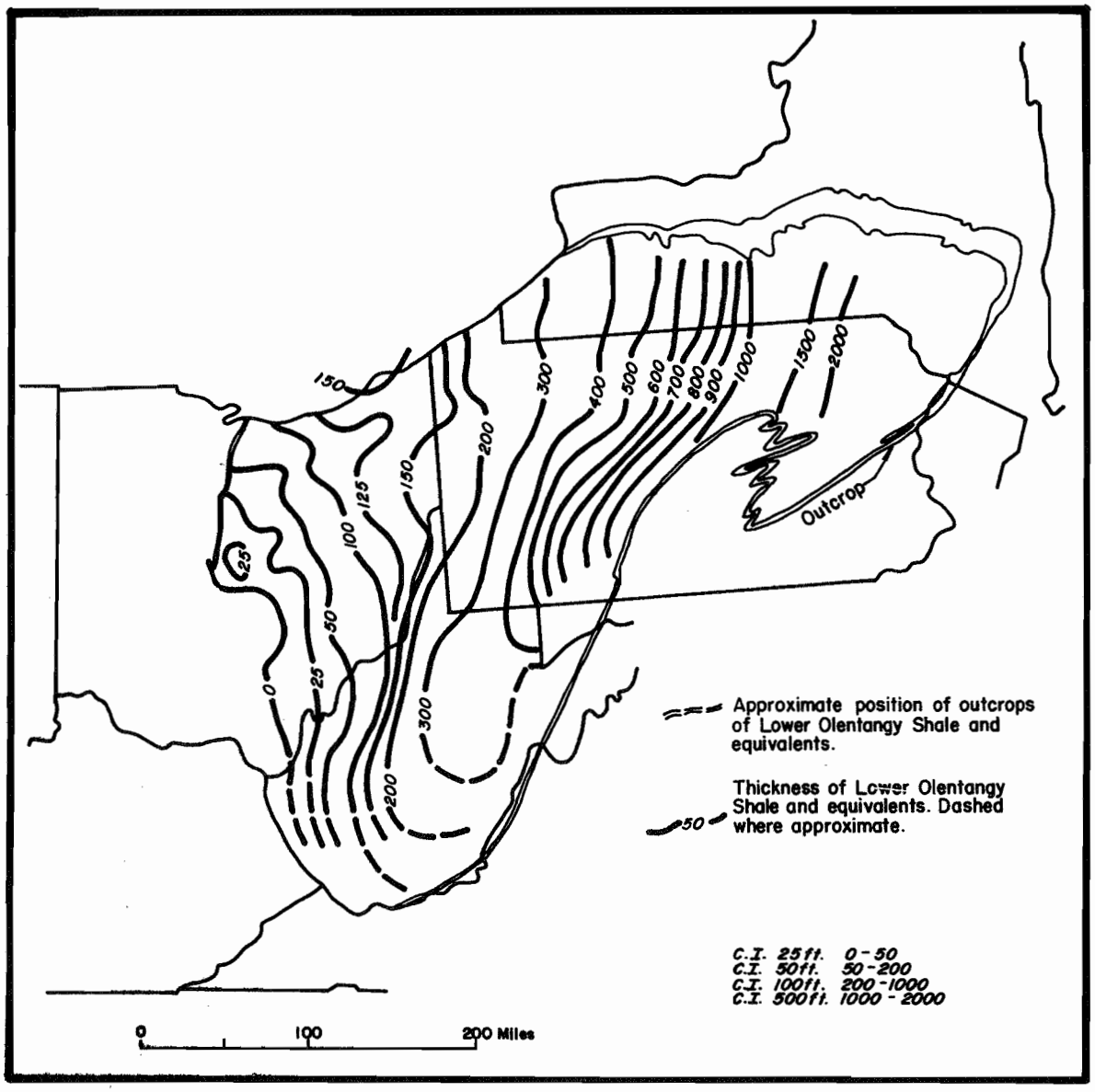


Figure 34 . Thickness and distribution of the Lower Olentangy Shale in the Appalachian basin. After Schwietering (1970).

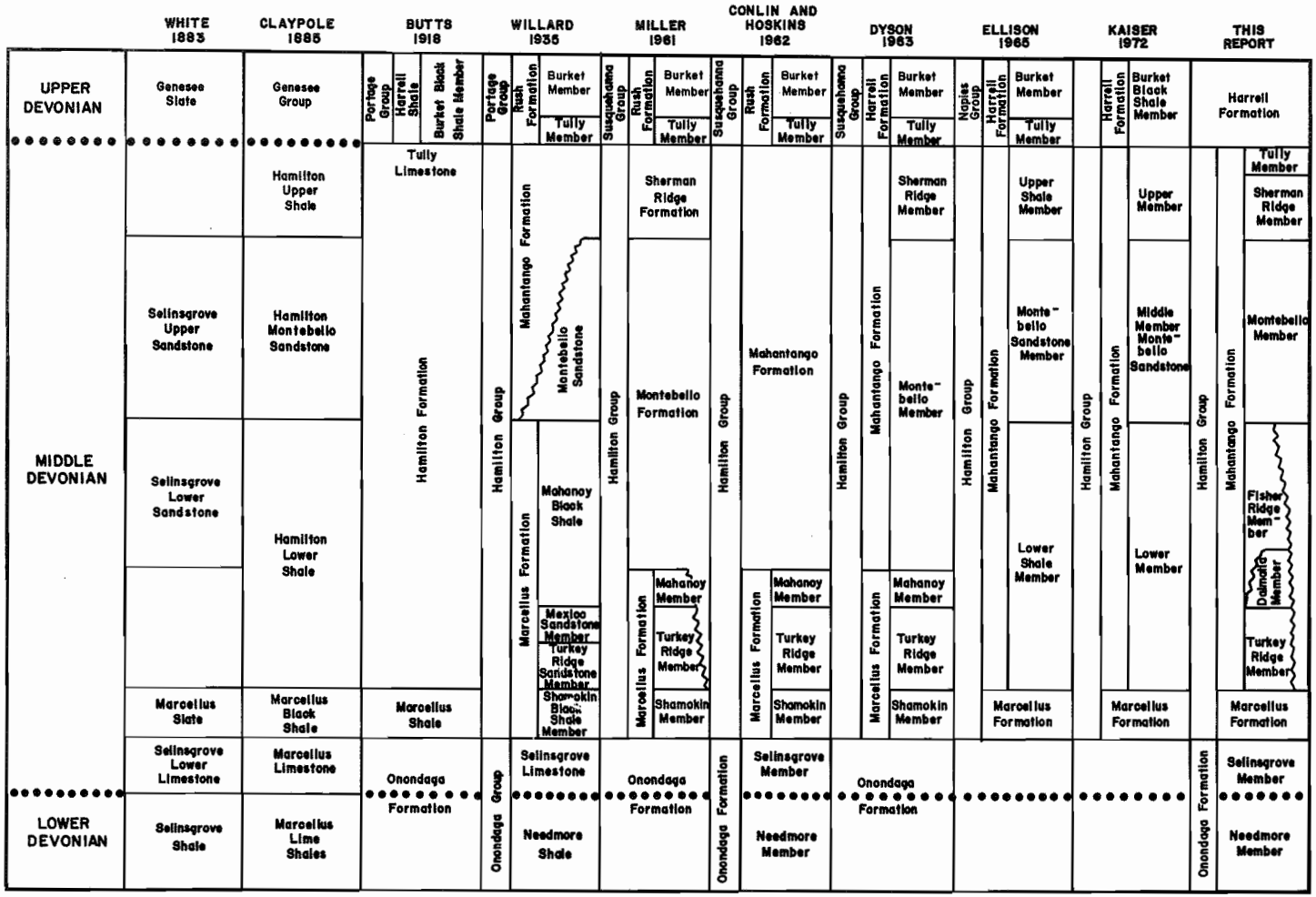


Figure 35. Correlation chart of Middle Devonian stratigraphic units, illustrating the change in nomenclature over the past 95 years in central Pennsylvania.

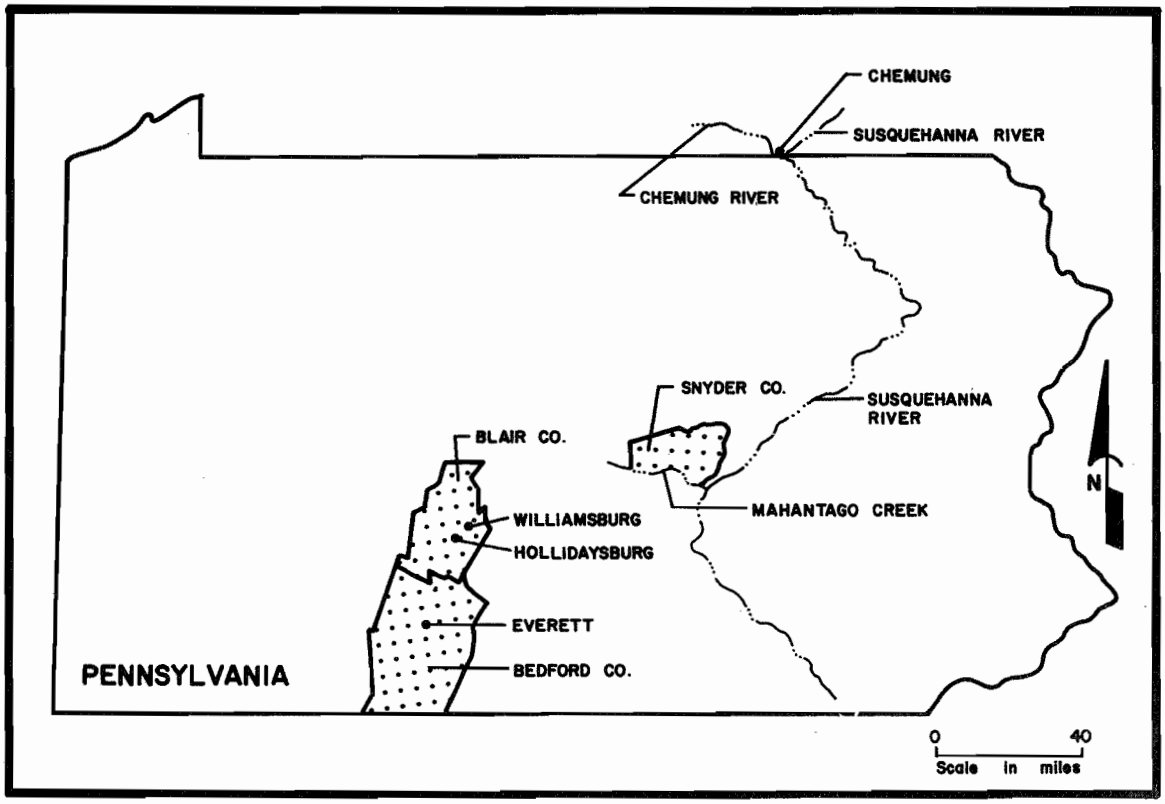


Figure 36. Index map identifying localities discussed in the stratigraphic discussion of the Upper and Middle Devonian units in Pennsylvania.

coarse clastics to fine clastics. The thickness of cycles ranges from 6 to 250 feet, the thicker cycles occurring in the coarser-grained sequences. A decrease in grain size away from the depocenter of the deltaic lobes occurs in conjunction with the vertical variation in grain size. Towards the margin of the lobes the coarser-grained beds become finer and are difficult to separate from the next overlying and underlying fine-grained units. The Mahanatango sequence in central Pennsylvania, primarily a thick sandstone unit lying between two thinner shaly units, is composed of over 60% sand. In south-central Pennsylvania, the Mahantango unit is composed completely of siltstone, shales and claystones with no appreciable amount of sand. Further south, along the West Virginia border, there is an increase in total sand indicating the possibility of another lobe to the south in West Virginia. Along the outcrops in central Pennsylvania, the Mahantango can be subdivided into six distinct lithologically mappable units from the bse upward, the Turkey Ridge, Dalamtia, Fisher Ridge, Montebello, Sherman Ridge and Tully. Along the outcrop the Mahantango Formation ranges in thickness from 1700 feet to 2500 feet (Faill and others, 1978) and thins to approximately 1600 feet in Bedford County (Ellison, 1965). The distribution of the Mahantango Formation in the subsurface is restricted to western Pennsylvania and most of West Virginia. The thickness and distribution of the Hamilton Group, which includes both the Marcellus and Mahantango Formations, is shown on figure 37. The Mahantango is equivalent to the Hamilton Group of New York, the lower part of the Millboro Shale in Virginia and the entire Millboro sequence of eastern Kentucky. The Lingle Limestone of Illinois, the North Vernon Limestone of Indiana and the Sellersburg Limestone of Kentucky are the stratigraphic equivalents of the Mahantango in the Illinois basin. In the Michigan basin, the Mahantango interval is occupied by the Dundee and Roger City Limestone and the lower part of the Traverse Group (plate 1). The physical stratigraphy of the Tully Limestone, the top of the Middle Devonian in the New York, Pennsylvania and West Virginia, was discussed previously within the framework of the New York reference section.

Upper Devonian

New York

Genesee Formation. The beds of the Genesee Group were described by Vanuxem (1840) and Hall (1840) from exposures found along the Genesee River valley below Portage, New York. Figure 38 is an index map showing localities cited in the stratigraphic discussion of the Genesee Formation. The name Genesee was first used for these rocks by Vanuxem (1840). Caster (1933) used the term Genesee Group of formations for the sequence in the Ithaca region which included the Genesee (Geneseo), Genundewa, West River, Stanish, and Middlesex formations. Chadwick (1935) redefined the Genesee Group to include all rocks above the Tully Limestone and below the Sonyea Formation in the area east of Canandaigua Lake (de Witt and Colton, 1959). Where the Tully is absent, the group includes all rocks between the Hamilton Group below and the Sonyea Formation above. In 1959, de Witt and Colton (1959) applied the name Genesee Formation for the rocks formerly called Genesee Group by Chadwick (1935). The reference section for the Genesee formation of de Witt and Colton is the outcrop section at Beards Creek near Leicester in western Livingston County where the section is complete and outcrops are accessible. In the reference area the Genesee Formation has been subdivided into four members, from the base upward, the Geneseo Shale Member, the Penn Yan Shale Member, the Genundewa Limestone Member, and the West River Shale Member. The Genesee Formation is 129 feet thick in the type section at Beards Creek (de Witt and Colton,

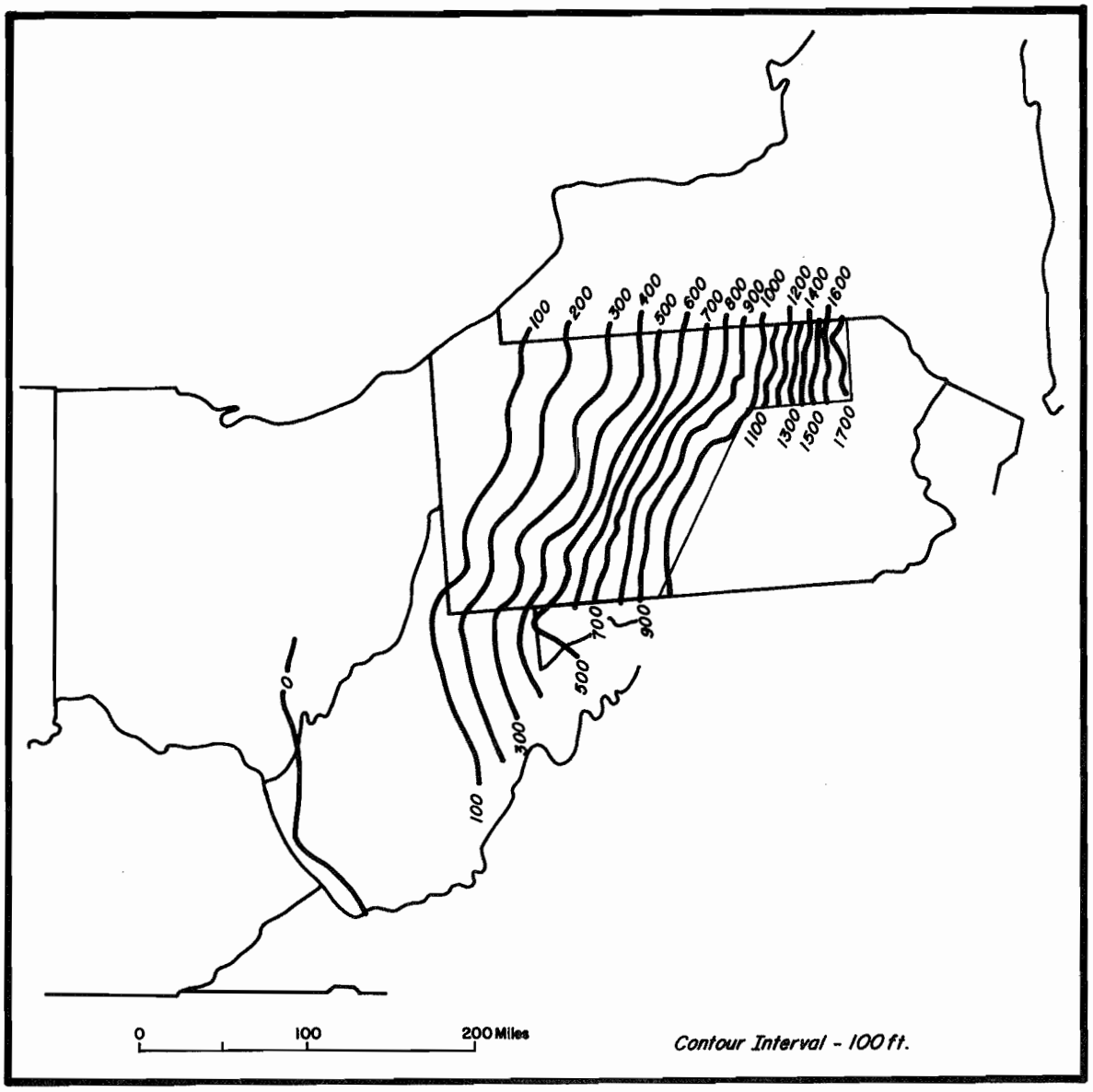


Figure 37. Thickness and subsurface distribution of the Hamilton Group in Pennsylvania and West Virginia. Modified from Schwietering (1981) and Piotrowski and Harper (1979).

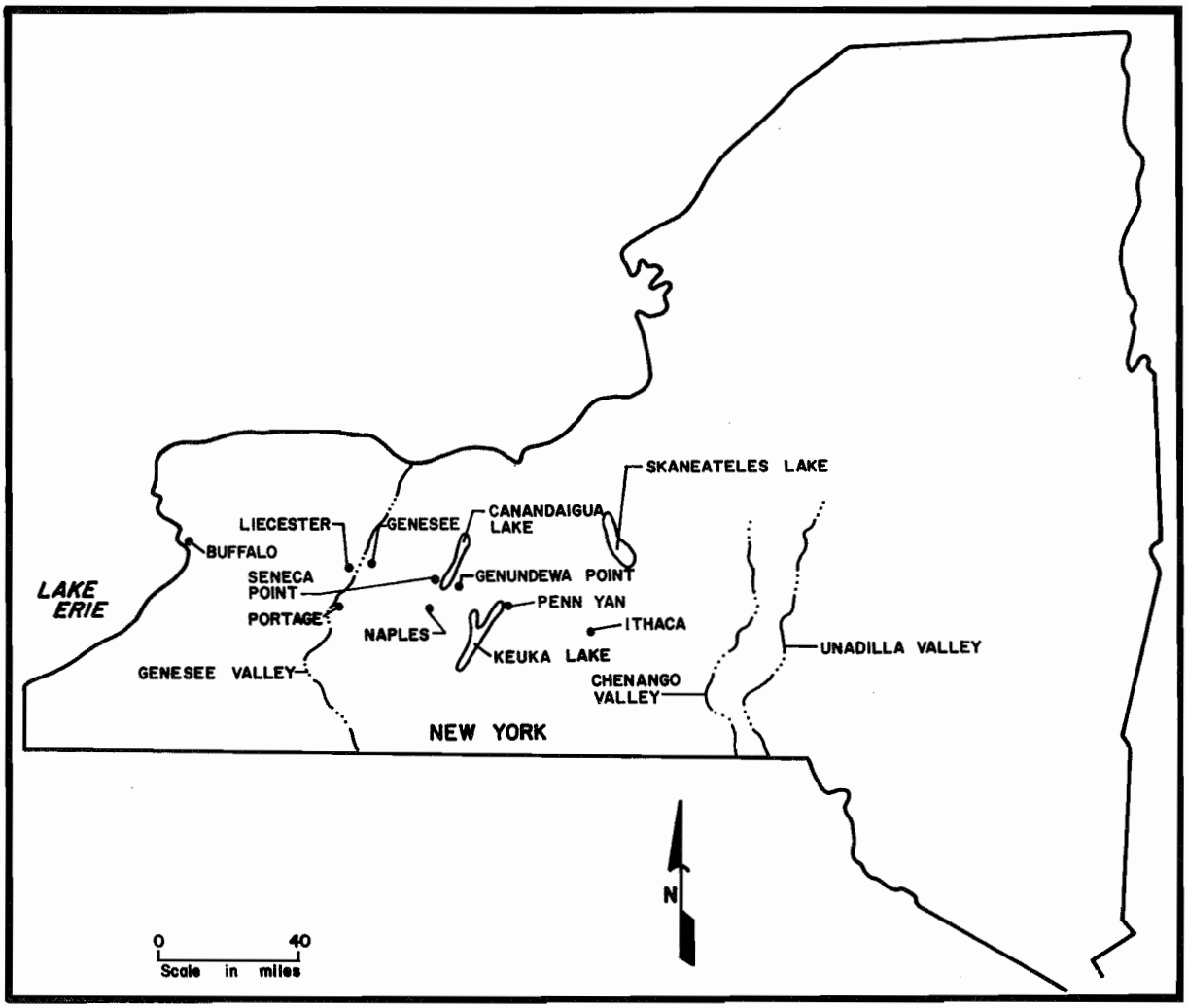


Figure 38. Index map identifying localities referenced in the stratigraphic discussion of the Genesee Formation.

1959). The following description of the members of the Genesee Formation is taken from de Witt and Colton (1959).

The name Geneseo Shale was first used by Chadwick (1920) for the shales exposed at Fall Brook, 1 3/4 miles south of the town of Geneseo. At this locality the Geneseo is 84 feet thick and characterized as a black, brittle, massive, finely-laminated shale. The lighter-colored shales occurring in the middle of the unit resemble the shales of the West River Shale Member above. The Geneseo Shale Member at the Fall Brook locality is restricted by de Witt and Colton to the 5-foot tongue of black shale at the base of the unit and a 5-foot tongue at the top of the 82 feet of outcropping shales. In the western New york area the Geneseo Shale Member rests unconformably upon the Moscow Formation of the Hamilton Group. The lithology of the Geneseo Member is characteristic of deposits in the distal basin facies of the northern Appalahian basin.

Conformably overlying the Geneseo Shale Member in the reference area is the Penn Yan Shale Member. The Penn Yan Member (Penn Yan Tongue of Grossman, 1944) was the name applied to the shales outcropping in streams along the south side of Keuka Lake outlet near the town of Penn Yan. At this locality the Penn Yan tongue is 140 feet thick and composed of light-colored shales and thin shaly limestones. The Penn Yan tongue was redesignated the Penn Yan Member of the Genesee Formation by de Witt and Colton on the basis that the Penn Yan is not a tongue of the West River as proposed by Grossman, but can be traced below the Genundewa which is overlain by the West River Shale. The Penn Yan thickens eastward across western New York from less than one foot in the Lake Erie area to approximately 170 feet thick near the town of Penn Yan.

Above the Penn Yan Member in the Genesee Formation reference section is the Genundewa Limestone Member. Named originally the Genundewa Limestone by Clarke (1903), the limestone has been redefined by de Witt and Colton as the Genundewa Limestone Member of the Genesee Formation. The type area is at Genundewa Point on the east side of Canandaigua Lake about 9 miles north of Naples, where it is seen to be composed of 12 feet of interbedded nodular limestone layers and dark gray calcareous shale. The unit is absent in outcrops along Lake Erie, and in the area east of the type section it grades laterally into the Crosby Sandstone.

The upper member of the Genesee Formation is the West River Shale. The name West River was proposed originally by Clarke and Luther (1904) for the dark shales outcropping above the Genundewa Limestone and below the Standish Flags in the West River Valley 3miles east of Canandaigua Lake. The West River Shale was redefined by de Witt and Colton as the West River Member of the Genesee Formation and the boundary was extended to incude all rocks between the Genundewa Shale Member and the Sonyea Formation. A new reference section proposed by de Witt and Colton is at Seneca Point Gully on the west side of Canandaigua Lake 9 miles north of Naples. At this locality the member consists of dark gray shales and sandstones with a few intervals of black shale and very dark gray argillaceous limestone nodules. The thickness is 132 feet.

Rickard (1975, plate 3) has illustrated graphically the stratigraphic framework of the Genesee Formation of the New York Devonian outcrop area. His interpretation is that all rocks of the Genesee Formation at the reference section in Genesee Valley are characteristic of deposits of the distal basin facies. He also recognizes that in the area of Lake Canandaigua, the Lodi Limestone occurs between the Geneseo and Penn Yan Shale Members. Between Lake Canandaigua and Lake Skaneateles the distal basin facies character of the Genesee formation grades into rocks characteristic of open shelf, slope

and proximal basin deposits. The West River Member intertongues laterally into the Milo and Ithaca sandstones and shales, the Genundewa Limestone into the Crosby Sandstone and the Penn Yann Member into the Renwick Shale and Sherburne Shale and Sandstone. East of the Chenango River Valley regon the open shelf, proximal basin facies character of the West River, Genundewa and Penn Yan Member grades into rocks characteristic of the diverse subtidal and delta facies: the Ostelic Shale and Sandstone below, and the Cincinnatus Shale and Sandstone above. East of the Unadillia Valley these rocks intertongue laterally into the Oneonta shales and sandstones of the piedmont and alluvial facies of Rickard (1975). The Geneseo Member can be traced eastward along the outcrop into the Unadillia Valley region before it grades laterally into the Unadillia shales and sandstones of hte open shelf, proximal facies and then into the Oneonta shales and sndstones of the piedmont and alluvial facies. These relationships are shown graphically on figure 39.

At the surface the Genesee Formation ranges in thickness from 30 feet along Lake Erie near Buffalo to over 1400 feet in the Unadillia valley region.

Only the highly organic, radioactive shale members of the distal basin facies of the Genesee Formation can be identified, traced, and correlated over the northern portion of the Appalachian basin. The Geneseo Member is recognized in the subsurface of New York and extreme northeastern Ohio. The Geneseo equivalent in the subsurface of north-central Pennsylvania is the radioactive unit referred to as the Burket-Geneseo-Renwick black shale sequence. This radioactive zone within the Genesee Formation has been identified and correlated southward into West Virginia. The black, radioactive shales of the Genesee Formation in the subsurface are interpreted as deposits of the distal basin facies. The distribution and thickness of the subsurface radioactive Genesee Formation is shown on figure 40.

The Genesee Formation equivalent in the outcrop section of southeastern Pennsylvania and West Virginia is the Harrell Shale within which the Geneseo Member equivalent is the Burket Shale Member. Further south in Virginia the Geneseo is in part equivalent with the Millboro Shale. In Ohio the basal "Upper" Olentangy Shale of central Ohio is correlative with the Genesee.

Beyond the subsurface limits of the Genesee in the southern portion of the Appalachian basin in Alabama, Georgia and Tenessee, the Genesee is correlative in part with the lower section of the Chattanooga Shale, whereas in Virginia the equivalent interval occurs within the Millboro Shale. In eastern Kentucky, the equivalent of the Genesee is the lower part of the "Upper" Olentangy Shale which can be correlated into Kentucky from the subsurface of Ohio.

The Squaw Bay Formation of Michigan, with possibly some of the lower part of the Antrim Shale, is designated as the stratigraphic equivalent of the Genesee Formation in the Michigan basin. In the Indiana portion of the Michigan basin the Genesee equivalent falls within the interval of the Selmier Member of the New Albany Shale, while the equivalent in northwestern Ohio is marked by a period of nondeposition or erosion.

In the Illinois basin the lower part of the Selmier Member of the New Albany Group is correlative with the Genesee interval in the Appalachian basin. The subsurface equivalent in western Illinois is the stratigraphic interval occupied inpart by the Sylamore Sandstone/Sweetland Creek Shale Formation of the New Albany Group.

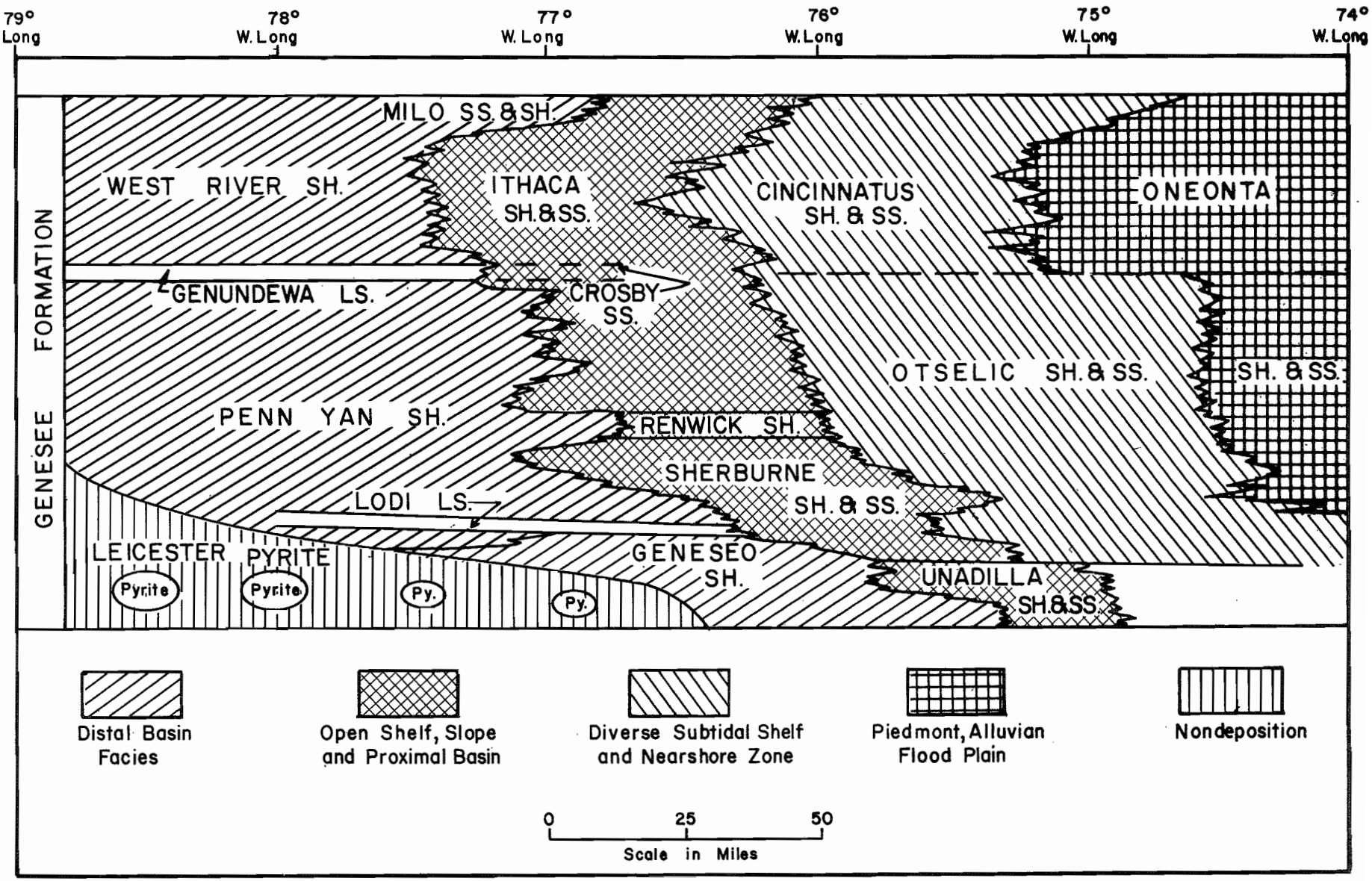


Figure 39. Schematic diagram of stratigraphic and facies relationships with the Genesee Formation. After Rickard (1975).

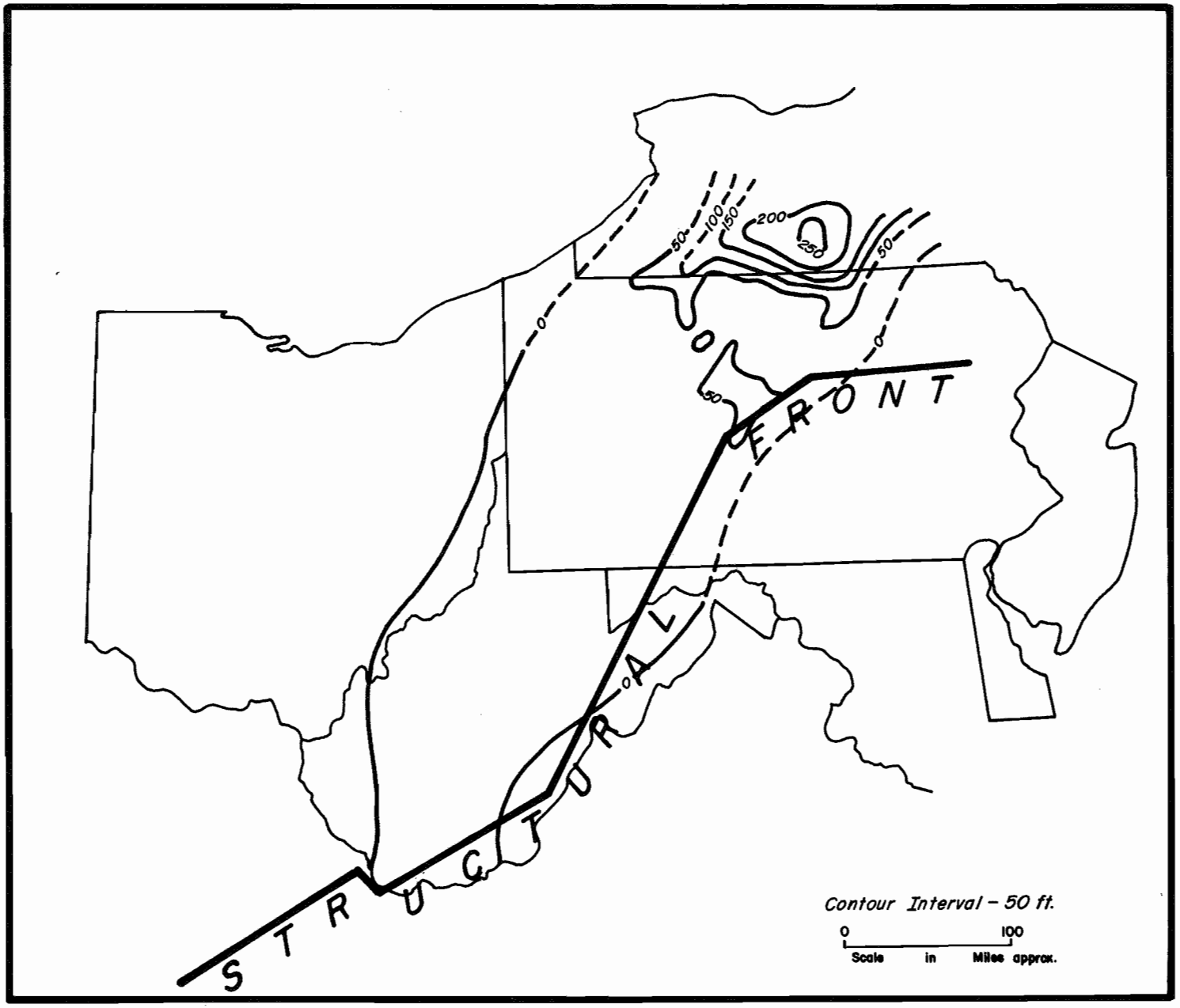


Figure 40 . Generalized distribution and thickness of radioactive Genesee Formation in the subsurface of the Appalachian basin.

The regional stratigraphic relationships and interbasin correlations for the Genesee interval are shown on correlation chart, plate 1.

Sonyea Formation. The name Sonyea was first applied by Chadwick (1933) for the sequence of rocks, previously designated Middlesex and Cashaqua, which crop out along Keshequa Creek, southwest of Sonyea in Groveland Township, Livingston County, New York. Localities cited in the discussion of the Sonyea Formation are identified on figure 41. Colton and de Witt (1958) selected their Buck Creek section (outcrop 10), 3 miles north of Sonyea in Mount Morris Township as the standard reference section for the Sonyea Formation becuase subdivisions of the unit (Middlesex, Pulteney, and Cashaqua Shale Members) were easily identified and the section was more accessible for study. The Sonyea Formation, 183 feet thick at the reference section, thins westward to approximately 45 feet in Erie County, New York along Lake Erie, and thickens to about 485 feet in Schuyler County near Watkins Glen in west-central New York (Colton and de Witt, 1958).

Rocks of the Sonyea Formation are part of a western thinning wedge of clastic sediments deposited within the framework of the prograding Catskill delta of Middle and Upper Devonian age. Sonyea rocks are composed of sediments that were deposited in a shallow sea during a cycle of deposition that begins with the deposition of organic-rich muds and continued with the deposition of light-colored muds and siltstones. The black organic shales are easily recognized and become useful stratigraphic markers in the thick nondescript sequences of light-colored shales, siltstones and mudstones that comprise the Middle and Upper Devonian sequence of western and west-central New York. In wet-central New York the Sonyea Formation has been subdivided into four members: (1) the Middlesex Shale Member, (2) the Pulteney Shale Member, (3) the Rock Stream Siltstone Member, and (4) the Cashaqua Shale. The following discussion of the members is summarized from Colton and de Witt, 1958.

The black shale underlying the Cashaqua Shale in the vicinity of Middlesex, northwestern Yates County, New York, was designated Middlesex by Clarke (1903). Later, the black shales underlying the Cashaqua Shale outcropping 0.8 miles southwest of the village of Middlesex was redesignated the Middlesex Shale Member of the Sonyea Formation by Colton and de Witt (1958). In the outcrop section from west-central New York to Lake Erie the Middlesex Shale Member is composed primarily of black or grayish to brownish-black petroliferous shale that appears massive on fresh exposure but fissile in weathered sections. Maximum outcrop thickness of 75 feet occurs near Keuka Lake, Steuben County, New York. The unit thins both east and west from the maximum development near Keuka Lake to a thickness of 6 feet along Lake Erie and 5 feet thick at Watkins Glen in Schuyler County in central New York. The highly organic black shales so useful in subdividing the Devonian-age shales in the outcrop sections are equally important in recognition and correlation of the units in the subsurface. The black shale facies are easily identified by interpretation of gamma ray logs because of the association of radioactive elements with the high organic carbon content of the shales. West of the Allegheny front the Middlesex Shale Member has been traced into the subsurface to the south and southwest of the outcrop into extreme southeastern Ohio and to the southern border of West Virginia before pinching out beneath the Rhinestreet Member of the West Falls Formation (Wallace et al., 1978; West, 1978; Piotrowski and Krajewski, 1977). The approximate subsurface distribution of the Middlesex Shale Member is shown on figure 42. The lighter-colored, nonradioactive shales occurring east-southeast of the eastern limit of the Middlesex Shale Member are considered to reflect deposits of the proximal basin and slope facies within the framework of the Catskill delta. The time-stratigraphic

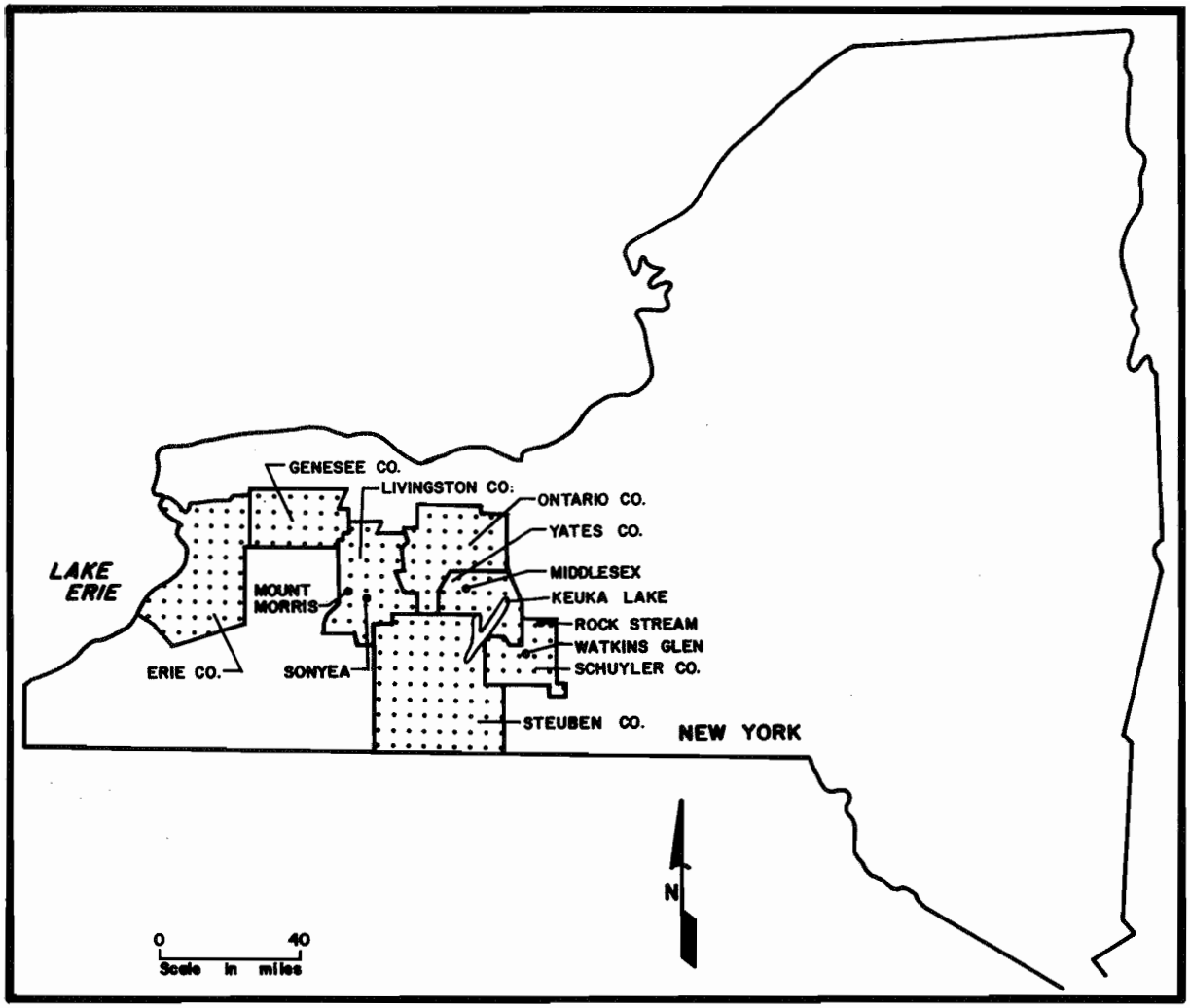


Figure 41. Index map identifying localities referenced in the stratigraphic discussion of the Sonyea Formation.

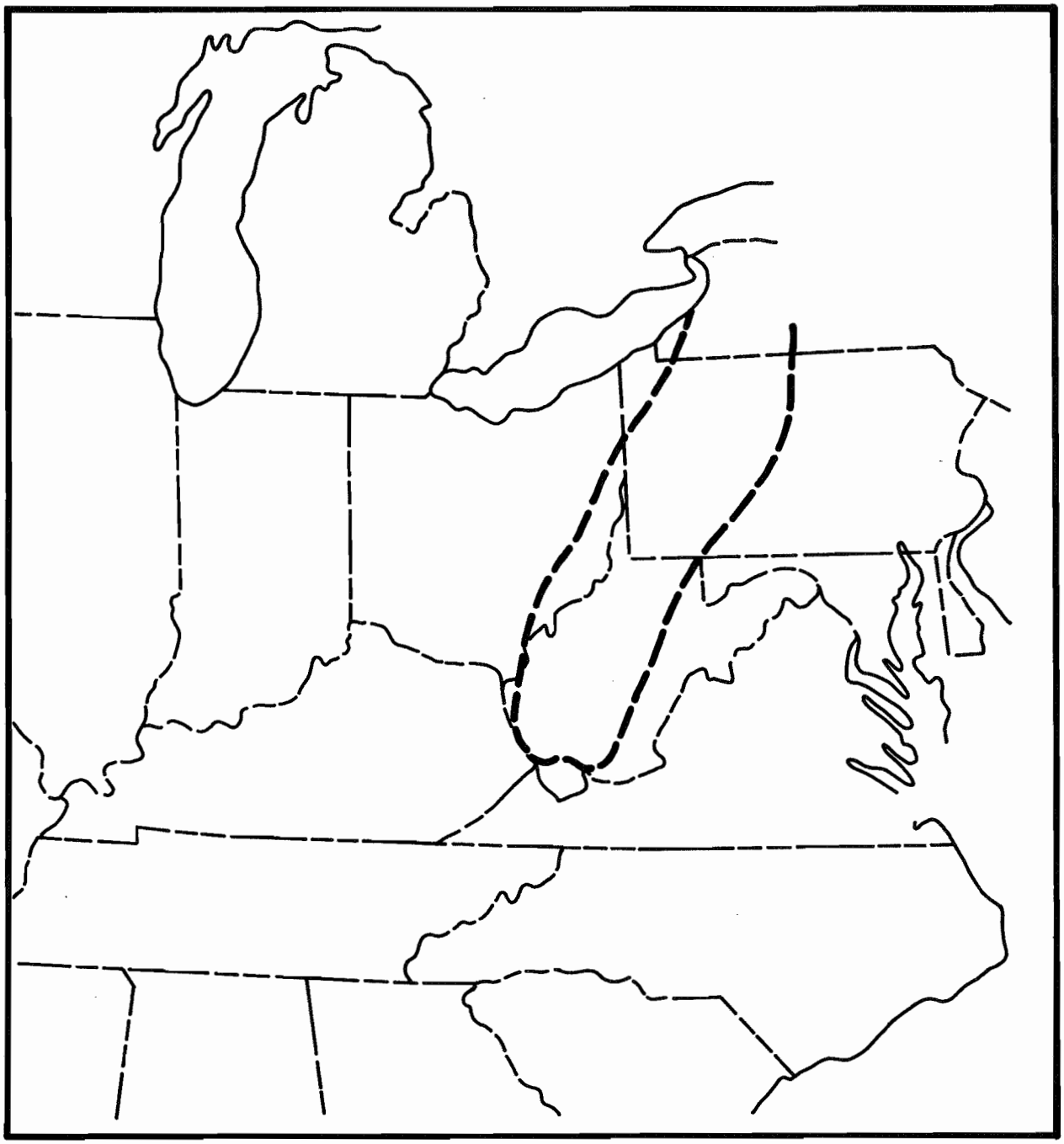


Figure 42. Approximate subsurface distribution of the Middlesex Shale Member of the Sonyea Formation.

equivalents to the Middlesex Shale Member in the light-colored shale facies of Pennsylvania, West Virginia and Virginia appear to occur within the interval of the Braillier Formation. The Sonyea section identified in the subsurface of southeastern Ohio from gamma ray logs is equivalent in part with the lower Olentangy Shales of central and northern Ohio.

The name Pulteney Shale Member of the Sonyea Formation has been designated for rocks which directly overlie the Middlesex Shale Member along the Devonian Shale outcrop from Erie County to Watkins Glen, Steuben County, New York (Colton and de Witt, 1958). The unit, composed primarily of silty dark-gray to dark brownish-gray shales with interbedded and interlaminated thin siltstones, thickens eastward from a few inches in western Genesee County to approximately 40 feet in Yates County, New York. The contact at the base of the Pulteney Shale Member appears to grade downward into the Middlesex Shale Member. The upper contact of the unit is also gradational upward into the Cashaqua Shale Member west of Ontario County, New York. East of Ontario County along the outcrop, the unit is overlain and in sharp contact with the Rock Stream Siltstone Member. For additional detail on the Pulteney Shale Member, the reader is referred to the work of Colton and de Witt (1958). Because the unit does not exhibit a distinctive gamma ray log signature, it has been impossible to correlate the Pulteney Shale Member into the subsurface of the Appalachian basin with any degree of confidence. However, the Pulteney Shale Member can be interpreted to correlate in part with the Braillier Formation of Pennsylvania and West Virginia because of the unit's stratigraphic position between the Middlesex Shale Member and the Rhinestreet Shale Member of the West Falls Formation.

Bradley and Pepper (1938) introduced the name Rock Spring Flagstone Member of the Cashaqua Shale for a series of flagstones present in the upper part of their Cashaqua Shale and designated Rock Stream in Reading Township, Schuyler County as type section (Colton and de Witt, 1958). In 1958, Colton and de Witt, Jr. redesignated the unit as the Rock Stream Siltstone Member of the Sonyea Formation and retained the type section assignment by Bradley and Pepper. The Rock Stream Member is composed primarily of medium- to light-gray and medium- to light-greenish-gray quartzose siltstone and medium- to dark-gray silty shale and shaly siltstone. The siltstone beds range in thickness from thin laminae to beds 9 feet thick. The unit is in sharp contact with the underlying Pulteney Shale Member where both units are exposed. Because the upper boundary intertongues with the Cashaqua Shale Member in a westward direction, the upper contact is less distinct. For a more detailed description of the unit as exposed in outcrop section, refer to the work of Colton and de Witt (1958). The Rock Stream Siltstone Member, because of a lack of a distinct gamma ray log signature, has not been identified widely in the subsurface of the Appalachian basin. Owing to the stratigraphic position of the unit between the Middlesex Shale Member and the Rhinestreet Shale Member of the West Falls Formation, the Rock Stream Member is equivalent, in part, with the Braillier Formation of Pennsylvania, West Virginia and Virginia. To the west it intertongues with and is stratigraphically equivalent with the Cashaqua Shale Member.

Hall (1840) gave the formational name Cashaqua to the soft gray mudrock and shale that crops out along the lower part of Cashaqua Creek in west-central Livingston County. As originally defined by Hall, the Cashaqua Shale, in terms of more recent studies by Colton and de Witt (1958), included all rocks between the top of the Middlesex Shale Member of the Sonyea Formation and the base of the Rhinestreet Member of the West Falls Formation (Colton and de Witt, 1958). Colton and de Witt (1958) redesignated Hall's Cashaqua Shale as the Cashaqua Shale of the Sonyea Formation and restricted the name

to the gray mudstone and shale facies exposed at Hall's type section. Brush Creek has now been designated the reference section because at the new locality the member is more completely exposed and more accessible. The Cashaqua Shale Member is composed largely of medium-gray and medium greenish-gray calcareous mudstone and some brownish-gray calcareous shale. The unit is more easily weathered than the rocks directly above and below and contains numerous spheroidal concretions and concretionary limestone layers. In the western part of the outcrop area the Cashaqua Shale Member grades downward into the Middlesex Shale Member. Where the Cashaqua Shale Member overlies the Pulteney Shale Member in the central part of the outcrop area, the basal contact is gradational downward into the Pulteney Shale Member and in the western part of the outcrop area the base of the unit intertongues with the siltstones of the Rock Stream Siltstone Member. The upper contact with the Rhinestreet Shale Member of the West Falls Formation is sharp and well defined. The Cashaqua Shale Member reaches maximum development of 158 feet on Buck Creek south of Mount Morris in Livingston County in the central part of the outcrop area and thins both east and west to approximately 40 feet along Lake Erie in western Erie County and to approximately 48 feet near Watkins Glen at the eastern end of the outcrop belt.

In the subsurface the Cashaqua Shale Member of the Sonyea Formation has been designated for the interval on gamma ray logs between the radioactive Middlesex Shale Member and the base of the radioactive Rhinestreet Shale Member of the West Falls Formation. The subsurface Cashaqua Shale Member has been correlated from the outcrop section into extreme southeastern Ohio, western Pennsylvania and West Virginia. Eastward, towards the source of the clastic sediments and into the proximal basin and slope facies within the Catskill delta framework, the subsurface Cashaqua Shale Member is equivalent in part to the Braillier Formation of central Pennsylvania, eastern West Virginia and Virginia. The Sonyea of Ohio identified in the subsurface of southeastern Ohio is equivalent in part to the upper Olentangy Shale of central and north-central Ohio.

The stratigraphic framework of the Sonyea Formation in the outcrop area can be seen on figures 43 and 44.

West Falls Formation. Because of their extensive stratigraphic investigations concerning the Upper Devonian rocks in western and west central New York, Pepper, de Witt, and Colton (1956) proposed the name West Falls Formation for the sequence of rock occurring between the top of the Cashaqua Member of the Sonyea Formation and the Pipe Creek Member of the Hanover shale. The type section was designated by them for exposures along Cazenovia Creek in central Erie County, New York. Localities referred toin the stratigraphic discussion of the West Falls Formatin are shown on figure 45. The four members recognized by Pepper, de Witt, and Colton (1956) at the type locality are, from the base upward: the Rhinestreet Shale Member, Gardeau Shale Member, West Hill Member and the Nunda Sandstone Member. The formation is exposed over an east-west outcrop belt approximately 110 miles long extending from Lake Erie to the Keuka Lake region in west central New York. The formation is composed of black, highly organic shales of the distal basin facies, lighter-colored shales, mudstones, and siltstones of the open shelf, proximal basin facies, as well as the diverse subtidal, delta, and red bed facies of the alluvial and piedmont environment recognized by Rickard (1975). The formation ranges in thickness from 415 feet in western Erie County to 1170 feet in eastern Steuben County in west central New York (Pepper, de Witt, and Colton, 1956). The following description of the members of the West Falls Formation is taken from Pepper, de Witt and Colton (1956).

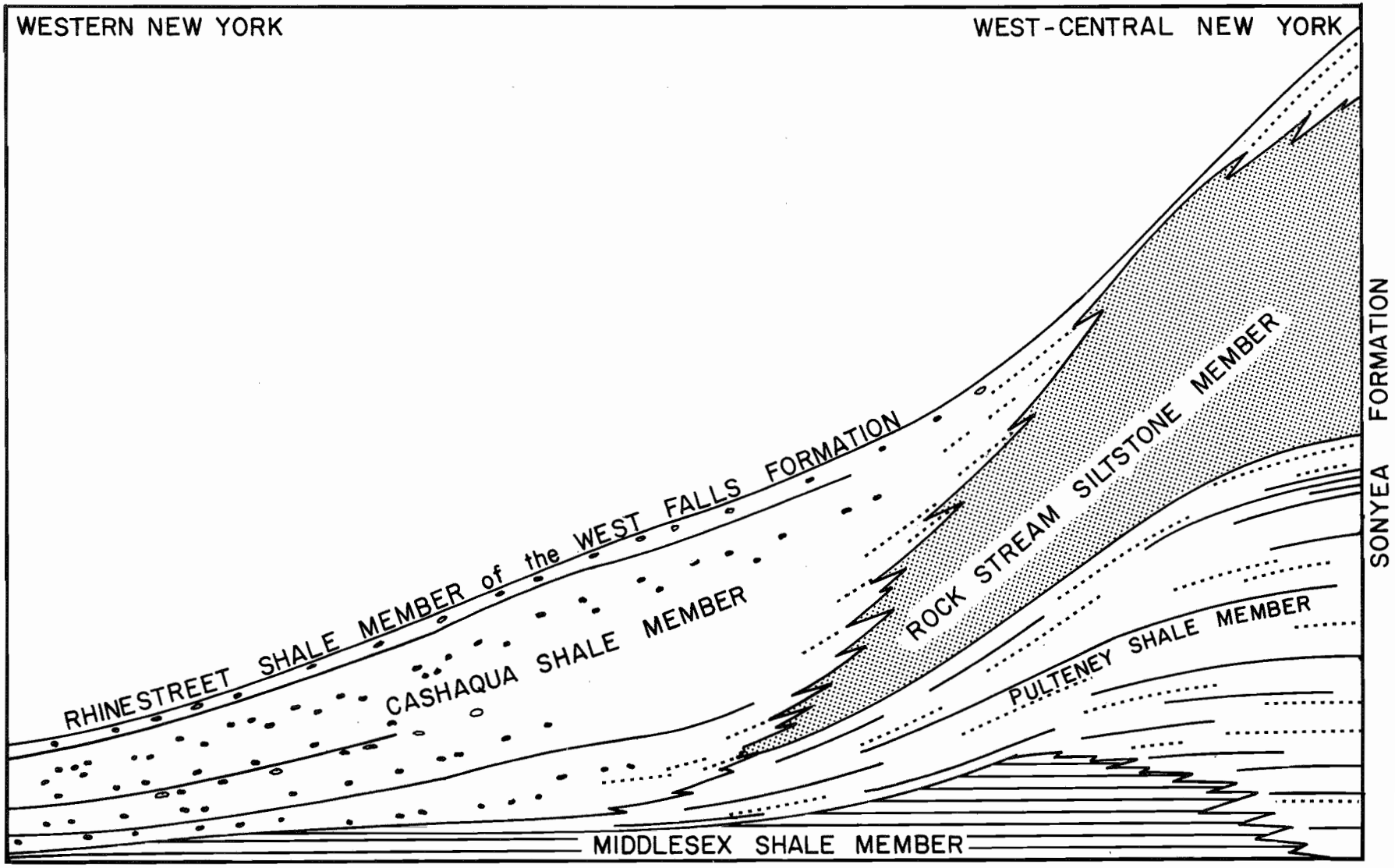


Figure 43 . Diagrammatic cross section showing the relationship of the members of the Sonyea Formation. Colton and de Witt (1958).

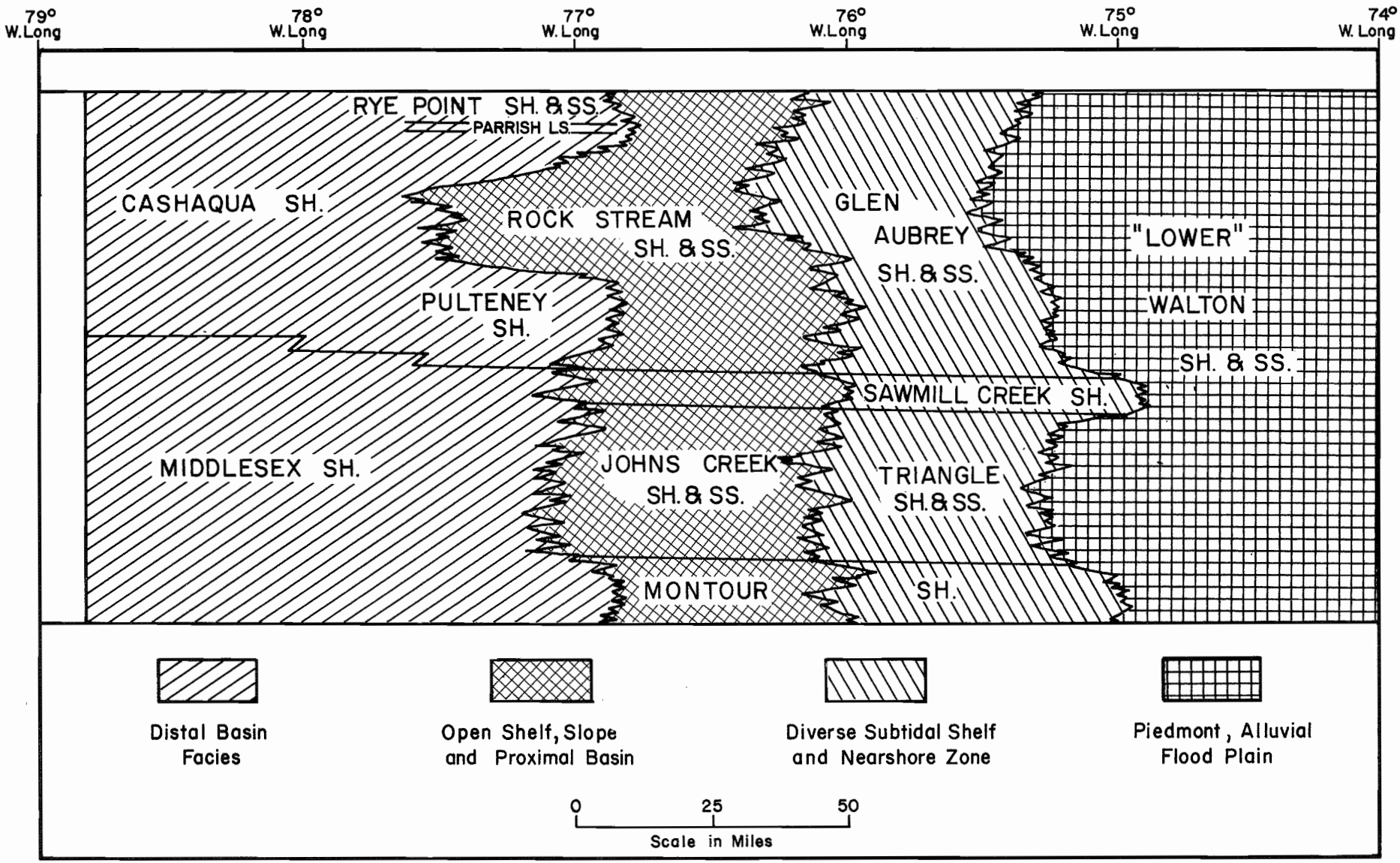


Figure 44. Schematic diagram of stratigraphic and facies relationships within the Sonyea Formation. After Rickard (1975).

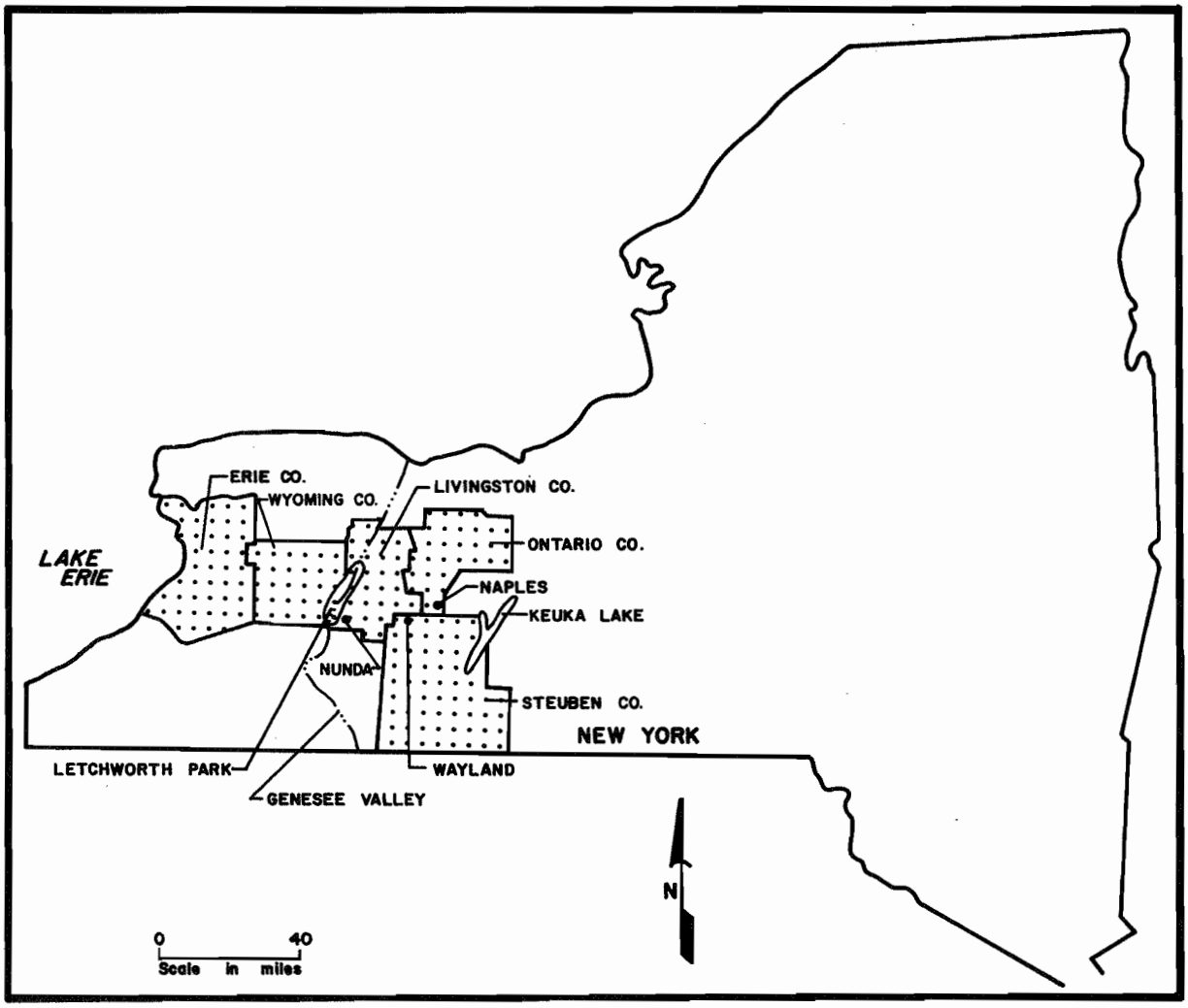


Figure 45 . Index map identifying localities referenced in the stratigraphic discussion of the West Falls Formation.

The basal unit of the West Falls Formation in the type area is the Rhinestreet Shale Member. The name Rhinestreet was first used by Clarke (1903) for the black shales exposed near Rhinestreet Road at Naples, New York. Pepper, de Witt, and Colton proposed that this shale sequence be called the Rhinestreet Shale Member of the West Falls Formation. The member is almost completely composed of interbedded black to dark-brown or dark-gray petroliferous shale occurring in beds of 2 inches to 4 feet in thickness. The upper part of the unit is lighter in color due to an increase in the medium-gray shale intervals. The darker black petroliferous shales are brittle and fissile upon weathering. Pyrite and nodular concretions are common in the lighter-colored shale beds. The Rhinestreet Member thins eastward from 195 feet near Lake Erie to 16 feet at the eastern end of the outcrop belt in western Steuben County. The black, petroliferous shales of the Rhinestreet thin both to the east and west from the type area as the lighter-colored upper shale beds intertongue successively lower and lower in the unit. The contact with the underlying Cashaqua Shale Member is generally sharp, while the top of the unit is transitional into the overlying Angola Member in western New York, and to the Gardeau Member of the type section.

The Gardeau Shale Member directly overlies the Rhinestreet Shale Member in the Genesee River type section. The name Gardeau Shale was first proposed by Hall (1840) for the sequence of rocks between the top of the Cashaqua Shale and the base of the Portage Group. Pepper, de Witt, and Colton (1956) redesignated the name as the Gardeau Shale Member of the West Falls Formation for the sequence exposed in the Letchworth Park area overlying the Rhinestreet Member and underlying the base of the West Hill Member of the West Falls Formation. Medium-gray, medium greenish-gray and dark greenish-gray shales interbedded with dark-gray to brownish-black shales with concretionary layers characterize the lithology of the Gardeau Member. Locally, cross beds of siltstone up to 4 feet thick are common in the upper part of the unit. The Gardeau Member is approximately 12 feet thick along the western edge of Wyoming County, reaches its maximum development of 525 feet at the type section, and thins eastward to 350 feet at Naples in central Livingston County. West of the outcrop section Pepper, de Witt, and Colton (1956) show the unit to interfinger with the upper part of the Rhinestreet Member and the lower part of the Angola Member. Rickard (1975) shows the Gardeau west of the type section interfingering with the upper part of the Rhinestreet.

In the western part of the outcrop area east of the Genesee River valley, Pepper, de Witt, and Colton (1956) recognized the Hatch Shale Member and the Grimes Siltstone Member of West Falls Formation. These members occupy the interval between the top of the Rhinestone Shale Member and the Gardeau Shale Member at the eastern end of the outcrop belt. Towards the west the Hatch and Grimes members appear to intertongue with the lower part of the Gardeau Shale Member. Luther (1903) applied the name Hatch shales and flags to the sequence of rocks extending upward from the Rhinestreet to the base of his Grimes Sandstone. This sequence was redesignated the Hatch Shale Member of the West Falls Formation by Pepper, de Witt, and Colton (1956). The unit is similar in composition to the basal Gardeau Member and reaches its maximum development of 400 feet in the outcrop at Urbana Glen in west central New York.

The name Grimes Sandstone was given by Luther (1903) for exposure in Grimes Glen at Naples, New York. This unit was redesignated the Grimes Siltstone Member of the West Falls Formation by Pepper, de Witt, and Colton. The Grimes Member is restricted in distribution to the eastern part of the outcrop belt from eastern Wyoming County to western Steuben County. The member attains its maximum outcrop development of 60 feet in southern Ontario County, New York. Light greenish-gray or bluish-gray siltstones

with some local interbeds of shale characterize the unit. The siltstones are massive, even bedded or cross-bedded with the more massive beds occurring in the bottom of the unit.

The West Hill Member was first called the West Hill Flags by Clarke (1903) and was applied by Clarke and Luther (1904) to the sequence of siltstones and shales overlying the Grimes and underlying the Nunda in the vicinity of West Hills at Naples, Ontario County, New York. The West Hills Member as defined by Pepper, de Witt, and Colton (1956) consists of a series of rocks intermediate in lithology between the Gardeau Shale Member of the Nunda Sandstone Member. The member is composed primarily of gray siltstones and silty gray shales which occur in beds from an inch to several feet thick. Cross bedding is common inthe thicker siltstone units. The West Hill Member, 35 feet thick at its eastern extent, thickens to 100 feet in the Genesee valley area and attains its maximum outcrop thickness of 240 feet in northeastern Steuben County.

The name Nunda Sandstone was applied by Clarke and Luther (1908) for exposure of massive siltstones and very fine-grained sandstones in Nunda Township, Livingston County, New York. The Nunda Sandstone was redesignated the Nunda Sandstone Member of the West Falls Formation by Pepper, de Witt, and Colton (1956). Greenish-gray to bluish-gray, thin-bedded to massive siltstone locally containing lenses of fine-grained sandstone characterize the Nunda sequence. Small amounts of medium-gray mudstone and silty shales are commonly present in small amounts in the lower part of the member. The Nunda thickens eastward from 2 feet at West Falls in Erie County to 170 feet in central Steuben County. The Nunda Siltstone Member intertongues with the upper part of the Angola Shale Member in the central part of the outcrop belt and pinches out in the vicinity of the west boundary of Wyoming County.

The following discussion of the stratigraphic framework and depositional environments of the West Falls Formation along the outcrop belt is graphically illustrated on figure 46.

The black shales of the Rhinestreet Shale Member in western New York are characteristic of distal basin facies deposits. Eastward in the vicinity of the Genesee valley region the Rhinestreet loses its black shale character and intertongues with sediments characteristic of open shelf, slope and proximal basin facies: the Midport Shale and Sandstone, Beers Hill Shale and Sandstone, Meads Creek Shale and Sandstone and the Grabeau Shale and Sandstone. West of the meridian passing through Seneca Lake, the rocks of the open shelf, slope and proximal basin facies give way by intertonguing with rocks characteristic of the diverse subtidal and delta Chemung facies. The Chemung sequence intertongues to the east with the sandstone, shales, and conglomerates of the upper Walton and Slide Mountain red bed units. The Angola Shale Member overlies the Rhinestreet Member in the western part of the outcrop belt. East of the Buffalo Meridian the Angola Shale Member grades laterally into the Nunda Shale Member. Both Angola and Nunda Member rocks are characteristic of open shelf, slope and proximal basin facies. Approximately at the meridian through Naples the open shelf, slope, proximal basin character of the rocks change and intertongue with rocks characteristic of the diverse subtidal and delta facies represented by the sandstone and shales of the upper Chemung sequence. East of the meridian through Cazenovia the Angola Member equivalent within the red bed alluvial and piedmont facies occurs within the upper part of the Slide Mountain sandstone, shale and conglomerate unit. The thickness of the West Falls Formation in the outcrop section ranges from 500 feet in western Erie County, New York to over 2600 feet in Schohaire County, eastern New York.

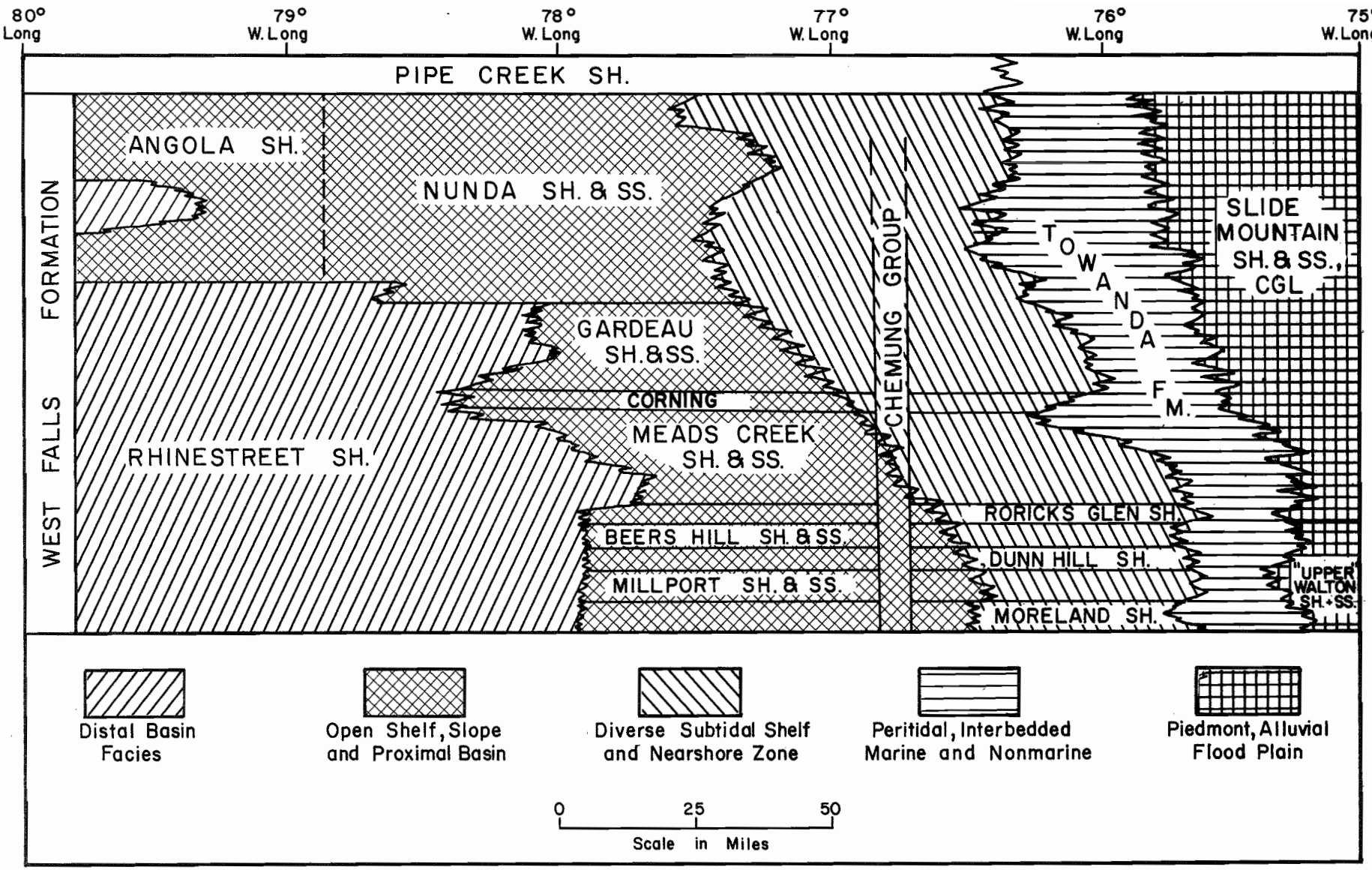


Figure 46 . Schematic diagram of stratigraphic and facies relationships within the West Falls Formation. After Rickard (1975).

Within the Appalachian Basin, the black shales of the distal basin facies of the Rhinestreet Shale Member are the only member of the West Falls Formation which can be identified and traced in the subsurface over wide areas; it has been correlated into western Pennsylvania, eastern Ohio, western West Virginia, eastern Kentucky, northeastern Tennessee and extreme western Virginia.

In the subsurface the Rhinestreet Member attains a maximum thickness of 175 feet in northwestern Pennsylvania and thins to a feather edge both in eastern Ohio and eastern Kentucky on the west side of the basin. The Rhinestreet also thins eastward in western Pennsylvania and western West Virginia in the central part of the basin. The distribution and thickness of the radioactive Rhinestreet Member in the subsurface is shown on figure 47. The Angola Member can be traced into the subsurface in a limited way in western New York, eastern Ohio and western Pennsylvania where it occupies the entire interval between the top of the Rhinestreet Member and the base of the Pipe Creek Member of the Hanover Group. Because of its limited distribution in the Appalachian basin, it was not selected as a mapping unit by Eastern Gas Shale Project stratigraphers.

Beyond the limits of the Rhinestreet and Pipe Creek Members, the West Falls Formation cannot be identified in the subsurface. The West Falls time-stratigraphic equivalent in Virginia occurs within the Brallier Formation; the equivalent of the West Falls Formation in eastern Kentucky and eastern Ohio is correlative with the upper part of the "Upper" Olentangy Shale of the central Ohio outcrop section. Correlation of the West Falls to the basin margins indicates that, in Tennessee, the West Falls is equivalent with the basal part of the Chattanooga Shale, while the equivalent in northwest Georgia and northeast Alabama is represented by a period of nondeposition and erosion. The correlation of the West Falls interval into the Michigan and Illinois basins is tenuous, but it appears that the interval falls within the lower part of the Grassy Creek Member of the New Albany Shale Group in Illinois and Kentucky and is correlative with the lower part of the Morgan Trail Member of the New Albany of Indiana. In the Michigan basin the equivalent stratigraphic interval to the West Falls Formation of New York is within the Antrim/Ellsworth Shale of Michigan.

The stratigraphic relationships and interbasin correlation of the West Falls Formation are shown on plate 1. Thus it is seen that in trying to correlate to extreme distances that the inconsistency of facies creates a difficult job in identifying and tracing a unit.

Java Formation. The name Java Formation was previously used by Pepper and de Witt (1950) to describe the sequence incorporating the Wiscoy Sandstone and its equivalent, the Hanover Shale. In previous investigations of Devonian rock outcrops in western New York, Pepper and de Witt (1951); Pepper, de Witt, and Colton (1956); Colton and de Witt (1958) and De Witt and Colton (1959) recognized the cyclic nature of the deposits making up the Middle and Upper Devonain sequences and assigned formational status to each recognizable cycle and delegated member status to recognized facies occurring within the cycle. To maintain consistency with this practice, de Witt (1960) proposed the name Java Formation for the depositional cycle which included the Wiscoy Sandstone and Hanover Shale. The Java Formation is named for Java Township, Wyoming County, New York, and the exposures along Beaver Creek above Angel Falls are designated as the type section (de Witt, 1960). The localities discussed in the stratigraphic summary of Java Formation are identified in figure 48. The formation extends along the outcrop eastward from the village of Silver Creek for more than 120

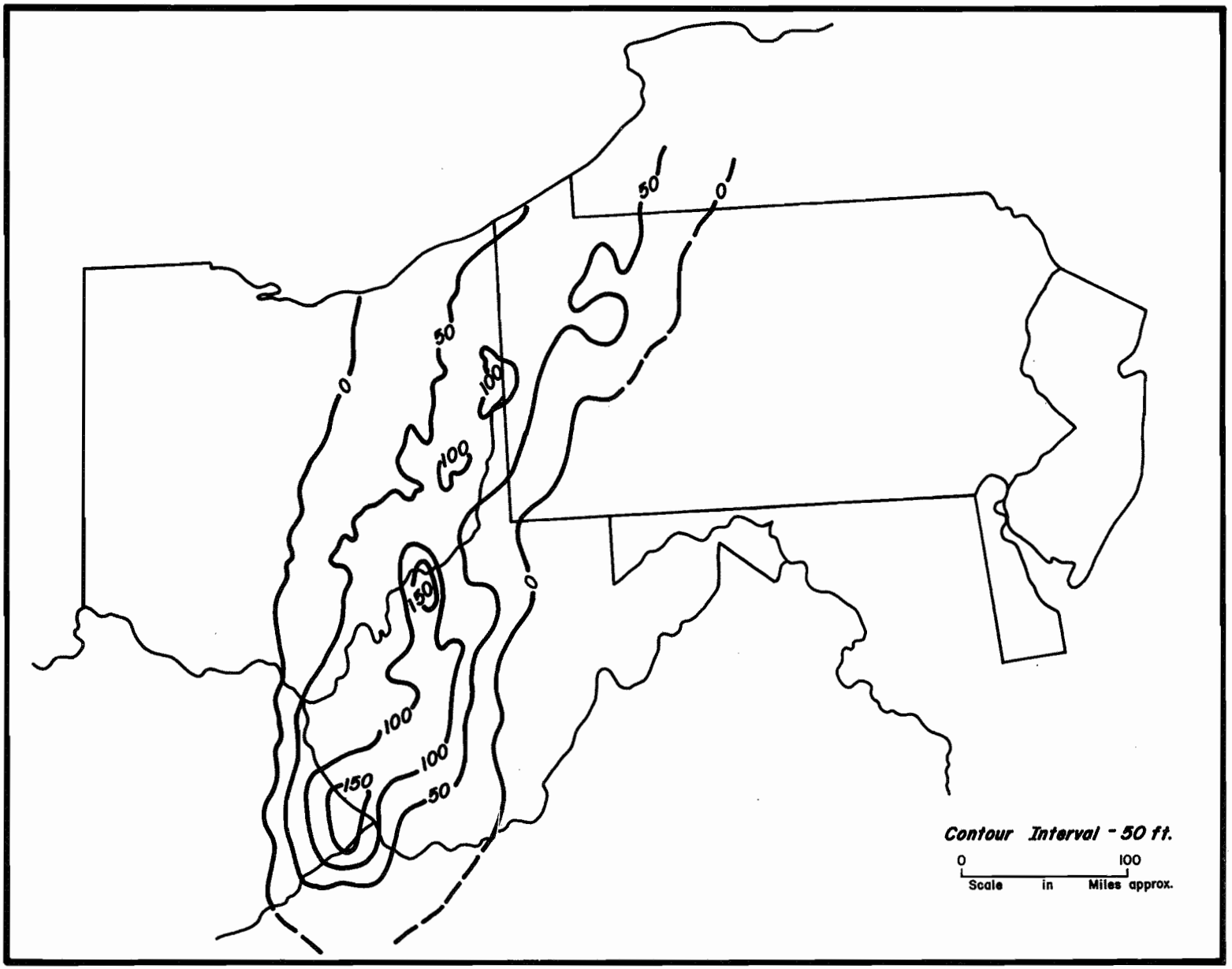


Figure 47. Geologic distribution and thickness of the radioactive Rhinestreet Shale Member.

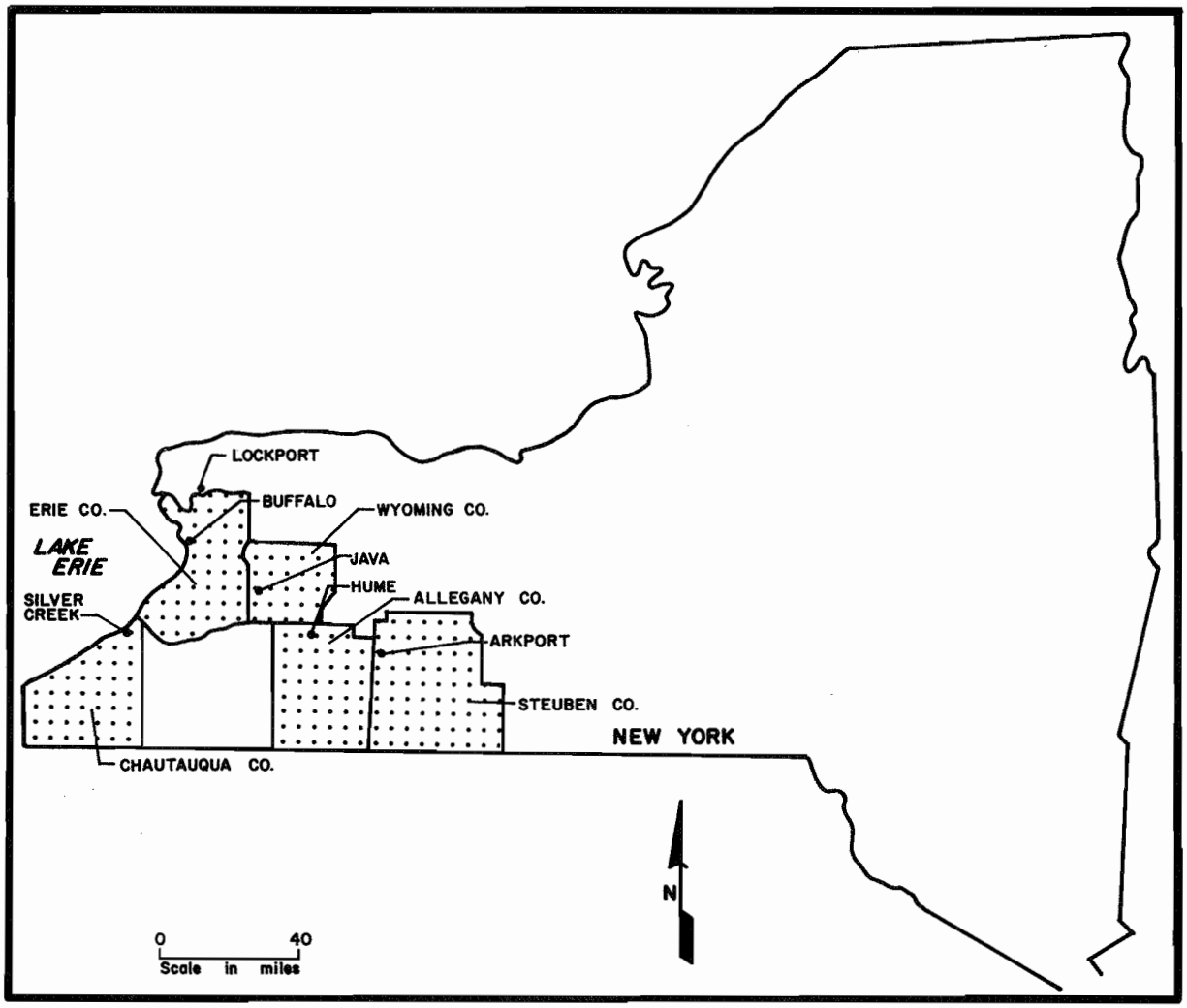


Figure 48. Index map identifying localities referenced in the stratigraphic discussion of the Java Formation.

miles into southeastern Steuben County. The formation, which is 94 feet thick at Silver Creek, thickens to over 200 feet in central and eastern Steuben County (de Witt, 1960). Three members are recognized in the Java Formation: the Pipe Creek Shale Member, the Hanover Shale Member, and the Wiscoy Sandstone Member. West of the meridian running through Lockport, New York, just east of Buffalo, the Pipe Creek Shale and the Hanover Shale Member comprise the entire Java Formation interval. East of the Lockport Meridian, the Pipe Creek and the Wiscoy Sandstone Members occupy the Java Formation interval. The following description of the members is taken from de Witt (1960).

Chadwick (1923) and Pepper and de Witt (1950) had previously used the term Pipe Creek Member as a subdivision of the Hanover Shale. The name Pipe Creek Member of the Java Formation was proposed by de Witt (1960) to define the basal unit of the Java Formation in western and west central New York. The type section of the member is in Pipe Creek Glen, Erie County, 13 miles west of the village of Java. The Pipe Creek at the type section is composed of black petroliferous shale at the base which grades upward into grayish-black to brownish-black shales. Pyrite nodules and coaly plant fragments are common in the member. The unit, a one-foot thick interval near the shore of Lake Erie, thickens to a maximum of 23 feet in the vicinity of Java, and then thins eastward to 3 feet near Arkport in extreme western Steuben County. The basal contact of the Pipe Creek is sharp, but the upper boundary is gradational into the overlying Hanover Shale Member.

The Hanover Shale, previously named by Chadwick (1933), and Pepper and de Witt (1950) for exposure on Silver Creek, Hanover Township, Chautauqua County, New York, was redefined the Hanover Shale Member of the Java Formation by de Witt. In the type area, the unit has a thickness of 92 feet, and is composed of medium-gray to medium greenish-gray calcareous shales and mudstones, containing abundant calcareous nodules and concretions. The top of the Hanover, in the extreme western end of the outcrop, is sharp beneath the overlying black shales of the Dunkirk Member of the Perrysburg Formation, whereas east of the meridian running through Buffalo, the top of the Hanover is gradational with the overlying Wiscoy Sandstone Member.

The Wiscoy Sandstone originally defined by Clarke (1899) and subsequently by Pepper and de Witt (1950) was redefined the Wiscoy Sandstone Member of the Java Formation by de Witt (1960). The type sectionis on Wiscoy Creek, Hume Township, Alleghany County, New York, whereas the unit is composed almost entirely of medium- to dark-gray and dark greenish-gray siltstones and very fine-grained sandstones which occur in the upper 15 feet of the Hanover Shale Member. The Wiscoy Sandstone Member intertongues into the Hanover Shale Member in a westerly direction from the type section.

The stratigraphic framework and east-west facies relationships along the outcrop belt are shown graphically on figure 49. Rickard (1975) interprets all of the rocks of the Java Formation west of Rochester, New York to be characteristic of the open shelf, slope, and proximal basin facies, but other stratigraphers would interpret Pipe Creek Shale lithologies as characteristic of the distal basin facies. East of Rochester the rocks of the open shelf, slope and proximal basin facies intertongue with rocks characteristic of Rickards (1957) diverse, subtidal, and delta facies incorporated within the interval of the Chemung sequence. East of the Skaneateles Lake, the Java equivalents within the alluvial and piedmont red bed facies occur within the Slide Mountain shale, sandstone and conglomerate sequence.

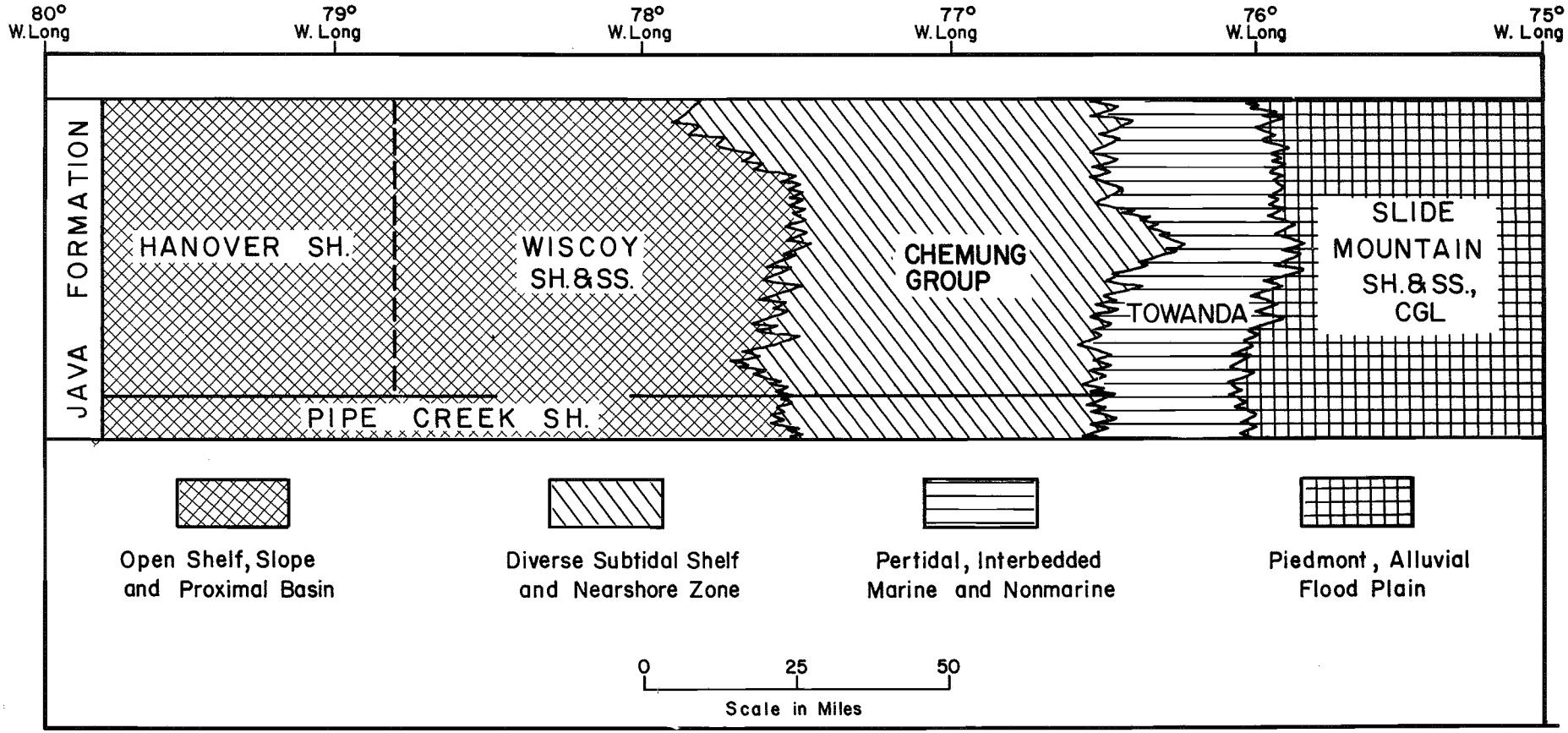


Figure 49. Schematic diagram of stratigraphic and facies relationships within the Java Formation. After Rickard (1975).

Little information is available on the subsurface thickness and distribution of the Java Formation. Schwietering (1979) prepared an isopach map of the radioactive shales of the Java Formation in West Virginia. He identified radioactive Java west of a line extending south from Pleasant County to Mercer County. West of the pinchout, the radioactive shale thickness increases to 25 feet at the extreme western boundary of West Virginia. This work strongly suggests radioactive Java in eastern Ohio and eastern Kentucky to be between zero and 25 feet thick, but the unit has not been defined in these states. In Ohio and eastern Kentucky the Java interval falls within the Upper Olentangy Shale sequence which includes the combined thicknesses of the radioactive Java, West Falls and Genesee Formations.

The stratigraphic equivalent of the Java Formation in the outcrop section of eastern Pennsylvania is within the red bed facies of the Catskill Formation. In southeastern West Virginia and western Virginia the time correlative with the Java is found within the Brallier Formation. Northward along the Allegheny Front in eastern West Virginia and west-central Virginia, the Java equivalent is within the diverse subtidal and delta facies of the Chemung sequence. The time equivalent in eastern Tennessee occurs within the Chattanooga Shale sequence, whereas in northwest Georgia and northeastern Alabama the time-stratigraphic equivalent the time-stratigraphic equivalent of the Java is marked by a period of nondeposition and/or erosion.

In the subsurface the Java is correlative with the upper part of the Upper Olentangy Shale in Ohio, eastern Kentucky and Tennessee. In south central Tennessee, the Java is correlative in part with the Chattanooga Shale.

The Java equivalent in the Michigan basin occurs within the Antrim/Ellsworth sequence, and in the Illinois basin the correlative of the Java occurs within the Grassy Creek Member of the New Albany Shale Group in Illinois and Kentucky, and within the Morgan Trail Member of the New Albany Shale in southwestern Indiana.

The regional, interbasin stratigraphic relationships are shown on plate 1.

Perrysburg Formation. This formation, which overlies the Hanover Shale and underlies the Laona Sandstone, is comprised of a thick sequence of interbedded black, brown and gray shales with occasional siltstones near the top. The unit, a black shale, was named Dunkirk; and the upper unit, gray shales and siltstones, was called the Portland. Chadwick (1919) renamed the upper unit, because, as cited by Pepper and de Witt (1951), the name Portland was preoccupied. Additionally, Pepper and de Witt (1951), following the precedent of applying formational rank to recognizable cycles of deposition within the Upper Devonain sequence, proposed that the name Perrysburg Formation be used for the entire sequence of rocks occurring between the top of the Hanover Shale and the base of the Laona Sandstone as originally defined by Hall (1941). The type locality for the Perrysburg Formation is along Big Indian Creek, Perrysburg Township, Cattauraugas County, New York. The localities cited in the stratigraphic discussion of the Perrysburg Formation are identified on figure 50. At the type locality the unit is 416 feet thick and composed of shales containing small amounts of siltstones, calcareous siltstones and silty limestones nodules. The contact at the base of the Perrysburg Formation is sharp where the black shales of the Dunkirk Member overlie the lighter-colored shales and siltstones of the Hanover. The Perrysburg Formation has been subdivided into 7 members over the extent of the outcrop belt between Lake Erie and central Steuben County. From west to southeast the defined members are: Dunkirk Shale Member, Gowanda Member, South

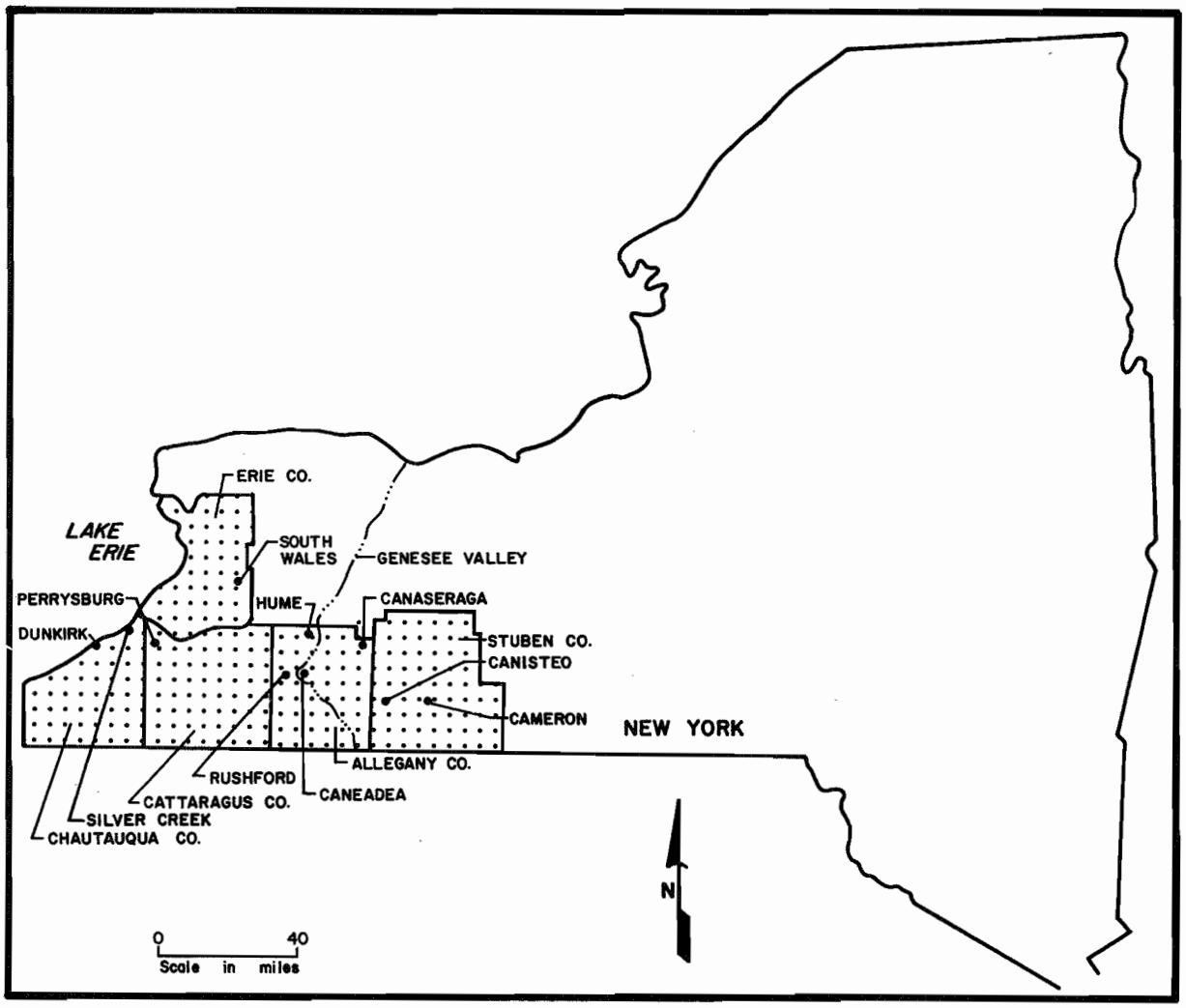


Figure 50 . Index map identifying localities referenced in the stratigraphic discussion of the Perrysburg Formation.

Wales Member, Hume Shale Member, Caneadea Member, Canaseraga Sandstone Member and Canisteo Shale Member.

The following description of the members of the formation is taken from Pepper and de Witt (1951).

The Dunkirk Shale named by Clarke (1903) was described by Luther (1903) as "a third black band, the Dunkirk Shale... is 55 feet thick. At the bottom thre are 35 feet of densely black silty shales like those in other black bands...." Chadwick (1923) used the name Dunkirk Shale for the black shale sequence in Chautauqua County which occurs between the Hanover Shale below and the Govanda Shale above. The Dunkirk of Pepper and de Witt (1951) is restricted to the 19 feet of black and 20 feet of olive-black and brownish-black shale resting on the Hanover Shale in the exposures on Walnut Creek south of the town of Silver Creek, Chautauqua County, New York. The base of the unit is sharp because of the contrast between the overlying black shales and the lighter gray Hanover Shale and Wiscoy Sandstone below. The upper boundary is transitional into the overlying units. The Dunkirk Shale thickens eastward from 40 feet in eastern Chautauqua County, and reaches its maximum outcrop thickness of 120 feet near Irish Gulf, Erie County from where it thins to 8 inches near Cameron in central Steuben County, New York.

The name South Wales Member was proposed by Pepper and de Witt (1951) for exposures in an unnamed tributary of the east branch of Cazenovia Creek three miles south of South Wales. Gray silty shale and mudstone with small amounts of black shale is the dominant lithology of the unit over the extent of its outcrop between Lake Erie and central Steuben County. Locally the top of the member is sharp where it is overlain by the black shale of the Gowanda Member. The South Wales Member has a thickness of 79 feet near Lake Erie, thins to a minimum of 13 feet in southern Livingston County and increases in thickness to the east and southeast to 87 feet near Cameron in central Steuben County.

The name Canaseraga Sandstone was applied by Chadwick (1923, 1924) for an arenaceous wedge which splits his Dunkirk. Bradley (Bradley and Pepper, 1958) at Chadwick's suggestion changed the name Canaseraga Sandstone to Dunkirk Sandstone; however, Pepper and de Witt (1951) re-applied the name Canaseraga Sandstone to these siltstones because they appear to be a definite unit in the Canaseraga Sandstone area and do not seem to be represented in the rock sequence in the vicinity of Dunkirk, Chautauqua County, New York. The type exposure on Slade Creek south of Canaseraga shows that the unit is composed of thin-bedded to massively-bedded siltstone with some interbeds of silty gray shale and black shales near the base. The top of the member is sharply defined where the soft shales of the Canisteo Member overlie the very hard fine-grained sandstone of the Canaseraga. The western limit of the Canaseraga Member is in the eastern Erie area, from where the unit thickens to just over 300 feet in central Steuben County in south central New York.

Originally the name Gowanda beds was applied by Chadwick (1919) to the sequence of black, brown, and gray shale, silty gray mudstone and thin- to thick-bedded gray siltstones occurring between the Dunkirk and the Laona Sandstone of Hall. Pepper and de Witt (1951) defined the Gowanda Member to include all the rocks between the South Wales Member and the base of the Laona Sandstone in exposures on Walnut Creek in eastern Chautauqua County. Because of the difficulty in tracing the unit over the wide area of Perrysburg Formation outcrop, Pepper and de Witt (1951) did not apply the name Gowanda to equivalent rock sequences to the east but adopted local names for the equivalent

eastern units. The Gowanda ranges in thickness between 210 and 276 feet in eastern Chautauqua County.

The name Hume Shale Member of the Perrysburg Formation was first applied by Pepper and de Witt (1951) to 70 feet of predominately black, brown and dark-gray shale exposed above the Canaseraga Sandstone Member along the banks of Wiscoy Creek at Mills Mills, Hume Township, Alleghany County, New York. In the Genesee River valley outcrops the Hume Shale is overlain by the Caneadea Member. The upper contact is generally sharp where massive siltstones or light-gray shale overlie the black shales of the Hume.

Chadwick (1933) gave the name Caneadea to a shale that is exposed in Caneadea Gorge west of the town of Caneadea. He places this shale above his Dunkirk and below the Rushford Sandstone which are exposed in Caneadea Gorge 3.3 miles east of Rushford in northwestern Allegany County, New York. The unit is composed of a sequence of gray thin-bedded siltstones interbedded with gray shales and a sequence of gray shale interbedded with thin gray siltstone beds. In northwestern Allegany County, the Caneadea Member is approxiamtely 280 feet thick.

Pepper and de Witt (1951) applied the name Canisteo Shale Member of the Perrysburg Formation to a sequence of approxiamtely 190 feet of soft bluish-gray to olive-drab shale overlying the Canaseraga Sandstone Member in the vicinity of Canisteo in western Steuben County. This shale is the basal part of a unit formerly called Gowanda by Chadwick (Bradley and Pepper, 1938). Locally the Canisteo contains silt and fine sand. The Canisteo in western Steuben County underlies fine- to medium-grained fossiliferous sandstone which contains some quartz pebbles ranging from 1/16 to 1/4 inches in diameter. The stratigraphic framework of the Perrysburg formation along the outcrop belt is shown in figure 51. The figure shows the eastern limit of the Dunkirk Shale Member (distal basin facies) to be in the vicinity of the meridian running through Buffalo, Eden and Cattaraugus. East of this meridian the distal basin facies wedge loses its character as it intertongues with rocks of the Caneadea Shale Member which characterize open shelf, slope and proximal basin depositional environments (facies). East of the meridian through Canandaiqua and Bath the open shelf, slope and proximal basin facies character again changes to the diverse subtidal and delta facies characterized by the Wellsville Shale and Sandstone. East of the meridian passing through Syracuse the rocks of the Towanda Formation reflect deposition in the peritidal, marine and nonmarine facies of Rickard (1975). Still further east, beyond the meridian through Cazenovia, the Perrysburg Formation equivalent is found within the lower part of the Sunfish Shale and Sandstone sequence which reflects deposition in the alluvial and piedmont red bed facies. Thus, from east to west the facies changes characterize a prograding sequence of delta beds.

In the northern part of the Appalachian basin the Perrysburg Formation in the outcrop belt of northeastern Pennsylvania is the stratigraphic equivalent and is correlative in part with the red beds of the Catskill Formation. The south-central Pennsylvania and Maryland time-stratigraphic equivalents fall within the red beds of the Hampshire Formation. Similarly, equivalents of the Perrysburg Formation in West Virginia and Virginia are correlative in part with the Chemung sequence, while in northeastern Tennessee the time-stratigraphic equivalent falls within the Chattanooga Shale sequence. In the Ohio portion of the Appalachian basin the Perrysburg is correlative with the lower part of the Ohio Shale Formation.

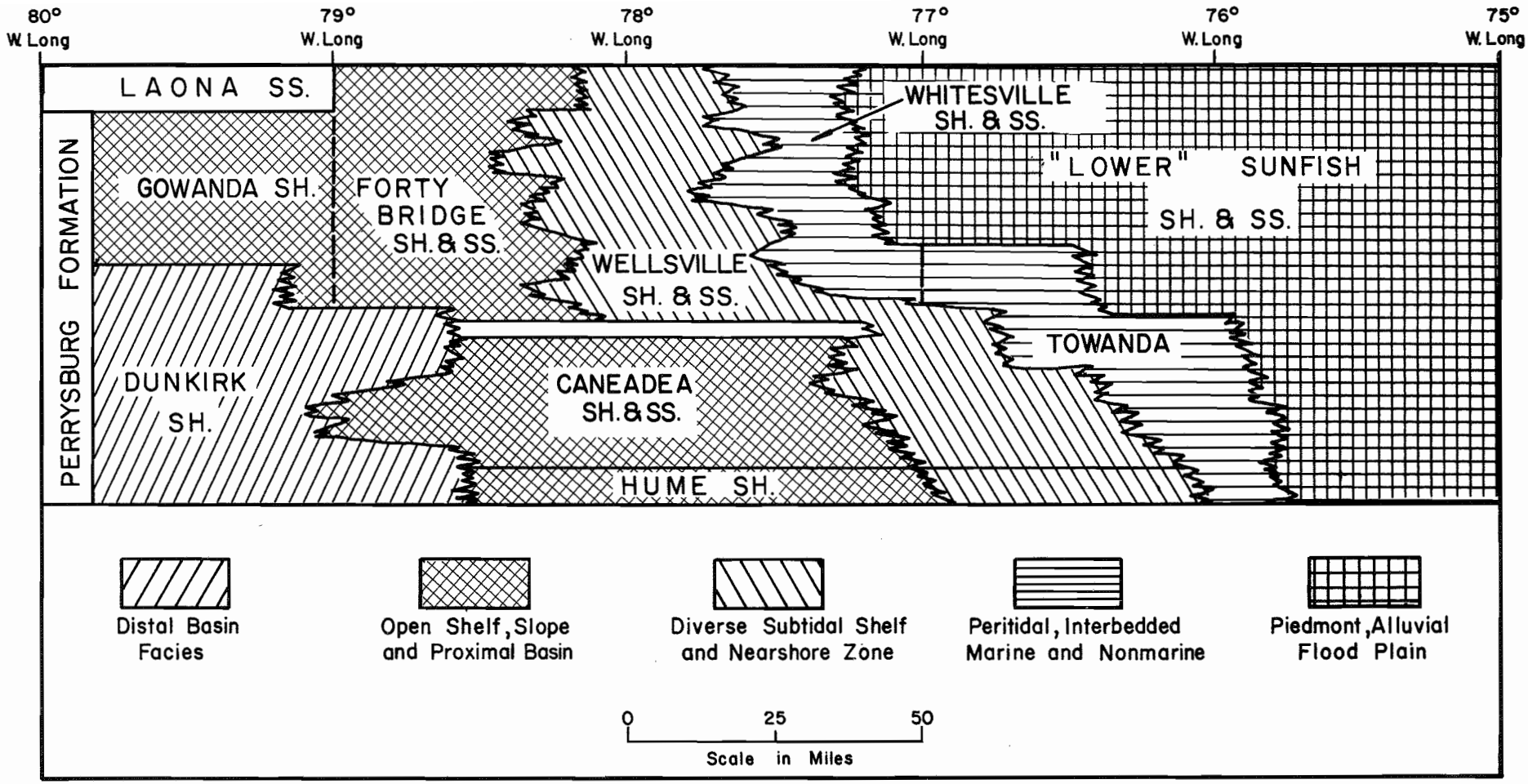


Figure 51. Schematic diagram of stratigraphic and facies relationships within the Perrysburg Formation. After Rickard (1975).

The Dunkirk Member can be identified and traced into the subsurface over most of the eastern and south-central portion of the Appalachian basin in northwestern Pennsylvania, eastern Ohio, western West Virginia, eastern Kentucky and Tennessee where it has been correlated with the "Lower" Huron Shale Member of the Ohio Shale. The thickness in the subsurface ranges from a feather edge in northwestern Pennsylvania to more than 300 feet in northeastern Ohio. The Perrysburg Formation equivalent in the subsurface of central and eastern West Virginia and Virginia is correlative, in part, with the Brallier Sandstone and Shale sequence. The distribution of the radioactive Dunkirk/"Lower" Huron Shale sequence is shown on figure 52.

The Perrysburg Formation stratigrahic equivalent in the Michigan basin is found within the Antrim/Ellsworth Shale sequence in Michigan, the Ohio Shale sequence of northwestern Ohio, and the Morgan Trail Member of the New Albany Shale in northeastern Indiana.

The stratigraphic equivalent in the Illinois basin is within the Morgan Trail Member of the New Albany Shale in southwestern Indiana and the Grassy Creek Member of the New Albany Shale Group in Illinois and northern Kentucky.

The regional and interbasin stratigraphic correlations are shown on plate 1.

Because the Perrysburg Formation is considered the top of the Devonian Shale sequence in the New York classic section, the physical stratigraphy section of the report will not include further discussion of the post-Perrysburg Formation stratigraphy. For Eastern Gas Shales Project work in the Appalachian basin, the procedure has been to use the stratigraphic nomenclature of the Ohio Devonian Shale sequence as the framework for the post-Perrysburg Upper Devonian sequence.

Ohio-Eastern Kentucky-West Virginia-Tennessee

The "Upper" Olentangy Member. The "Upper" Olentangy Member is exposed along the outcrop in southern Ohio and northeastern Kentucky. It is recognizable in the subsurface of eastern Ohio, eastern Kentucky, and southwestern West Virginia. In the subsurface the "Upper' Olentangy Member is composed of varying amounts of greenish-gray, medium to dark gray and black shales with minor amounts of gray limestone. In eastern Ohio the base of the "Upper" Olentangy Member is marked by a highly radioactive bed of dark carbonaceous shale. The unit attains a thickness of approximately 30 feet in the outcrop area of central Ohio. Eastward in the subsurface the "Upper' Olentangy thickens to more than 800 feet along the Ohio-West Virginia border and the equivalent units in central New York and central Pennsylvania attain thickness in excess of 2000 feet, figure 53. The "Upper" Olentangy Member can be correlated in the Appalachian basin with the Genesee, Sonyea, West Falls and Java Groups of New York and Pennsylvania, the upper part of the Millboro and lower part of the Brallier in Virginia, and the lower part of the Chattanooga Shale in central Tennessee. The member in the Illinois basin is equivalent in part with the Selmier and Grassy Creek Members of the New Albany Group in Kentucky and Illinois and the Selmier and Morgan Trail Members of the New Albany Shale in Indiana. In the Michigan basin the "Upper" Olentangy equivalents occur within the lower part of the Antrim/Ellsworth sequence, plate 1.

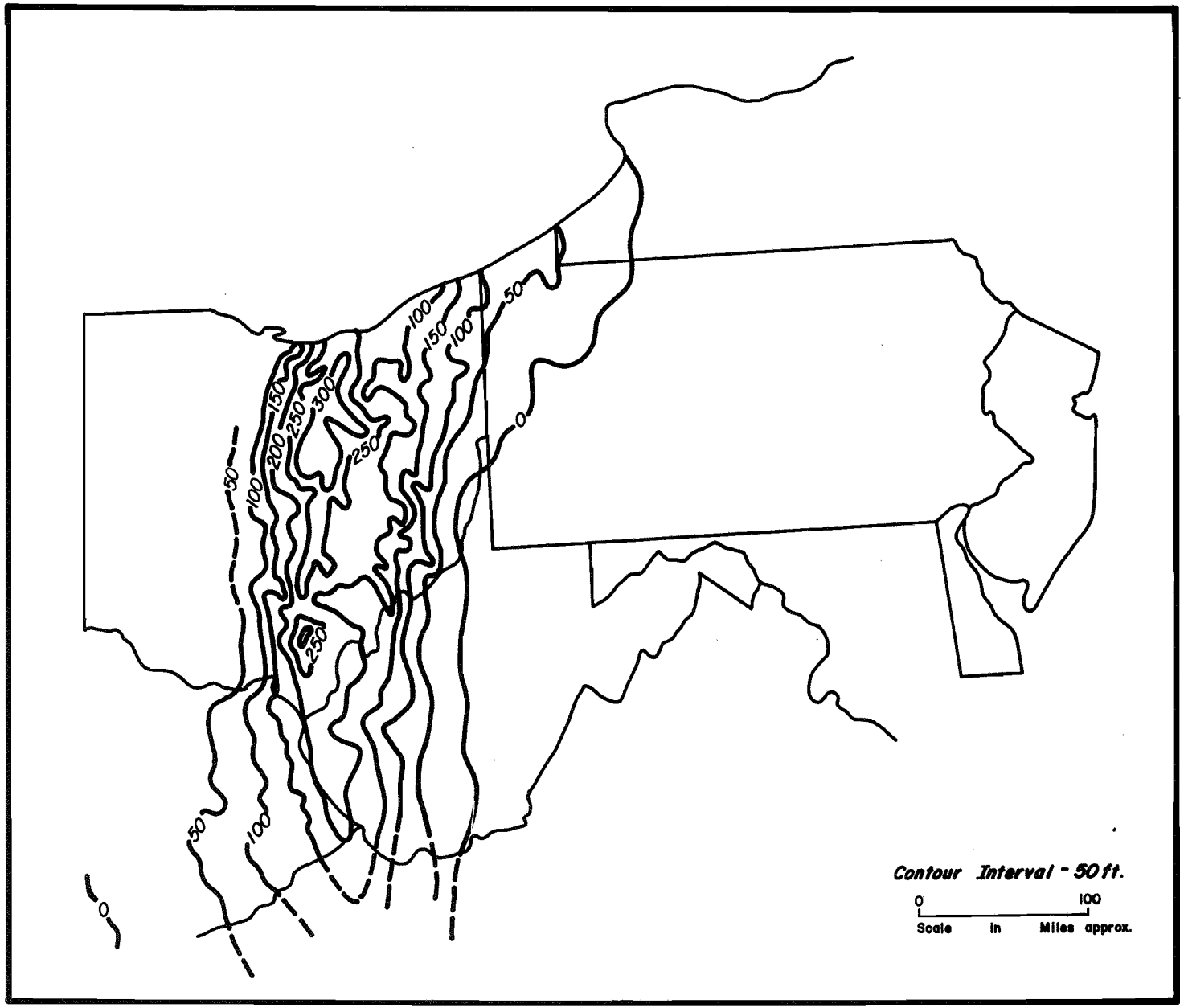


Figure 52 . Generalized thickness and distribution of the radioactive Dunkirk/"Lower" Huron Member in the Appalachian basin.

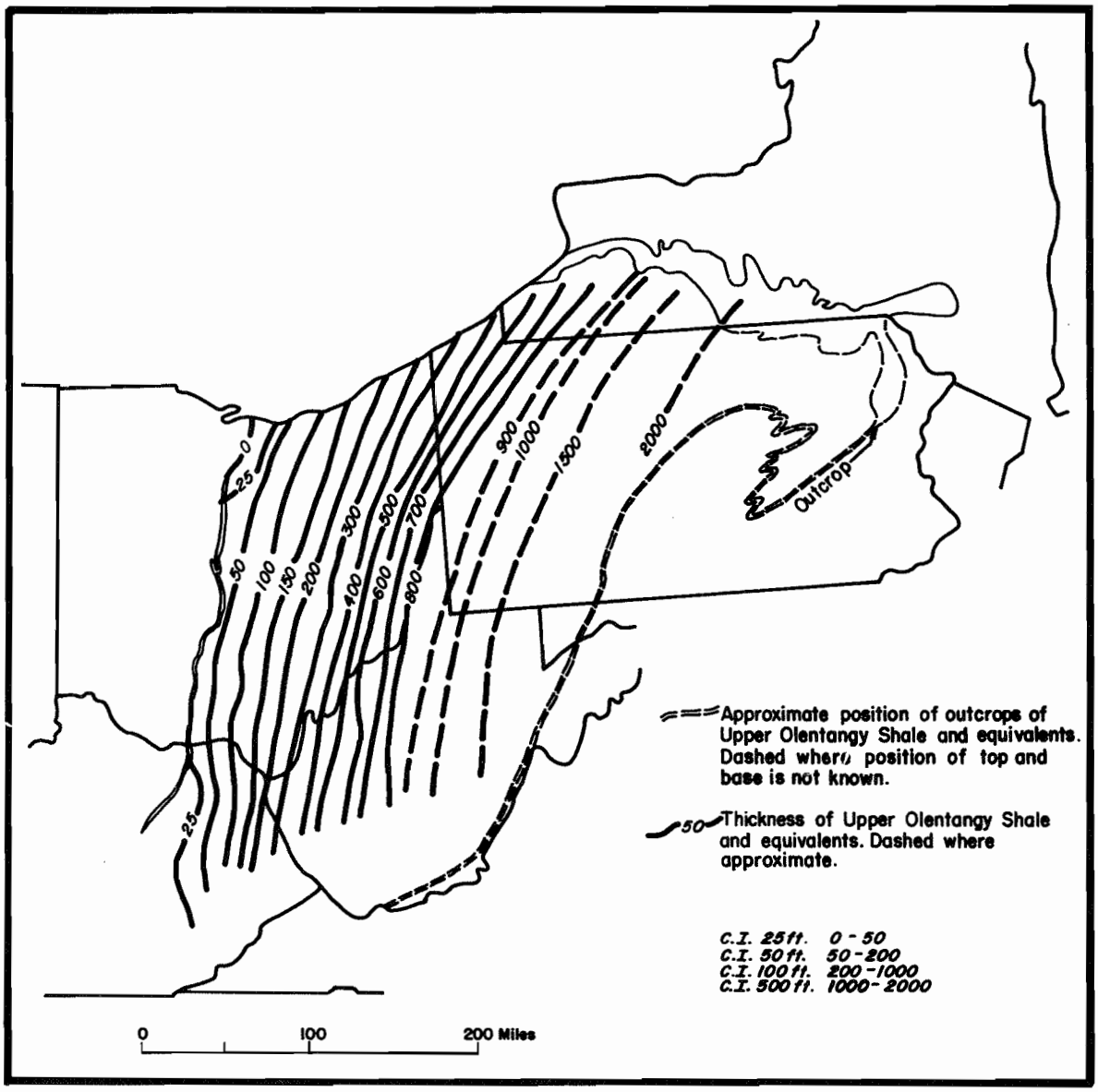


Figure 53 . Thickness and distribution of the Upper Olentangy Shale in the Appalachian basin. After Schwietering (1970).

Ohio Shale. Andrews (1871) applied the name "Ohio Slate" for exposures of black carbonaceous shales in southern Ohio. Shaler (1877) a few years later applied the name Ohio Shale to this sequence of rock. In northern Ohio the Ohio Shale sequence can be subdivided into three distinct units to which Newberry (1871) applied the names, in ascending order Huron Shale, Erie Shale, and Cleveland Shale. Prosser (1903) proposed the name Chagrin Shale for Newberry's preoccupied term Erie Shale (Schwietering, 1970). From the time of Newberry's descriptions to the present, there has been disagreement concerning the age and stratigraphic framework of the Ohio Shale. One of the major problems leading to the disagreements between investigators was the fact that none of the three units can be observed and studied at a single locality. Schwietering (1970) provides a synopsis of the development of the stratigraphic framework now accepted for the Ohio Shale. The most widely accepted stratigraphic arrangement for the Ohio Shale was proposed by Pepper and others (1954), who proposed that the Chagrin Shale was a wedge of gray shale and siltstone which intertongues with the overlying Cleveland Shale and underlying Huron Shale. West of the pinchout of the Chagrin Shale the Huron and Cleveland Shales combine to form the Ohio Shale. Along the outcrop belt in central and southern Ohio the unit consists predominantly of dark brown to black carbonaceous shale with local interbeds of gray to greenish-gray mudbeds and shales. Thin argillaceous limestones with cone-in-cone structure are characteristic of the upper part of the shale while large septarian concretions, up to 3 feet in diameter, are common only in the lower part of the unit. The Ohio Shale ranges in thickness from 250 feet along the outcrop belt in southern Ohio to over 400 feet in the central and northern part of the state. Eastern Gas Shales Project stratigraphers in Ohio have followed the stratigraphic framework of Schwietering (1970) which, except for dividing the Huron Shale into an upper and a lower member, generally follows that proposed by Pepper and others (1954). The thickness and distribution of the Ohio Shale in the subsurface is shown on figure 54.

Huron Shale. The name Huron Shale was proposed by Newberry (1870) for the sequence of dark brown to black, silty shales cropping out in central Ohio. The type section of the Huron Shale occurs along the Huron River in north-central Ohio. The Huron, which rests disconformably over the Middle Devonian Front Limestone in north-central Ohio, interfingers with the overlying Chagrin Shale. Eastern Gas Shales Project investigators have been able to subdivide the Huron Shale in the subsurface into a "lower" and "upper" member on the basis of gamma response from geophysical logs. In the subsurface of eastern Ohio the dark brown and black "Cinnamon" shales of the drillers are separated into two units by an interval of bluish-gray and gray shale. Schwietering (1970) considers the two "Cinnamon" shale units the equivalents of the Huron Shales and that they correspond to the "upper" and "lower" members. The "upper" and "lower" members consist of black to dark brown, carbonaceous, radioactive shale separated by a wedge of lighter-colored less radioactive shale. The black, radioactive "lower" member comprises the greater part of the formation and has a wider distribution than the upper unit. The subsurface thickness and distribution of the lower unit, as shown by figure 55, generally reflects the distribution of the Huron Shale in Ohio and adjoining states. The Huron Formation correlated with the Canadaway Group in New York, the lower member being traceable into the Dunkirk black shales of the reference section. The surface equivalents in West Virginia and Virginia occur within the basal part of the Chemung sandstones and siltstone sequence. Further eastward the eqivalent intervals occur within the Catskill lithofacies of New York and Pennsylvania and the Hampshire lithofacies of West Virginia and Virginia. In the Michigan basin the Huron is correlative, in part, with the Antrim/

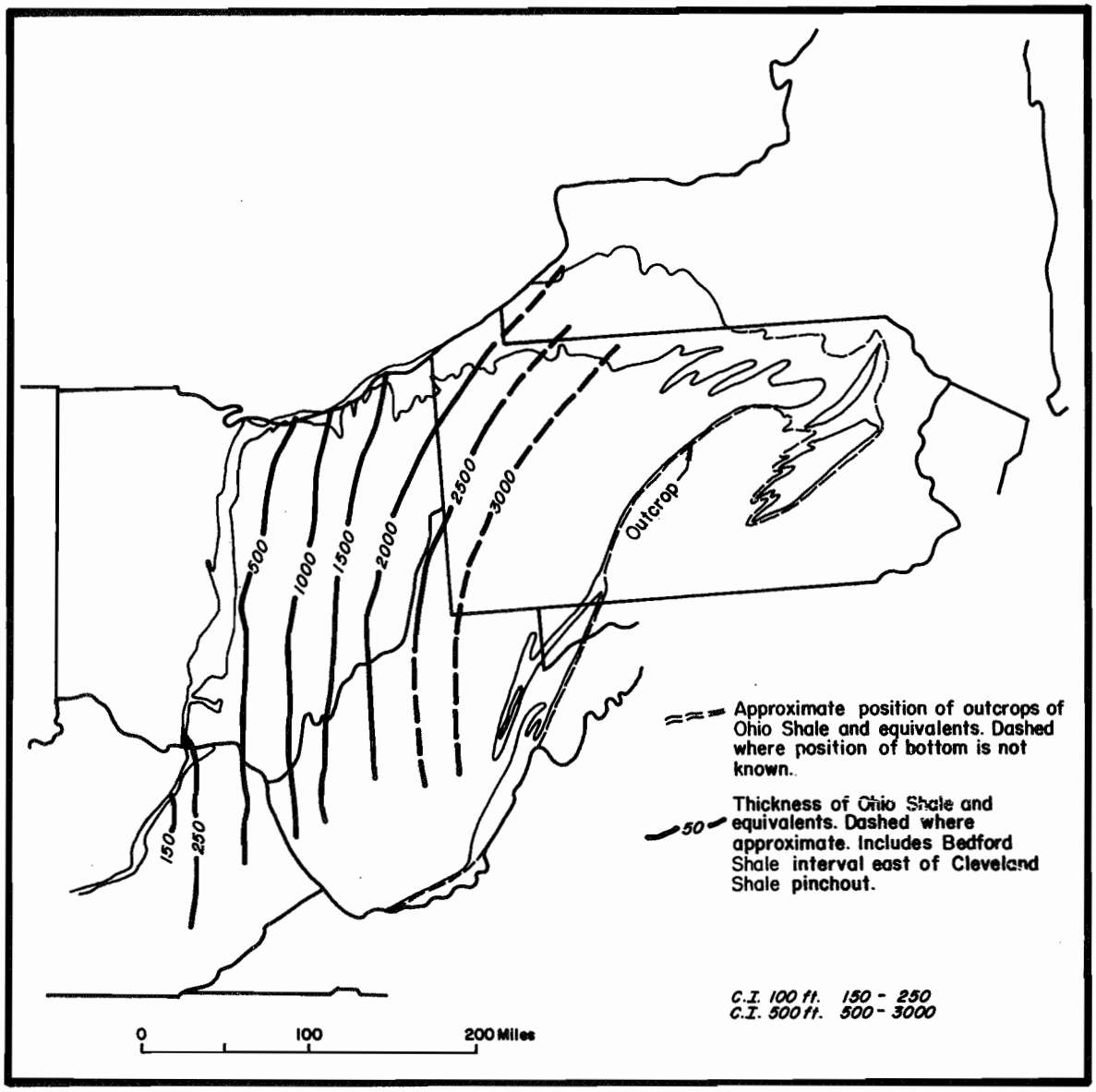


Figure 54. Thickness and distribution of the Ohio Shale in Ohio and adjoining regions. After Schwietering (1970).

Figure 55 . Generalized distribution of the radioactive "lower" Huron Member in Ohio and adjoining regions.

Ellsworth sequence. The Huron stratigraphic equivalent in the Illinois basin occurs within the New Albany shale. The stratigraphic framework of the Huron and the inter- and intrabasin correlations are shown on plate 1.

Chagrin Shale. The name Chagrin Shale was first used by Prosser (1903) to replace the preoccupied term "Erie Shale" proposed originally by Newberry (1871). Exposures along the banks of the Chagrin River east of Cleveland have been designated the type section of the formation. The Chagrin is composed primarily of blue-gray clay shales and blue and gray mudstones interbedded with discontinuous gray siltstone beds up to 2 inches thick. East of Cleveland along the Ohio-Pennsylvania border the upper part of the Chagrin contains thick to massive beds of siltstone and sandstone. In the subsurface it is difficult to separate the Chagrin from the Bedford Shale beyond the eastern limit of the Cleveland Shale. The Chagrin thins toward the west and interfingers with the Huron Shale below and the Cleveland Shale above. The Chagrin, present in the subsurface throughout eastern Ohio, ranges in thickness along the outcrop belt from a feather edge near the western limit through Erie and Huron Counties, Ohio, to more than 1200 feet in northeastern Ohio along the Pennsylvanian border (Hoover, 1960). Stauffer (1944) reports a thickness of 460 feet from a core in the Akron, Ohio area. Because of the difficulty in separating the Chagrin from the Bedford east of the Cleveland Shale pinchout, the thickness and distribution of the unit was not mapped by Eastern Gas Shale Project investigators. Eastward from the Ohio-Pennsylvanian state line the Chagrin is correlative with the Conneaut Group and the lower part of the Conewango Group of New York. Further eastward the units pass into the Catskill redbed lithofacies. To the southeast in West Virginia and Virginia, the Chagrin is correlative in part with the Chemung siltstones and sandstone while the equivalent southward in Tennessee and Alabama occur within the Gassaway Member of the Chattanooga Shale. In the Michigan and Illinois basins the Chagrin equivalents occur within the Grassy Creek Member of the New Albany Shale Group in Illinois and the Antrim/Ellsworth sequence in Michigan. These correlations are shown on plate 1.

Cleveland Shale. The term Cleveland shale was given by Newberry (1871) for exposures of black bituminous shale underlying the Bedford Shale along Doan Brook in the eastern part of Cleveland, Ohio. Originally, the Cleveland was described as the grayish to black shale occurring between the Chagrin and the Bedford. Cushing (1912) subdivided the sequence into two units, the Olmstead Member of the Cleveland below and the Cleveland Shale above. The Cleveland is composed primarily of bluish-black to brown-black shale which turns coffee-brown in outcrop. The shale ranges from compact and massive in fresh exposures but becomes fissile, brittle and thinly laminated when weathered. Irregularly shaped concretinary masses occur locally, but are not of the spherical forms which are characteristic of concretions in the Huron. Pyrite and thin siliceous limestone beds with cone-in-cone structure are typically found in the Cleveland. At the type section the shale has a thickness of 25 to 50 feet. Along the outcrop belt the Cleveland pinches out in the vicinity of the Lake County-Ashtabula County line. Westward the unit thickens to 60 feet in the vicinity of Erie County. The subsurface distribution and thickness of the radioactive Cleveland Shale is shown on figure 56.

The Olmsted Member of the Cleveland was named by Cushing (1912) for 15 to 20 feet of soft bluish-gray and gray clay interbedded shale, thin gray to brown siltstones and thin limestone layers exhibiting cone-in-cone structures. Pepper and others (1954) consider the Olmsted to be a transitional lithology resulting from the intertonguing of the black shales of the Cleveland and the gray shales of the Chagrin. The Olmsted has a very

Figure 56. Thickness and distribution of the radioactive Cleveland Shale in Ohio and adjoining states.

local distribution and is confined only to the area west of Cleveland. The Cleveland Shale is correlative with the Conneaut and Conewango Groups in New York, the upper Chemung and the Hampshire Formations of West Virginia, the upper part Chemung Formation of Virginia, the Gassaway Member of the Chattanooga Shale in central Tennessee and the Chattanooga Shale of northeastern Alabama. In the Illinois basin the Cleveland Shale is considered equivalent with the upper part of the Camp Run and the Clegg Creek Members of the New Albany in Indiana and with the upper Grassy Creek member and the Hannibal-Saverton interval in Illinois. The Michigan basin equivalent is within the upper part of the Antrim/Ellsworth sequence. The stratigraphic relationships and the inter- and intrabasin correlations are shown on plate 1.

Pennsylvania-West Virginia-Virginia-Eastern Kentucky

In south-central Pennsylvania and eastern West Virginia, the absence of black radioactive shales in the subsurface along the Allegheny Front makes it difficult to use the combined New York and Ohio Upper Devonian black shale stratigraphic framework. Along the Allegheny Front in Pennsylvania and West Virginia, a coarser clastic lithofacies of sandstones and siltstones dominates the sequence and the local formation names: Harrell, Brallier, Chemung and Hampshire have been adopted. The following Upper Devonian stratigraphic discussion is summarized from Butts (1918), Hasson and Dennison (1978), and Woodward (1945).

Harrell Shale. The name Harrell Shale was proposed by Butts (1918) for exposure along the right-of-way of the Petersburg Branch of the Pennsylvania Railroad midway between Hollidaysburg and Williamsburg, Blair County, Pennsylvania. Butts (1918) subdivided the Portage Group in Pennsylvania into two formations, an upper unit designated Brallier and a lower unit, the Harrell, which includes the Burket black shale member at the base. The Harrell consists of dark gray, thinly laminated, fissile to platy shale underlain in local areas by the dark grayish to black fissile to thinly laminated Burket Shale member which attains a thickness of approximately 80 feet in the type area. The thickness of the Harrell is about 240 feet in the central part of the outcrop area, along the Allegheny front, in south-central Pennsylvania, Maryland and eastern West Virginia. The unit thins by gradation eastward into the coarser clastics of the Brallier Formation while to the southwest it loses its identity as a separate formation as it intertongues with the darker gray shales of the Millboro Formation. The thickness and distribution of the Harrell is shown on figure 57. The Harrell, overlain everywhere in the outcrop area by olive-gray shales and siltstones, lies locally upon a limestone believed by Butts (1918) to be an extension of the Tully Limestone into Pennsylvania. The Genesee Formation of New York, western Pennsylvania, and western West Virginia is considered the correlative of the Harrell in the type section. In central Pennsylvania, Maryland, eastern West Virginia, and Virginia the Harrell equivalent is incorporated within the Millboro Shale. The equivalent of the Harrell in central Tennessee occurs within the base of the Dowelltown Member of the base Chattanooga Shale. In the Illinois basin, the Harrell is correlative in part with the lower part of the Selmier Shale, while in the Michigan basin the unit correlates in part with the Squaw Bay limestone in Michigan and the base of the Antrim Shale in Indiana. These stratigraphic relationships are shown on plate 1.

Figure 57 . Thickness and distribution of the Harrell Shale. After Woodward (1943).

Brallier Formation. The Brallier Formation was named by Butts (1918) for exposures near Brallier Station on the Huntington and Broadtop Railroad approximately five miles northeast of Everett, Bedford County, Pennsylvania. The formation is a thick sequence of firm, green to olive-brown finely micaceous shales interbedded with thin layers of fine-grained, smooth-surfaced green sandstones occurring in beds 1 inch to 5 inches in thickness (Woodward, 1943). In the areas of Pennsylvania, Maryland, West Virginia and Virginia, studied by Hasson and Dennison (1978) the unit is composed of interbedded shales and siltstones. The shales are characteristically thickly laminated, medium to dark gray and weather to olive or light olive gray chips; the siltstones, light to medium gray in fresh exposure to yellowish gray where weathered, occur in sharply bounded beds ranging in thickness from 0.1 to 1 foot thick and exhibit sedimentary structures attributable to turbidity currents. The thin bedded nature of the formation produces flags with numerous types of sedimentary structures on the bedding surface. Common markings are dimples, striations, rill marks, and poorly defined ripple marks. The thickness of the Brallier, which ranges from 500 feet in extreme western West Virginia to over 2000 feet along the Allegheny Front, is shown on figure 58. The Brallier of eastern West Virginia and central Pennsylvania is considered to be equivalent of the Sonyea and West Falls Formations of New York and northern Pennsylvania. In Virginia, the unit climbs stratigraphically and is considered the equivalent of the Sonyea, West Falls and "Lower" Huron Shale Member of the Ohio Shale. The Brallier interval of West Virginia and Virginia falls within the Dowelltown Member of the Chattanooga Shale in central Tennessee. The Illinois basin equivalents of the Brallier occupy the lower part of the Grassy Creek Member of the New Albany Shale in Kentucky and Illinois and the Morgan Trail and Camp Run Members of the New Albany of Indiana. In the Michigan basin the stratigraphic equivalent of the Brallier occurs within the Antrim/Ellsworth black shale sequence. See plate 1 for these stratigraphic relationships.

Chemung Formation. The name Chemung was applied by Hall (1839) to exposures at Chemung Narrows on the Chemung River, 11 miles southeast of Elmira, New York. The base of the formation is arbitrarily picked at the first occurrence where large fossils such as Leiorhynchus, Productella, Spirifer, and Leptodesma appear in the section above the thick mass of Brallier Shale (Butts, 1918). The top of the formation corresponds roughly with the first appearance of red shale and sandstone characteristic of the Hampshire Formation. The Chemung is a thick sequence of sandstones and shales which can be differentiated from the underlying Brallier on the basis of its abundant marine fauna and the fact that it is predominently sandstone while the Brallier is predominently shale. The size of the sand grains in the Chemung sandstones, which coarsen upwards from the underlying Brallier, range from fine to coarse to conglomeratic and the color grades from gray to greenish gray, red brown or light purple. Bedding ranges from a few feet thick to massive beds 45 to 50 feet thick. The fossils, the character of the bedding, and the presence of sedimentary structures indicate a shallow marine, nearshore depositional environment with some evidence of littoral transport. Near the top of the unit, the intertonguing relationship between the Chemung and Hampshire Formations shows the transition between the continental and nearshore marine facies. The Chemung has a wide distribution over central and western Pennsylvania, West Virginia and central Virginia. The thickness ranges from 1000 feet in western West Virginia and western Pennsylvania to greater than 3300 feet along the Allegheny Front in Rockingham County, Virginia (fig. 59). The stratigraphic equivalents of the Chemung of West Virginia in New York and northern Pennsylvania include the Canadaway and Conneaut Formations. In central Tennessee, the interval correlates in part with the Dowelltown and Gassaway Members of

Figure 58 . Thickness and distribution of the Brallier Formation. After Woodward (1943).

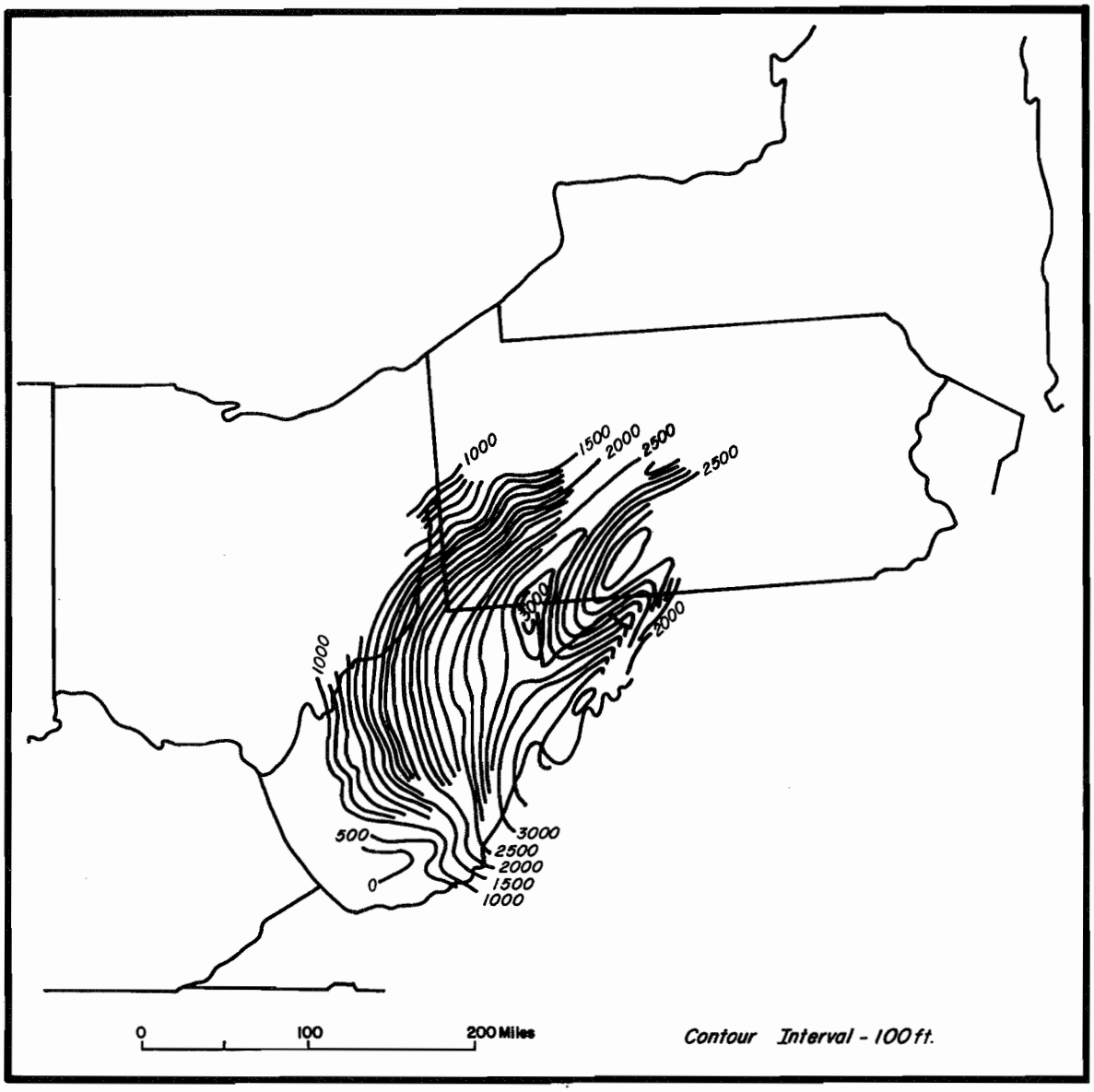


Figure 59. Thickness and distribution of the Chemung Formation. After Woodward (1943).

the Chattanooga Shale and the lower part of the Chattanooga of northeastern Alabama. The Chemung of Virginia expands timewise to include the Canadaway, Conneaut, and Conewango of New York, the entire Ohio Shale section of Ohio, the upper half of the Chattanooga in central Tennessee and the entire Chattanooga Shale section of northeast Alabama. The Chemung equivalents in the Illinois basin occur in the upper part of the Grassy Creek Member of the New Albany Shale in Kentucky and Illinois and the Camp Run and Clegg Creek Members of the New Albany in Indiana. In the Michigan basin, the Chemung interval occurs within the upper part of the Antrim/Ellsworth sequence (plate 1).

Hampshire Formation. The name Hampshire was first used by Dalton (1892) for exposures of rock in Hampshire County, West Virginia, and later revived by Woodward (1943) for rocks previously called "Catskill Formation" (fig. 60). The Hampshire Formation by definition includes the red and green sandstones and shales which overlie the Chemung and occur below the beds of the "Pocono Facies" (Woodward, 1943). The formation is a thick monotonous sequence of non-marine sandstones and shale. The dominant color is red, but locally occurrences of green sandstone and thin-bedded greenish shales and sandstones are common. The unit contains numerous fine- to coarse-grained micaceous sandstones which are locally arkosic and conglomeratic. These beds range in thickness from a few inches to 30 feet with the more massive sandstones exhibiting well-developed cross bedding and ripple marks. The intervening shale units are green and red, soft, blocky to bumpy mudstones and shales ranging in thickness from a few feet to greater than 100 feet. The flaggy nature of the weathered formation, the cross bedding, and the red and green color are characteristic of the formation along the outcrop belt. The red and green color of the formation lead most investigators to postulate a subaerial environment of deposition under partially arid conditions for the formation. The Hampshire has a wide distribution and ranges in thickness from a feather edge in western Pennsylvania and West Virginia to greater than 4500 feet in east-central Pennsylvania (fig. 61). The Hampshire Formation of West Virginia is considered equivalent to the Conewango Formation of New York, the upper part of the Chagrin and Cleveland Shales of Ohio and Kentucky and the upper part of the Chattanooga Shale in central Tennessee and northeastern Alabama. The equivalent in the Michigan basin is within the upper part of the Antrim/Ellsworth sequence and in the Illinois basin the stratigraphic equivalent is within the upper part of the New Albany Shale. These stratigraphic relationships are shown on plate 1.

Millboro Shale. In the Virginia portion of the Appalachian basin, beyond where the Eastern Gas Shales Project stratigraphic framework is adaptable, Butts (1940) proposed the name Millboro Shale as a mapping unit where he could not recognize and separate the Marcellus-Naples interval of the Romney Formation (Tioga Bentonite to base of Brallier Formation), Hasson and Dennison (1978). The reference section for the formation is at Millboro Springs, Bath County, Virginia. The localities referenced in the discussion of the Millboro are identified on figure 62. It was Butts' intention to use the term Millboro only in areas where the silty shales of the Hamilton Formation were absent and the dark shades of the Millboro could not be subdivided. The Millboro is composed almost entirely of black fissile shale which weathers to light gray on weathered surfaces. Some interbeds of gray shale occur in the Millboro sequence, but they make up only a small part of the unit. The black shales are characteristically brittle and split into thin firm flakes. Along the outcrop belt, the Millboro extends from Highland and Augusta Counties, Virginia

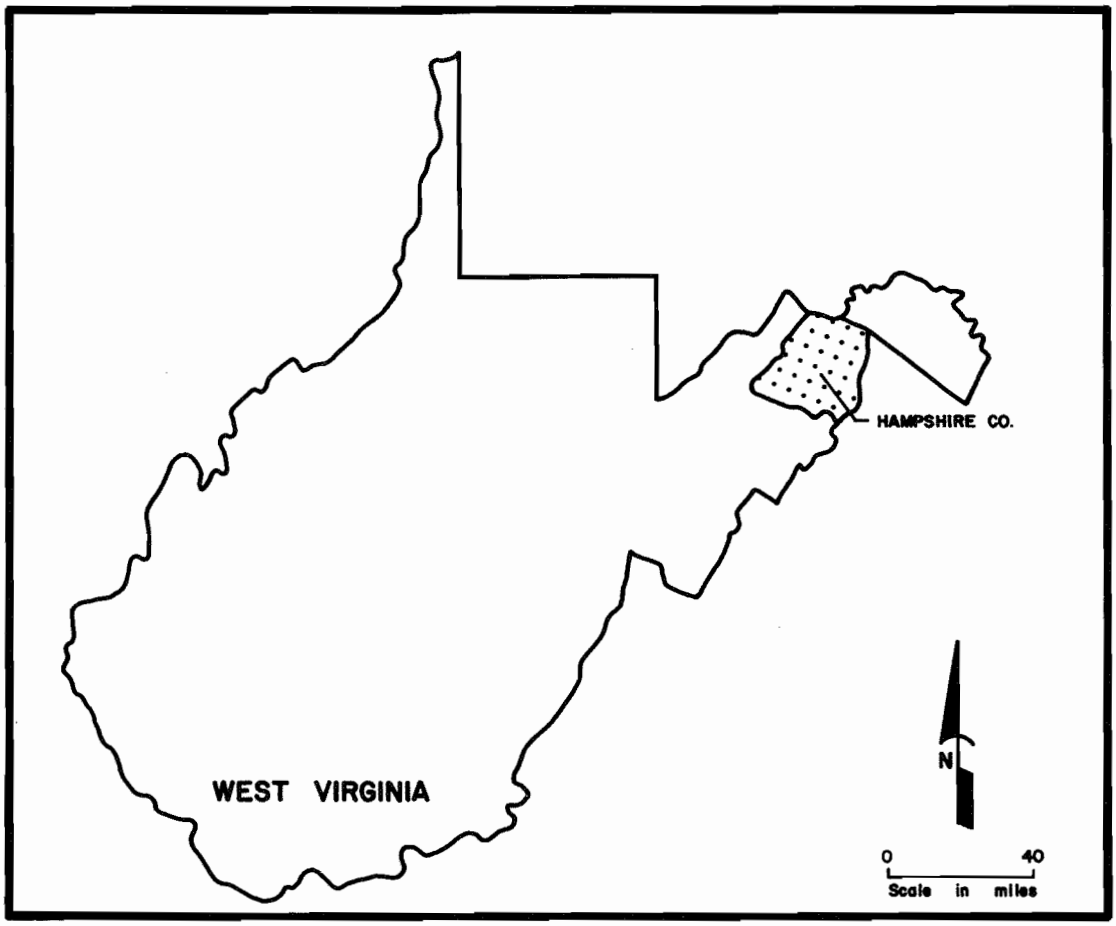


Figure 60. Index map identifying localities in West Virginia referenced in the stratigraphic discussion.

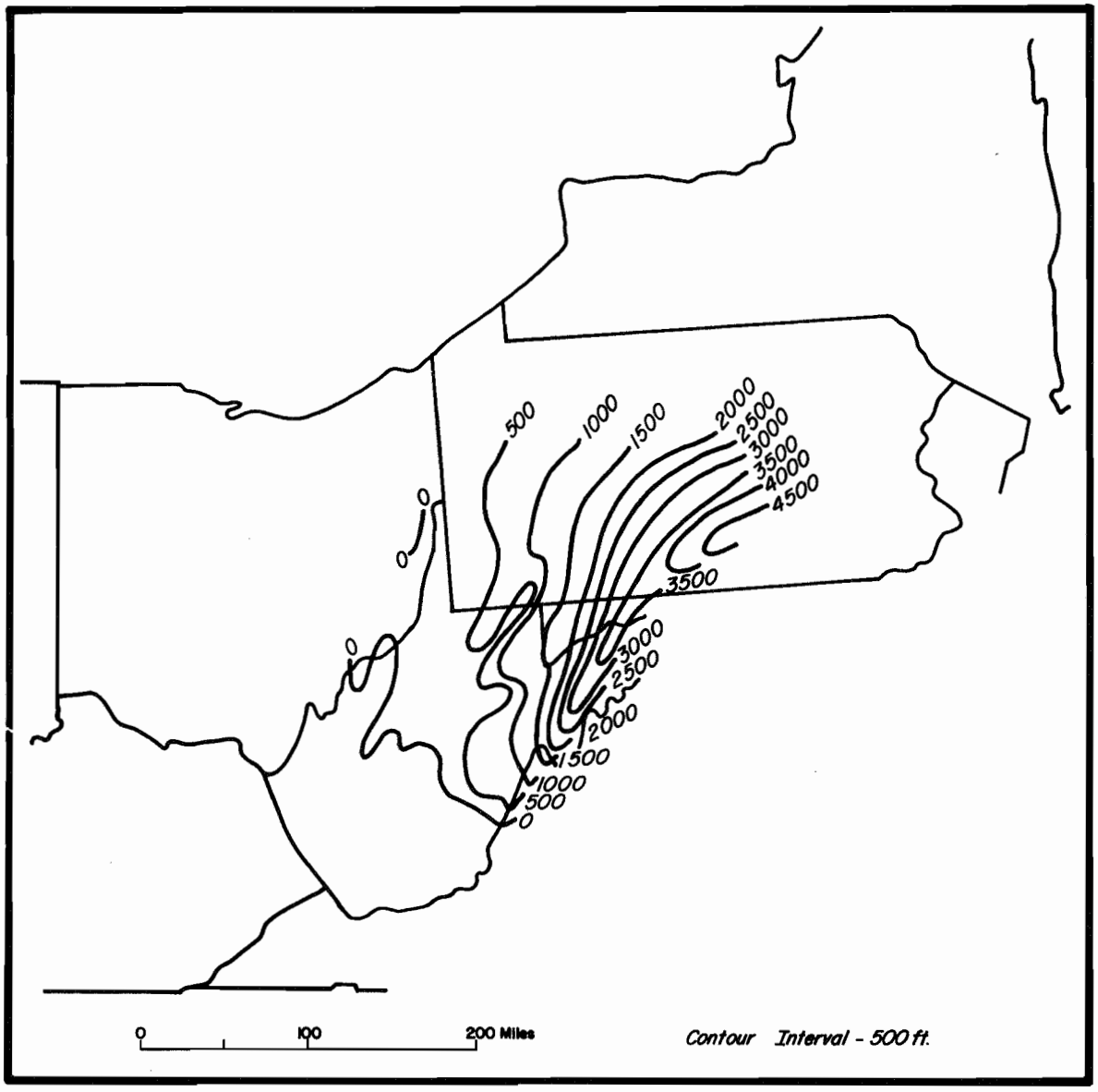


Figure 61. Thickness and distribution of the Hampshire formation. After Woodward (1943).

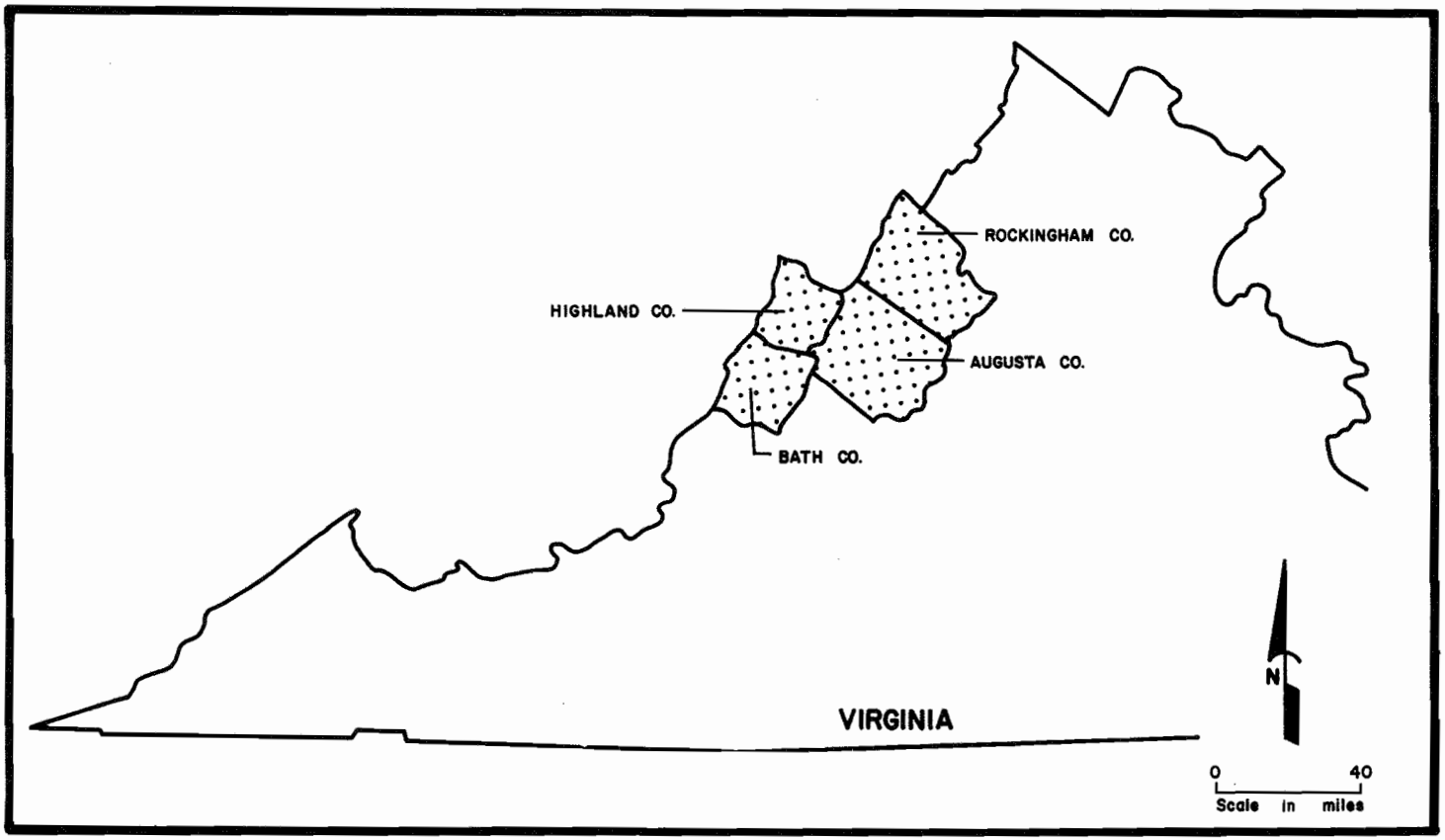


Figure 62 . Index map identifying localities in Virginia referenced in the stratigraphic discussion.

southwestward to Tennessee. Within the outcrop belt the formation ranges in thickness from 200 feet to 1000 feet (Butts, 1940). Hasson and Dennison (1978) estimate the thickness of the Millboro at the type section to be approximately 1500 feet. The Millboro Formation at the type section to approximately 1500 feet. The Millboro Formation of Virginia extends across the Middle-Upper Devonian boundary. The equivalent stratigraphic interval in West Virginia includes the Marcellus, Mahantango, Tully, Harrell and the basal part of the Brallier Formation. In New York and northern Pennsylvania the Millboro interval is occupied by the Hamilton, Tully, Genesee and Sonyea Formations. The lower part of the Chattanooga Shale in central Tennessee is considered the equivalent of the upper Millboro of Virginia. The correlations of equivalent units in the Michigan and Illinois basins and other local regions are shown on plate 1.

Tennessee-Alabama

Chattanooga Shale. Hayes (1981) was the first to apply a geographic name "Chattanooga black shale" for exposures of shale in the north end of Cameron Hill within the city limits of Chattanooga, Tennessee. The shale had been recognized much earlier by Frost (1833, 1837, 1840, 1841, 1843) who referred to the unit simply as "aluminous slate" or "aluminous shale." Safford (1841) in his discussion of the five major stratigraphic divisions of Middle Tennessee referred to the sequence only as "black bituminous slate" or "black slate" and in 1856 and 1859 referred to it as "black shale." The above nomenclatural history and the following discussions are summarized from Conant and Swanson (1961). For over 75 years geologists have had conflicting opinions on the age of the Chattanooga Shale. Many investigators prefer an Upper Devonian age for the Chattanooga and an equal number favor an Early Mississippian age. Some investigators believe the Chattanooga transgress time and is both Upper Devonian and Lower Mississippian in age. The current and most widely accepted view on the age of the Chattanooga in central Tennessee grew out of an extensive study of conodonts by Hass (1953) who concluded the shales were Late Devonian in age. Since 1900 many investigators have proposed subdivisions for the Chattanooga Shale sequence. The historical evolution of the stratigraphic framework of the Chattanooga is discussed by Conant and Swanson (1961, p. 21). In the outcrop belt of central Tennessee, the Chattanooga has been subdivided by Conant and Swanson (1961) into three members, in ascending order, the Hardin Sandstone, and the Dowelltown and Gassaway Members.

The Hardin Sandstone Member has limited distribution in southwestern Tennessee where it attains a thickness of 15 feet. The Hardin is a light to dark gray, very fine-grained sandstone which in many areas resembles siltstone. The unit is phosphatic locally and contains pyrite spherulites and concretions.

The Dowelltown Member is composed of a basal unit composed entirely of black, bituminous shale and an upper unit which is composed of interbedded black bituminous shale and light- to dark-gray claystones occurring in individual beds up to several inches thick.

The upper Gassaway Member throughout the outcrop area is a nearly massive, homogeneous unit of black bituminous shale. Characteristically, the individual shale beds of the Gassaway member are somewhat more massive than the beds of the Dowelltown. On a fresh break, a strong petroliferous odor is emitted from the black shale.

The Chattanooga Shale ranges in thickness from a feather edge to a maximum thickness of greater than 40 feet in northern Alabama. The general distribution and thickness of the Chattanooga is shown on figure 63. The Chattanooga Shale in central Tennessee is correlative with the Upper Olentangy and Ohio Shale sequences in eastern Kentucky and Ohio; the Harrell Shale, Brallier and Chemung Formation and the base of the Hampshire in West Virginia; the upper part of the Millboro Shale, the Brallier and Chemung Formation of Virginia and the Genesee, Sonyea, West Falls, Java, Canadaway, Conneaut and Conewango Formations of New York and Pennsylvania. In the Michigan basin, the Antrim/Ellsworth sequence is considered correlative with the Chattanooga while the New Albany Shale is the equivalent in the Illinois basin. The Chattanooga of northeastern Alabama is restricted to only the upper part of the Upper Devonian. Plate I shows the stratigraphic relationships and tentative correlations of these units throughout the Appalachian, Michigan and Illinois basins.

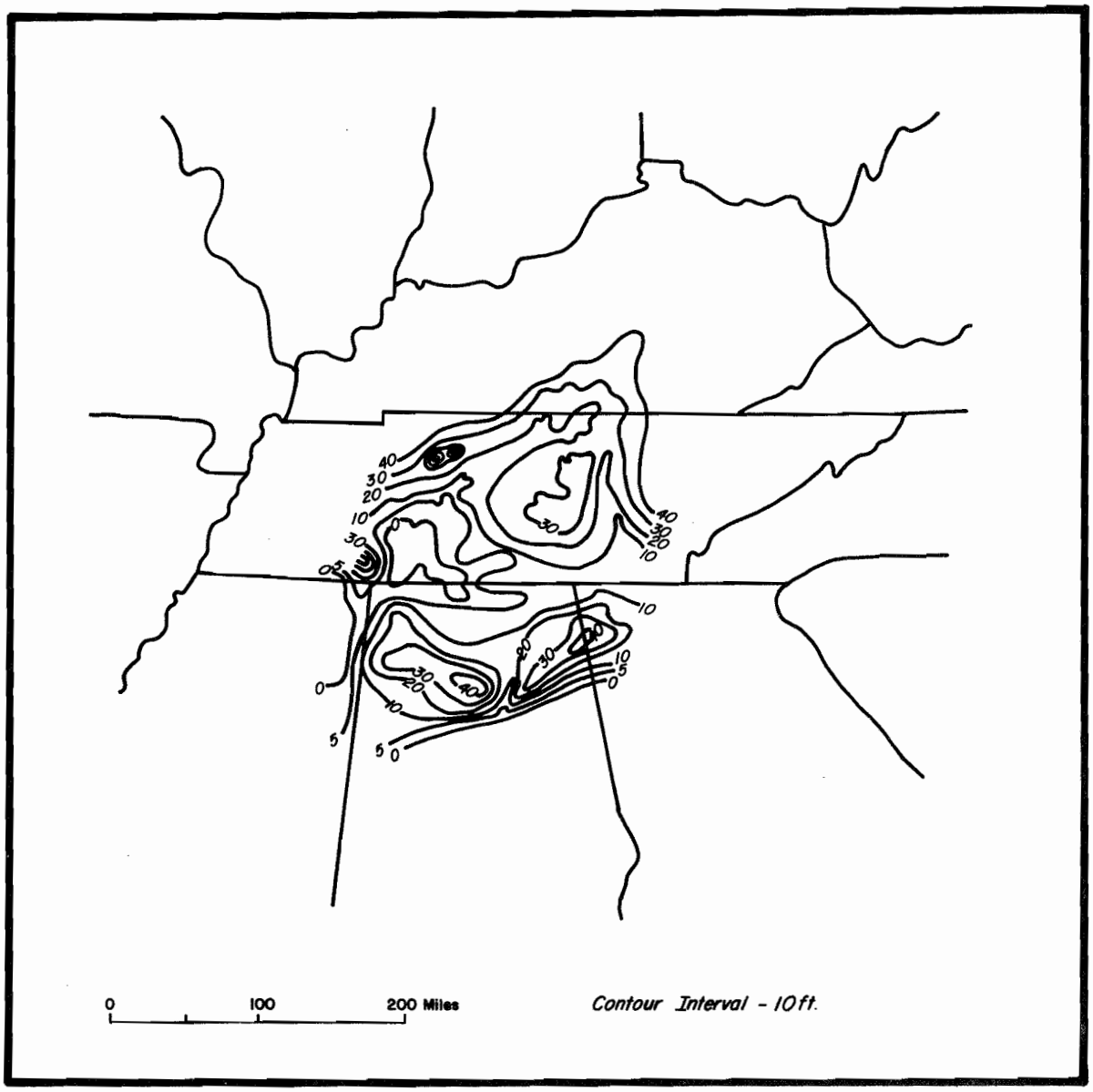


Figure 63 . Thickness and distribution of the Chattanooga Shale. After Conant and Swanson (1961).

MICHIGAN BASIN

Introduction

The Middle and Upper Devonian rocks deposited in the Michigan and Illinois basins are distinct facies, reflecting depositional environments further from the source area. The Middle Devonian of the Michigan basin is primarily a carbonate evaporite facies reflecting normal shallow marine shelf to basin environments in contrast with the clastic facies of the Hamilton Group in the northern Appalachian basin which is representative of deposition within the westward prograding Catskill delta complex.

The Eastern Gas Shales Project investigations within the Michigan basin were restricted to characterization and resource inventory estimates of only the Upper Devonian, organic-rich Antrim/Ellsworth shale sequence. However, since the Middle Devonian formations of the Michigan basin are correlative, within the stratigraphic framework of the Devonian System, with formations in the organic-rich facies of the northern Appalachian basin, the scope of the physical stratigraphy will include discussions of the Middle Devonian Detroit River, Dundee, Rogers City Formations, and the Traverse Group of Michigan; the Detroit River and Traverse Formations of northern Indiana; and the Detroit River, Dundee, Silica and Ten Mile Creek Formations in northwestern Ohio.

Middle Devonian

Michigan

Detroit River Group. Lane (1893, 1895) applied the name "Monroe beds" for the strata occurring between the base of the Dundee Limestone and the lowermost gypsiferous bed of the "Monroe beds" sequence. Lane (1895, 1899) recognized the Sylvania sandstone in southeastern Michigan and northwestern Ohio and separated the "Monroe beds" into the "Monroe above the Sylvania sandstone" and the "Monroe below the Sylvania sandstone." Lane, Prosser, Sherzer and Grabau (1909) divided the sequence into "Lower Monroe, or Bass Island series," "Middle Monroe" consisting of the Sylvania sandstone, and "Upper Monroe, or Detroit River series" and assigned the entire "Monroe" to the Upper Silurian. Stauffer (1916) considered the "Lower Monroe" Upper Silurian, and the Sylvania and "Upper Monroe" to be Devonian in age. Williams (1922) propsoed the term "Bass Islands," "Sylvania," and "Detroit River" be used in describing the sequence. Lane, Prosser, Sherzer and Grabau (1909) divided the Detroit River ("Upper Monroe") Group from the top downward into the Lucas, Amherstburg, Anderdon and Flat Rock formations. Later work by Landes (1951), based upon structural and geographic position, suggested the Flat Rock Formation belonged with the Lucas formation. The Anderdon, on faunal evidence on Ehlers (1950), lies above the Lucas at the top of the Detroit River Group in the type area. Lades (1951) places the Sylvania Sandstone in the Detroit River Group and considers it a member of the Amherstburg formation.

The type section for the Detroit River Series of Lane and others (1909) occurs along the Detroit River between Detroit and Monroe, Michigan where the entire sequence is exposed. The group, present throughout the entire Michigan basin, overlies the Bois Blanc Formation of Middle Devonian age except in western and southern Michigan where it overlies rocks of Silurian age. The Detroit River sequence, made up principally of beds of

dolomities, anhydrite, dark brown or black limestones and sandstone, ranges in thickness from approximately 250 feet along the margins of the basin to over 1600 feet near the center of the basin (fig. 64). The group was deposited within a framework of rapidly changing environmental conditions which varied throughout the time of deposition from a shelf to basin carbonate sequence, including sabkha and lagoon to basin centered evaporate consitions in the upper part (Gardner, 1974).

Dundee Limestone. The strata now designated Dundee were first noted by Houghton (1838) in the bed of the Rasin River at Dundee, Monguagon and Amherstburg, Michigan (Basset, 1935). Hubbard (1839, 1840) discussed these strata and correlated them with the "Cliff limestone" of Indiana. Later this sequence was assigned a Helderberg age by Winchell (1861) and Rominger (1876). The term Dundee limestone was first used by Lane (1892) who assigned the limestone an upper Helderberg age. The Dundee limestone, as currently described, rests disconformably on the Detroit River Group and is overlain by shales and limestones of the Rogers City Limestone.

The Dundee Limestone consists principally of buff to brownish-gray coarsely crystalline limestone. In the central basin the unit is composed both of limestone and dolomite with small amounts of chert in the base of the unit at widely separated localities. In the subsurface of the eastern part of the basin, a sandstone up to 10 feet thick is developed at the base. The Dundee ranges in thickness from 0 feet in western Michigan to more than 400 feet in east-central Michigan (fig. 65). The present state of knowledge indicates the Dundee to be a biostromal shelf carbonate which grades westward into evaporites of lagoonal, and sabkha facies (Gardner, 1974). The Dundee Limestone correlates with the Dundee of northwestern Ohio and the lower portion of the Traverse Formation in northern Indiana. On the basis of fauna, a number of workers have concluded that the Dundee and Delaware Formations of Michigan and Ohio are correlative and grade laterally into the Onondaga Formation, making the Marcellus correlative to some unit higher than the Dundee of Michigan, probably the Rogers City (Sandford, 1967).

Rogers City Limestone. The name Rogers City Limestone was proposed by Ehlers and Radabaugh (1938) for those 72 feet of strata directly below the Bell Shale which were originally defined as part of the Dundee in the Michigan Limestone and Chemical Company Quarry at Rogers City. It is separated from the underlying Dundee on the basis of fauna. The unit, predominantly limestone in the eastern half of the state, consists of both limestone and dolomite and is completely dolomite in local areas in the western half of the state. The formation averages 70 feet in thickness in surface outcrop, but in the subsurface 125 feet of Rogers City was reported in a boring in Arenac County, Michigan (Cohee and Underwood, 1945). The unit consists predominately of dark brown to black, very fine-grained limestone with a resinous luster that becomes lighter along the basin margins (Sanford, 1969).

The formation is correlative with the Marcellus shale of southwestern Ontario and New York and the lower part of the Traverse Formation in northern Indiana (plate 1).

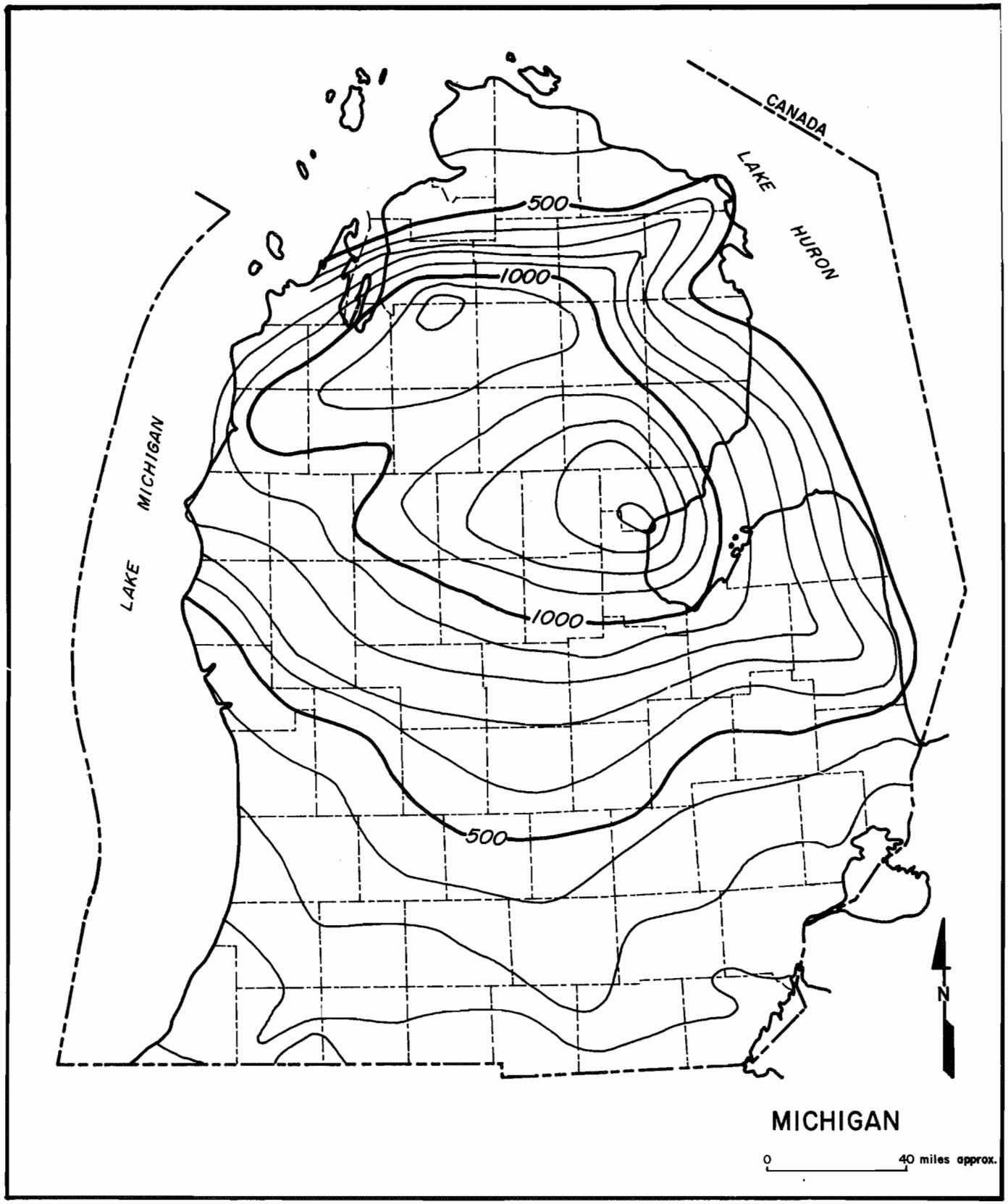


Figure 64. Thickness and distribution of the Detroit River Group in Michigan. After Cohee (1947).

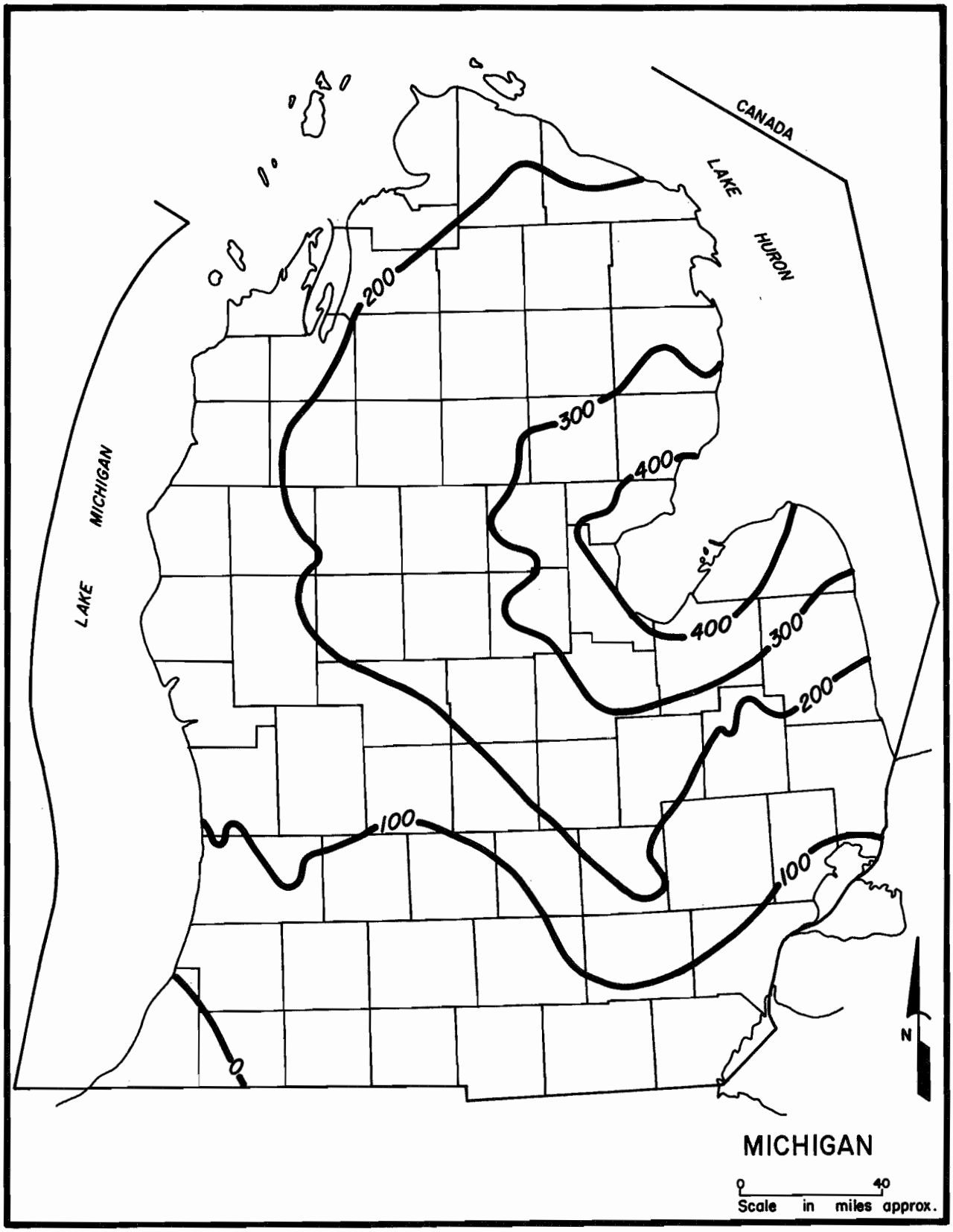


Figure 65. Thickness and distribution of the Dundee Limestone in Michigan. After Gardner (1974).

Traverse Group. Warthin and Cooper (1943), in their report on the Traverse Group in the Thunder Bay region of Michigan, credit Douglas (1841) with first naming the rocks now termed Traverse Group. He assigned the names "Little Traverse Bay Limestone" to the sequence, but Winchell (1871) changed the name to the "Little Traverse Bay Group." Lane (1893) was the first to introduce the name Traverse Group for bluish-gray shales and limestones or dolomites 100 to 600 feet thick which overlie the Dundee limestone and underlie the Antrim shale. Attempts to subdivide the unit in the Thunder Bay region into stages, series and formations were made by Grabau (1902), Grabau and Shimer (1910), Ver Wiebe (1927), Pohl (1930), and Warthin and Cooper (1939). The current subdivisions of the Traverse Group (Warthin and Cooper, 1943) divided the group into eleven formations, including from top to base: the Squaw Bay, Thunder Bay, Potter Farm, Norway Point, Four Mile Dam, Alpena, Newton Creek, Grenshaw, Ferron Point, Rockport Quarry and the Bell. The Traverse Group rests disconformably upon the Rogers City Limestone, whereas the relationship with the overlying Antrim is not certain because the contact is not exposed in the outcrop area.

The Traverse Group and its equivalents in northwestern Ohio and Indiana occupies almost the entire geographical area of the Michigan basin. Over its extent, the group ranges in thickness from 100 feet along the southern margin of the basin to over 875 feet in the Saginaw area (fig. 66). The Group in eastern Michigan consists primarily of argillaceous limestones and shales; to the west, the limestones are less argillaceous and the shales more calcareous. In the thumb area of southeastern Michigan, the Traverse consists almost entirely of shales in the lower part and shales and limestone in the upper part. In the southern part of the basin in northern Indiana the Traverse is almost completely light-gray to gray crystalline limestone. The Group was deposited under environmental conditions ranging from shallow shelf with muddy influx in the east to lagoonal in the west (Gardner, 1974). The Traverse Group is the lateral equivalent of the Hamilton Group of Ontario and New York and its clastic equivalents throughout the Appalachian basin. The Squaw Bay Formation, the upper unit of the Traverse, is considered correlative with the Genesee Formation of New York. In the Illinois basin, Traverse equivalents are the Sellersburg Limestone of Kentucky, the Lingle Limestone of Illinois and the North Vernon limestone of Indiana; the Squaw Bay Formation equivalent in Illinois is within the lower part of the New Albany Shale (plate 1).

The stratigrahic discussion of the formations within the Traverse Group is summarized from Warthin and Cooper (1943).

Bell Shale. The Bell Shale was named by Grabau (1909) for shales believed to be exposed in clay pits near the former settlement of Bell, Presque Isle County, Michigan. In the reference area it is composed of soft calcareous mudstone with possible thin limestone lenses and attains a thickness of about 80 feet. The shale, which rests in unconformable contact over the Rogers City Formation in Presque Isle County, has been assigned a Hamilton age and is probably equivalent with the middle Skaneateles Formation of New York (plate 1).

Ferron Point Formation. The name Ferron Point Formation was given by Warthin and Cooper (1935) for the sequence of clays and limestone exposed in the Rock Port Quarry one mile south of Ferron Point on Lake Huron. At the type section the unit is 18 feet thick and is composed of thin, alternating beds of gray to blue-gray argillaceous limestones, calcareous shales and bluish-gray claystone. On the basis of fauna and

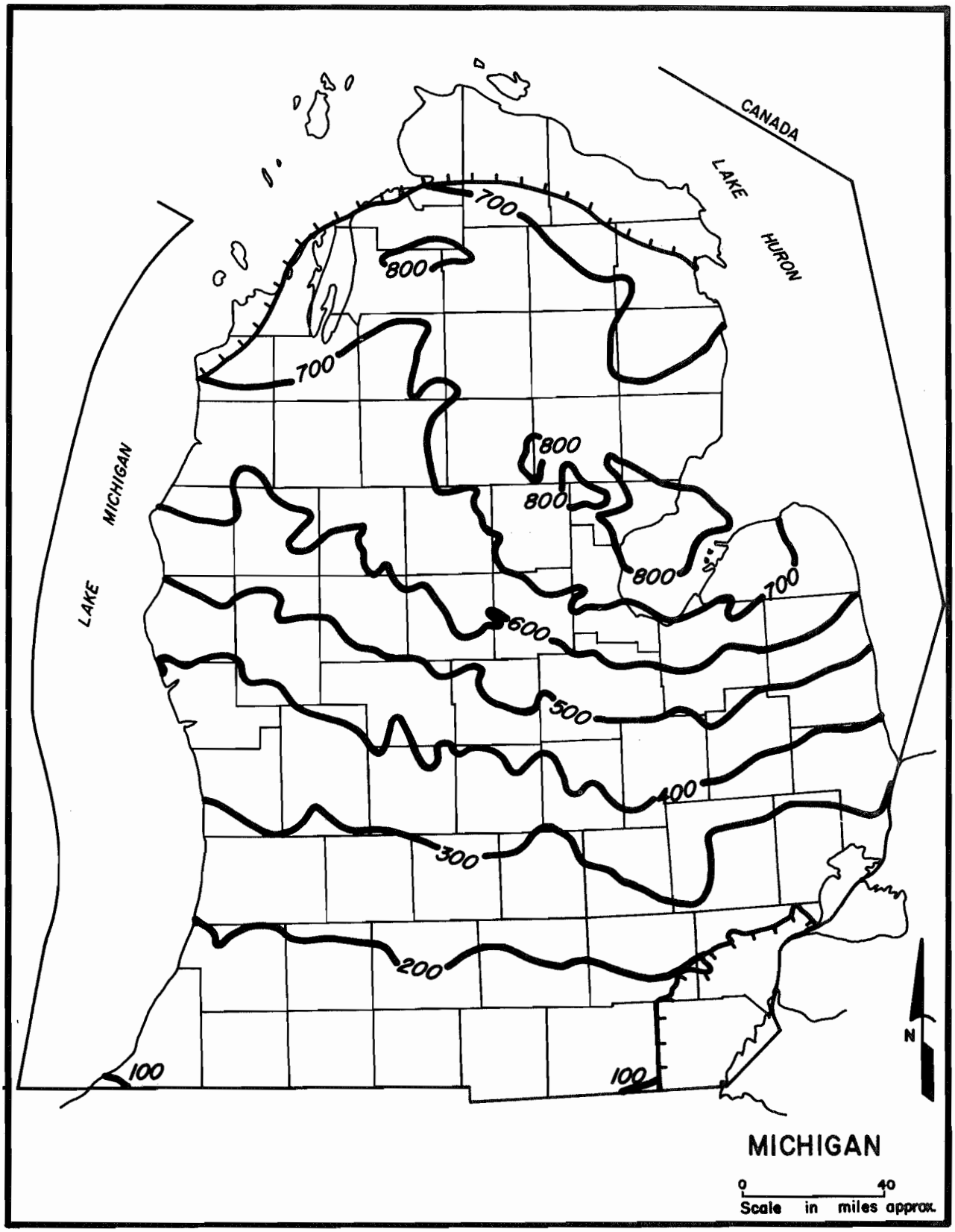


Figure 66. Thickness and distribution of the Traverse Group in Michigan. After Cohee (1947).

subsurface correlations, the Silica Shales of northwestern Ohio appears to represent the southern extension of the Ferron Point Shale.

Grenshaw Formation. The Grenshaw Formation was named by Warthin and Cooper (1939) for exposures in the NE ½ of T. 32 N., R. 8 E., Alpena County, near Grenshaw School. Warthin and Cooper (1943) extended the limits of the Grenshaw formation to include 58 additional feet of strata overlying the sequence at the type section. The formation in the reference area consists of 116 feet of alternating gray calcereous shales and gray argillaceous limestones, occuring in beds ranging from 1 to 25 feet thick. The Killians Member, conspicuous because of its gray to black color, is not the only bed of black limestone which occurs in the Traverse Group.

Newton Creek Limestone. The Newton Creek Limestone was named by Cooper and Warthin (1941) for exposures in the quarry of the Michigan Alkali Company at Alpena, Michigan. At the type locality the unit is 25 feet thick and is composed of dark-brown fossiliferous crystalline limestones. The brownish color is due principally to the interstitial petroleum content which extends laterally over quite long distances.

Alpena Limestone. The name Alpena Limestone was applied by Grabau (1902) for rock exposed in quarries near Alpena, Michigan (SE ¼, Sec. 14 and SW ¼, Sec. 13, T. 31 N., R. 8 W.) Since Grabau's studies, continued operations in the quarries have exposed a much thicker section. When the pit reached a depth of 125 feet, Ver Wiebe (1927) proposed the name Alpena be applied to the entire exposed section. Warthin and Cooper (1943) have concluded that the name Alpena Limestone is more applicable if restricted to the beds originally described by Grabau plus about 40 feet of subjacent limestone. The redefined Alpena at the type locality is 79 feet thick and consists of white to light gray, massive fossiliferous limestones with many bioherms. The massive limestone beds are separated by one-foot beds of bluish-gray highly calcareous shale.

Four Mile Dam Formation. The name Four Mile Dam Formation was applied by Cooper and Warthin (1941) for beds lying between the Alpena Limestone and the Norway Point Formation at the base of Four Mile Dam on Thunder Bay River. The unit, 8 feet thick at the type section, is a light gray locally brecciated biohermal limestone. Because of the biohermal nature of the formation, it is difficult to designate a typical lithology or estimated overall thickness of the unit.

On the basis of the discovery of a fauna with Centerfield affinities in the Four Mile Dam Formation, the unit is now considered correlative with the "Coral Zone" of the Widder beds in Ontario and the Centerfield Limestone of Hamilton Group of New York (Warthin and Cooper, 1943) and the Ten Mile Creek Dolomite of northwestern Ohio (Sanford, 1967) (plate 1).

Norway Point Formation. Warthin and Cooper (1941) designated the rocks exposed below the Norway Point Dam on the Thunder Bay River the Norway Point Formation. At this location the top or bottom of the unit are not exposed but the most characteristic beds of the formation can be observed. The maximum exposed thickness of the unit is 45 feet, but it may reach 55 to 60 feet within the region. The formation consists of thick,

bluish-gray clay and calcareous shale beds and thin interbeds of gray to brown, fine to coarse crystalline fossiliferous limestone. Because the beds were deposited on an irregular biohermal surface, many of the upper beds overlap lower beds along the margins and over the hummocks. The Norway Point Formation is tentatively correlated to some part of the Ludlowville Formation of New York, probably the lower Wanakah Shale, but possible as high as the Tichenor Limestone. It is the youngest formation in Michigan with definite Hamilton affinities (plate 1).

Potter Farm Formation. The farm of E.M. Potter, Section 18, 19 and 20 T. 31 N., R. 8 E., Alpena County was designated the type section for the Potter Farm Formation (Warthin and Cooper, 1935). The formation ranges between 68 and 74 feet in outcrop and consists primarily of argillaceous, fossiliferous limestone and gray calcareous shales with interbeds of coarser crystalline fossiliferous limestones. The unit disconformably overlies the Norway Point Formation and tentatively correlates with the Middle Devonian Cedar Valley Formation of Illinois and the Tully Limestone of New York (Cooper, 1942) (plate 1).

Thunder Bay Limestone. The name Thunder Bay Limestone was first used by Douglass (1841) for beds of fossiliferous gray limestone and gray clay and shale occurring on South Cape of Thunder Bay. The sequence is overlain by black bituminous shale and overlies black bituminous limestone. Grabau (1902) used the term Thunder Bay Series for 130 feet of clays, shales and limestones overlying the Alpena limestone and forming the upper shale unit of the Traverse Group on Thunder Bay at and adjacent to Alpena. Warthin and Cooper (1935) restricted their Thunder Bay stage by removing from the top their designated Squaw Bay Limestone. The type locality for the Thunder Bay Formation is given in the original description as "the south cape of Thunder Bay." This locality is in fact Partridge Point, about three miles south of Alpena. The exposure is on the east shore of the point near its tip. The unit consists of light-gray argillaceous limestone and gray calcareous shales, ranging in thickness from 15 feet (Warthin and Cooper, 1943) to 90 feet (Sanford, 1967). The Thunder Bay and Potter Farm Formations are considered equivalent to part or all of the Moscow-Tully-Geneseo of New York. Recognizable affinities between the fauna of Michigan and New York sections strongly suggest a Tully age for the Potter Farm and Thunder Bay Formation (plate 1).

Ohio

The stratigraphic nomenclature in Ohio above the Dundee Limestone is tied to stratigraphic sequences with type sections in Ohio rather than Michigan. In Ohio the Middle Devonian units above the Dundee are the Silica Formation and the Ten Mile Creek Dolomite. The Upper Devonian in northwestern Ohio is represented by the Ohio Shale. The physical stratigraphy of these units is described in the following paragraphs:

Silica Formation. The Silica Shale was named by Stewart (1927) for exposures of bluish-gray shales in the quarry of the Sandusky Cement Company, one-half mile north of the village of Silica, Lucas County, Ohio. The unit was raised to formational status by Cooper and others (1942) and included by Ehlers and others (1951) as a formation in the Traverse Group (Janssens, 1970). The Silica of northwestern Ohio consists of fossiliferous,

bluish-gray to brownish-gray shale with interbeds of argillaceous, fossiliferous, fine- to medium-crystalline limestones. The unit increases in thickness from 10 feet at the type section to 54 feet at the Medusa Portland Cement quarry in Lucas County, Ohio. The Silica rests with unconformable contact upon the Dundee Limestone and is overlain unconformably by the Ten Mile Creek Dolomite.

The formation is correlative with the Rockport Quarry Limestone and Ferron Point Formatin in Michigan, the Plum Brook Shale of northern Ohio, the "Lower" Olentangy Shale of central Ohio, and is correlative in part with the Hamilton Group (Skaneateles Formation) of the northern Appalachian basin. The thickness and distribution of the Silica Formation in northeastern Ohio is shown on figure 67.

Tenmile Creek Dolomite. The Tenmile Creek Dolomite was named by J.E. Carmen for exposure along Tenmile Creek in the SE ¼ Sec. 19, Sylvania Township, Lucas County, Ohio (Stewart, 1938). The unit, made up of gray to bluish-gray, dense to crystalline dolomite containing modular chert with minor interbeds of shaly dolomite and shale, decreases in thickness southward from a maximum thickness of 54 feet in northwestern Fulton County (fig. 68).

The Tenmile Creek Dolomite has been correlated with the Centerfield Limestone Member of the Ludlowville Formation of New York, the Fourmile Dam Formation in northern Michigan and the Hungry Hollow Formation of southwestern Ontario. The Tenmile Creek Dolomite is overlain in unconformable relationship by the Ohio (Antrim) Shale.

Upper Devonian

Michigan-Indiana

Squaw Bay Limestone. The Squaw Bay Limestone was named by Warthin and Cooper (1935) for exposures three miles south of Alpena on the shore of Lake Huron. Sanford (1967) did not include the Squaw Bay Limestone in the Traverse Group, considering it a separate formation of Upper Devonian age. However, current usage by the Michigan Geological Survey and Michigan Geological Society consider the Squaw Bay Formation as part of the Traverse Group, but consider the uppermost Traverse Upper Devonian in age. The unit consists of brown limestone and brownish-gray crystalline dolomite that rests with abrupt disconformity on top of the Thunder Bay Formation. At the type locality the formation ranges in thickness from 3 to 12 feet, but reaches a thickness of 55 feet in the center of the basin.

The Squaw Bay interfingers with black or dark gray bituminous shale of the Antrim Shale and Kettle Point Formations of Ontario and is considered to represent a basinal facies of these formations during the initial stage of Late Devonian sedimentation (Sanford, 1967). Cooper (1942) correlated the Squaw Bay with the Genundewa Formation of New York (plate 1).

Antrim/Ellsworth Shale. The following discussion of the development of the Antrim nomenclatures is summarized from Tarbell (1941). Black shales which are now called

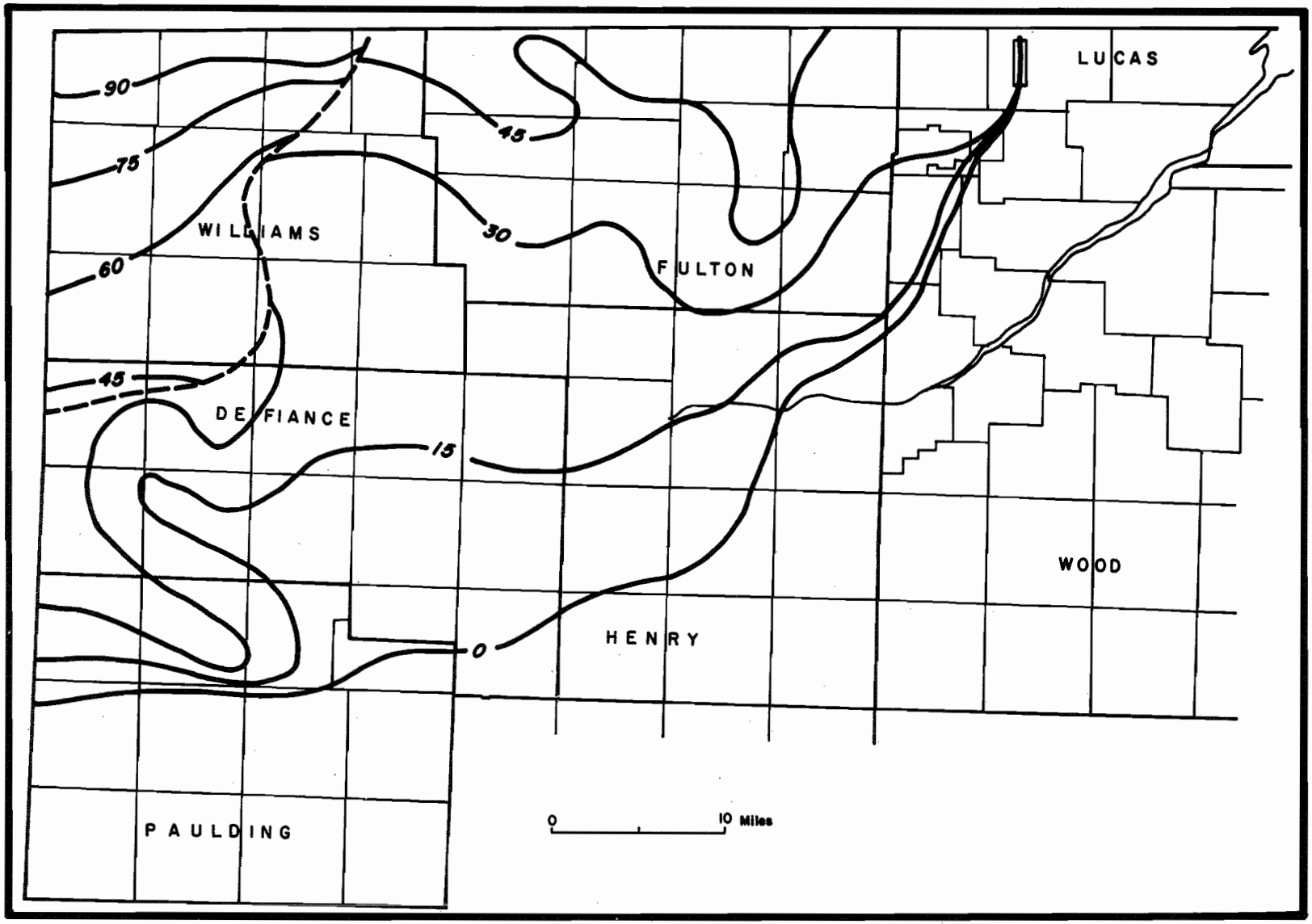


Figure 67 . Thickness of Silica Formation. After Janssens (1970).

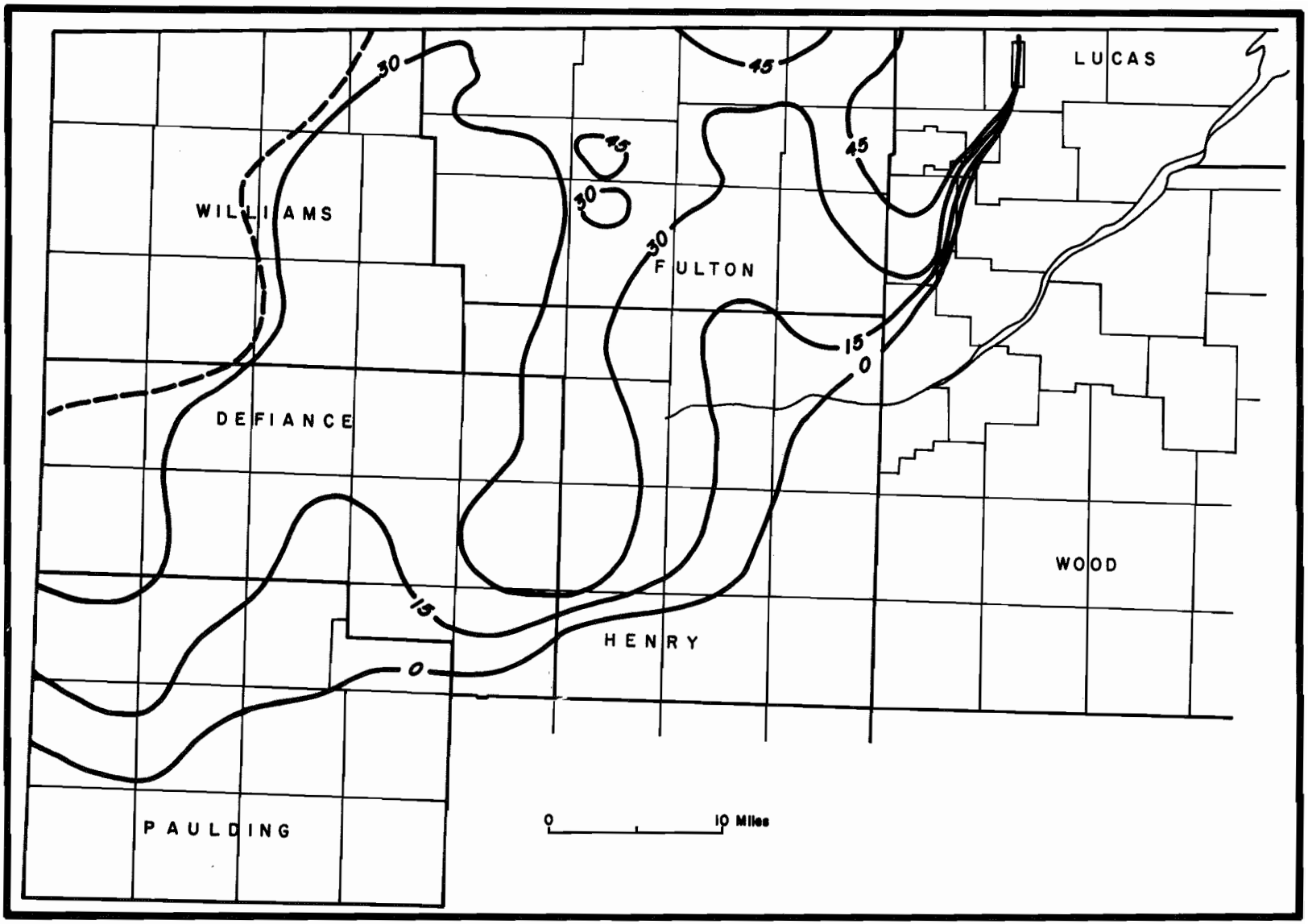


Figure 68 . Thickness of Tenmile Creek Dolomite and Traverse Formation. After Janssens (1970).

Antrim were first cited in the literature by Douglass (1841), who did not name the unit but considered it the equivalent to the Upper Devonian shales of New York. Winchell (1861) designated the same black shales, plus overlying green shale and sandstone, the Huron Group and correlated the Huron Group with the Portage Group of New York. Rominger (1876) thought the name Huron should apply only to the basal black shales of Winchell's Huron Group because the overlying beds contained a fauna found in the Cuyahoga shale of Ohio which was considered to be Mississippian in age. Rominger correlated the shales of Michigan with the Genesee of New York since he believed the shales in Michigan rested directly on beds of Hamilton age. Wright (1895) applied the name St. Clair to the black shales and higher strata which were correlated with the Ohio, Erie, Cleveland, and Bedford Shales. Lane (1901) proposed to substitute the name Antrim because it is the county in which the black shales designated St. Clair by Wright occur. Morse (1938) points out the best black shale exposures noted by Lane (1901) are located about one mile south of Norwood, Charlevoix County, along the southeast boundary of Sec. 2, T. 32 N., R. 9 W., Antrim County, Michigan.

The Antrim consists of brown to dark gray to black bituminous shale which, locally, contain thin interbeds of light gray shales or thin limestones near the base. The middle of the unit is uniformly black, but grades upward into lighter gray shales in the top. The Antrim has a maximum thickness of about 550 feet in the vicinity of Saginaw Bay but thins rapidly westward where it intertongues with 700 to 800 feet of normal marine shale of combined Antrim/Ellsworth Formation (fig. 69). The thicker black shales reflect deposition of organic matter near the depocenter of a deep stratified anoxic basin.

The fauna of the Antrim indicates a late Devonian age for at least the lower beds of the formation (Cooper, 1942). Conodont assemblages suggest much of the Finger Lakes, Cohocton, Cassadaga, and Bradford Stages are represented in the Antrim (plate 1).

Ellsworth Shale. The organic-poor shales above the Antrim were first described by Douglass (1855) from an outcrop on Grand Traverse Bay, T. 31 N. Newcombe (1935) proposed the name Ellsworth for these shale beds and designated exposures 1½ miles south of Ellsworth in the Petrosky Portland Cement Company quarry the type section (Sec. 26, T. 32 N., R. 8 W., Antrim County, Michigan). At the type section the Ellsworth consists of 30 to 40 feet of greenish-gray shale with thin lenses of red shale, limestone and dolomite common. The Ellsworth, near its eastern boundary, has a maximum thickness of 600 feet and thins to approxiamtely 400 feet in western Michigan (Sanford, 1967). The physical properties of the Ellsworth shale indicate deposition upon a stable shelf or slope under moderate depths of water. The combined thickness of the Antrim/Ellsworth sequence in the Michigan basin is shown on figure 69. Correlations between the Devonian rocks of New York, northern Michigan and southeastern Michigan and Ohio are summarized on figure 70.

In the Indiana portion of the Michigan basin, the stratigraphic nomenclature is the same as used in Michigan, but the formational boundaries do not occupy the same positions within the framework of the Middle and Upper Devonian reference section. The stratigraphic relationships existing between the Michigan and Indiana portions of the Michigan basin are shown on plate 1.

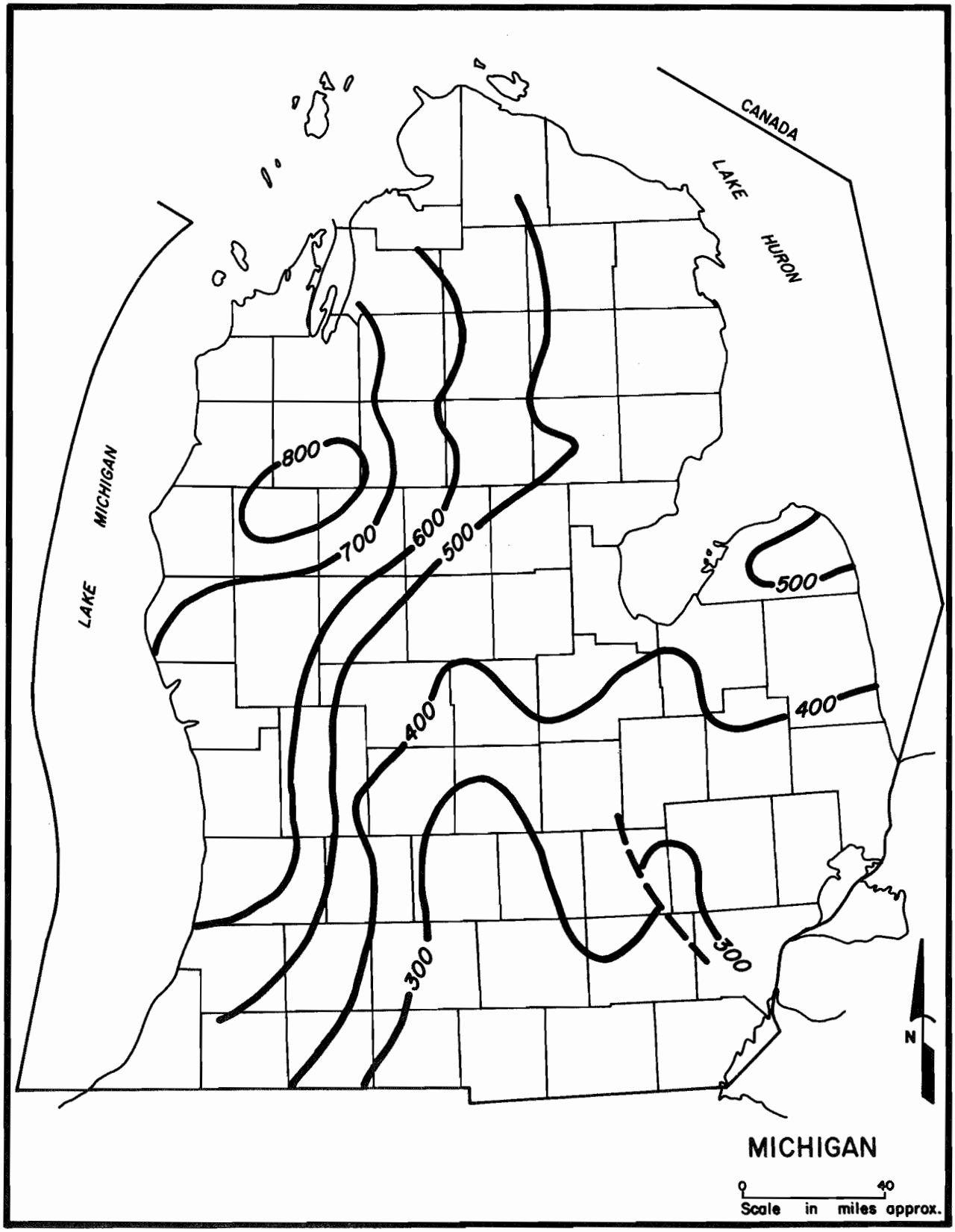


Figure 69 . Thickness and distribution of the Antrim/Ellsworth Shales in Michigan. After Mound Facility (1980).

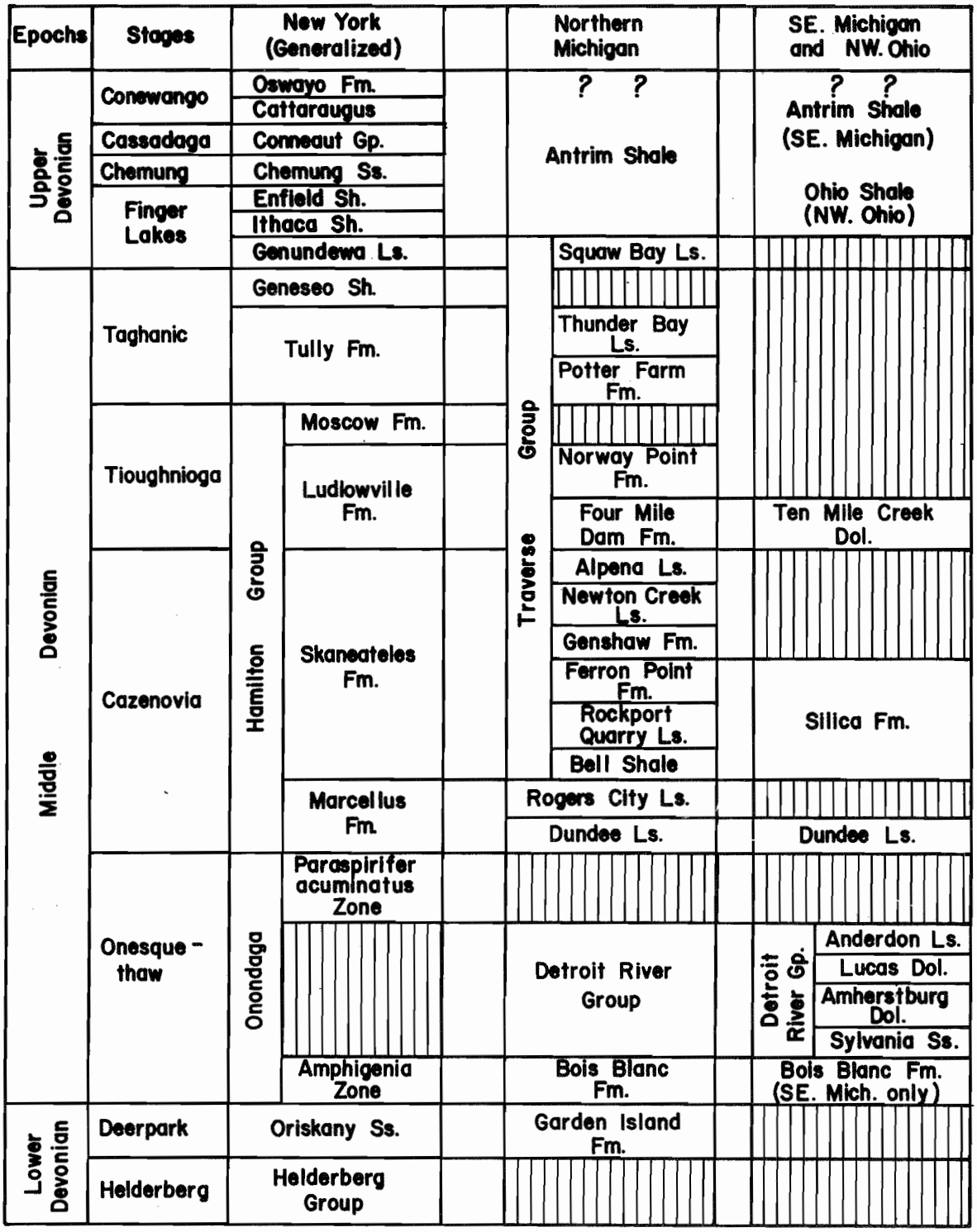


Figure 70 . Correlation of the Devonian rocks of New York, northern Michigan, and southeastern Michigan and northwestern Ohio. After Ehlers, Stumm and Kesling (1951).

Ohio

Ohio (Antrim) Shale. The Ohio Shale in northwestern Ohio is only 100 feet thick along the Michigan-Ohio border. The black shale is a southward continuation of the Antrim Shale of the Michigan basin which has a thickness of approximately 175 feet in the Ann Arbor, Michigan region. Since the Ohio Shale of northwestern Ohio is more closely associated to the Antrim than to the Ohio Shale of northern Ohio, the reader is referred to the prior summary of the Antrim for the physical stratigraphic discussion.

ILLINOIS BASIN

Eastern Gas Shales Project investigations in the Illinois basin were restricted to intensive studies of the characterization and mineral resource inventory and potential of the Late Devonian New Albany Shale. However, as in the case of the Michigan basin, Middle Devonian carbonate rocks in the Illinois basin, equivalent to the fine-textured clastic Hamilton sequence in New York and the northern Appalachian basin, will be included in the discussion of the physical stratigraphy of the Illinois basin. The discussion will first treat the Upper and Middle Devonian stratigraphic units of Illinois and then address stratigraphic units within the stratigraphic frameworks of Kentucky and Indiana.

The "Handbook of Illinois Stratigraphy" (Willman and others, 1975) and "The New Albany Shale Group of Illinois" (Cluff and others, 1981) are the primary sources of reference for the stratigraphic discussions of the Middle and Upper Devonian sequence in Illinois.

Middle Devonian

Illinois

Grand Tower Limestone. The Grand Tower Limestone (Keyes, 1894) is named for Grand Tower, Jackson County, Illinois. Although a type section was not designated by Keyes, it is currently accepted that the 157 feet of the formation exposed at Devils Bake Oven, one-half mile north of Grand Tower, is the type section (SW¼, SE¼, NE¼, Sec. 23, T. 10 S., R. 4 W.) The unit is predominately coarse-grained, light gray, medium- to thick-bedded, cross-bedded, fossiliferous limestone. In the center and eastern part of the basin the Grand Tower is principally dolomites. The Tioga Bentonite Bed is present throughout the basin near the top of the formation. The Grand Tower ranges from 240 feet in southern Gallatin County to a feather edge around the northern, western and southwestern margins of the basin (fig. 71). A major unconformity occurs at the base of the formation.

The Grand Tower Limestone correlates with the Jeffersonville Limestone of Indiana and Kentucky, the Detroit River Formation in the Michigan and the Onondaga Formation of New York and the northern Appalachian Basin (plate 1).

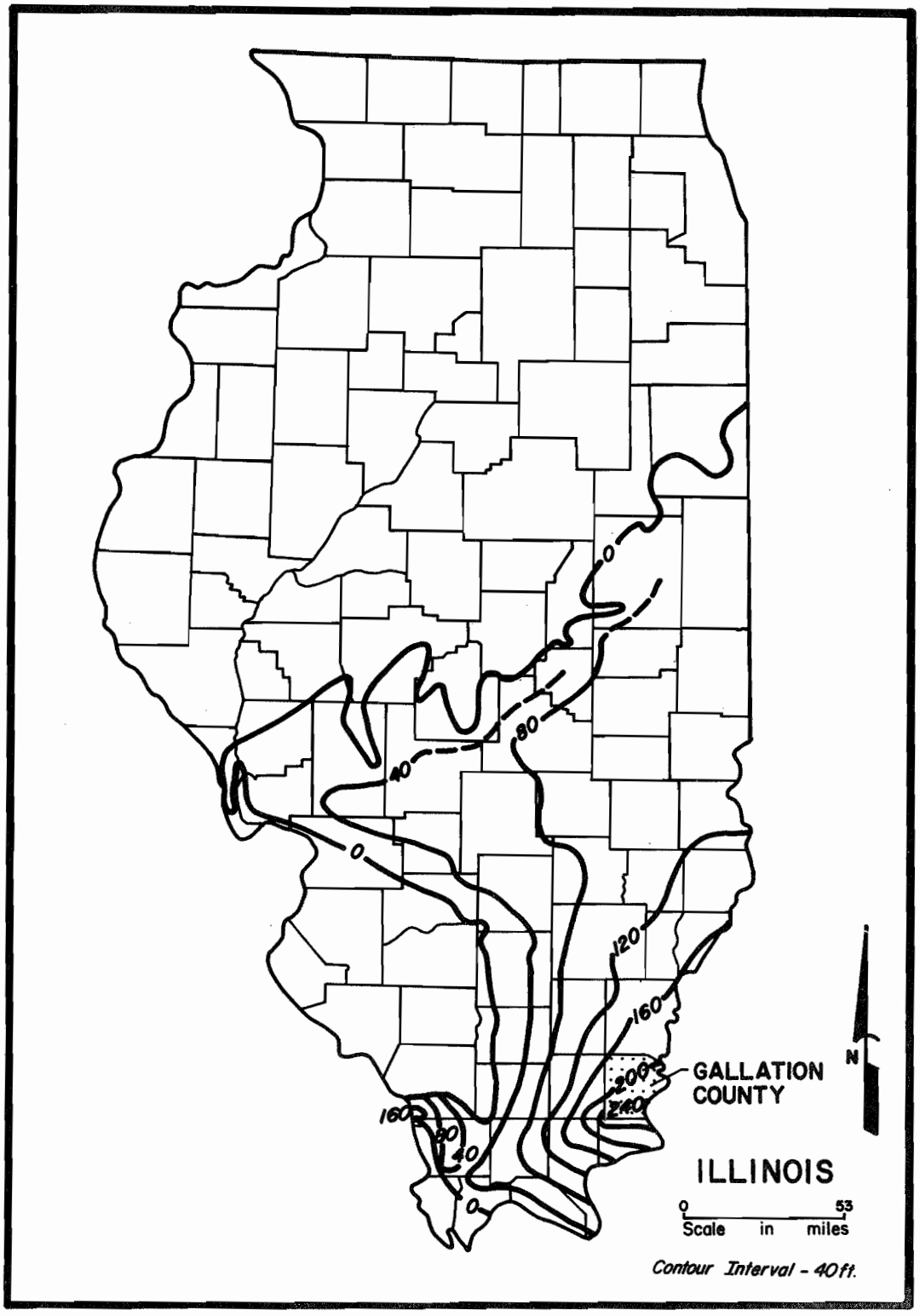


Figure 71. Thickness and distribution of the Grand Tower Limestone in Illinois. After North (1969).

Lingle Limestone Formation. The Lingle Formation (Savage, 1920; Weller, 1944; North, 1969) is named for Lingle Creek in southern Union County, Illinois (SE¼, SW¼, SW¼, Sec. 26, T. 135, R. 2 W.) The unit has a wide distribution in southern Illinois and generally overlaps the Grand Tower Limestone along the margins of the basin. The formation, a sequence of mixed limestone and shales, more argillaceous, shaly, darker colored and finer grained than the Grand Tower below, attains a maximum thickness of 110 feet in Union County (fig. 72). North (1969) interprets the upper part of the Lingle as grading eastward and intertonguing into the New Albany Shale.

Within the Illinois basin the Lingle Formation correlates with the Sellersburg Limestone of Kentucky and the North Vernon Limestone in Indiana. In the Appalachian basin the unit is equivalent with the Hamilton Group in New York, "Lower Olentangy" of Ohio, the Mahantango of Pennsylvania and West Virginia and in part with the Traverse Group in the Michigan basin (plate 1).

New Albany Shale Group. The New Albany Shale was named by Borden (1874) for exposures along the Ohio River in the vicinity of New Albany, Floyd County, Indiana. The New Albany was elevated to group status in Illinois (Collinson and Atherton, 1975) but remains classified as a formation in Indiana (Shaver et al., 1970). The classification proposed by Cluff and others (1981) is the latest of many schemes proposed over the years for subdividing and classifying the New Albany in Illinois into an acceptable stratigraphic framework. The proposed subdivision divides the group into nine formations in Illinois. The formations are, in ascending order: the Blocher Shale, Sylamore Sandstone, Selmier Shale, Sweetland Creek Shale, Grassy Creek Shale, Saverton Shale, Louisiana Limestone, Horton Creek Formation and Hannibal Shale. At no single place are the formations all present and to some extent each formation grades laterally into another. The following discussion is summarized from Cluff and others (1981).

Blocher Shale. The Blocher Shale (Campbell, 1946; Lineback, 1968) is named for the town of Blocher in Scott County, Indiana. Lineback (1968, 1970) and Collinson and others (1967) traced the Blocher from the outcrop in southeastern Indiana into the subsurface of Illinois and North (1969) mapped the unit in the subsurface. Campbell (1946) placed the lower eight feet of the New Albany at the type section in the Blocher even though only the lower 2.2 feet were calcareous. Lineback (1968, 1970) revised the Blocher by placing the top at the base of the Selmier member. Cluff and others (1981) redefined the formation to include only the calcareous black shale at the base of the New Albany. The Blocher consists of brownish-black to grayish-black finely laminated, carbonaceous, calcareous dolomitic shales with organic contents of up to 5 to 10 percent organic carbon by weight. Interbeds of fine-grained limestone, dolomite, calcareous sandstone, and phosphatic sandstone are common. The Blocher ranges from three feet thick in outcrop to a maximum of 90 feet in Hardin County, Illinois (fig. 73). The fine texture, planar laminations and scarcity of current generated sedimentary structures suggest a quiet water hemipelagic environment of deposition for the Blocher Shale.

The Blocher grades laterally north and west into the upper part of the Lingle Formation and disconformably overlies the North Vernon Limestone in Indiana and the Sellersburg Limestone in western Kentucky. A Middle Devonian age for the Blocher Shale best fits the currently restricted definition. The Blocher correlates in part with the Traverse Group of the Michigan and within the upper Hamilton Group of New York and the northern Appalachian basin (plate 1).

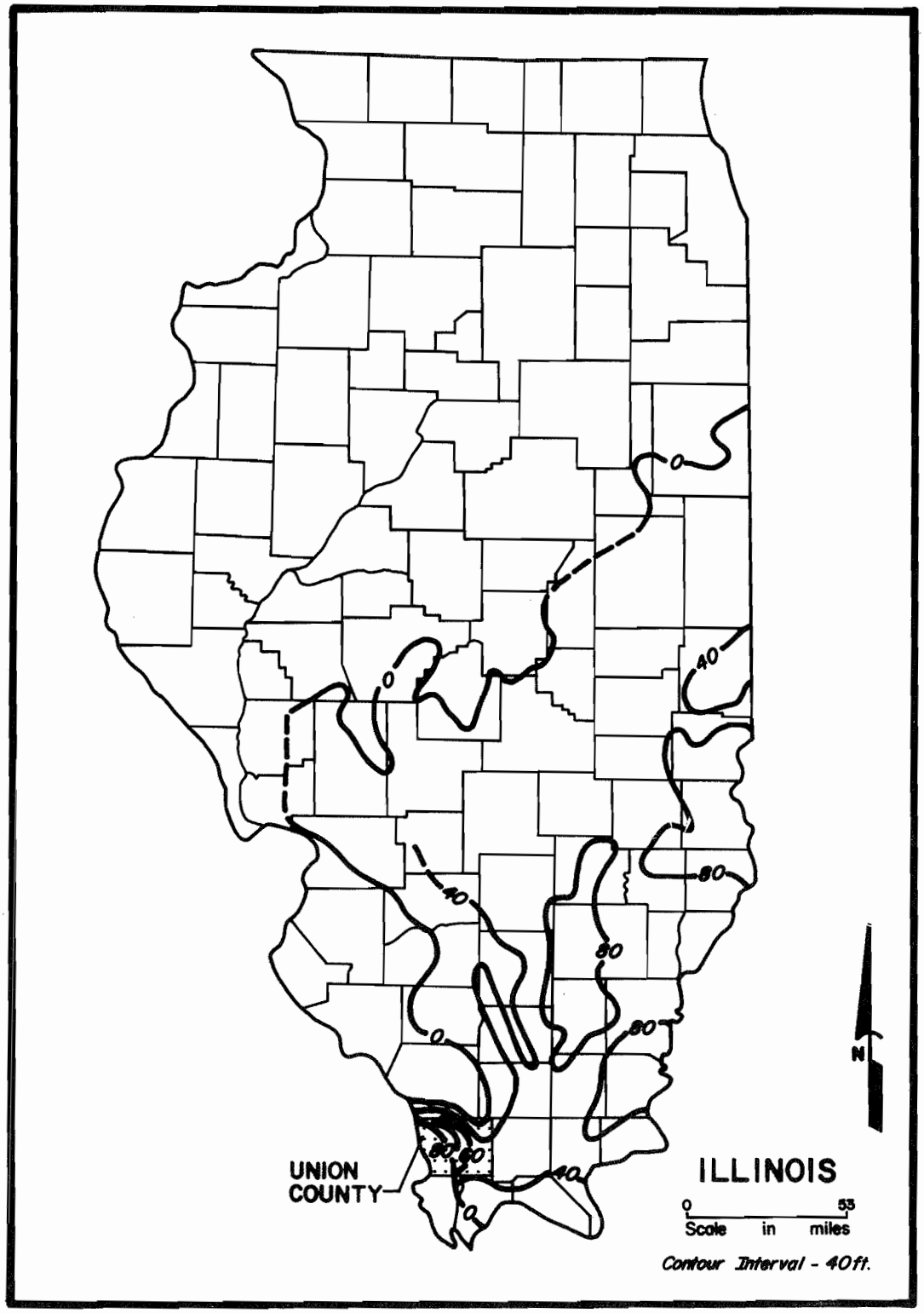


Figure 72 . Thickness and distribution of the Lingle Formation. Modified from North (1969).

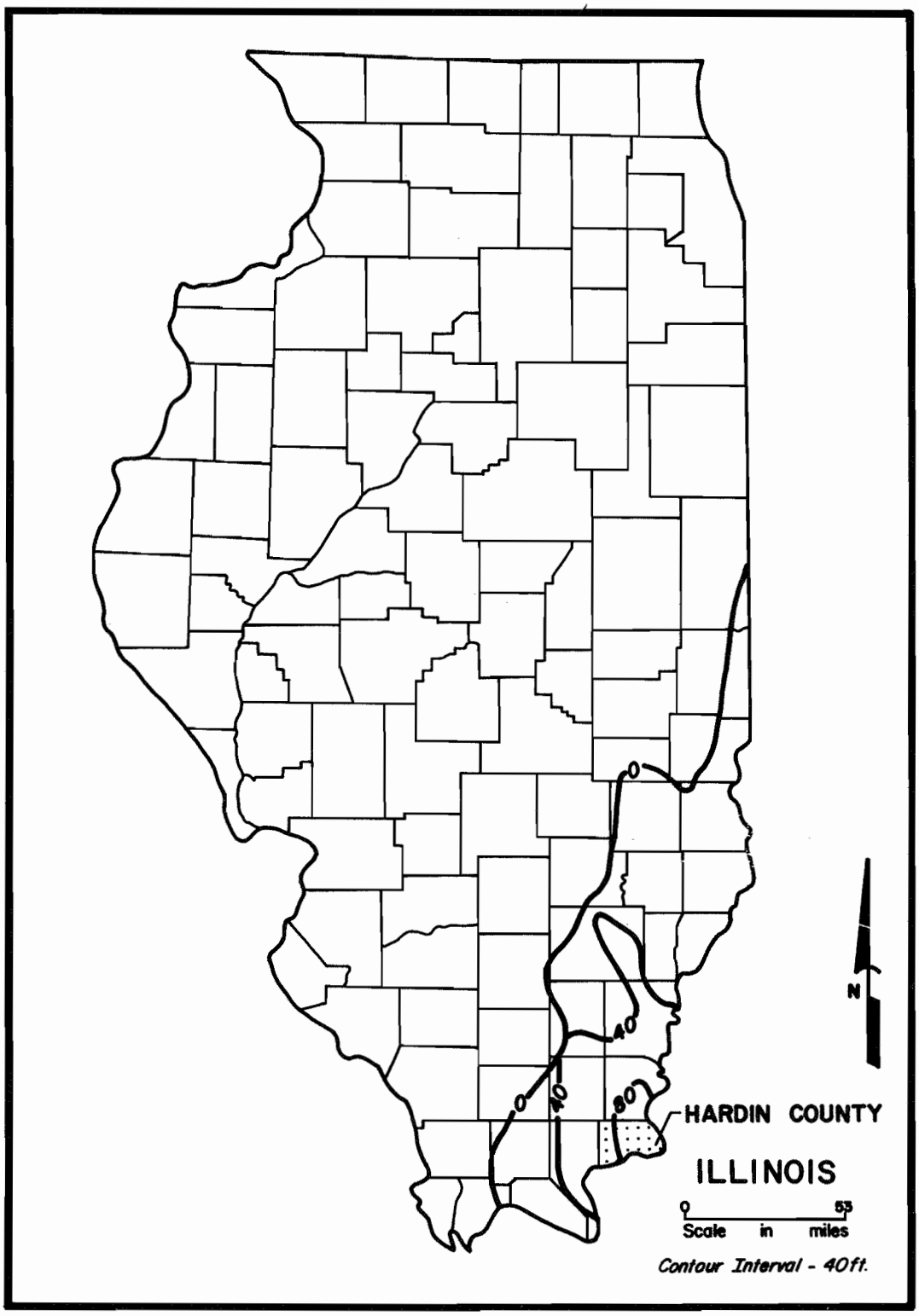


Figure 73 . Thickness and distribution of Blocher Shale in Illinois. After Cluff and others (1981).

Indiana

The Middle and Upper Devonian nomenclature used for the Indiana portions of the Illinois basin is based upon correlation and subdivision of the sequence from type sections located in Indiana. The following discussion of the physical stratigraphy of the North Vernon Limestone and the New Albany is summarized from Lineback (1968, 1970).

North Vernon Limestone. Bordon (1876), in his study of Jennings County, first described the North Vernon Limestone for exposures near North Vernon. This was the first of eight geographic names applied to the limestone in addition to a host of other names based upon composition lithology and fauna. The following discussion of the nomenclature is summarized from Murray (1955). Kindle (1899) proposed the name "Sellersburg beds" for the sequence between the base of the New Albany Shale and the lowest beds worked in the cement quarries. In a restricted sense the name "Sellersburg Limestone" was proposed by Siebenthal (1901) to include only the white to gray crystalline limestone which occurs between the New Albany and the cement rock which had been referred to by various investigators as the Crinoidal Limestone. Butts (1915) proposed that the name Sellersburg Limestone be restored to the original usage of Kindle, that the name "Beechwood Limestone member" be used for the "Sellersburg Limestone" of Siebenthal and that the "Silver Creek Hydraulic Limestone" of Siebenthal be reduced to member rank and called the "Silver Creek Limestone Member." Rocks of Hamilton age beneath the natural cement rock, recognized by Sutton and Sutton (1937) were named "Speeds" and designated the basal member of the Sellersburg Formation. Campbell (1942) raised the "Speeds," "Silver Creek" and "Beechwood" from member rank to formation rank and named two additional formations within the Hamilton group. He assigned the name "Deputy Formation" to the unit above the "Speeds" and below the Silver Creek and the name "Swanville Formation" to a thick-bedded, crystalline limestone which lies between the New Albany and the "Silver Creek."

The names North Vernon and Sellersburg of Indiana are both synonymous with rocks of the Hamilton sequence in the standard section of New York. The name Sellersburg is most applicable in Clark and Scott counties where the sequence can be subdivided into the Beechwood, Silver Creek and Speed lithologies. The North Vernon Limestone nomenclature applies primarily in Bartholomew, Jennings and Jefferson Counties where the entire Hamilton sequence is composed of relatively homogeneous limestone.

The North Vernon Limestone is a light- to medium-fine- to medium-crystalline argillaceous limestone with glauconite, phosphate pellets, and chert nodules as minor constituents. In outcrop the unit ranges in thickness from a feather edge to a maximum of 25 feet, but thickens to 120 feet in the subsurface of southwestern Posey County (fig. 74).

The North Vernon Limestone contains a Middle Devonian fauna with affinities to the Hamilton Group of New York and the northern Appalachian basin and is correlated with the Sellersburg Limestone of Kentucky and the Traverse Group of the Michigan basin (plate 1).

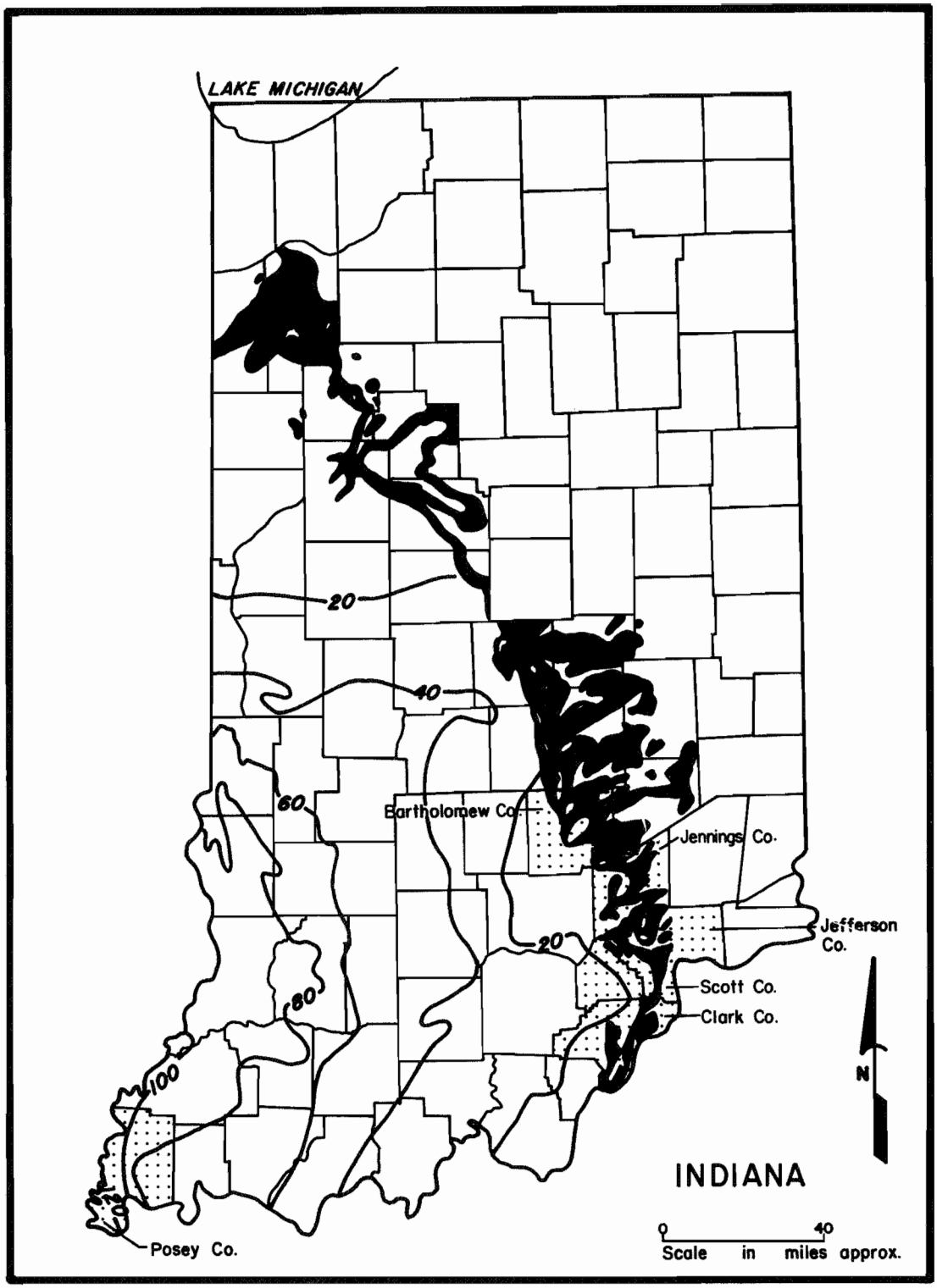


Figure 74. Map showing thickness of North Vernon Limestone. After Lineback (1970).

Upper Devonian

Illinois

New Albany Shale Group (cont. from page 138)

Sylamore Sandstone. The Sylamore Sandstone (Penrose, 1981) is the basal Upper Devonian formation in parts of central and western Illinois. The unit is named for exposures along Sylamore Creek, Stone County, Arkansas. The sandstone occurs over much of northern and western Illinois. Maximum thickness is approximately 3 feet, but the more common thickness is only a few inches. Typically, the Sylamore consists of rounded to subrounded, medium- to coarse-grained calcareous, or dolomitic, argillaceous sandstone. Phosphate nodules, conodonts, fish teeth and phosphatic brachiopods are common inclusions. Excpet in extreme southwestern Illinois and the area of the Sangamon arch, where the Sylamore Sandstone overlies Silurian carbonates, the unit overlies limestones of Middle Devonian age (Lingle, Cedar Valley) and marks the unconformity at the base of the New Albany Shale. The thin, persistent nature of the Sylamore clearly indicates deposition along the shore of a transgressive sea.

Conodont faunas suggest a correlation between the Sylamore and one or more of the sandy beds in the Upper Blocher or Lower Selmier (Sweetland Creek) Shales. Collinson and others (1967) correlate the Sylamore with the Hardin Sandstone, the basal member of the Chattanooga Shale in the Tennessee portion of the Appalachian basin. Within the stratigraphic framework of the New York standard reference section, the Blocher Formation correlates best with the interval occupied by the Tully Limestone of New York and the northern Appalachian basin (plate 1).

Selmier Shale. Lineback (1968, 1970) named the Selmier Member of the New Albany Shales for exposures in the Berry Materials Company quarry at North Vernon, Indiana near the Selmier State Forest in Jennings County, Indiana. At the type New Albany section for the Illinois basin, the distinctive olive-gray and black shales occurring in the interval between the Grassy Creek and Blocher Shales, referred to as an "unnamed shale" by Meents and Swann (1965), were assigned to the Sweetland Creek Shale by Collinson et al. (1967) and North (1969). Bassett and Hasenmueller of the Indiana Geological Survey demonstrated that the Selmier of Lineback (1968, 1970) on the Indiana outcrop is traceable into only the upper portion of this distinctive olive-gray and black unit in the Illinois basin. Detailed correlations indicated the Sweetland Creek Shale of western Illinois is stratigraphically higher than the "unnamed shale" of southeastern Illinois and that most of the Sweetland Creek grades laterally westward into the lower part of the Grassy Creek shales in southeastern Illinois. These stratigraphic relationships are shown on figure 75.

The Selmier, as revised by Cluff and others (1981), is composed of greenish-gray, gray and black shales which underlie the black shales of the Grassy Creek Shale and overlie the calcareous black shale of the Blocher in conformable stratigraphic relationship. The unit, which has a thickness of 17.5 feet at the type section, reaches a maximum thickness of greater than 200 feet in Hardin County, Illinois (fig. 76).

Sweetland Creek Shale. The name Sweetland Creek Shale was used by Udden (1899) to describe all the Devonian Shale exposed at Sweetland Creek in Muscatine County, Iowa. Workman and Gillette (1956) discarded Sweetland Creek and redefined Grassy Creek Shale

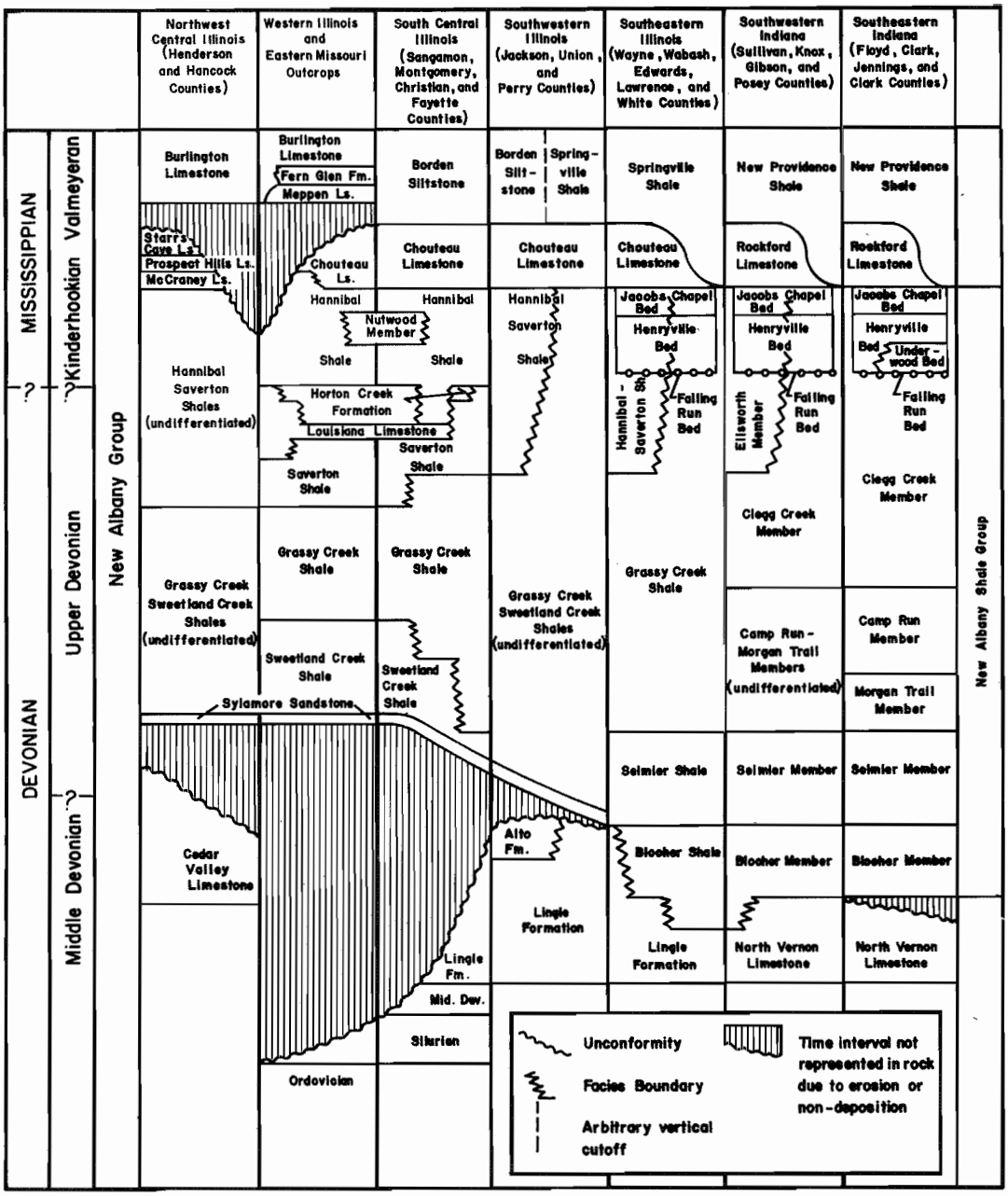


Figure 75. Physical correlation diagram of the New Albany Shale across the Illinois basin. After Cluff and others (1981).

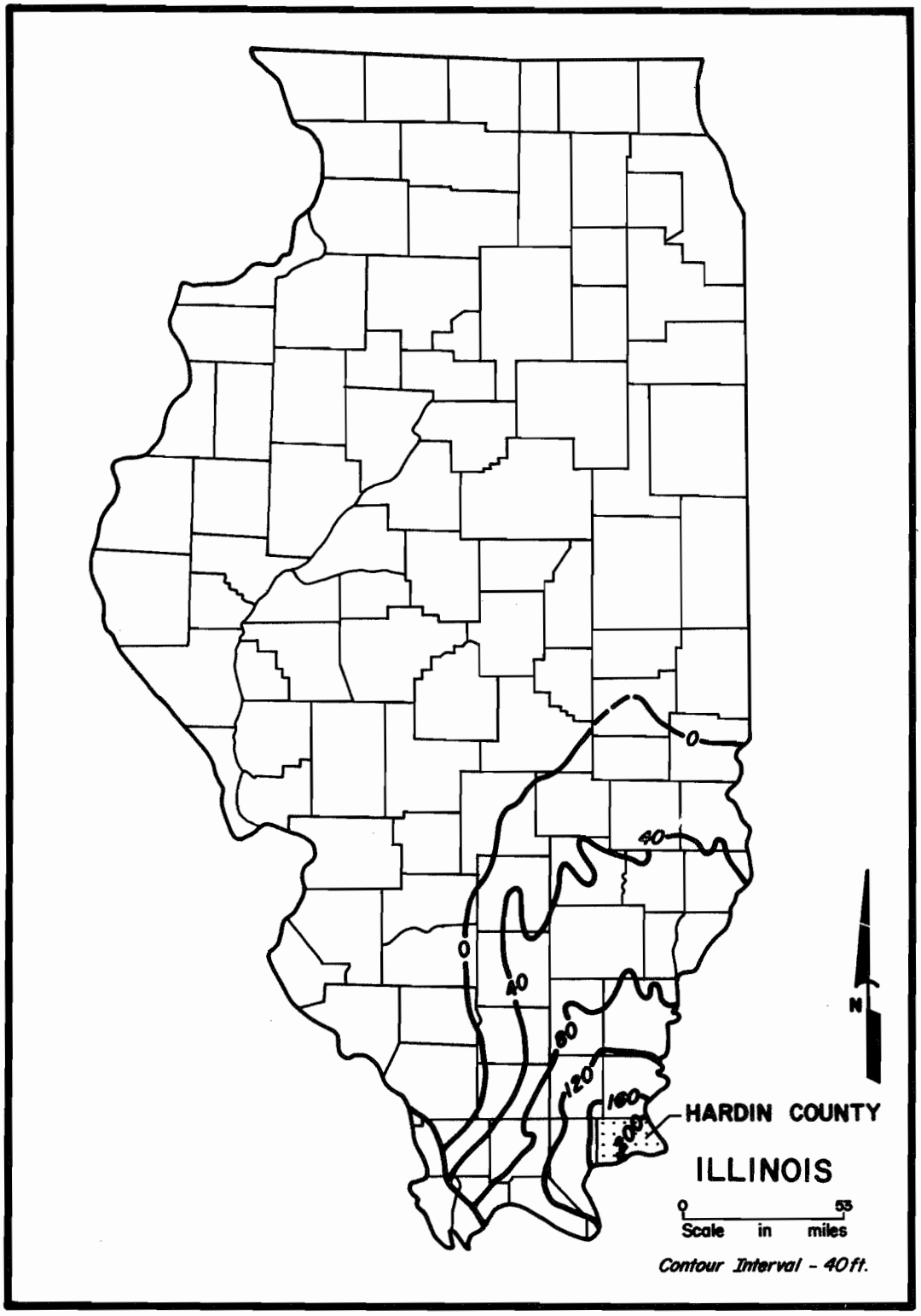


Figure 76. Thickness and distribution of the Selmier Shale in Illinois. After Cluff and others (1981).

to include the Sweetland Creek beds. Collinson et al. (1967) restrict the Grassy Creek to the dominantly black and brownish-black shales and reinstated the term Sweetland for the underlying olive-gray and green shales and extended the term eastward into the Illinois basin to include the "unnamed shale" of Meents and Swann (1965). The formation consists of alternating beds of dark greenish-gray, grayish-green shales with minor amounts of olive-gray to olive-black shale. Organic content of the shales ranges from 1 to 3 percent. The unit is poorly bedded, thickly or poorly laminated shale, moderately bioturbated, with few or no burrows. The Sweetland Creek Shale is distinguished in the subsurface in central Illinois and parts of southwestern Illinois, but is not differentiated from the Grassy Creek Shale in the southeastern Illinois portion of the Illinois basin.

Grassy Creek Shale. The Grassy Creek Shale was named by Keyes (1898) for exposures in Grassy Creek, Pike County, Missouri. Originally the unit included all black, gray and green shale above the Cedar Valley Limestone and below the Louisiana Limestone. Keyes (1912) later differentiated the upper gray shale as Saverton Shale. The Grassy Creek was further restricted by Collinson et al. (1967) by assigning the lower gray and green shale to the Sweetland Creek Shale. The unit was correlated from the western, southwestern and central portions of Illinois into the Illinois basin by Collinson et al. (1967) and North (1969). As currently defined, the Grassy Creek is restricted to the predominantly black shale interval in the middle and upper part of the New Albany Shale Group (Cluff and others, 1981). In the Illinois basin the formation consists of brownish-black to grayish-black, thinly laminated, pyritic, carbonaceous shales whose organic carbon contents range from 4 to 15 percent by weight. Characteristically the unit is composed of even planar-parallel laminae 20 microns to 1 millimeter thick which are composed of silt-sized quartz and feldspar grains that are tightly cemented by carbonate and pyrite. Other laminae are composed of concretrations of amorphous organic matter, Tasmanites, and pyrite. The Grassy Creek Shale reaches a maximum thickness of 160 feet in eastern Hardin County, Illinois and adjacent Kentucky (fig. 77).

The Grassy Creek Shale of southeastern Illinois is probably the physical and time equivalent of the Morgan Trail, Camp Run and Clegg Creek Member of the Indiana New Albany sequence (plate 1).

Saverton Shale. The Saverton Shale (Keyes, 1912) is named for the town of Saverton, Ralls County, Missouri. It consists of alternating beds of greenish-gray, dark greenish-gray and olive black shales of low organic content, ranging from 0.3 to 3 percent by weight. The greenish-gray to olive black shales are characterized by thin-discontinuous planar-parallel laminae composed of alternately high and low concentrations of organic matter. The greenish-gray beds are generally non-laminated. The upper portion of the unit usually consists of massive, bioturbated, greenish-gray mudstone with less than 1 percent organic carbon. The Saverton is recognized as a distinct formation only in central and western Illinois and cannot be mapped separately from the overlying Hannibal Shale where the intervening Louisiana and Horton Creek units are missing.

Because of the complicated facies relationships with underlying and overlying formations, the Saverton is probably the most difficult of all the New Albany formations to correlate. Across the area of distribution the upper and lower boundaries of the formation shift vertically in the section. The Saverton conformably overlies the Grassy Creek and grades laterally towards the south and east into the upper part of the Grassy Creek.

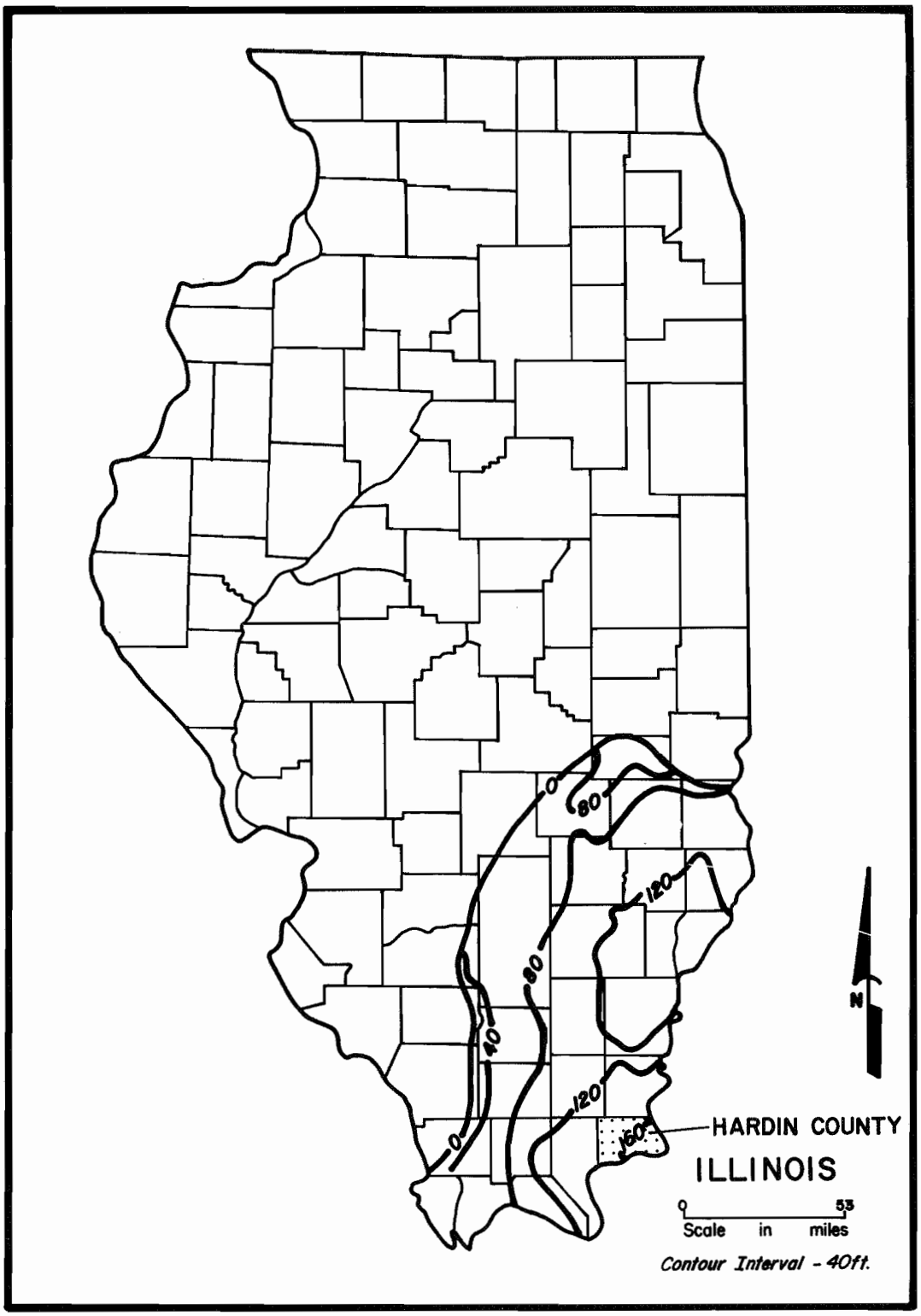


Figure 77. Thickness of Grassy Creek Shale in Illinois. After Cluff and others (1981).

In the Illinois basin the Saverton Shale is correlative, in part, with the Clegg Creek Member of the New Albany Formation of Indiana and the upper portion of the Grassy Creek Member in Kentucky. The Saverton is equivalent to the upper part of the Antrim formation in the Michigan basin, the Cleveland Member of the Ohio Shale in Ohio and the west central portion of the Appalachian basin, and the Chattanooga Shale of Tennessee and northeastern Alabama (plate 1).

Louisiana Limestone. The Louisiana Limestone was named by Keyes (1892) for exposures along the banks of the Mississippi River in the vicinity of the town of Louisiana, Pike County, Missouri. The formation is a light tan to light gray, fossiliferous, irregularly-bedded, micritic limestone containing thin interbeds of shales and dolomites. Recognizable Louisiana Limestone is restricted to western Illinois and cannot be identified in the Illinois portion of the Illinois basin.

Horton Creek Formation. The name Horton Creek Formation was proposed by Conklin and Conklin (1973) for exposures of limestones, siltstones, sandstones, and shales originally placed in the "Glen Park" Formation of Illinois and designated the basal member of the Hannibal Shale in western Illinois. The type section is in the south bank of Horton Creek, Sec. 6, T. 6 S., R. 5 W., Pike County, Illinois. The formation is composed of siltstones, shales, sandy limestones, micritic limestones, oolitic limestones, limestone conglomerates and dolomites. The clastic deposits included in the Horton Creek are similar to Hannibal and Upper Saverton Shales, and consist of light to dark greenish-gray, highly bioturbated, calcareous, generally unfossiliferous shales and siltstones. The carbonates are tan to gray, argillaceous, sparsely fossiliferous, micritic limestone and dolomites.

The Horton Creek can be distinguished as a separate formation only in the central and west-central Illinois where it attains a maximum thickness of 60 feet. In the Illinois basin the unit cannot be identified and separated from within the Saverton-Hannibal Shale sequence.

Lithostratigraphic studies indicate that the shales and siltstones occurring between the Louisiana Limestone and the Hamburg Oolite Bed, assigned to the Horton Creek, are laterally equivalent with the upper part of the Devonian Louisiana Limestone and the Saverton Shale. Conodont evidence has not been successful in defining the Horton Creek as either latest Devonian or earliest Mississippian or in determining if the formation straddles the boundary.

Hannibal Shale. The Hannibal Shale was named by Keyes (1982) for exposures along the Mississippi bluffs at the city of Hannibal, Marion County, Missouri. The sequence of rocks was raised to group status in western Illinois by Workman and Gillette (1956) and subdivided into the Glen Prk, Maple Hill and English River Formations. Collinson (1961) returned the Hannibal Shale to its original formational status. The Hannibal is composed of greenish-gray, grayish-green to yellow-green mudstones and shales with an organic carbon content at less than 1 percent. The mudstones, mostly silty clay shales, generally have a high silt content consisting principally of quartz, feldspar, dolomite and coarse-grained mica. Abundant bioturbation and lack of primary sedimentary structure, bedding and lamination are characteristic of the Hannibal mudstones. The Hannibal attains a maximum thickness of 110 feet in western Illinois where it can be mapped as a distinct

formation. Because the Louisiana Limestone and Horton Creek are not identifiable in the Illinois basin, the Hannibal cannot be separated from the Saverton. The thickness of the combined Hannibal Shale-Horton Creek Formation-Louisiana Limestone-Saverton Shale interval ranges from 160 feet in central Illinois to just over 30 feet in the Illinois basin (fig. 78).

Based upon conodont studies, Collinson et al. (1971) place the base of the Mississippian near the base of the Hannibal shale. The Devonian-Mississippian boundary is located within the Hannibal-Saverton interval at the base of the greenish-gray shales in the upper part of the interval.

The New Albany Shale Group of Illinois and the New Albany Shale of Indiana and Kentucky are correlative for the most part throughout the Illinois basin. The Blocher and Selmier Formations of Illinois are essentially equivalent to the Blocher Member and the Selmier Member of southwestern Indiana and northwestern Kentucky. The Morgan Trail and Camp Run members of the New Albany Formation in Indiana are equivalent to the Grassy Creek Member of Kentucky, and the Grassy Creek and Sweetland Creek Formations of southeastern Illinois. The upper units of the Illinois New Albany sequence, the Saverton, Louisiana, Horton Creek and Hannibal, are equivalent with the Clegg Creek Member of the New Albany in Indiana and the upper part of the Grassy Creek member in Kentucky (plate 1).

Indiana

New Albany Shale. Borden (1874) proposed the name "New Albany black slate" for the sequence of slatelike rocks lying above the crinoidal limestone and capped by a ferruginous limestone (Lineback, 1970). The type area is along the Ohio River at New Albany, Floyd County, Indiana (fig. 79). The formation later became known as the New Albany Shale in references by Batchley and Ashley (1898) and Ashley (1899) and included the sequence of black shales occurring between the Sellersburg Limestone below and the Rockford Limestone above. Campbell (1946) elevated the New Albany Shale to group status and subdivided the sequence into formations and members using paleontologic, lithologic and joint pattern criteria. Since many of Campbell's subdivisions proved unmappable over even short distances, formational and member rankings seemed inappropriate. Lineback (1968) reassigned formation rank to the New Albany and subdivided the formation in southeastern Indiana and northern Kentucky into five lithologically distinct, laterally persistent units of member rank. The shale members in ascending order are: (1) Blocher, (2) Selmier, (3) Morgan Trail, (4) Camp Run and (5) Clegg Creek. The New Albany is composed primarily of dark brown to black, organic-rich and greenish-gray, organic-poor shales with minor amounts of sandstone, siltstone, pyrite and dolomite. The black shale facies dominates in southwestern Indiana and the greenish-gray shale facies occurs primarily in the northern portion of the Illinois basin and the western part of the Michigan basin. In outcrop, near the type section, the New Albany attains an approximate thickness of 100 feet. Over its areal extent in Indiana, the unit ranges in thickness from 85 feet in Harrison County to 309 feet in Posey County (fig. 79).

The Blocher Member of the New Albany Shale was first named by Campbell (1946) for exposures near Blocher, Scott County, Indiana (SW¼ Sec. 9, T. 3 N., R. 8 E.) (fig. _____). As defined by Lineback, the Blocher corresponds to the formation as defined by Campbell (1946) except that the upper boundary occurs at the base of the greenish-gray

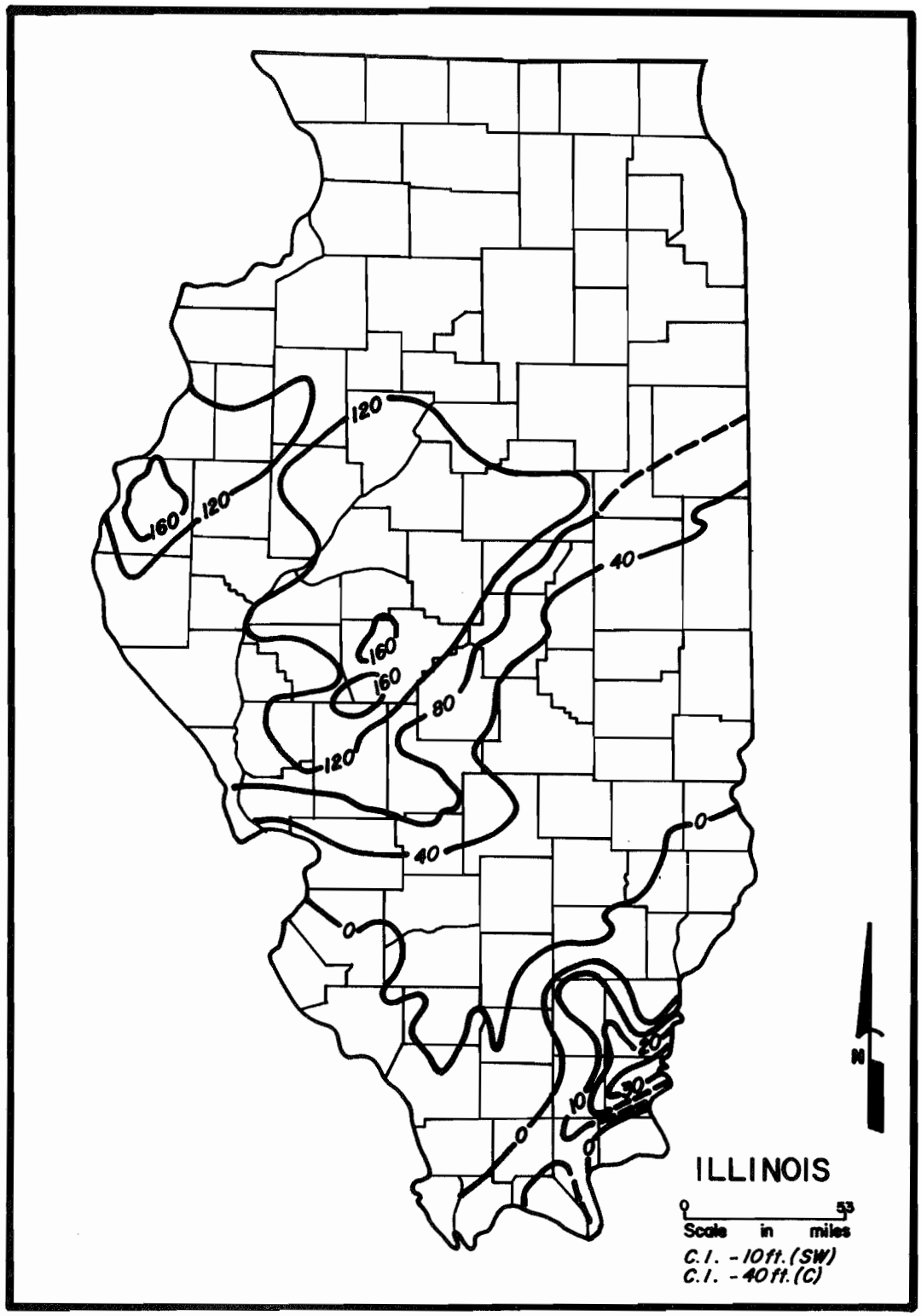


Figure 78. Combined thickness of Hannibal Shale-Horton Creek Formation-Louisiana Limestone-Saverton Shale in Illinois.

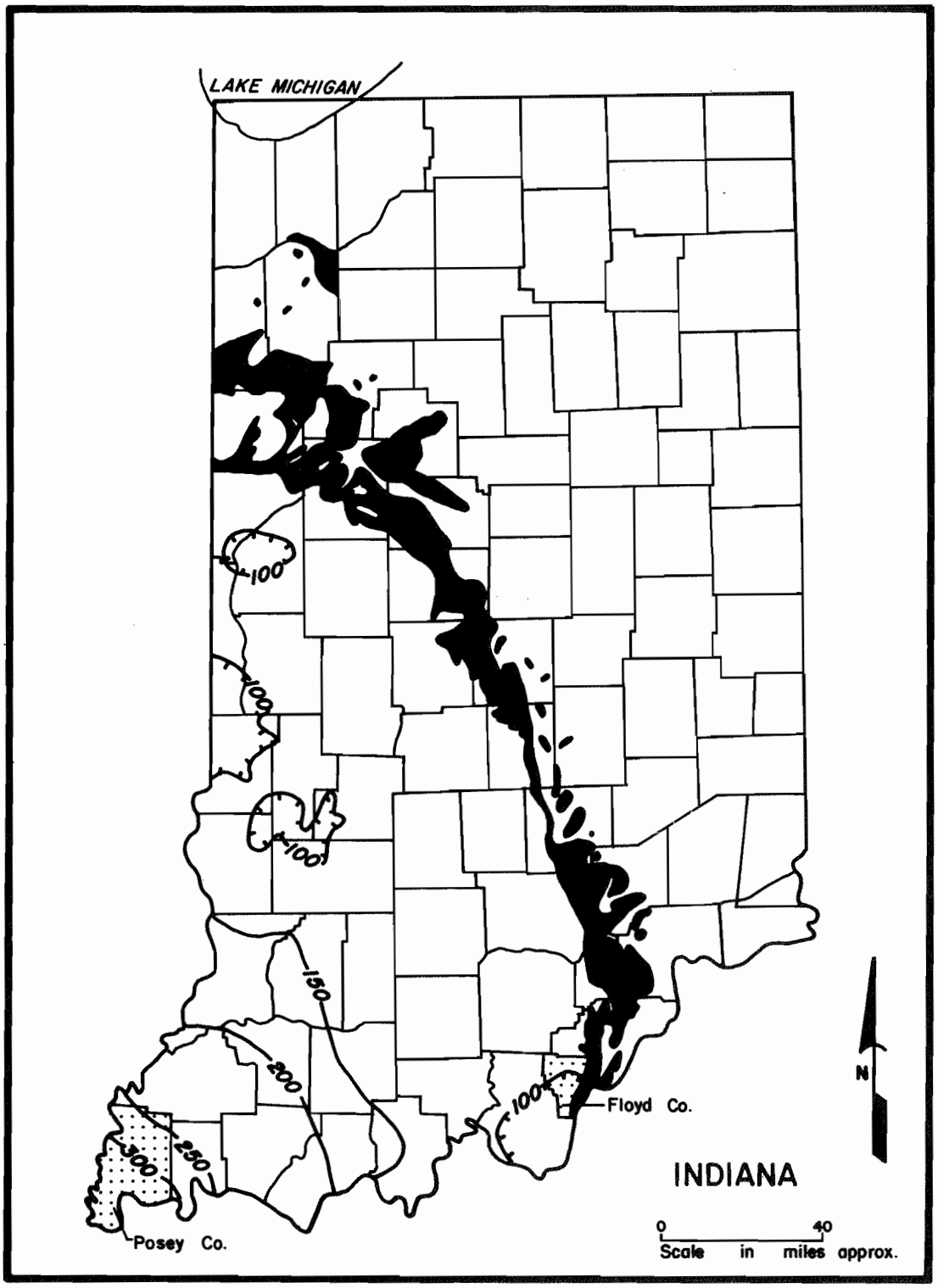


Figure 79. Map showing thickness of New Albany Shale. After Lineback (1970).

shale of the Selmier Member. The Blocher Member is composed of carbon-rich, dark brown to black shale with an organic content ranging from 10 to 20 percent. The black shales are interbedded with micritic dolomites, which range up to 1 foot thick and emit a petroliferous odor when freshly broken. Dolomicritic concretions and lenticular beds of dolomitic quartzose are present in the member locally. The Blocher, 3 to 15 feet thick in the outcrop area, attains a maximum thickness of 85 feet in extreme southwestern Indiana (fig. 80).

The black, carbon-rich limestone which occurs locally at the base of the Blocher is considered the equivalent of the Alto Formation of Illinois.

The term Selmier Member of the New Albany Shale of Indiana, as defined by Lineback (1968), applies to the greenish-gray mudstone that overlies the Blocher Member along the south wall of the Berry Materials Company quarry at the north edge of North Vernon, Jennings County, Indiana (fig. 81). The name originates from the Selmier State Forest one mile northeast of the type section. The Member consists of greenish-gray mudstones with thin interbeds of brownish-black and olive-brown fissile shale, dolomite, dolomitic sandstone, and concretionary dolomites. The formation reaches approximately 50 feet in thickness in the subsurface of southwestern Indiana (fig. _____).

The Selmier is correlative, in part, with the Sweetland Creek Shale in central and western Illinois and the Antrim shale of the Michigan basin. Tentative correlation is made with the Genesee and Sonyea Formations of New York, Pennsylvania, and West Virginia and the lower part of the "Upper Olentangy" of Ohio and eastern Kentucky (plate 1).

The name Morgan Trail Member was proposed by Lineback (1968) for brownish-black, carbon-rich, fissile, quartzose, pyritic beds occuring above the Selmier at the same type locality as for the Blocher, Scott County, Indiana (NW½, Sec. 16, T. 3 N., R. 8 E.) The name comes from a roadside park commemorating the Civil War Confederate raider, John Hunt Morgan. The member ranges in thickness from 24 to 20 feet, increasing in thickness as the Selmier member thins. The Morgan Trail is not recognized in the subsurface because the diagnostic features of the member are not identifiable from well cuttings.

The member is, in part, equivalent with the Antrim of the Michigan basin and the lower part of the Grassy Creek Shale in the Illinois portion of the Illinois basin (plate 1).

The Camp Run Member was named by Lineback (1968) for exposures along the south side of U.S. Highway 31W at the Interstate Highway 65 overpass west of Sellersburg (SE¼, Lot 110, Clark's Grant), Clark County, Indiana (fig. 82). The member is named for a small creek which flows northeast of the type section. The Camp Run is composed of interbedded greenish-gray to olive-gray mudstone and shale and brownish-black, carbon-rich, fissile, pyritic shale. The greenish-gray beds, ranging in thickness from less than 0.1 feet to 1.1. feet, are separated by brownish-black beds 0.4 to 4.5 feet thick. The Camp Run Member, which cannot be identified in the subsurface, has a thickness ranging from 14 to 18 feet in the outcrop section.

The Camp Run is correlative, in part, with the Antrim/Ellsworth sequence in the Michigan basin, the upper part of the Grassy Creek shale in Illinois and Kentucky and the Ohio Shale in the subsurface of Ohio, West Virginia, and Eastern Kentucky (plate 1).

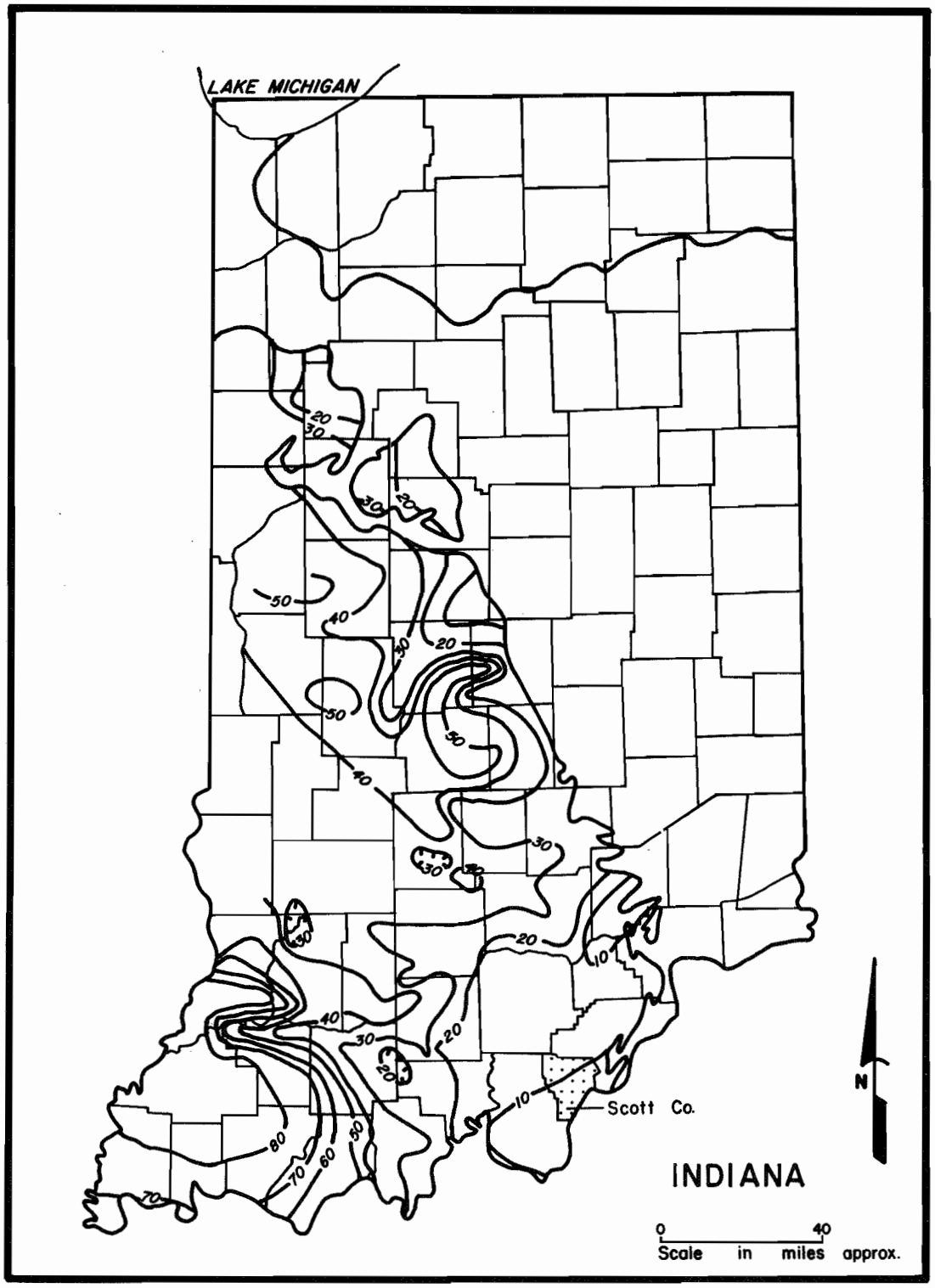


Figure 80 .Thickness of the Blocher Shale in Indiana. After Lineback (1970).

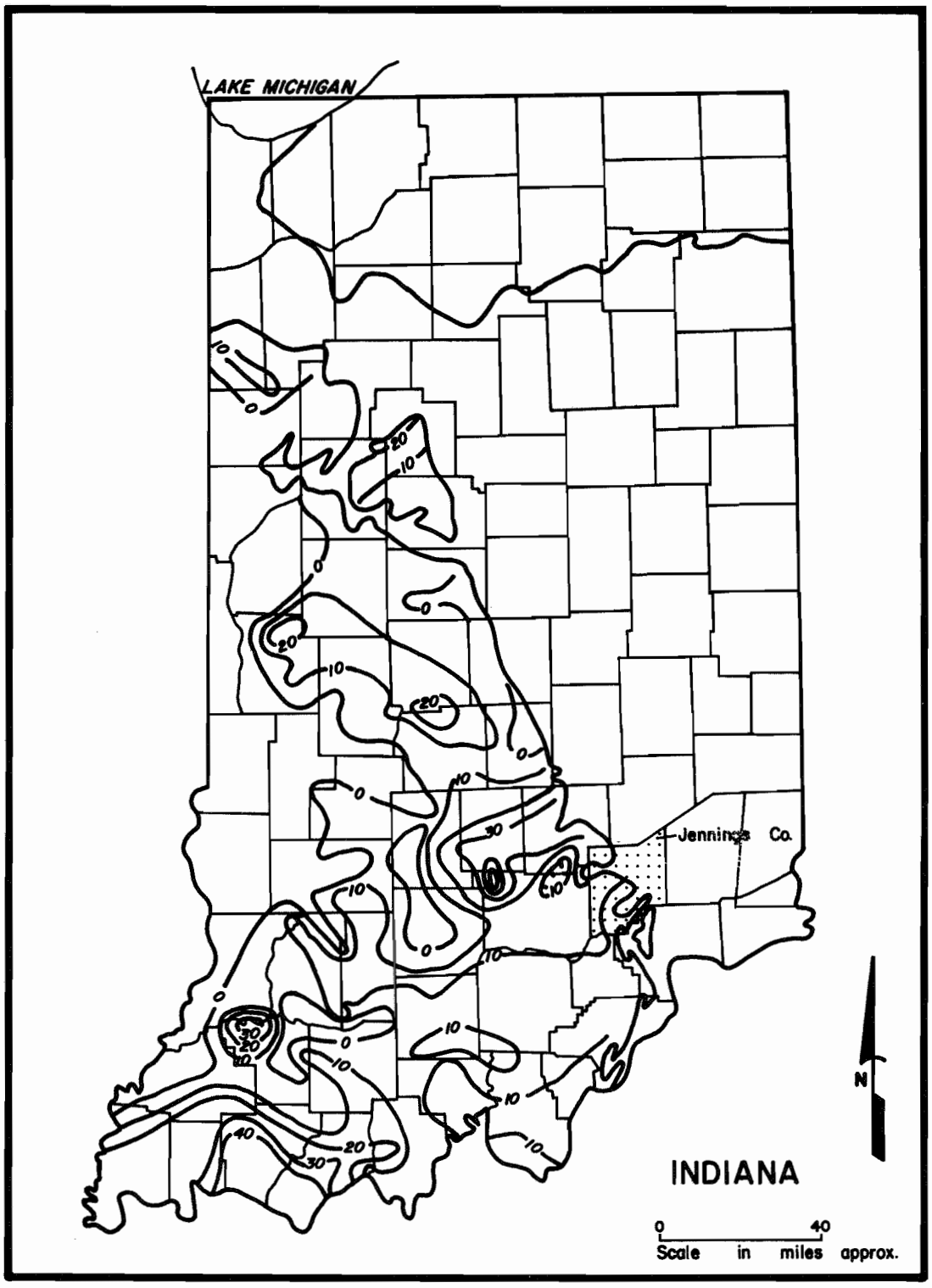


Figure 81. Thickness of the Selmier Shale in Indiana. After Lineback (1970).

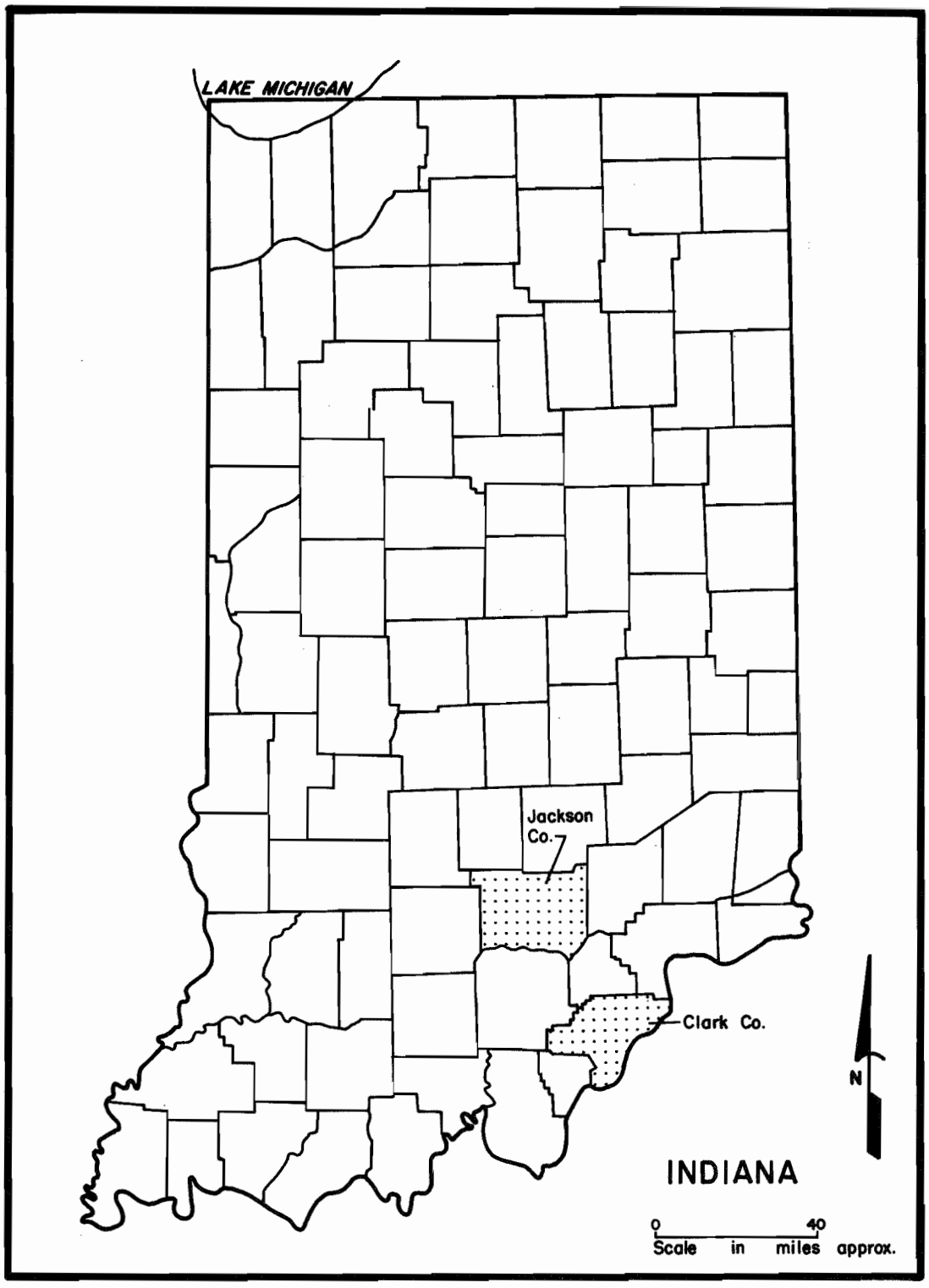


Figure 82. Index map identifying localities referenced in the stratigraphic discussion of the Camp Run and Clegg Creek Members of the New Albany Shale in Indiana.

The Clegg Creek Member was named by Lineback (1968) for exposures in a road cut along Indiana Highway 160 (N¼, E¼, Lot 240, Clark's Grant) two miles southeast of Henryville, Clark County, Indiana (fig. 82). The name is taken from a tributary to Silver Creek, approximately two miles upstream from the type locality. The Clegg Creek Member is a massively bedded, brownish black, carbon-rich, fissile, quartzose, pyritic shale with a few greenish-gray shale and mudstone beds near the top. The unit, which cannot be recognized in the subsurface, is 42 feet thick in Clark County and 60 feet thick in Jackson County.

The Clegg Creek Member grades laterally into the greenish-gray shale sequence of the Ellsworth shale in the Indiana portion of the Michigan basin and is equivalent, in part, with the Saverton-Hannibal shale sequence in Illinois, the Ohio Shale in the subsurface of Ohio, West Virginia and eastern Kentucky and the Chattanooga Shale of central Tennessee and northeastern Alabama (plate 1). Faunal evidence indicates a late Devonian age for most of the Clegg Creek, but that the upper few feet of the unit are early Mississippian (Kinderhookian) in age.

The Middle and Upper Devonian stratigraphic framework adopted for the Kentucky portion of the Illinois basin is a combination of terms used in Indiana and Illinois. Middle Devonian stratigraphic terms are extensions of Indiana terminology into Kentucky, while the Upper Devonian terms were derived primarily from the Illinois stratigrahic framework. The physical stratigraphy and correlations of these units have previously been described within the Illinois and Indiana discussions and will not be repeated for Kentucky.

The thickness and distribution of the Middle Devonian rocks and the Upper Devonian (New Albany Shale) for the Illinois basin are shown on figures 83 and 84.

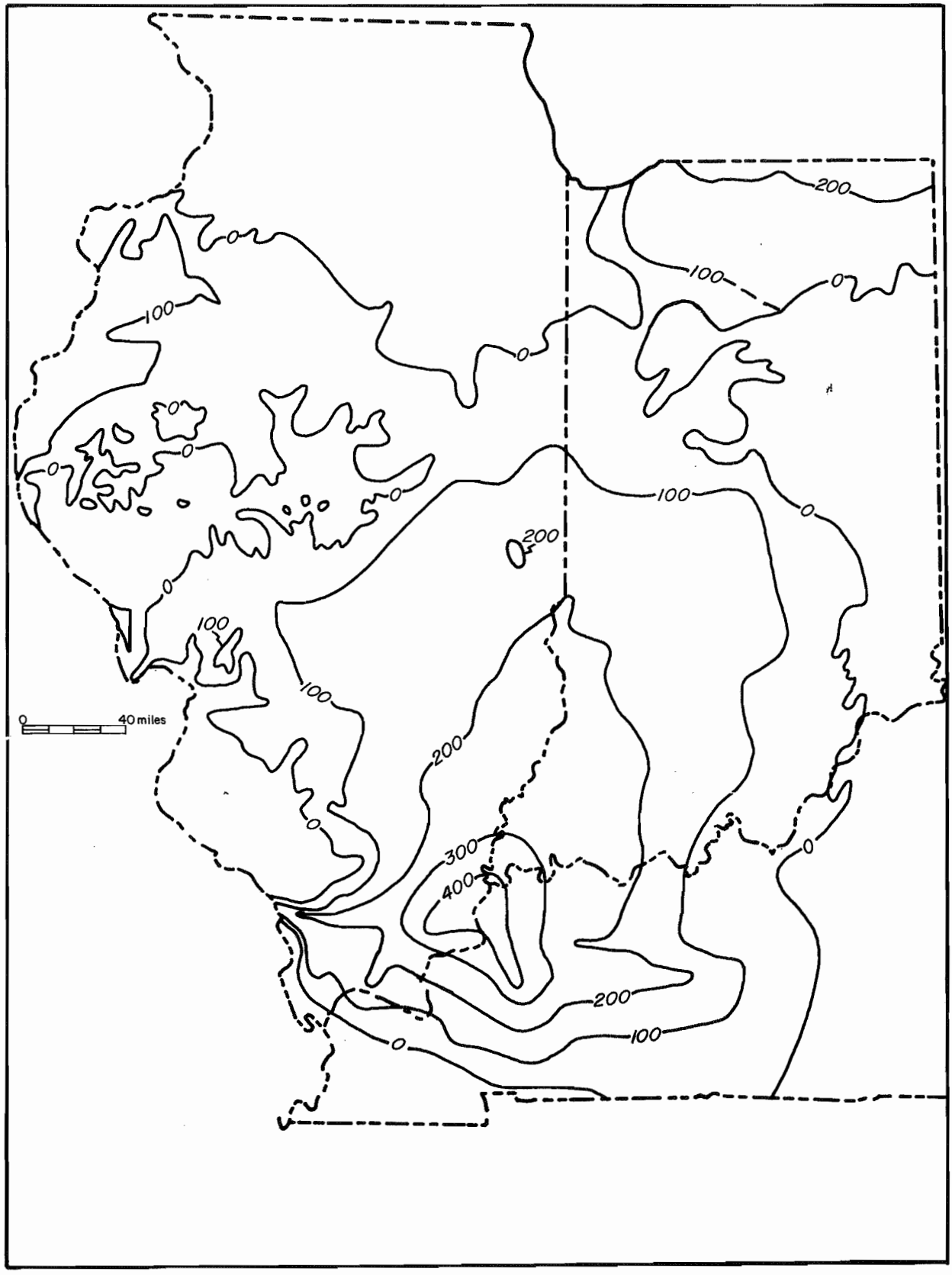


Figure 83. Thickness of Middle Devonian rocks in the Illinois basin. Modified from Collinson et al. (1967).

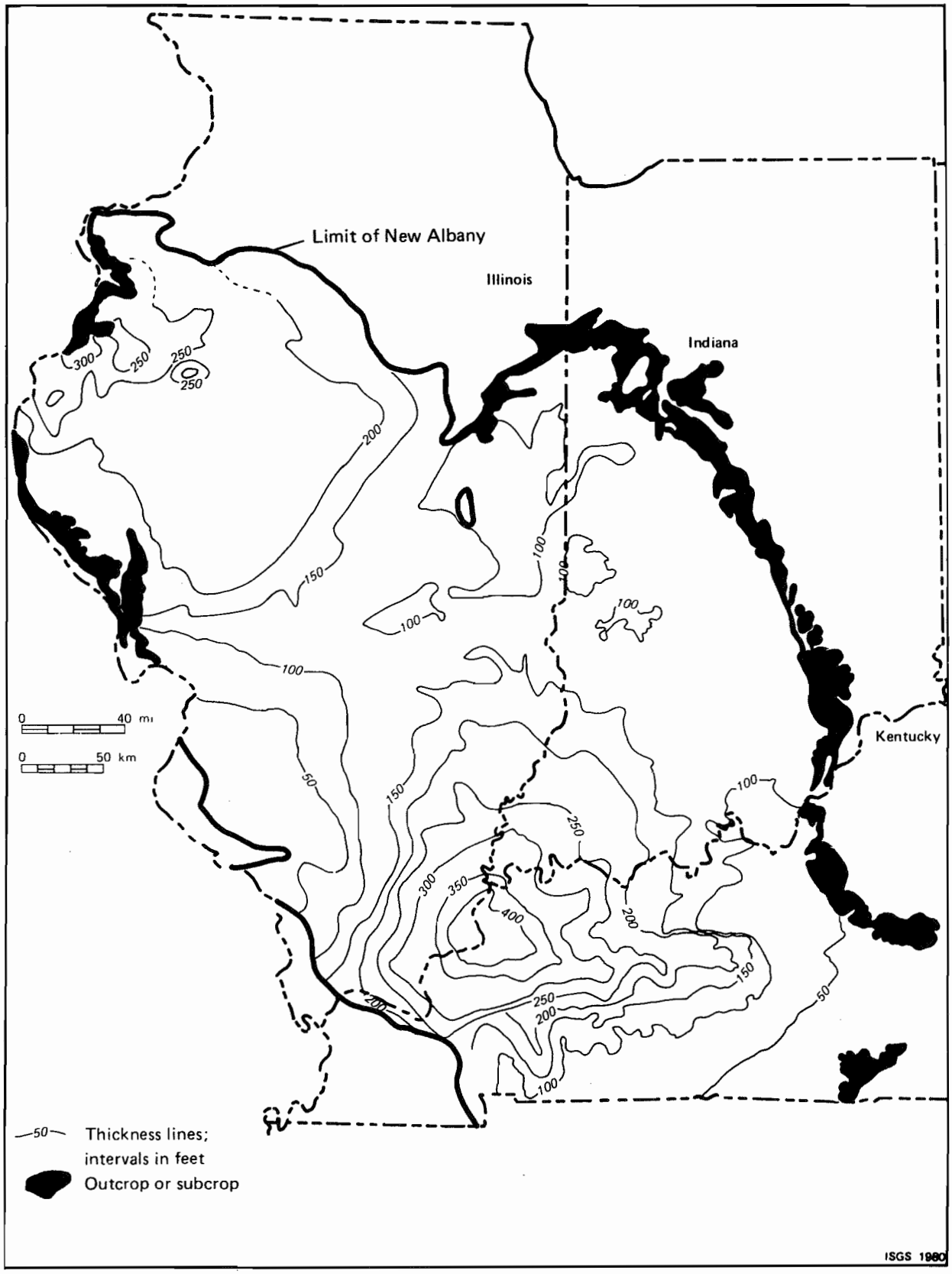


Figure 84. Thickness of the New Albany Shale Group in the Illinois basin. After Reinbold (1978), Bassett and Hasenmueller (1978), and Schwalb and Potter (1978).

UNCONFORMITIES, DIASTEMS, AND HARDGROUNDS

Introduction

Several discontinuities are recognized within the Middle and Upper Devonian sequence by Eastern Gas Shales Project workers. These disconformable surfaces formed as a result of a combination of sea-level fluctuation and tectonic activity. These hiatuses are frequently and easily recognized along the basinal margins. Breaks in the record which approach the basin centers are less frequent, but of greater significance because their development signifies a major withdrawal of the epicontinental sea.

The stratigraphic framework developed and used by various Eastern Gas Shales Project researchers recognizes, in general, unconformities at the base of the Onesquethaw Stage and in the Taghanic Stage, separating the Middle and Upper Devonian. These unconformities represent major eustatic sea-level variations of extended duration which resulted in erosion and/or nondeposition within the basins. Unconformities of less regional extent are recognized along the cratonic margins of individual basins and are considered to have developed in response to more local, subtle sea-level oscillations.

In addition to the development of regional unconformities that separate the Middle and Upper Devonian, numerous minor discontinuities are present due to nondeposition. These breaks, referred to as diastems, are considered to be most numerous along the margins of the stable craton and diminish in extent and number toward the center of the subsiding basin. Diastems are difficult, at best, to recognize in the subsurface because of the lack of stratigraphic and paleontologic control. Other shorter gaps in sedimentation, where the mud-water interface has been lithified as a result of chemical and biological activity, are referred to as hardgrounds. These breaks in sedimentation are of limited areal extent and have not generally been recognized in outcrop or subsurface sections by Eastern Gas Shale Project investigators.

Factors to be considered in recognizing and evaluating these types of disconformities include the: (1) nature of the materials between surfaces, (2) duration, (3) paleontological variation between the surfaces, (4) areal extent and, (5) the reasons for development. In general, identification of minor disconformities by Eastern Gas Shales Project workers has been limited to the outcrop. Major disconformities, also recognizable in surface outcrops, have been recognized and projected into the subsurface by Eastern Gas Shales Project investigators on the basis of evidence available from examination of well samples, fossils and geophysical logs. Plates 2 through 11 show the stratigraphic positions of the more extensive major Middle and Upper Devonian unconformities recognized by Eastern Gas Shales Project investigators in the Appalachian, Illinois, and Michigan basins. Figure 85 shows the location of these cross sections.

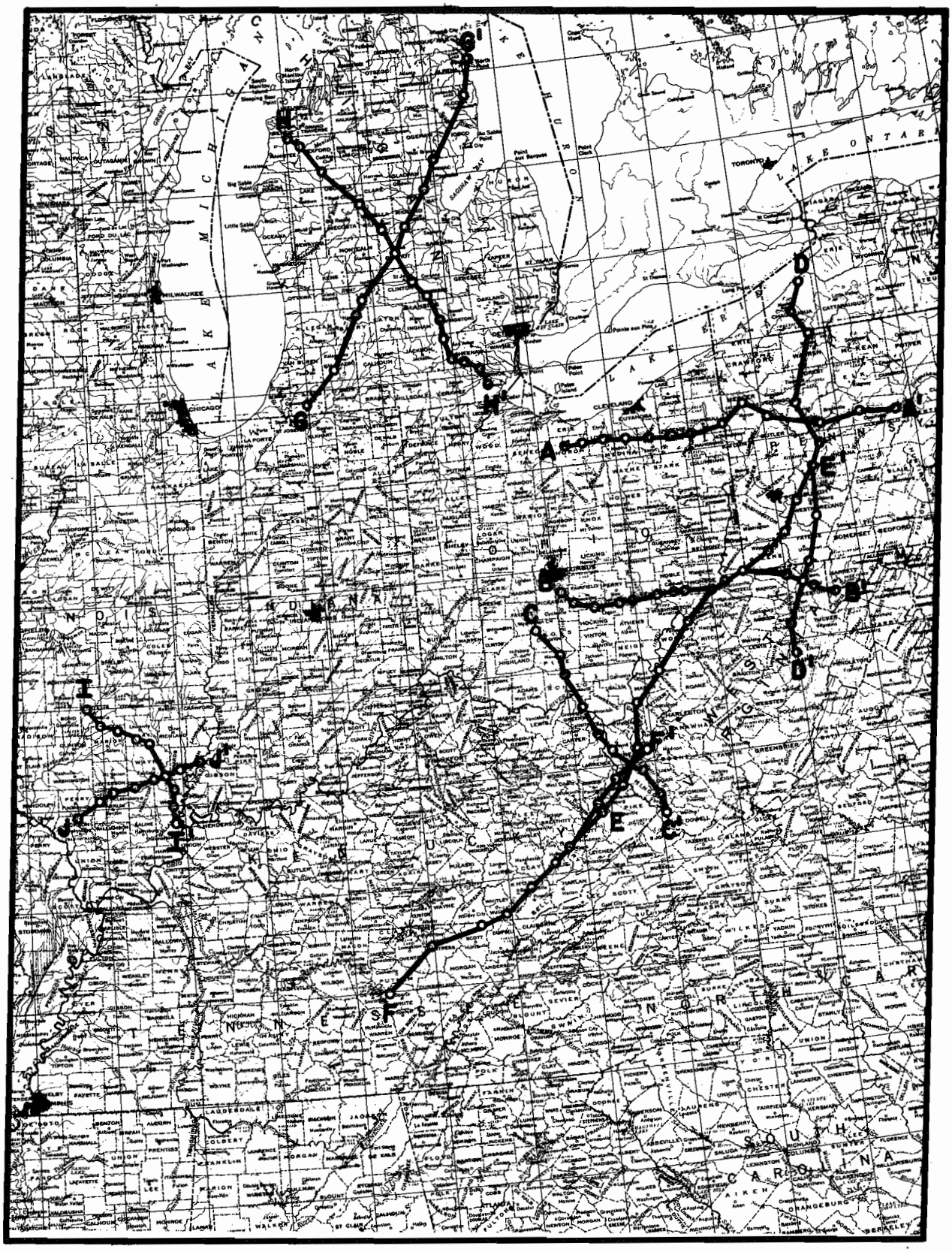


Figure 85 . Index map showing locations of cross sections, plates 2 through 11 in appendix.

Appalachian Basin

During the Middle and Upper Devonian period the Appalachian basin was a relatively shallow, elliptical, northeast-southwest oriented basin which received most of its clastic sediment from an eastern source. The subsiding basin is outlined by a series of disconformities along the southern, western and northern margins where rocks of successive stages lap onto the edge of the stable craton. Figure 86 is a detailed sea-level fluctuation curve of the Devonian System for the Appalachian basin generated by Dennison and Head (1975) and Dennison (1978). In the Appalachian basin local unconformities are interpreted to be the result of minor oscillations in sea-level, whereas major eustatic sea-level variations are responsible for the development of regionally extensive unconformities which record partial or complete withdrawal of the sea from the deeper portions of the basin. During the Deerpark Stage, withdrawal of the epicontinental sea resulted in a major lowering of sea level along much of the craton. This break in deposition, known as the Wallbridge Discontinuity, separates the Deerpark and Helderberg Stages (fig. 86). Large areas of the craton were exposed to subaerial erosion during this period, while deposition was restricted to the deeper areas of the basin in which the Appalachian seaway was still present. A rise in sea level during late Deerpark time is considered by many investigators (Wheeler, 1963; Oliver et al., 1967; Dennison, 1971; Dennison and Head, 1975) to reflect the initial pulsation of the Acadian orogeny and brought to a close the Wallbridge Discontinuity. Clastic deposition is represented by the Needmore Shale but was restricted to the deeper portions of the central Appalachian basin. However, because of limited distribution of the Needmore throughout the basin, the Eastern Gas Shales Project stratigraphers have agreed to consider the base of the Devonian-aged clastic sequence at the base of the Marcellus Shale rather than trying to correlate along the Wallbridge Discontinuity.

Along the southwestern and western margin of the present basin a disconformable surface is recognized between the Middle Devonian carbonate sequence (Onondaga) and overlying Devonian shales (Oliver et al., 1967; Schwietering, 1970; Tillman, 1970; Provo, 1977; Swager, 1978; Roen et al., 1978; Potter et al., 1982). A facies change from fine-grained clastic (Marcellus Shale) to carbonate (Delaware Limestone) is recognized in central Ohio along the western margin of the Appalachian basin. The disconformable surface between the Columbus (Onondaga equivalent) and Delaware Limestones, recognized in the central Ohio outcrop (Hoover, 1960; Dennison and Head, 1975), cannot be traced into the subsurface. This contact in the subsurface of New York (Rickard, 1964; Van Tyne et al., 1979) and in the deeper portions of the basin (Roen et al., 1978; Piotrowski and Krajewski, 1977; Majckszak and Honeycutt, 1980; and Schwietering, 1981) is considered to be conformable.

Sea-level fluctuations during the Middle Devonian Erian Series are recorded by the deposition of several thin limestones within the prograding Catskill delta complex in the northern portion of the basin. A drop in sea level during the late Tioughnioga-Taghanic Stages (fig. 86), considered to have developed in response to infilling of the basin, produced a major unconformity along the cratonic margins separating the Middle and Upper Devonian (Dennison and Head, 1975). Within the deeper portions of the basin, sedimentation appears to have been continuous where the Genesee Formation of New

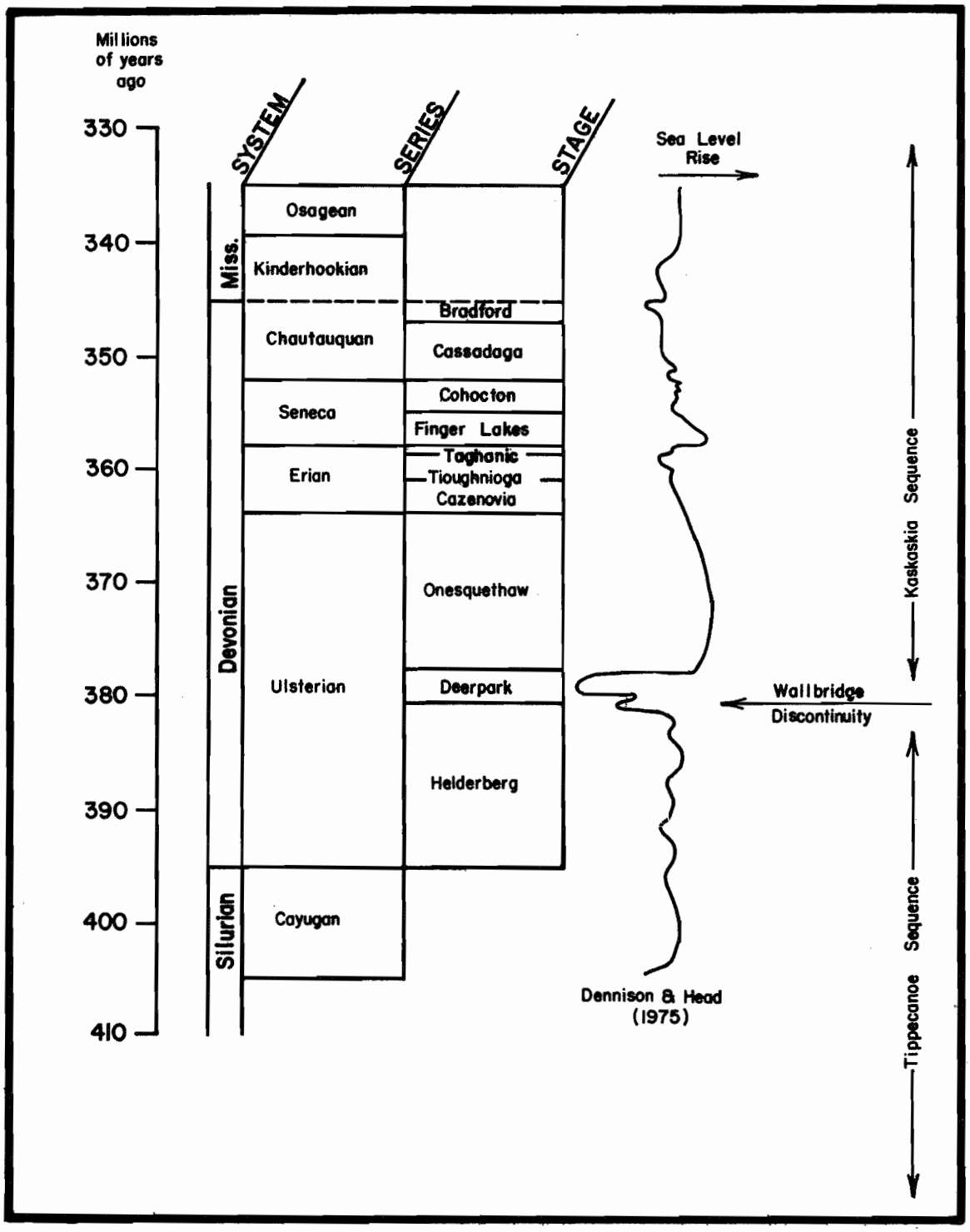


Figure 86. Sea-level fluctuation curve for Appalachian basin Upper Silurian, Devonian, and Lower Mississippian. After Dennison and Head (1975).

York conformably overlies the Middle Devonian-aged Tully Limestone. The recognition and placement of this unconformity along the basin margins and within the basin was based upon lithologic and faunal evidence (Oliver et al., 1967; Heckel, 1975; Rickard, 1975; Dennison and Head, 1975). Along the western boundary of the Appalachian basin the same unconformable surface divides the Olentangy Shale sequence into lower (Middle Devonian) and upper (Upper Devonian) members (Tillman, 1970). To the north the sea level drop is represented by a hiatus between the Tully Limestone and the underlying shales of the Hamilton Group (Heckel, 1975; de Witt and Colton, 1978). Heckel (1975) divided the Tully into an upper and lower member on the basis of a second unconformity he recognized and described from surface outcrops.

The Middle and Upper Devonian sequences are separated along the western and northwestern portions of the Appalachian basin by either a shale-on-shale or by a shale-on-limestone unconformity. In the eastern areas of the basin the boundary is marked by the conformable contact between the Tully Limestone and the overlying shale sequence. Plates 2 through 7 show this surface throughout the Appalachian basin. Figure 87 shows the supercrop of the Upper Devonian units upon the unconformable Middle Devonian surface which basinward becomes conformable at the aforementioned Genesee Formation-Tully contact. A structure contour map on the unconformity shows the relatively uniform nature of this surface (fig. 88). The potential for local disconformities within the Upper Devonian, possibly as diastems, exists along the western basinal margins in response to a combination of shifting deltas and sea-level fluctuation. One possible disconformity between the Upper Olentangy Shale and the overlying Ohio Shale sequence was noted in the outcrop by Tillman (1970). However, recognition of these potential shale-on-shale disconformities within the Devonian sequence are limited and poorly documented.

Michigan Basin

The Michigan basin is a relatively shallow intracratonic basin which extends into extreme northwestern Ohio and northern Indiana. The black shale sequence ranges from Upper Devonian through Lower Mississippian in age. However, in this report, discussion is confined to the Devonian-aged strata. Plate 1 shows the stratigraphic relationship within the Michigan basin and correlation with facies from the Appalachian and Illinois basin.

The Antrim Shale conformably overlies Upper Devonian Limestones in the center of the Michigan basin but along the basin margins the base of the unit unconformably overlies older Middle Devonian and carbonates. Cross sections throughout the Michigan basin show this relationship (Ells, 1978; Lilienthal, 1978). The upper contact between the Antrim/Ellsworth Shale and the overlying Bedford/Berea complex and their equivalents is considered conformable. Within the Devonian shales of the Michigan basin no discontinuities have been recognized (Tetra Tech, 1981).

Several discontinuities recognized in the Middle Devonian clastic sequence in the Appalachian basin are recognized within the Michigan basin carbonate sequence. One unconformable surface, developed during the Taghanic, separates Middle and Upper Devonian carbonates in the center of the basin and Middle Devonian carbonates from the Upper Devonian Antrim Shale along the basin margins. Cross sections G-G' and H-H' show

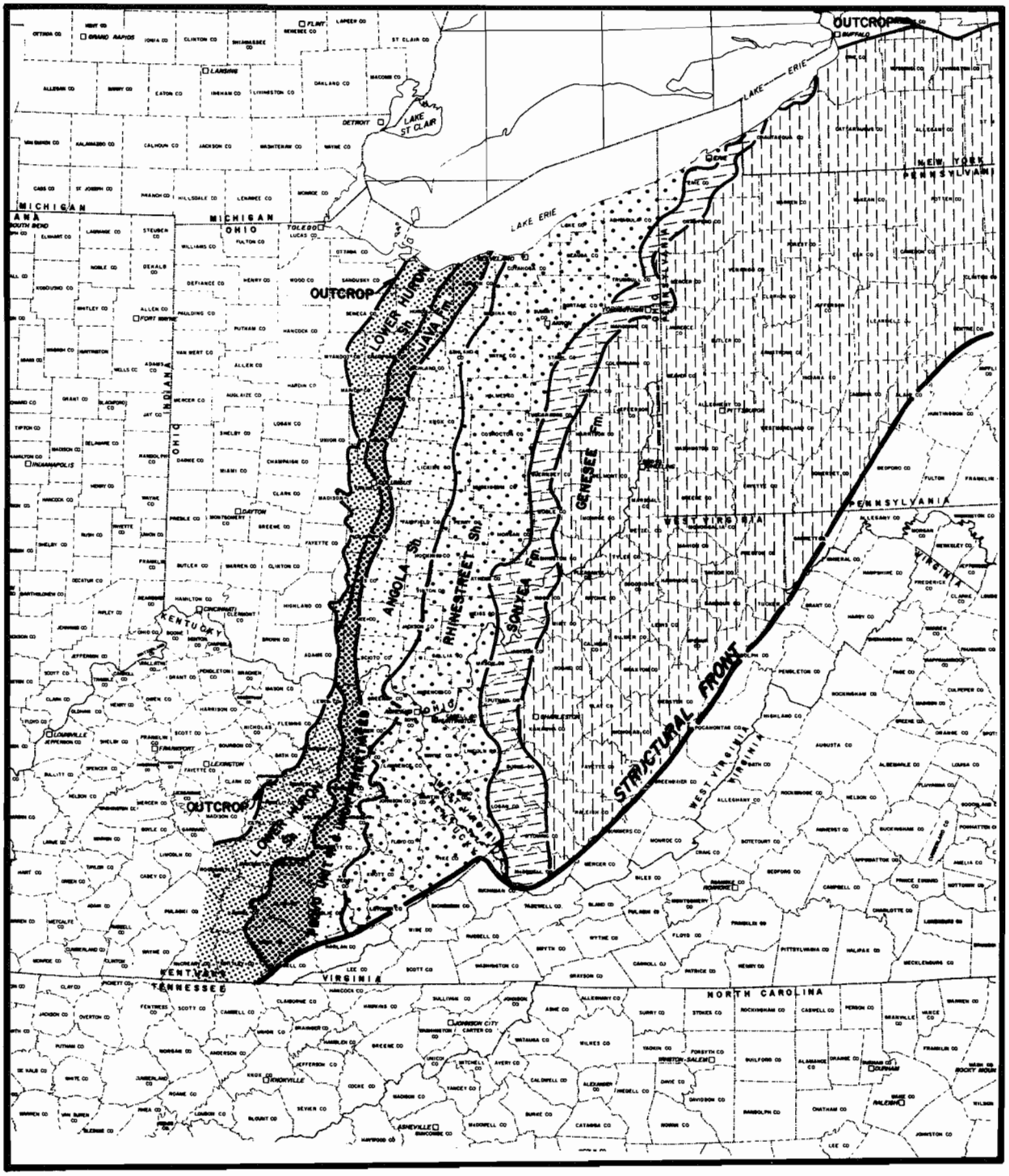


Figure 87 . Map showing the supercrop of the Upper Devonian strata overlying Middle-Upper Devonian unconformity.

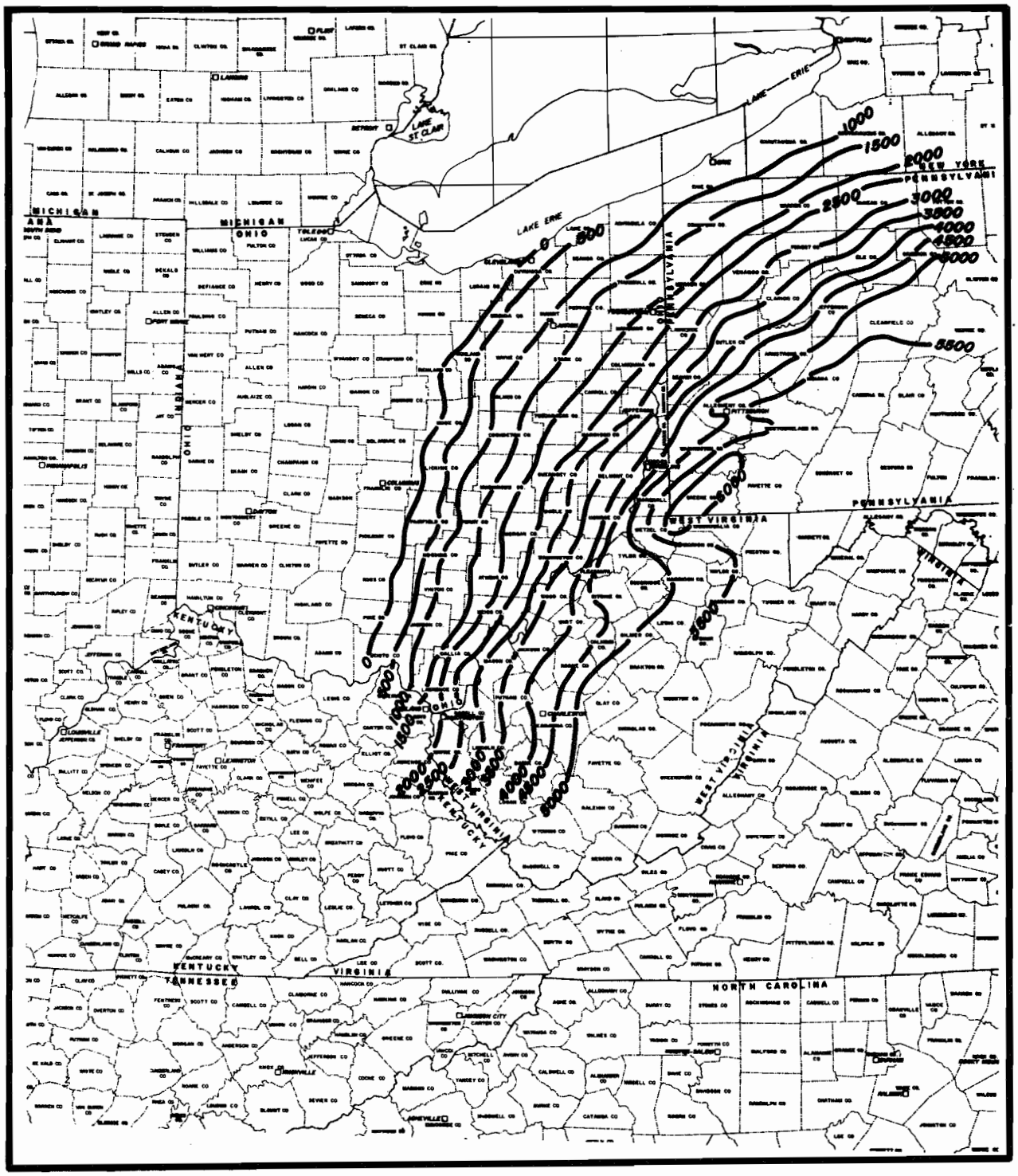


Figure 88 . Structure contour map on the Middle-Upper Devonian unconformity.

the areal extent of this unconformity in Michigan (plates 8 and 9). Other discontinuities within the Middle Devonian carbonate sequence, shown on plate 1, are not discussed further because they cannot be easily identified in the subsurface.

Illinois Basin

The Illinois basin was a shallow, slowly subsiding intracratonic basin throughout deposition of the Devonian shales. As described by various workers from the Illinois State Geological Survey, the basin was oriented northwest-southeast with southern and western depositional centers separated by a central thin zone (Bergstrom et al., 1980).

Sedimentation was continuous or nearly so in the deep basin where the New Albany Shale conformably overlies Middle Devonian aged limestones (Cluff et al., 1981). Along the basin margins a disconformable contact exists where the New Albany overlies Middle Devonian and older carbonates. In the eastern portion of the basin southwest of the Cincinnati arch, the New Albany paraconformably overlies Middle Devonian aged limestones (Bassett and Hasenmueller, 1977). Along the extreme southern margin of the basin the same paraconformable relationship exists between the New Albany and the underlying carbonate sequences. Toward the northern and western margins of the basin the Sylamore Sandstone, the basal member of the New Albany Group beyond the areal extent of the Blocher Shale, marks an unconformity between the New Albany and underlying Middle Devonian and older carbonates (Bergstrom et al., 1980; Tetra Tech, 1981). Plates 10 and 11 show the stratigraphic relationship between the unconformable surfaces along the western and southwestern cratonic margins and the conformable surfaces which exist in the deeper basin. The transition shown on the cross sections from conformable to unconformable surfaces is approximate. The Sylamore is extremely thin, generally less than three feet, and is not easily distinguishable on geophysical logs, so it was not included within the stratigraphic framework on Eastern Gas Shales Prject subsurface cross sections.

Diastemic breaks have not been reported in the Devonian sequence, but their absence does not preclude their occurrence. As previously discussed, these breaks would be extremely difficult to recognize. If developed, they would most likely occur along the margins of the stable craton and possibly along the central thin zone.

The New Albany Group is conformably overlain by the Chouteau Limestone (Kinderhookian) and its equivalents over most of the Illinois basin (Bassett and Hasenmueller, 1977; Reinbold, 1978). However, along the western and northwestern portions of the basin, an erosional unconformity exists between the New Albany and the overlying Mississippian Valmeyerian aged carbonates (Cluff et al., 1981). A possible diastem noted by Cluff and others (1981) in southern Illinois between the New Albany and Springville Shales (Valmeyerian), is interpreted as representing a period of either slow or nondeposition.

TECTONIC ANALYSIS

Introduction

The tectonic history of the eastern United States is of primary importance in understanding the distribution of clastic sediments and the development of structures and related fractures. The distribution and geometric configuration of various lithofacies was controlled to a large degree by either penecontemporaneously developing structures or by the rejuvenation of movement along pre-existing structures. Fractures were developed in conjunction with the structural activity and formed both syn-depositionally and post-depositionally. The geographic distribution of some of the larger, more regional structures of importance to the Eastern Gas Shales Project in the Appalachian, Michigan and Illinois basins are shown on plate 12.

The development of extensive natural fracture systems resulted from several episodes of tectonic activity. These fracture systems are considered necessary if the black Devonian Shale facies is to be productive. The effect of structural deformation and the subsequent development of natural fractures on shale reservoirs in eastern Kentucky and western West Virginia is well-documented in shale gas fields such as Cottageville and Big Sandy (fig. 89). Episodes of vertical tectonism, which correlate with periods of plate separation, are responsible for the formation and rejuvenation of fracture systems along the trace of existing faults of the Rome trough. Data collected by Shumaker and other workers indicate that basement faulting influenced sediment deposition in the trough region and that apparent episodic rejuvenation along some of the basement fault planes produced fracturing in the younger, overlying rock units. An important element in the development of conjugate fractures in shales is the effect of horizontal tectonism resulting from compressive stresses. This effect, often apparent even when some distance away from the originating structural event, is considered a major factor in the formation of fractured shale reservoirs. As discussed by Overbey (1978), the understanding of vertical and horizontal tectonics and fracture development is useful not only in creating a scenario for basin evolution, but also suggests the potential of using stress fold orientation, stress magnitudes, and stress gradients to detect zones of intense fracturing. In addition, the data may be useful in determining the method of artificial stimulation most applicable for the unconventional shale reservoir.

Natural Fractures

Investigations conducted by numerous workers during the Eastern Gas Shales Project have demonstrated the importance of natural fracture systems when evaluating the gas deliverability potential of the Devonian Shales. The development of fracture systems appears to be one of the single most important criteria necessary for the establishment of economic production. Wells penetrating the low-pressure Devonian Shale reservoir must intersect on extensive natural fracture system to sustain an acceptable rate of delivery since gas produced from the shale sequence is dependent to a large degree upon the source

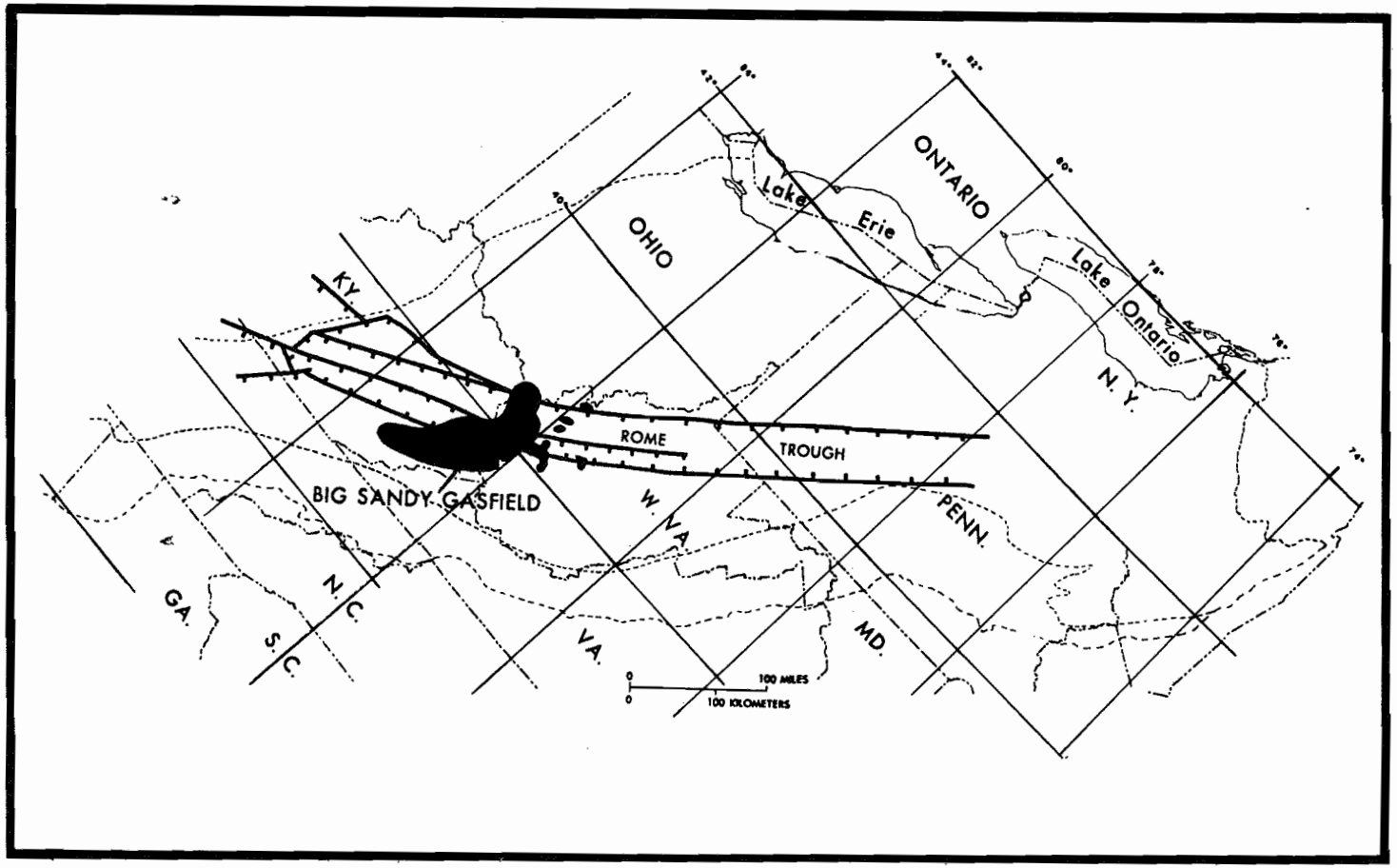


Figure 89. Map showing relation of Rome trough to Big Sandy and Cottageville shale gas fields. After Harris (1978).

rock thickness, the areal extent of the fracture system, and the volume of fracture porosity (gas reservoir space) in the shale (Walker, 1980). The susceptibility of different shales to natural fracturing is dependent upon their lithologic characteristics, bed thickness, and their proximity to areas that are undergoing various states of stress.

Natural fracture systems most commonly occur in response to stresses related to tectonic events developed during the evolution of sedimentary and structural basins. However, not all natural fracture systems are structurally related and many develop as a result of stresses originating from other nontectonic processes. Two nontectonic processes suggested for development of fracture systems in the Devonian shales are related to stresses originating from the effects of loading and unloading of rocks within sedimentary basins and earth tides. The systematic joint set which is global in extent is believed by Blanchet (1957) to be the result of rhythmically repeated gravitational pull of the moon and sun on the earth's crust. Superimposed on this global joint set are regional and local joint sets associated with tectonic events and fracture sets formed by overburden-related stresses.

The presence of these fracture systems provides the secondary porosity necessary for the accumulation and deliverability of commercial quantities of viable shale gas.

STRUCTURE-RELATED FRACTURES

The highest concentrations of fractures in the Devonian Shale sequence in the eastern United States depositional basins are generally found in folded and faulted structural terrains. Fractures associated with folds are usually associated with variable stress fields with the rock undergoing many different stress orientations during the folding. The orientation and density of fractures formed during episodes of folding are related to the magnitude and orientation of the principal stress directions, the lithology of the rock and the thickness of the bedding. Most of the fold-developed fractures do not parallel the axis of the fold but develop at some angle to the axis (Stearns and Friedman, 1972). Also, the fracture intensity on the folds is greatest where the rate of change of dip is highest, not necessarily where the dips are steepest.

Fault-associated fractures are generally generated within a homogeneous stress field and the fractures are the product of the same stresses which produced the major fault. These fractures generally exhibit the same orientation as the master fault. The concentration and distribution of fault-associated fracture zones is extremely variable and not necessarily associated with the size of the master fault. Large faults may have narrow fracture zones, whereas wide zones of fractures may be associated with small faults.

Regional tectonic forces are created during episodes involving crustal plate collisions and separations. The compressive forces generated during periods of oceanic closure and plate consumption produced fractures systems associated with thrust-faulting, reverse faulting, decollement structures and associated folding. These compression-associated fractures were formed primarily during the Acadian and Allegheny orogenies.

Normal faulting, rifting and some folding associated with regional and local tensional forces were responsible for the development of many local and regional fracture

systems occurring within the Devonian shales. Some of these fractures, formed prior to the deposition of the shale sequence during the Cambrian to Ordovician spreading, may have been re-activated during some later period of structural activity (i.e., the Rome trough) or during plate separation following the Allegheny orogeny.

OVERBURDEN-RELATED FRACTURES

Stresses resulting from loading or removal of overburden can also induce fracturing of rock. Pressures generated by weight of the overburden can be resolved into a combination of compressive and tensile forces. Burial of the Devonian Shales beneath the aggregate weight of Mississippian, Pennsylvania, Permian and younger beds may have stressed and fractured the shales by compression during compaction or during uplift and erosion by expansion relese. Fracture systems which develop from overburden loading are the result of stresses developing from diagenetic volume changes in the rock caused by differentials in pressure, temperature, mineral conversions and inhomogeneities in the make-up of the rock itself. When overburden is removed from a sedimentary sequence by uplift and erosion, there is a release of fluid pressure and an accompanying increase in volume resulting from expansion or mineral transformations. The volume change generally results in the formation of small shear fractures and joints within the rock strata. Inasmuch as the Allegheny orogeny involved the collision of two rather large land masses, the mountains generated must have been higher by several magnitudes than the present-day Appalachian Mountains. A logical corollary to this observation should then address the missing column of sediments generated by their erosion. In the eastern United States there are no Permian-age sediments younger than the Dunkirk Group, which some investigators consider to be transitional with the Monogehela series. Triassic rocks have been recognized in the Newark basin and Jurassic sediments have been reported from Michigan. Aside from these occurrences, the Permian-Triassic sequence is missing, presumably through erosion after uplift. Supporting evidence for this hypothesis comes from the metamorphic rank of upper Pennsylvania and Dunkard (Washington and Green) coals. To generate bituminous coal of this rank, assuming an average geothermal gradient, would require several thousand feet of sediment. Thus, it is hypothesized that between 5,000 and 10,000 feet of sediment has been removed from western Pennsylvania, eastern Ohio, West Virginia, and eastern Kentucky (Murany, 1982). Data from Illinois regarding coal rank supports this hypothesis, suggesting that between approximately 4500 and 6500 feet of Permian-Triassic and possibly younger sediments have been removed by erosion (Damberger, 1971). The stress field which developed in response to the removal of this magnitude of rock by uplift and erosion was most likely responsible for the development of systematic extension fracture systems throughout the Appalachian basin.

Extension fractures also develop due to rock expansion after repeated episodes of glacial on-loading and off-loading. These fractures develop perpendicular to the glaciated surface and form as the result of the release of compressive stress imposed by the weight of the glacial ice. Repeated episodes of this cycle cause the rock to fail as the result of fatigue. During the Pleistocene Epoch the Devonian Shale near the surface, generally less than 800 feet in depth, was subject to repeated stresses during glacial advance and retreat. The repetition of these glacially-induced forces produced areas of high fracture density at shallow depth. The areas of historic shale gas production along the southern shoreline of Lake Erie are considered an example of glacially-induced fractures.

BASIN SUBSIDENCE FRACTURES

The circumference of the earth is about 24,000 miles with surficial curvature approximately 1^{o} for every 60 miles of horizontal distance. Thus, many basins which exhibit an average down-to-the-axis gradient of less than one minute per mile exist in which their true shape ranges from convex or bowed outward to something approaching horizontal, rather than the trational view of a concave or bowed inward basin (Dallamus, 1958). These basins or portions of these basins which exhibit an average gradient of less than one minute per mile were formed in a compressive state since rocks deposited in a basin with the approximate upward curvature of the earth's surface assume lesser area as the basin approaches a true plane. Continued subsidence of lithified sediment, when extended below a certain critical depth, creates an average gradient of greater than one degree per minute and a concave curvature is established in which lithified sediment, unable to yield to plastic flow, is extended in tension as individual beds attempt to adjust to assume a curved surface of greater area than the true plane. In this theoretical state, curvilateral extension of the lithified sediment is accomplished by essentially vertical fracturing, with the fractures developing approximately parallel to the basin axis, which corresponds to the axis of maximum subsidence (Baldwin, 1979). Although there is no direct evidence to link this mechanism of fracturing to fractures observed in the Devonian shales of the Appalachian, Illinois, and Michigan basins, it is possible that the stress field associated with this theoretical model might be responsible for some of the regional fractures observed in the basins.

REGIONAL FRACTURES

Regional fracture systems occur over an entire area and are considered to have originated independently of local structural development. These systems consist of two distinct sets which form perpendicular to one another and exhibit a distinct and consistent orientation throughout a region. It has been theorized that these fractures, also known as orthogonal fracture systems because of the orthogonal pattern, were formed by "earth tide" forces which induce brittle fracture by repeated low-level cyclic stressing of the earth's crust (Walker, 1980). The "earth tide" forces are created by the gravitational pull of the planets (primarily the sun and moon) on the earth's crust. These small stresses are analogous to the rise and fall of the ocean tides and have been rhythmically repeated throughout geologic time. The cumulative effect of these forces causes the earth's crust to fracture through fatigue similar to the way in which metal fails when subjected to repeated stresses (Blanchet, 1957). In the northern hemisphere, the primary orientation of the fractures and joints are northeast and northwest. Regional fractures in the Devonian Shale sequence are too widely spaced to provide the fracture profile necessary to produce commercial reservoir conditions, but may account for the occurrence of "flash" production that is occasionally encountered during drilling operations.

FRACTURE TYPE

Fractures are propagated in rock as either shear fractures in which one side of the fracture is displaced relative to the other or as extension fractures in which the rock faces separate and move apart. Shear fractures form in response to compressive forces and occur commonly at angles of 30^{o} but less than 45^{o} to the direction of the major stress. Extension fractures are formed primarily as a result of tension stresses, but can form indirectly from compressive forces which set up perpendicular tension forces. They may also be formed in response to a relaxation of the compressive stress field. Extension fractures develop at right angles to the direction of tensional stress or parallel to the compressive stress orientation (Walker, 1980).

The graphic presentation of the triaxial stress field shows the relationships between orientation and attitude of fractures and the principal stress directions for both a shearing mode, compressive, and an extension mode, tensile (fig. 90). Such fractures formed under a single state of stress are designated conjugate fracture sets; a complete conjugate fracture pattern includes a left-lateral and right-lateral (compressive), and an extension (tensile) pattern.

CONTROLLING FACTORS

Factors which influence the development and propagation of fractures in rocks include the rock lithology, the thickness of individual beds, and the distribution of the earth stresses. The lithologic characteristics may be the single most important factor in susceptibility of a rock to fracturing; the more ductile or plastic a rock is, the less likely it is to develop fracture. All rocks become more ductile with increased depth of burial as the confining pressures become greater (Handlin et al., 1963). Shales exhibit the greatest range between ductile and brittle fracture behavior due to their variable lithologic composition. The Devonian sequence in the Appalachian basin varies in lithology from distal basin, organic-rich black shales to the silty, thin-bedded turbidites, and exhibits a corresponding range in fracture development. In addition to lithologic composition, bed thickness is an important consideration in determining a rocks susceptibility to fracture. Work by Harris and others (1960) demonstrated that under similar conditions a thin bed will contain more fractures than a thick bed. Gas production from the Devonian Shales, dependent to a large degree upon the presence of natural fractures, may also be enhanced by the presence of shale laminations (Schwalb and Norris, 1980). The presence of thin siltstone beds, interbedded shales, and greenish-gray laminae contribute to the increased porosity and permeability necessary to establish a commercial reservoir.

The structural position of a rock in relation to the stresses imposed on it will control the degree to which fractures develop. In faulted areas deformed by either compressive or tensile stresses, fracture intensity will be greatest near the zone of brittle rupture and diminish away from the fault. In rocks subject to folding, the fracture density is highest where the rate of change in dip is most prounounced.

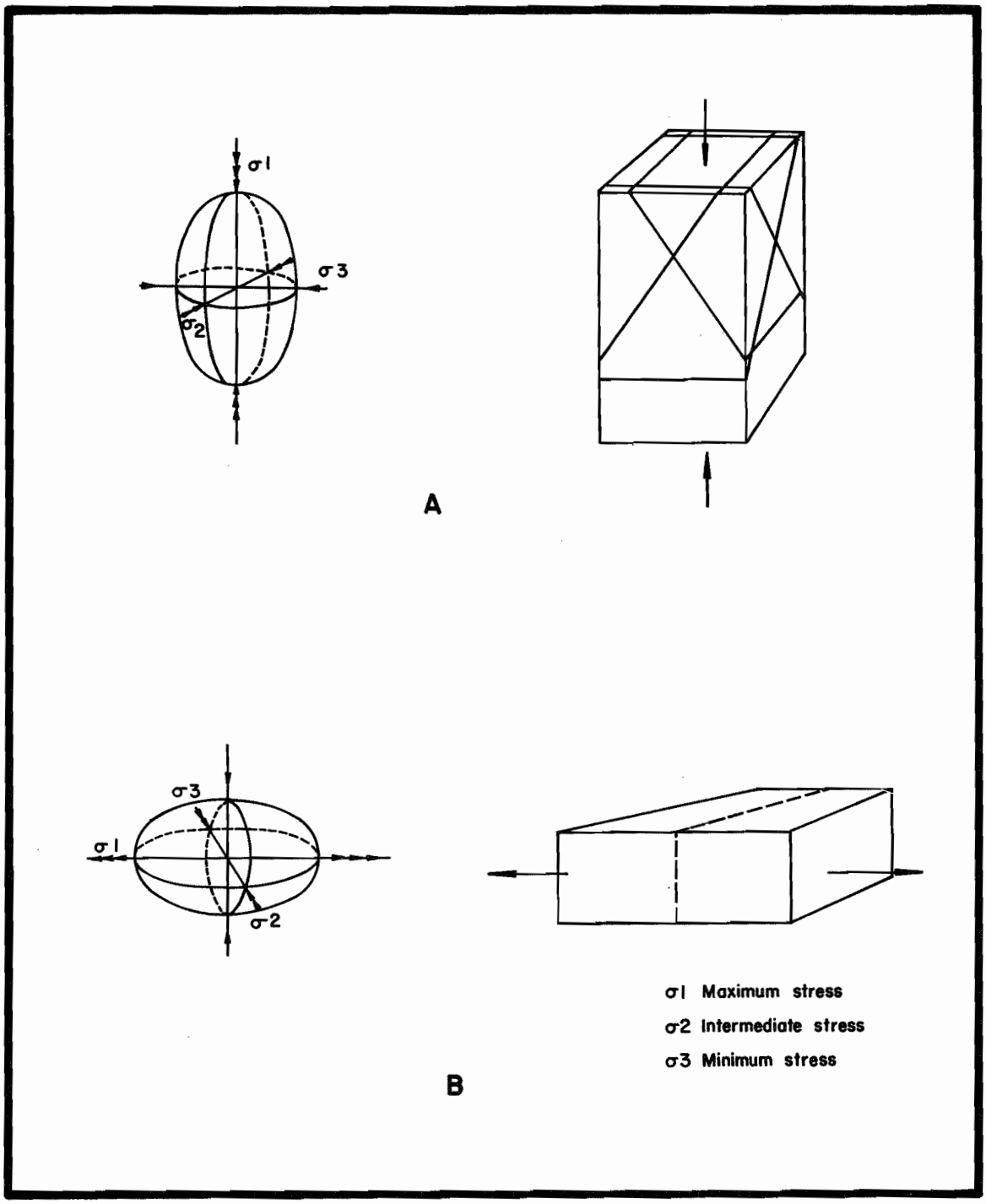


Figure 90. Graphic presentation of triaxial stresses showing (A) Compressive stress ellipsoid and potential shear planes and (B) Tensile stress ellipsoid and shear plane. Modified from Billings (1972).

Acadian Orogeny

INTRODUCTION--APPALACHIAN BASIN

Studies conducted under the auspices of the Eastern Gas Shales Project have outlined the stratigraphic development and the influence of local structural deformation in the Appalachian basin, but only limited attempts have been made to place the various phases of structural evolution in a plate tectonic framework (Harris, 1978; de Wys, 1979; Ettensohn and Barron, 1981; Zielinski and McIver, 1982). During the early Paleozoic, deformation along the eastern margin of the evolving North American plate was the result of tensile stress developed by plate separation. The structural style evolving from this type of deformation is characterized by the occurrence of incipient rifting between the cratonic margin and the trailing passive continental margin (fig. 91). Deformation of the eastern North American plate, beginning during the initial stages of closure of the Proto-Atlantic Ocean and culminating with the Late Paleozoic Allegheny orogeny, resulted primarily from compressive stresses generated by the interaction of the converging plates (Graham et al., 1975; Dennison and Textoris, 1978). These compressive forces produced three sequences of orogenic activity: the Taconic, Acadian, and Allegheny episodes. In the Appalachian basin, these sequences of orogenic activity from the Middle to Late Paleozoic are recorded primarily by the accumulation of stacked deltas: Queenstown, Catskill, Bedford, Mauch Chunk, and Pottsville, among others. To the east, igneous and metamorphic sequences recording these orogenic events are well-documented in the Northern Appalachian-Maritime Province Avalon belt and the Carolina slate belt in the central and southern Appalachians.

Complicating the interpretation of the Acadian and earlier orogenic events is the deformation produced by the advent of the Allegheny orogeny and later tectonic events. The Taconic and Acadian orogenic episodes are considered to represent progressive stages of consumption of the Proto-Atlantic oceanic plate by the North American plate possibly along several arc-trench systems (Bird and Dewey, 1970). Following consumption of the Proto-Atlantic and deformation produced by collision with the European plate, the African plate moved into position and began to interact with the North American plate. This event marked the maximum extent of closure of the Proto-Atlantic and began the plate-to-plate interaction that culminated in the Allegheny orogeny. Graham and others (1975) proposed that this suturing of the respective plates proceeded from north to south with the various periods of orogenic activity representing progressive stages of closure of the Proto-Atlantic. The interpretation considers the formation of the Appalachians as a part of the Caledonide-Appalachian-Mauritanide belt.

PLATE TECTONIC MODEL

The initial pulsation of the Appalachian orogeny is considered to have begun during Middle Devonian time (approximately 370 million years ago) and continued episodically throughout the rest of the Devonian. Within the Appalachian basin, the influx of

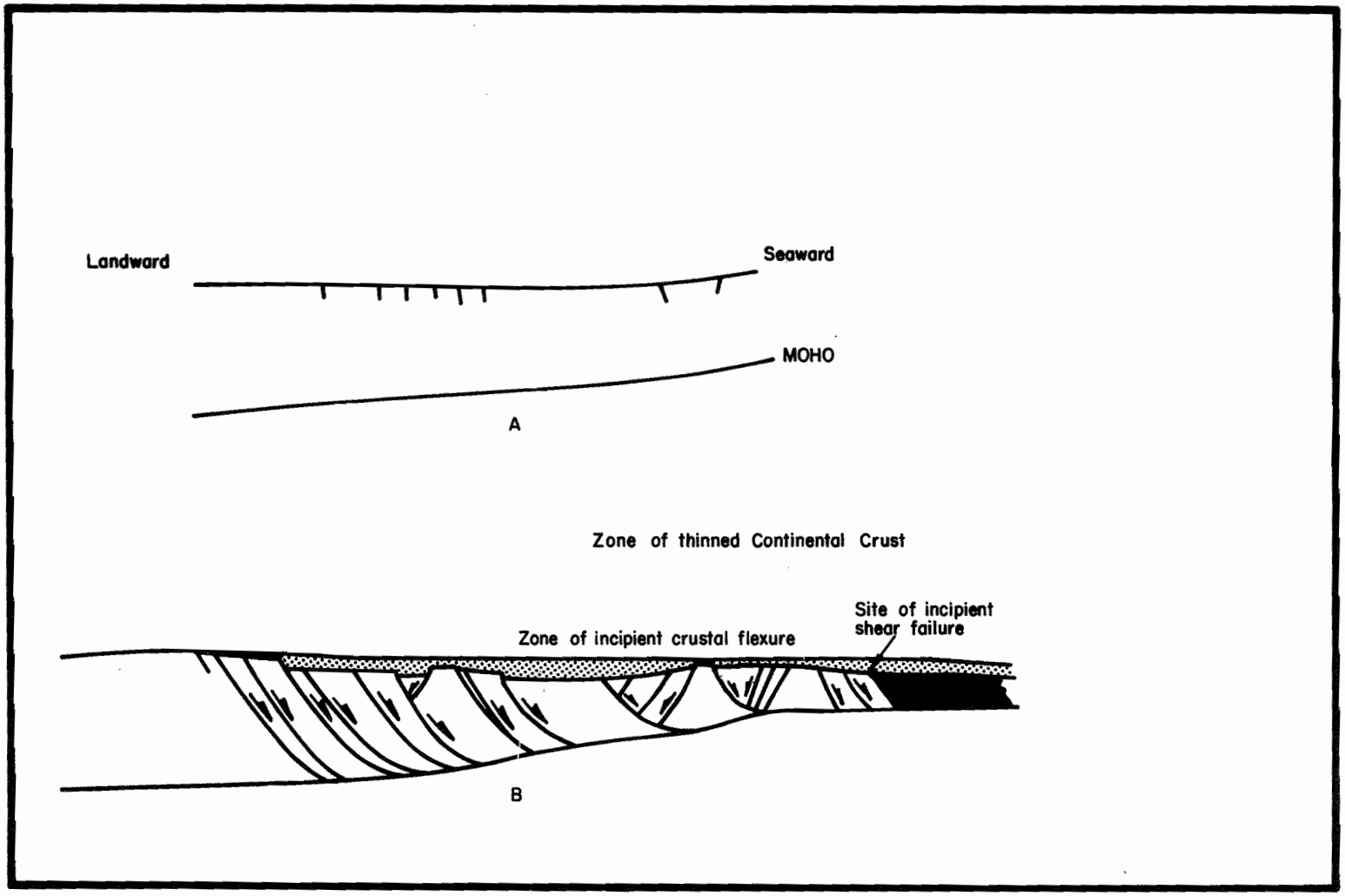


Figure 91. Schematic diagram showing the evolution of the continental margin. (A) Incipient stage of rifting formed in response to plate separation. (B) Continued plate extension producing a series of normal faults along the continental margin. (Modified from Cohen, 1982).

prograding sediment, the rapid lateral facies changes, and the interfingering of marine and nonmarine sediments can best be explained with the framework of a prograding delta model of deposition. Tectonic activity during the Acadian and later events produced both syn- and post-depositional deformation of the Devonian basin. Large thrust sheets characteristic of thin-skinned tectonic deformation developed in the fold-thrust belt while, away from the fold-thrust belt in the forelands, the deformation was less intense and resulted in the formation of small-scale anticlines, synclines, and brittle fractures. The plate interactions also provided the mechanism for the reactivation of previously existing structures and the subsequent development of fractures in the younger overlying rocks.

On the basis of basin geometry, the structural history, and the sedimentary record, the Appalachian basin is considered to represent a composite foreland basin having the characteristics of both retroarc and peripheral basins. However, because of the structural complexity and incomplete section, an exact classification of tectonic style is difficult. In general, the Devonian shale depositional basin appears to exhibit many of the characteristics primarily associated with retroarc foreland basins. Cumulative subsidence in the structurally active Appalachian basin is much greater than exhibited by intercratonic basins such as the Illinois basin (fig. 92). Much of the following review of retroarc basin characteristics is summarized from Dickinson and Yarborough (1976).

Retroarc Foreland Basin

Retroarc foreland basins develop behind the zone of plate consumption in lee of the continental margin magmatic belt. These features form during episodes of plate convergence in which the leading portion of the oceanic plate is subducted beneath the continental plate (fig. 93). The basin, formed by flexural subsidence, develops in response to a combination of continuing movement by the continental plate and by tectonic loading. Development of a fold-thrust belt occurs when the crust becomes sufficiently plastic to accommodate contraction as the plates continue to converge. In the Appalachian basin, the fold-thrust complex was initiated during the arc-plate phase (Acadian orogeny) and culminated during the plate-to-plate interactoin of the Late Paleozoic Allegheny orogeny when large sheets of the crystalline Appalachian mountains were thrust westward (Murany, 1982). Seismic reflection lines shot under the auspices of COCORP indicate that at least a portion of the sedimentary rock column has been preserved beneath these thrust sheets in the central and southern Appalachians. Recent estimates suggest that portions of the fold-thrust complex have been displaced at least 260 kilometers (Cook et al., 1980).

Interpretation of the Acadian orogenic episodes in the central and southern Appalachians is difficult because of the lack of structural depositional patterns. The compressive stresses generated during plate interaction diminish away from the origin, but were of sufficient magnitude to re-activate existing structures formed during earlier structural events and to be propagated through the basin as a series of arches and troughs, in a theoretical sine-wave pattern (Murany, 1982). Included in this category of significant structures within the basin that influenced Devonian Shale deposition are the Cincinnati and Central West Virginia arch complexes and the Rome trough. The Burning Springs anticline, Cambridge arch, and other smaller thin-skinned tectonic features were formed post-depositionally.

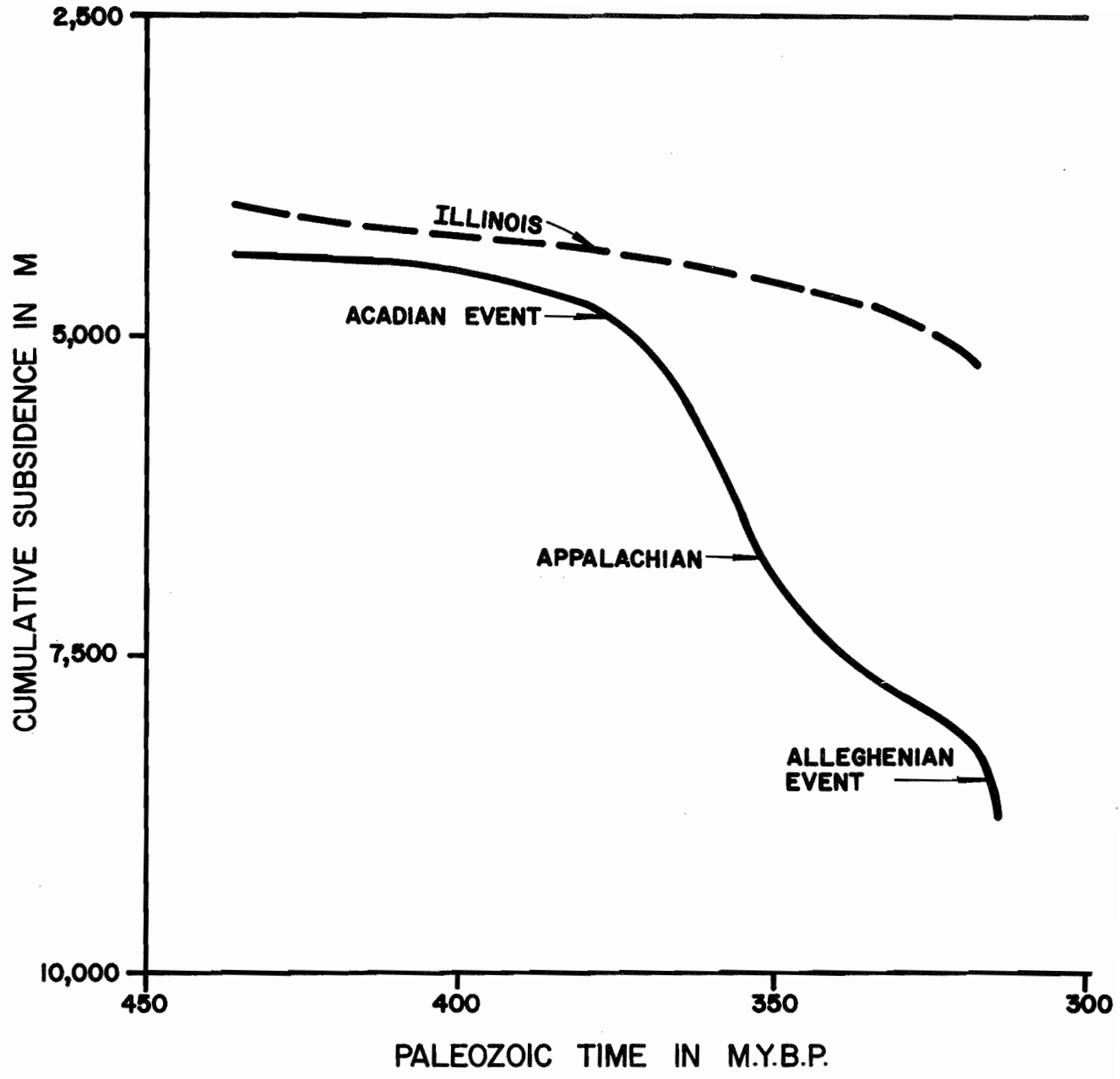


Figure 92. Approximate cumulative subsidence in the Appalachian and Illinois basins through the Paleozoic. From Dickinson and Yarborough (1976).

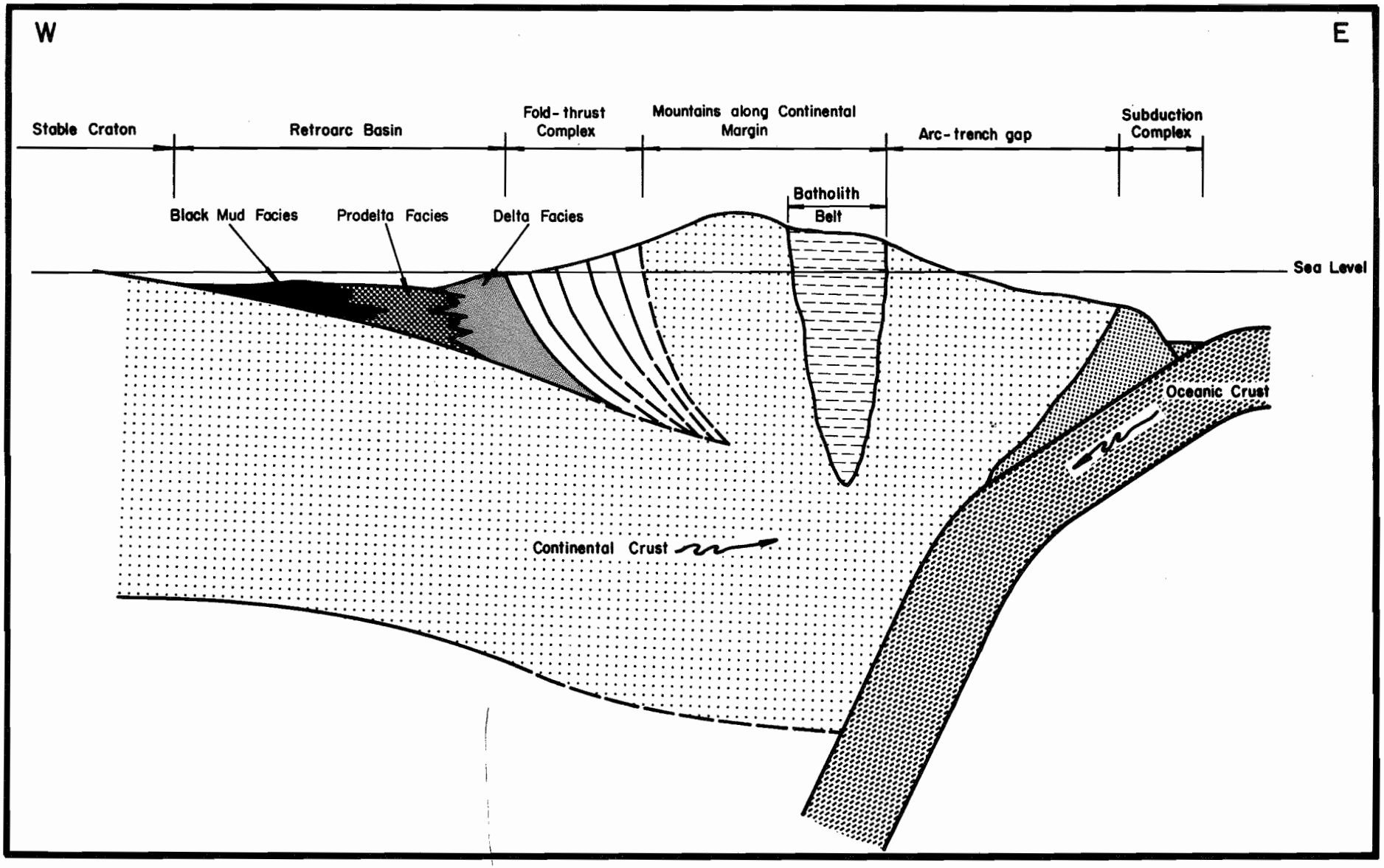


Figure 93. Schematic diagram illustrating a possible interpretation of the formation of the Appalachian basin as a retroarc foreland basin. General retroarc basin diagram modified from Dickinson and Yarborough (1976).

Fluvio-deltaic complexes derived primarily from the rising orogenic highlands constitute perhaps the most characteristic stratigraphic sequence formed in retroarc basins. The aforementioned sequence of stacked Paleozoic deltas are a salient feature of uplift and erosion from a rising source east of the subsiding basin. In addition, shallow marine facies are common in the distal portions of the basin away from the influence of the fluvio-deltaic sequences. However, deeper marine facies are not generally present in this structurally influenced basin.

Vertical Tectonics

Plate tectonic theory not only involves large-scale horizontal motions but also significant vertical motion of the crust. The forces which generate the vertical displacement originate from plate interaction. There are three general mechanisms by which the subsidence or uplift may be accomplished: (1) changes in crustal thickness which result from extension or compression; (2) lithospheric expansion or contraction, and (3) crustal flexure which forms in response to structural or sedimentary loading (Dickinson and Yarborough, 1976). A few examples of Appalachian basin structures believed to have formed as a result of vertical tectonics are summarized in the following paragraphs.

The Rome trough is considered to have been formed during the Late Precambrian-Cambrian stage of Proto-Atlantic Ocean expansion. In eastern Kentucky and western West Virginia the trough forms an asymmetric graben, characterized by a series of en echelon normal faults along the northern limb and a single steep scarp along the southern limb. In western Pennsylvania the structure is expressed as a series of down-to-the-basin normal faults (Wagner, 1976). Harris (1978) postulates a northeastward extension of the Rome trough and suggests that the Rome trough and Moorman syncline of western Kentucky form an aulacogen which he called the Eastern Interior aulacogen. The approximate location of the Rome trough is shown in figure 94.

Development of the trough/graben complex allowed a thick sequence of Early to Middle Paleozoic sediment to accumulate, but by the time the Devonian Shale sequence was being deposited, subsidence in the graben had essentially ceased and only moderately influenced sedimentation (fig. 95). However, both syn- and post-depositional tectonic activity along the faults produced a series of fractures in the overlying strata (fig. 96). These natural fracture systems are considered to be of primary importance in providing the secondary porosity and permeability in the Big Sandy, Cottageville, and other shale gas fields in Kentucky and West Virginia (Shumaker, et al., 1978; de Wys and Shumaker, 1978).

The Cincinnati arch forms the western margin of the Appalachian basin and represents a positive structural feature during deposition of the Devonian shales. It is unclear whether the arch complex formed as the result of uplift or represents a stable platform between two actively subsiding basins. The Devonian sequence in the arch area indicates the arch had an influence on deposition during the period. During the Erian Series, distal basin sediments extended onto the arch; however, a post-Erian drop in sea level or uplift of the arch removed most of the sediment, producing an erosional unconformity during the Taghanic Stage. The progressive onlap of younger Upper Devonian sediments onto the arch complex suggest the arch was once again a positive feature during the Upper Devonian.

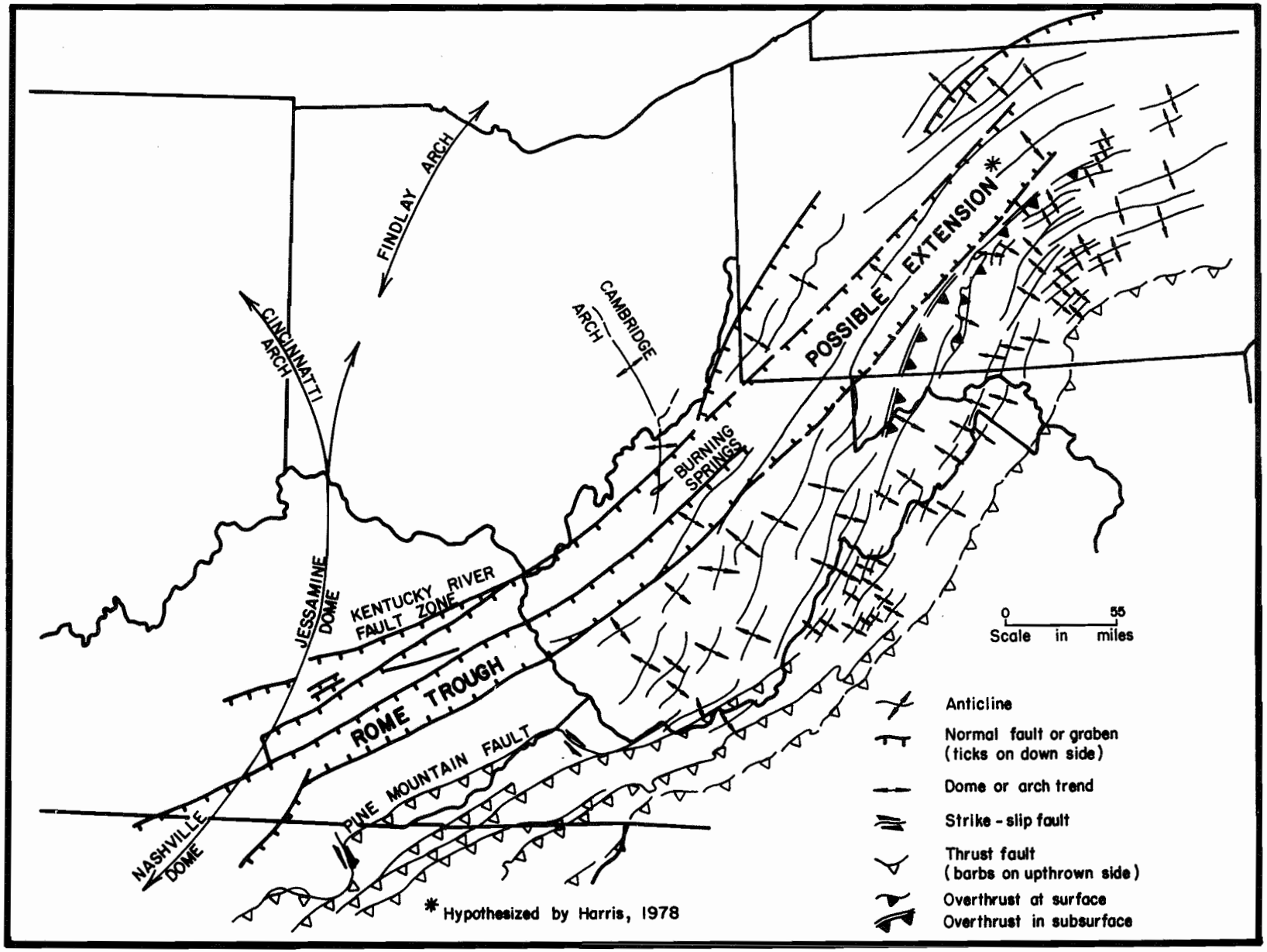


Figure 94 . Approximate location of the Rome trough in relation to other structures in the Appalachian basin. Modified from Komar and Bolyard (1979) and Wagner (1976).

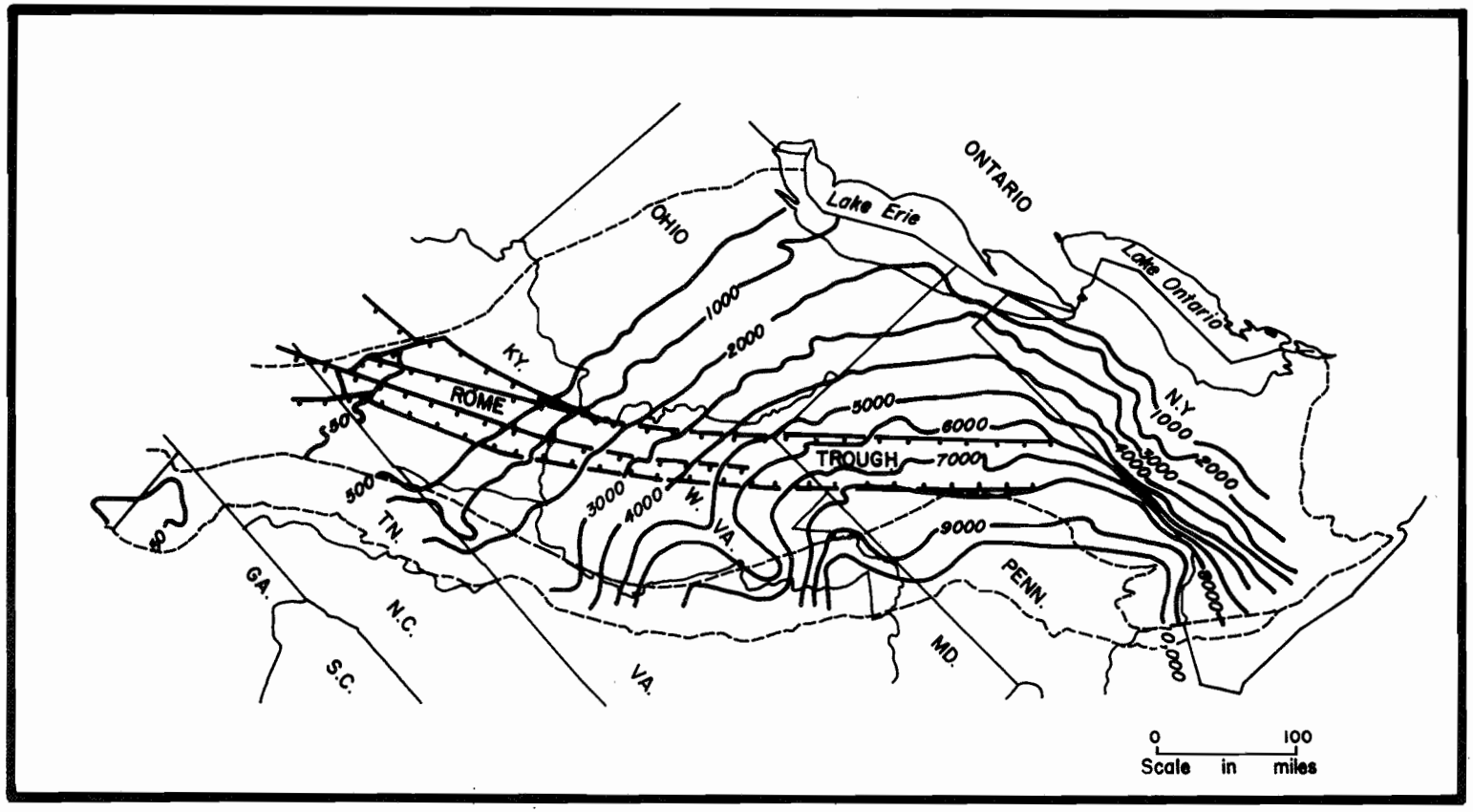


Figure 95 . Isopach map showing the relation of Devonian aged rocks to the Rome trough. Note the uniform distribution of sediment in the vicinity to the trough. From Harris (1978).

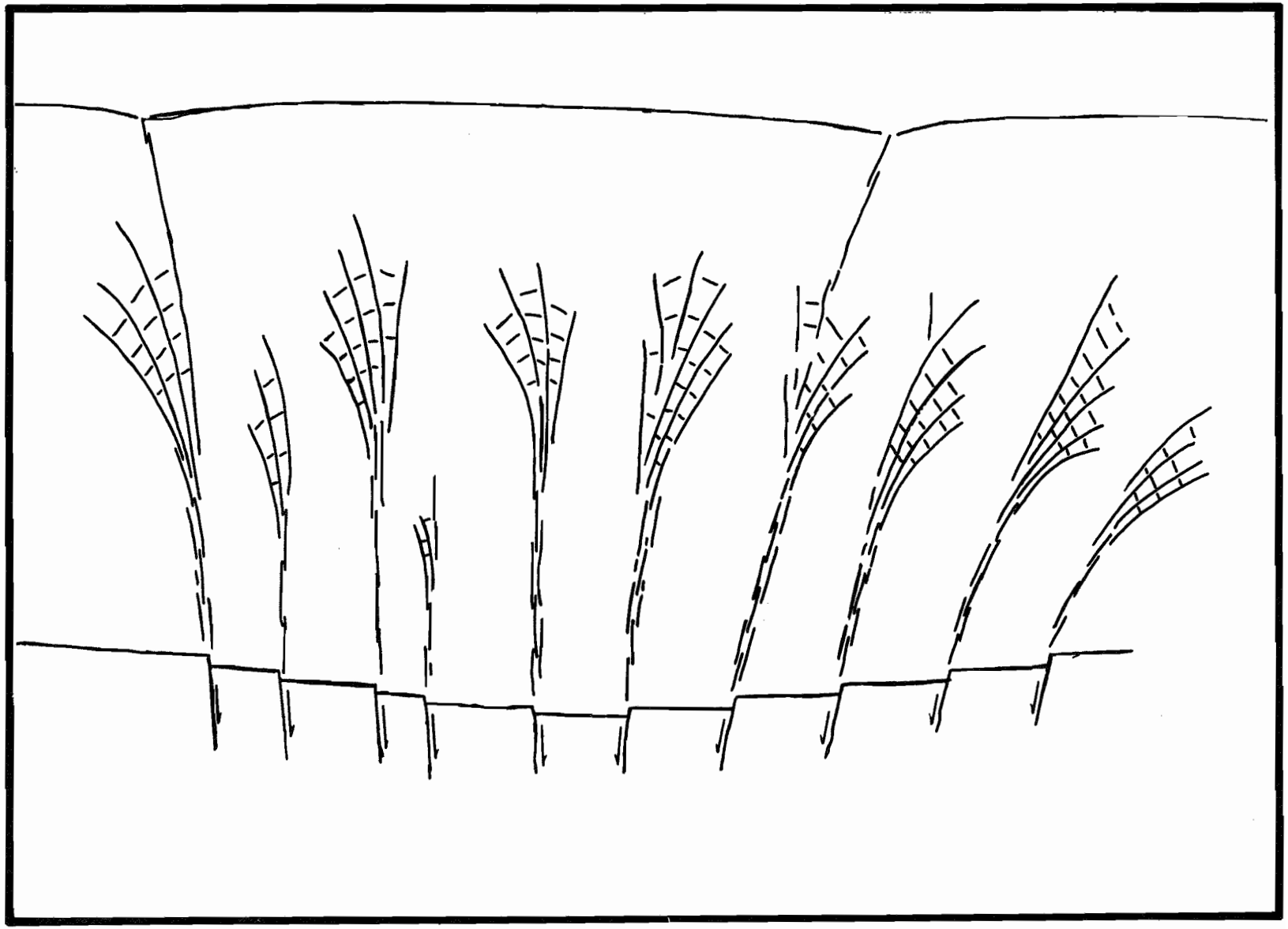


Figure 96 . Fractures generated by deep-seated basement faulting propagated upward into Devonian shales. After Overbey (1976).

Similar structural and depositional histories existed during the Middle Devonian in the area of the Central West Virginia arch (Zielinski and McIver, 1982). During deposition of the Mahantango, the arch, trending approximately north-northeast (fig. 97), appears to have been a positive vertical tectonic feature which restricted the east-west movement of sediment and trapped thicker accumulations along the east side of the arch. The arch and other structural features exerted less influence on depositional patterns during the latter stages of the westward progradation (fig. 98 through 103). This and other local examples of interbasin vertical tectonics may have influenced the depositional patterns of the Devonian, producing thick shale sequences with accompanying thins along the axis of positive features.

Thin-Skinned Tectonics

Fractures in the Devonian Shale sequence were also created in areas associated with this style of tectonic deformation. Projections of the Acadian orogenic style of deformation into the central and southern Appalachian regions is primarily on structural interpretation of features found in the New England, Maritime and Newfoundland portion of the northern Appalachians.

Van der Voo (1979), in an attempt to explain the absence of the Acadian orogenic elements in the central and southern Appalachian basin, has proposed a hypothesis suggesting left lateral strike-slip displacement of New England and the Maritime Appalachians. If the New England and Maritime Appalachians are palinspastically restored to a position opposite the central and southern Appalachians, the missing structural province characteristic of an arc-continent collision is present. The left lateral transform motion of the New England-Maritime block probably originated as the African plate moved into position with the North American plate during continued post-Acadian closure of the Proto-Atlantic.

Several bentonite marker beds, the Tioga and Center Hill, among others, have been recognized in the Middle and Upper Devonian aged strata and suggest that closure of the Proto-Atlantic had reached that point where the subduction of the oceanic plate beneath the continent had progressed to the point where volcanism became active. The volcanic eruption which was responsible for deposition of the Tioga is considered as having originated along the 38th Parallel fracture zone and occurred during an early stage of the Acadian orogeny (Dennison and Textoris, 1978).

Episodic Acadian orogenic activity not only produced a zone of intense structural deformation along the eastern margin of the Appalachian basin, but also controlled, in varying degrees, local structures and sedimentation where the shale was either adjacent to or subject to overthrust faulting. Overthrust faults form as a rsult of large-scale compressive stresses such as those produced during the Acadian and Allegheny orogenic periods of plate convergence. Thin-skinned overthrust structural style throughout the Appalachian Plateau Province have been discussed by Rodgers (1963), Gwinn (1964), and Harris and Millici (1977), among others. The thrust sheets consist of blocks of Paleozoic strata overlying low angle reverse faults which were displaced along slip or decollement surfaces of incompetent shale and/or salt sequences. Along the eastern margin of the Appalachian basin the compressive forces generated by converging plate interaction thrust the overlying sequences westward and northward.

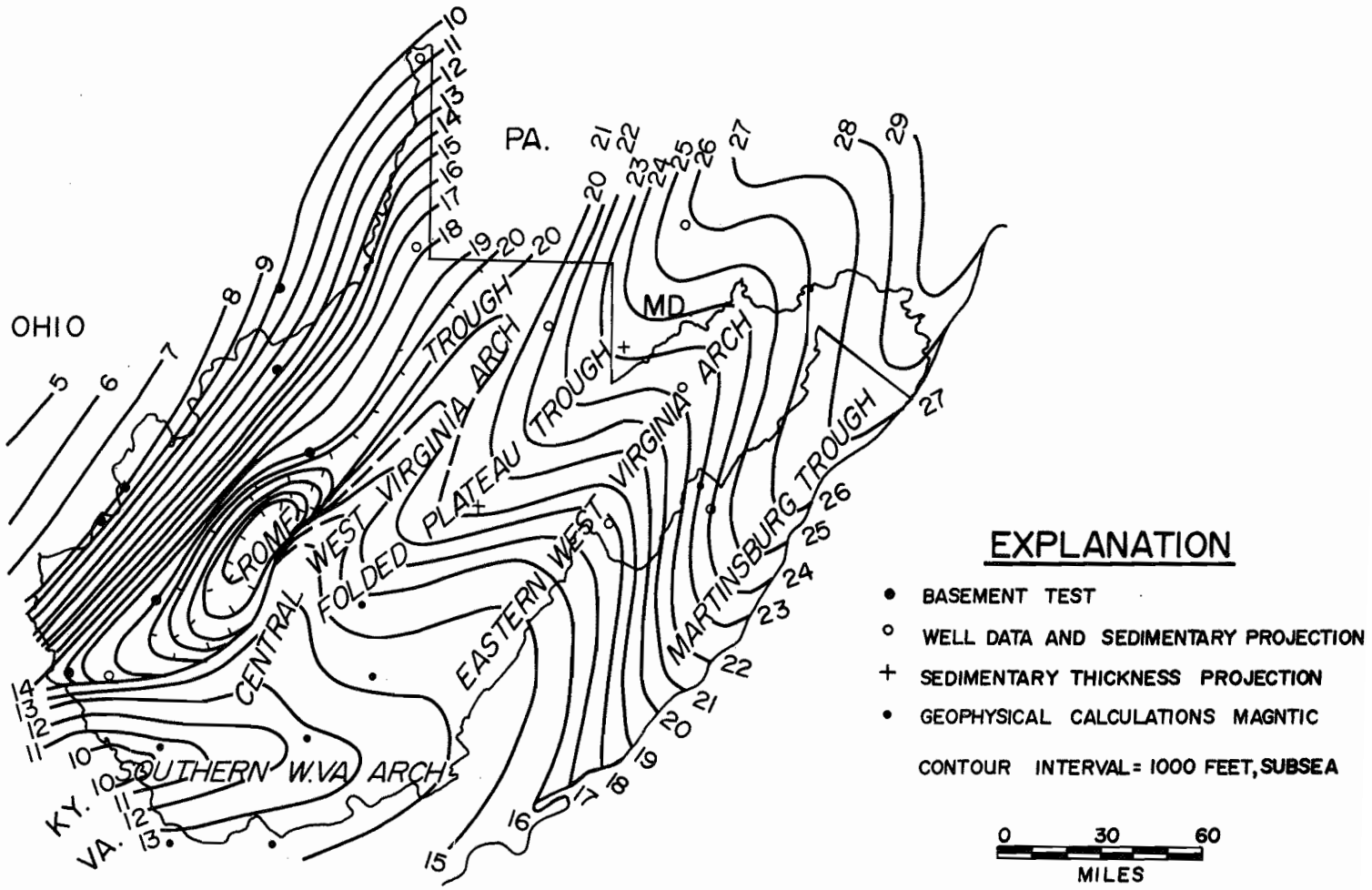


Figure 97. Basement depth map of West Virginia. From SAI (1980), after Kulander et al. (1977).

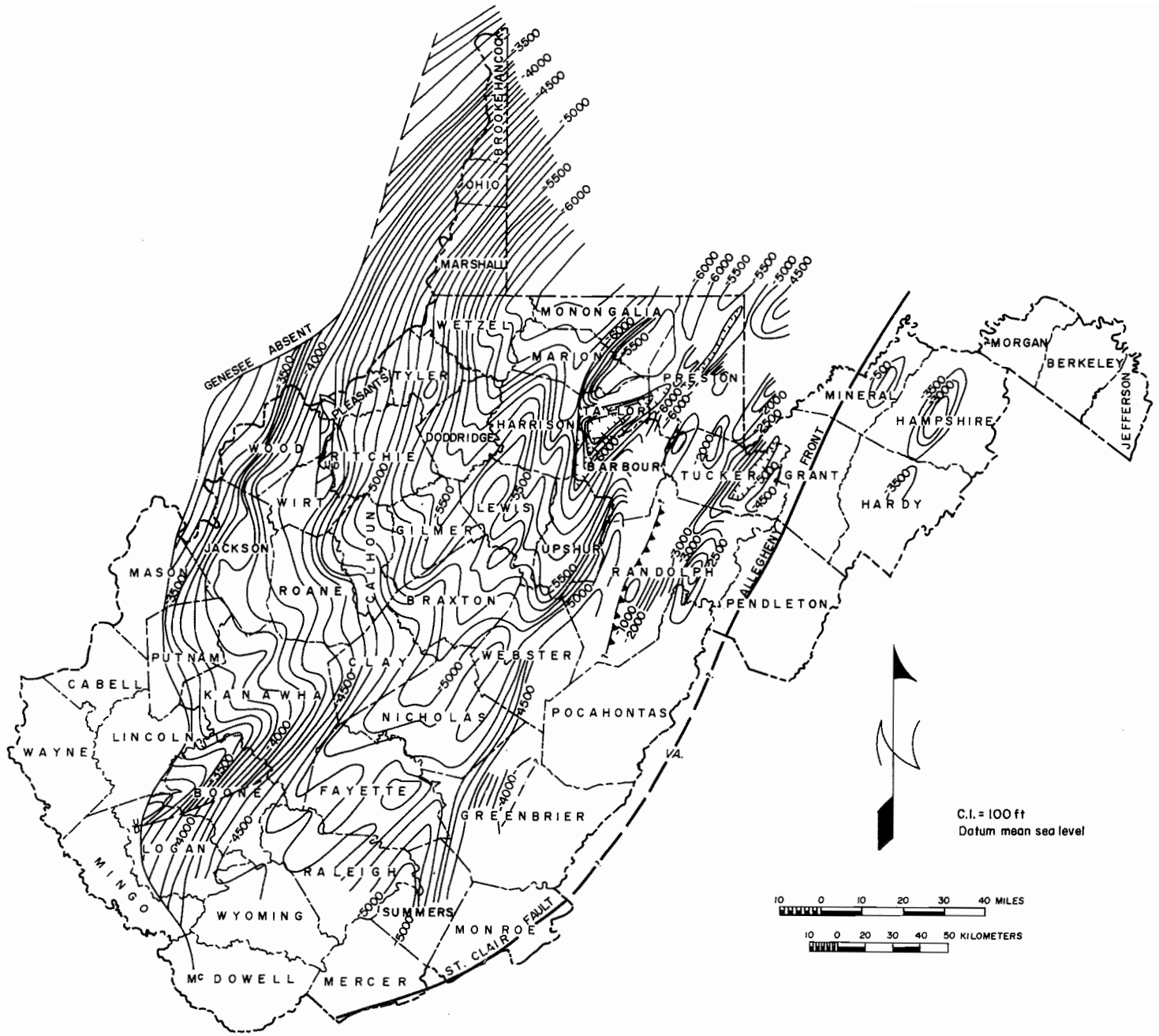


Figure 98 . Structure contour map on the base of the Genesee Formation. From SAI (1980), after Schwietering (1979).

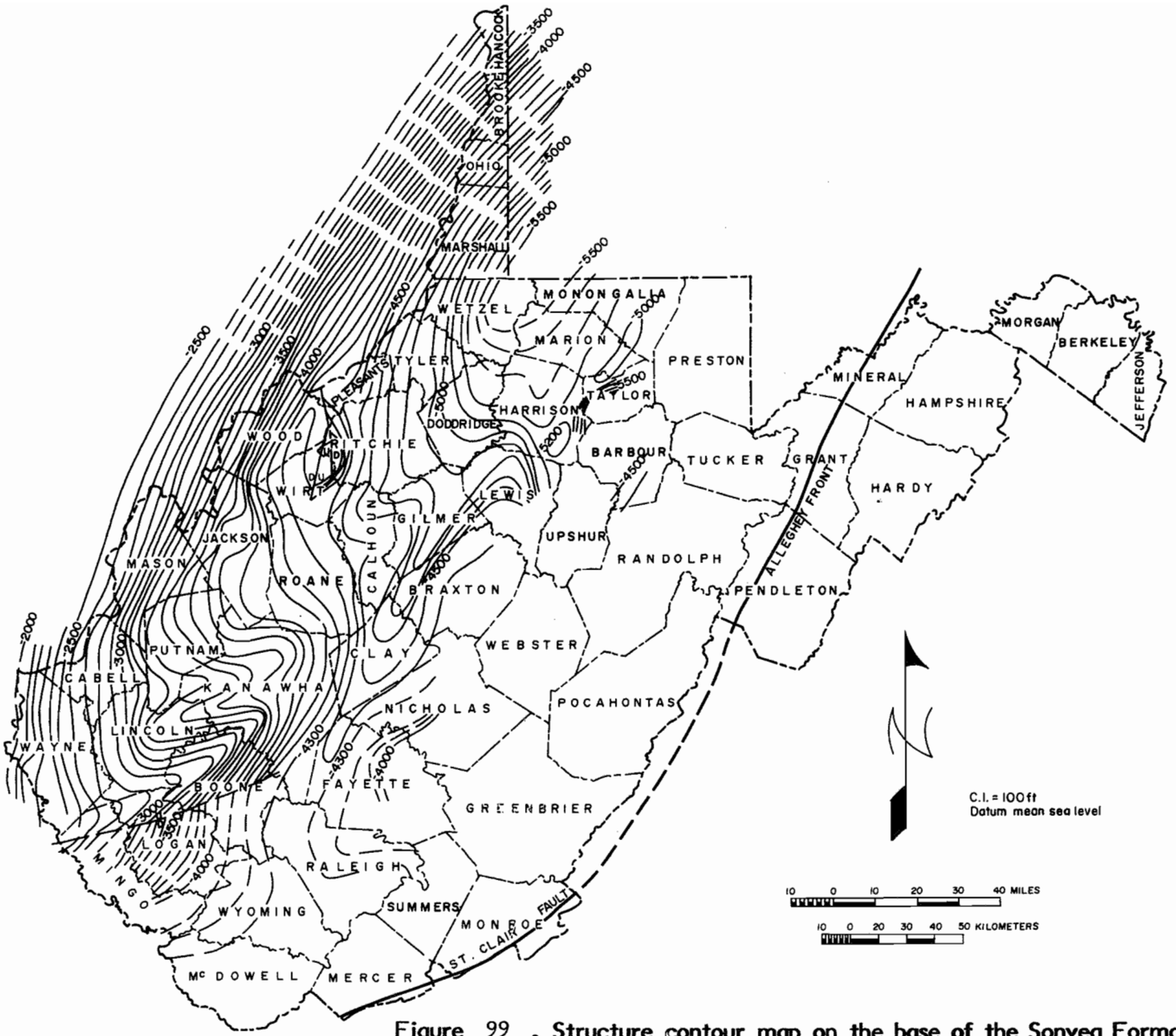


Figure 99. Structure contour map on the base of the Sonyea Formation. From SAI (1980), after Schwietering (1979).

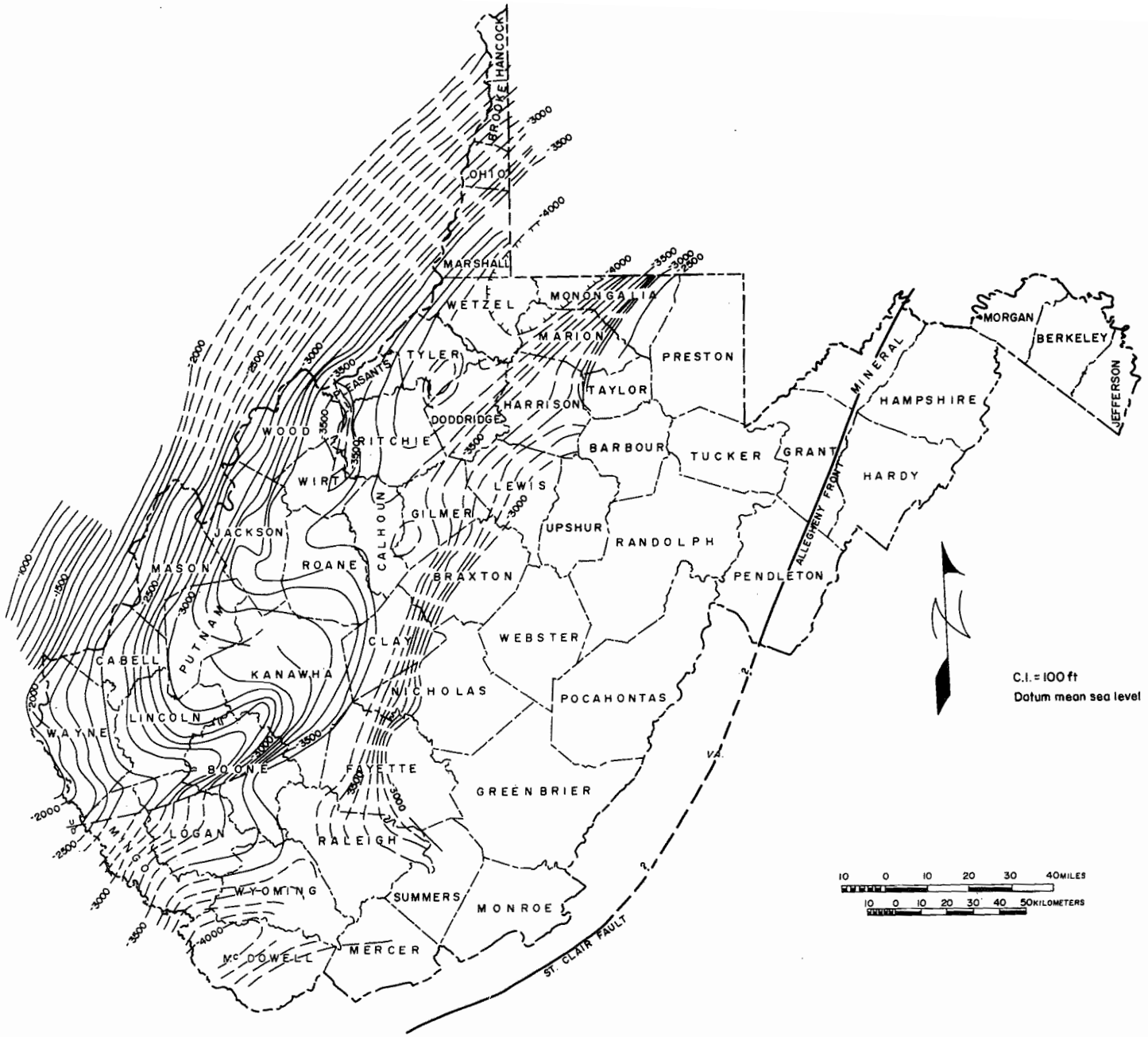


Figure 100 . Structure contour map on the base of the West Falls Formation. From SAI (1980), after Schwietering (1979).

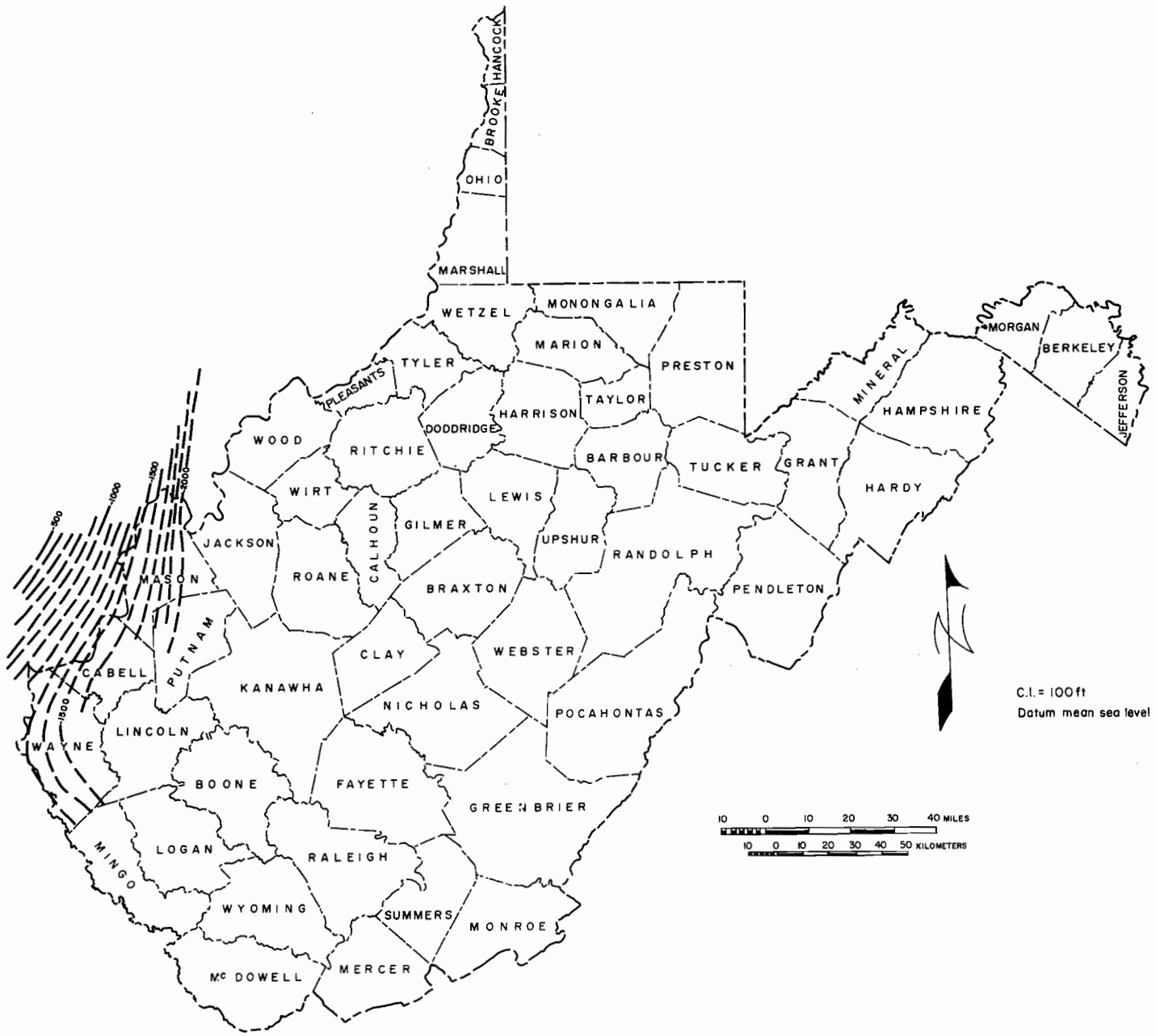


Figure 101 . Structure contour map on the base of the Java Formation. From SAI (1980), after Schwietering (1979).

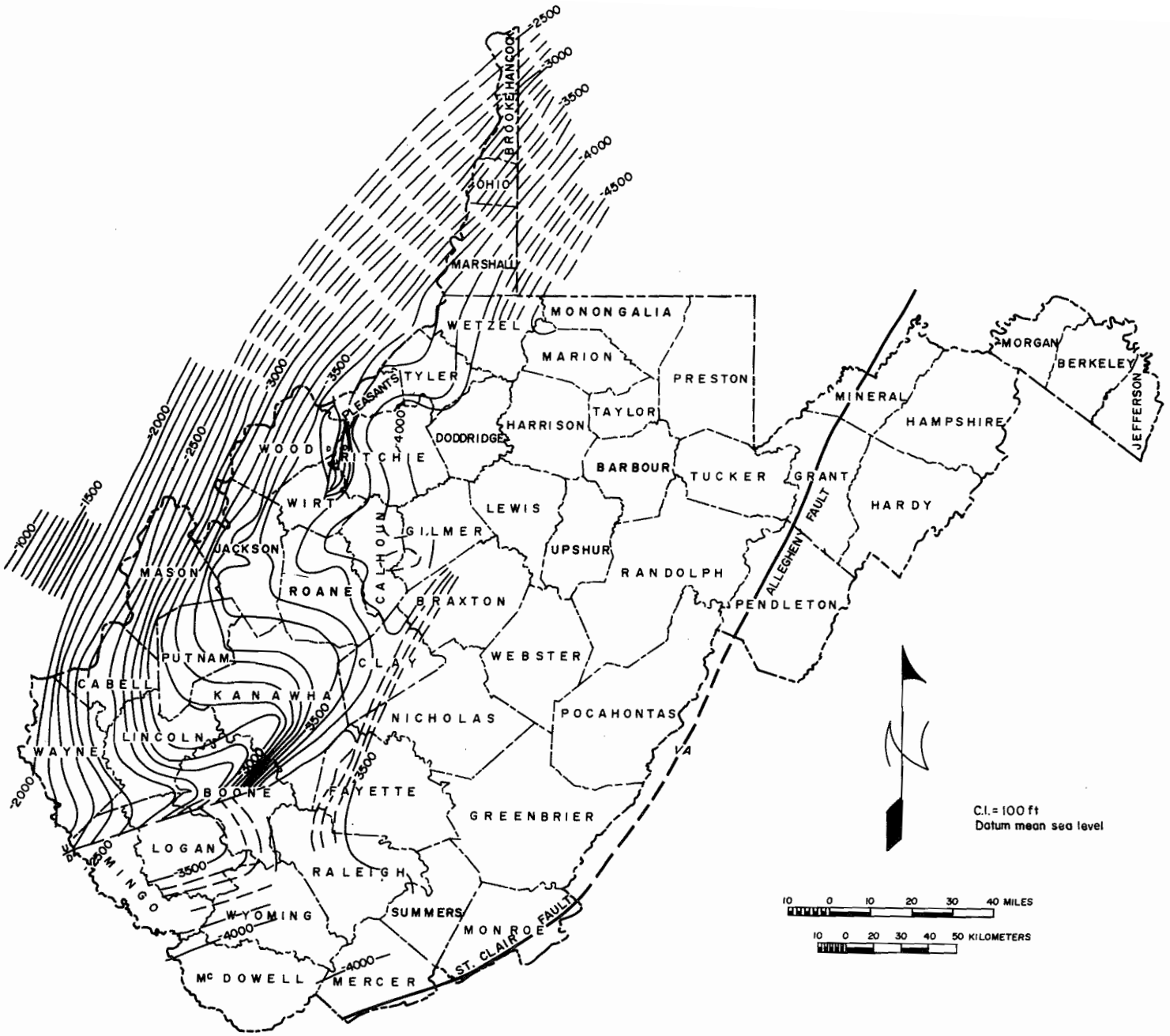


Figure 102 . Structure contour map on the base of the Huron Member of the Ohio Shale. From SAI (1980), after Schwietering (1978).

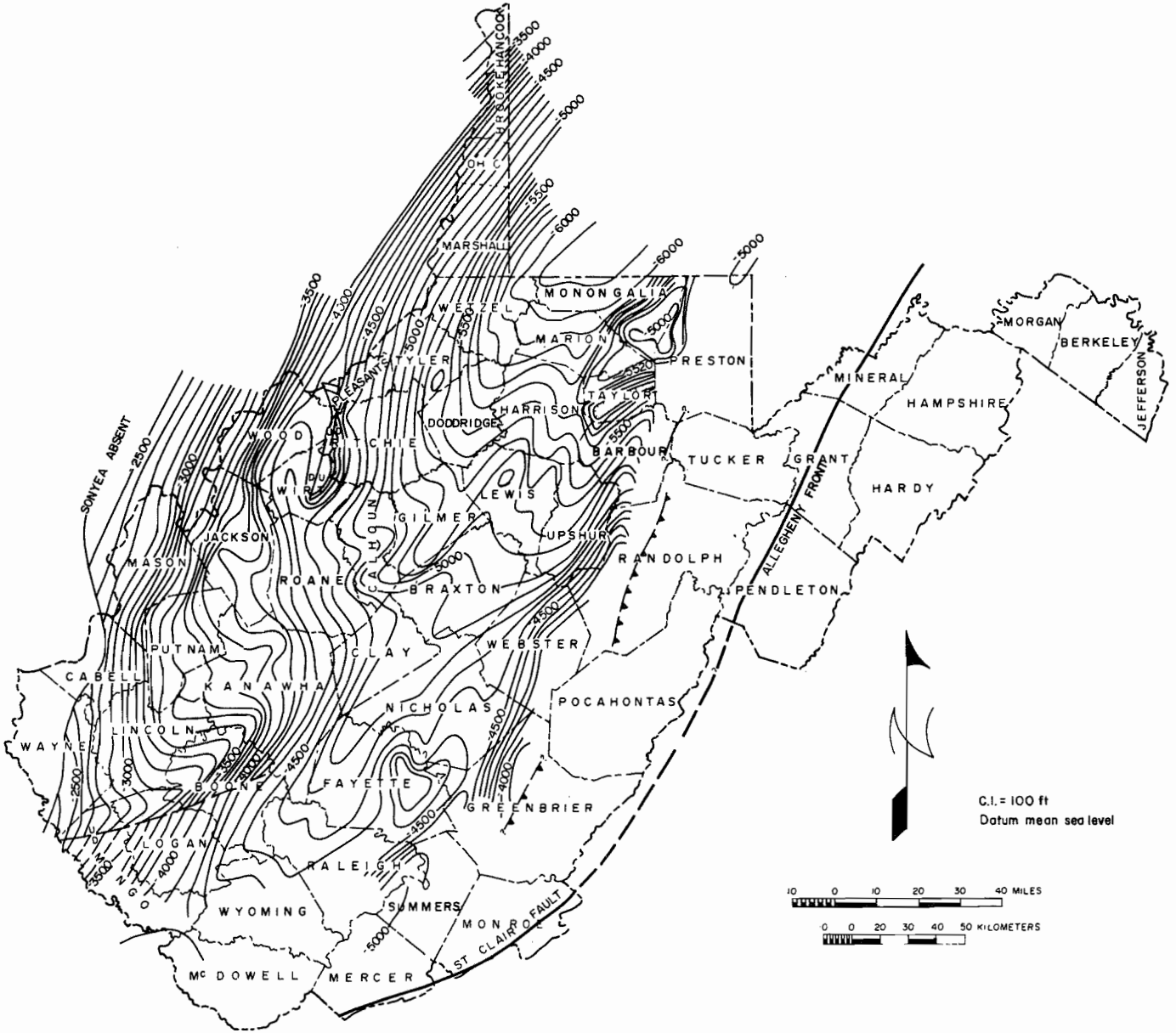


Figure 103. Structure contour map on the base of the Cleveland Member of the Ohio Shale. From SAI (1980), after Schwietering (1978).

During thrusting, the detached thrust sheets were not restricted to gliding along the same slip surface, but rather ramped upward away from the master fault zone. In the east, the decollement surfaces are in the Cambrian-aged shales immediately overlying the crystalline basement. Westward, away from the source of compression, the slip surface ramps upward from one incompetent horizon to another; from east to west the decollement surfaces are found in Cambrian-aged shales, Upper Ordovician shales, the Silurian Salina salt section, and the Middle and Upper Devonian shales.

An overthrust block sliding along a thrust zone would be prone to brittle fracture where it encountered resistance by older faults which cut the slip plane or where the incompetent strata in which the decollement zone developed pinches out. Folding and/or faulting associated with the disruptions along the slip surfaces will actuate fracturing in the overlying beds of the thrust plate (fig. 104). The decollement surface associated with the Pine Mountain Overthrust occurs within the Devonian shale sequence while both the Burning Springs anticline and Cambridge arch represent thin-skinned deformation associated with movement along decollement surfaces in the Silurian Salina salt.

Geological data indicate that the Pine Mountain Overthrust of southeastern Kentucky and northeastern Tennessee was thrust westward on glide planes developed in the Devonian-aged Chattanooga Shale and was displaced a minimum of several miles (Harris and Millici, 1977). The thrust is considered to have occurred during the Allegheny orogeny when the North American plate collided with the African plate. In the Pine Mountain block the Devonian shale attains a thickness of 700 feet which approximates a three-fold thickneing of the normal sequence. The anomolous thickness is interpreted to be the result of imbricate faulting and bed repetition along the sole of the fault (Zafar and Wilson, 1978). Within the thrust block, production from the Devonian Shales and overlying Mississippian sequence is due primarily to secondary fracture porosity and permeability associated with folding and faulting within the Pine Mountain Overthrust system.

The Burning Springs anticline formed in response to thin-skinned tectonic displacement by low-angle thrust faulting along a Silurian salt decollement surface. The structure follows the approximate western boundary of the Salina F4 salt, which pinches out beneath the structure (Clifford and Collins, 1974). The salt served as a glide plane along which the overlying strata was displaced westward. Frictional resistance to movement at the salt pinch resulted in formation of the decollement structure (Collins and Smith, 1977). The north plunging anticline, consisting of three sinuous en echelon elongate domes extending from north-central West Virginia into southeastern Ohio, was formed by imbricate thrusting of the overlying strata. The structure is distinguished from other structures of the foreland fold belt by its tight, steep folds and by its north-south orientation, which cuts across the general northeast-southwest trend of the forelands. The rock between the surface and the Middle Devonian Huntersville Chert and between the Devonian Oriskany Sandstone through the Lower Paleozoic section is relatively undeformed. However, the interval from the top of the Huntersville Chert to the base of the Oriskany Sandstone is intensely deformed and thickened as the result of thrusting. The total interval has been measured at 1843 feet, some 1658 feet thicker than the average regional vertical thickness (Woodward, 1959).

The Cambridge arch is a gentle, rather weak fold which trends to the north-northwest from northern Washington County to Guernsey County and, while continuing, diminishes to the north. The arch, a shallow thin-skinned tectonic structure, may be delineated by mapping several of the overlying Upper Paleozoic horizons. The structure

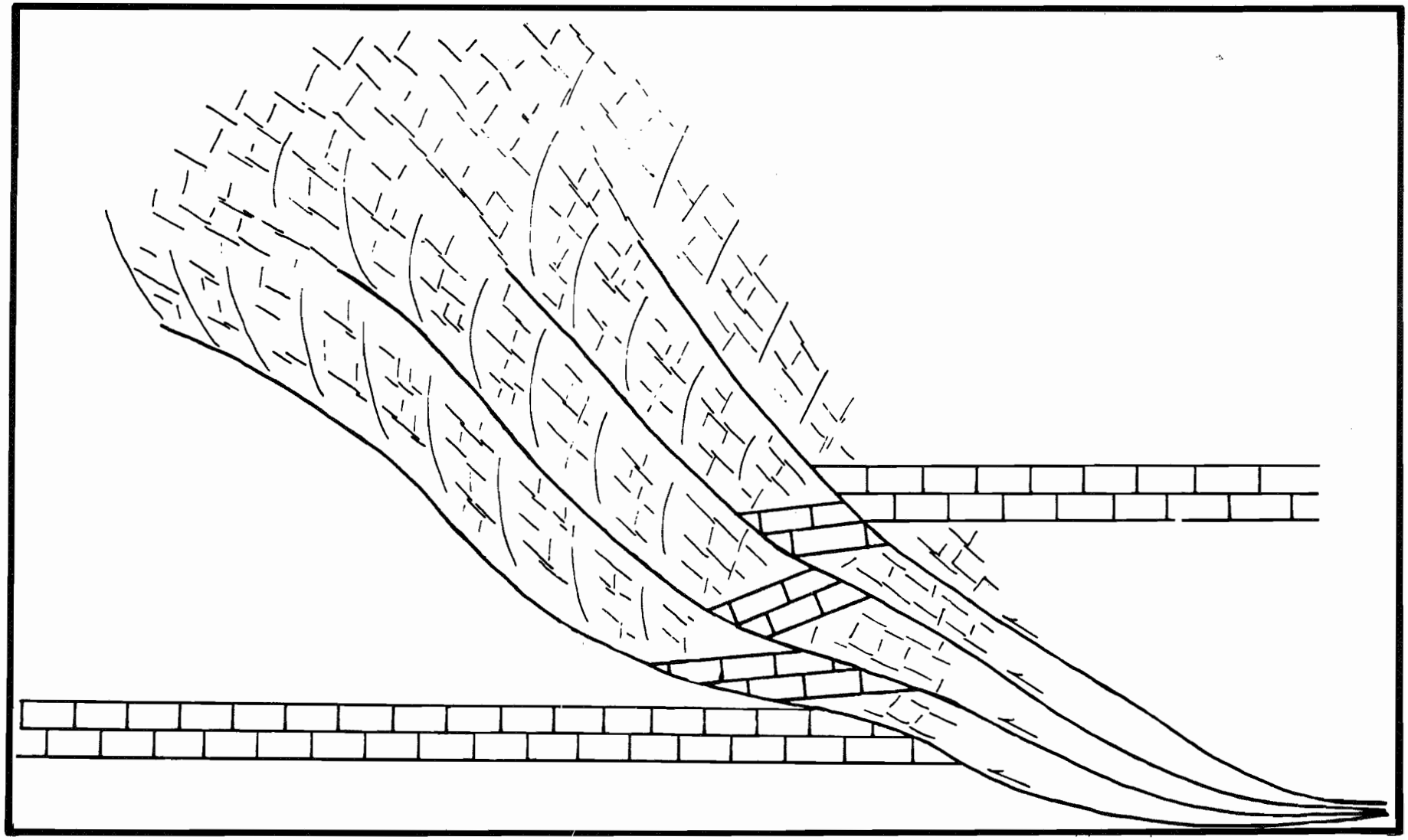


Figure 104 . Fractures generated by low-angle thrust faulting during the Appalachian orogeny. After Overbey (1976).

follows the approximate western limit of the Salina E Salt, which acted as a decollement surface in much the same manner that the Salina F4 salt served in the formation of the Burning Springs anticline. The Cambridge arch has been interpreted by Clifford and Collins (1974) to be the result of movement of a southeastward thickening block of rock overlying the Salina to the northwest along a salt glide plane. The western limit of the decollement surface is interpreted to correspond to a postulated vertical tear fault (or series of faults). Strata east of the E salt pinch-out are approximately 300 feet higher than the strata west of the structure (Clifford and Collins, 1974). Plate 13 is a cross section along the crest of the Cambridge arch showing zones in which oil and/or gas shows have been encountered in the shale. These shows are thought to be the result of secondary porosity developed by decollement-related fracturing.

The development of other large thrust sheets in the Appalachian basin suggests that the foreland fold belt is underlain by additional potential decollement zones in the Salina salt section. Walker (1980) considers the limits of the fold belt from southern New York to West Virginia to be coincident with the limits of the Salina salt basin. Rodgers (1963) postulated the existence of a thrust sheet or series of thrusts which extend from the Burning Springs anticline in West Virginia in central Pennsylvania's Clearfield County. Frey (1973) shows the Salina salt decollement structures developed in the anticlinal belt of south-central New York and north-central Pennsylvania.

Assuming that the decollement zones ramped upward from the Silurian Salina salt sequence into the Devonian Shales in the characteristic thin-skinned tectonic style, subtle small-scale decollement zones should be present in eastern Ohio, northwestern Pennsylvania, and western New York, west and north of the folds present along the edge of the fold belt.

INTRODUCTION - MICHIGAN AND ILLINOIS BASINS

Investigations of the Devonian Shale sequence in both the Michigan and Illinois basins have concentrated upon the stratigraphic correlation and geochemical analysis of the shales within the basin. Limited studies have dealt with the structural evolution of these basins since both are relatively stable intracratonic basins.

The structural evolution of the Michigan and Illinois basins was not directly affected by the Acadian revolution. Their main association with the tectonics of the Acadian revolution was that they served as basins for the accumulation of sediment eroded from the Acadian highlands. However, periods of plate convergence and separation may have influenced structures which had originated, in part, during incipient stages of rifting in these intracratonic basins. The stresses generated during the plate interaction, which culminated with the Acadian and Allegheny orogenies, may have been sufficient to have initiated movement along existing zones of weakness which, in turn, resulted in the formation of fracture systems in the overlying rock. The structural symmetry and relative simplicity of both basins are shown by several cross-sections (plates 8 through 11). The depth to the top of the Devonian Shale sequence varies from just a few tens of feet near the shale subcrop to approximately 2500 to 3500 feet below sea level in the Michigan and Illinois basins.

The mapped structures in the southern part of the Illinois basin indicate a more complex tectonic history for the Illinois basin than for the Michigan basin. The basin is considered to have been initially bounded along the western, eastern, and northern margins by a series of stable arches, but was open to the south. The modern basin's configuration evolved with uplift and faulting of the southern rim. In the Illinois basin, structural deformation consists of a series of east-west trending fault systems and a less extensive northeastward trending system.

PLATE TECTONIC MODEL

Infracratonic Basins

In basins formed during different phases of plate separation and rifting of the continental crust subsidence occurs, in part, as the result of crustal attenuation. Once initiated, additional subsidence may result from crustal flexure which develops in response to sedimentary loading (Dickinson and Yarborough, 1976). Extensional structures are the primary tectonic features that form in the rifted basin setting. These basins, which originate from tensile stresses resulting from plate separation and incipient rifting, exhibit the following general characteristics: (1) a regular, symmetric basin profile; (2) thinning of the continental crust underlying the basin, and (3) a limited amount of structural deformation dominated by extension features.

Infracratonic basins are intracratonic basins that evolved primarily as the result of attenuation of the continental crust. The presence of unusually dense igneous-metamorphic assemblages in portions of the basement complex suggests that both the Michigan and Illinois basins originated as the result of crustal attenuation (Dickinson and Yarborough, 1976). Both basins display a high degree of symmetry with the flanks dipping gently basinward and merging with the boundary arches without structural discordance. In the Michigan basin the most prominent structural feature, besides the surrounding platform arches which rim the basin, is the northwest-southeast trending, basement-involved Howell anticline and fault system in the extreme southeastern portion of the Devonian sedimentary basin. These structures are on trend with the general basin-wide northwest-southeast structural orientation and limited data suggest fracturing of the Devonian Shales over these structures.

The Illinois basin is a roughly oval structural depression centered in southeastern Illinois (fig. 105). As in the case of the Michigan basin, the Illinois basin is rimmed by a series of broad gentle arches. The primary structural features include the east-west trending Moorman syncline-Rough Creek fault system and the northeast-southwest Wabash Valley fault system. Geologically, the Moorman-Rough Creek system consists of a series of normal faults which, in western Kentucky, formed a graben complex that was subject to both pre- and post-Devonian episodes of reversal. Harris (1978) suggested the possibility that the Moorman syncline is the western portion of the Eastern Interior aulacogen, extending from the Mississippi Embayment to the north-central Pennsylvania (fig. 106). However, the hypothesis remains unproved at present.

The stratigraphic sequence in both the Michigan and Illinois basins is typical of infracratonic basins. The sediments include shallow marine carbonates and marine

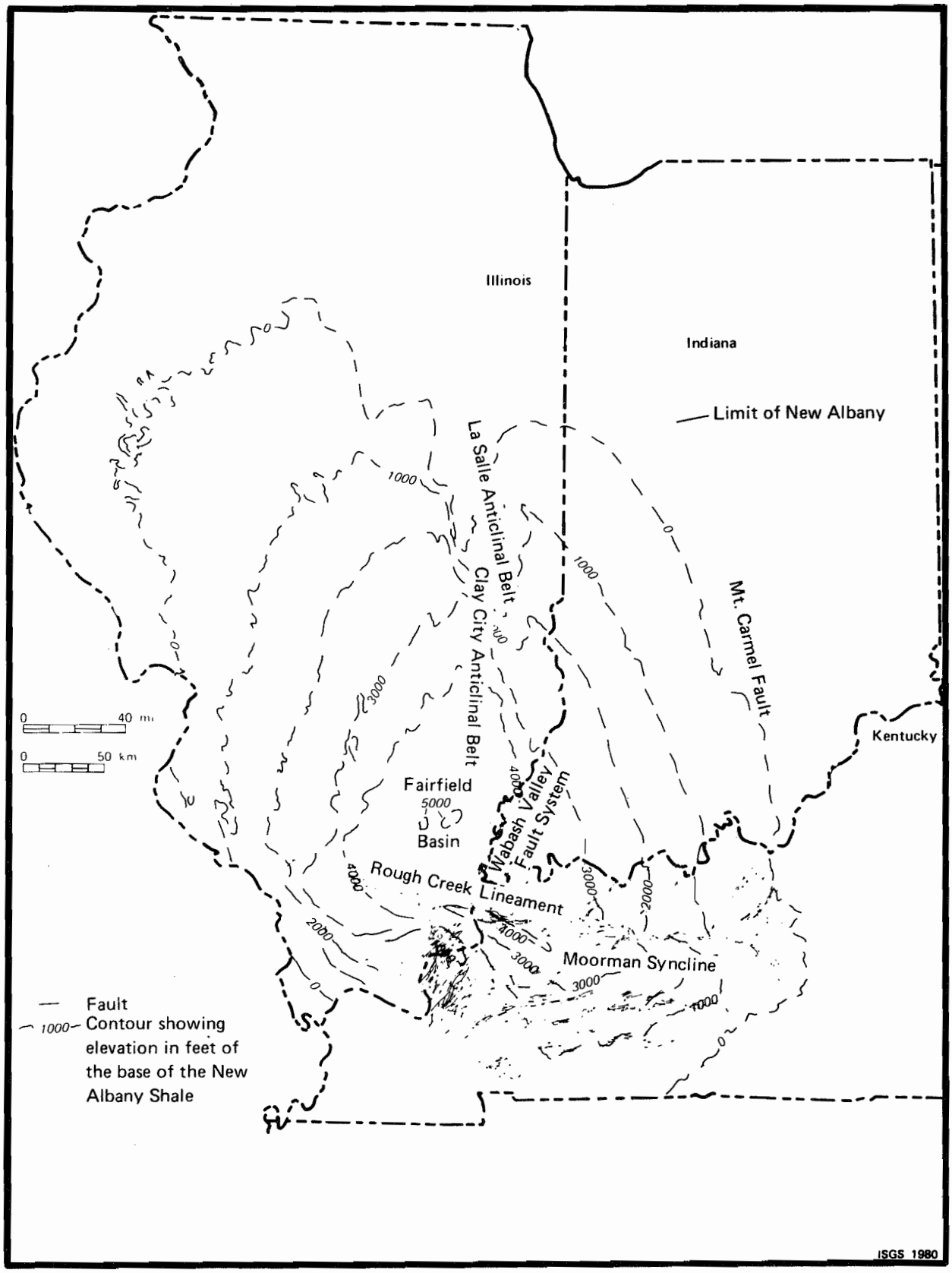


Figure 105. Geologic structure on the base of the New Albany Shale. From Illinois State Geol. Survey, Lineback (1980), after Stevenson and Whiting (1967); Bassett and Hasenmueller (1978); and Schwalb and Potter (1978).

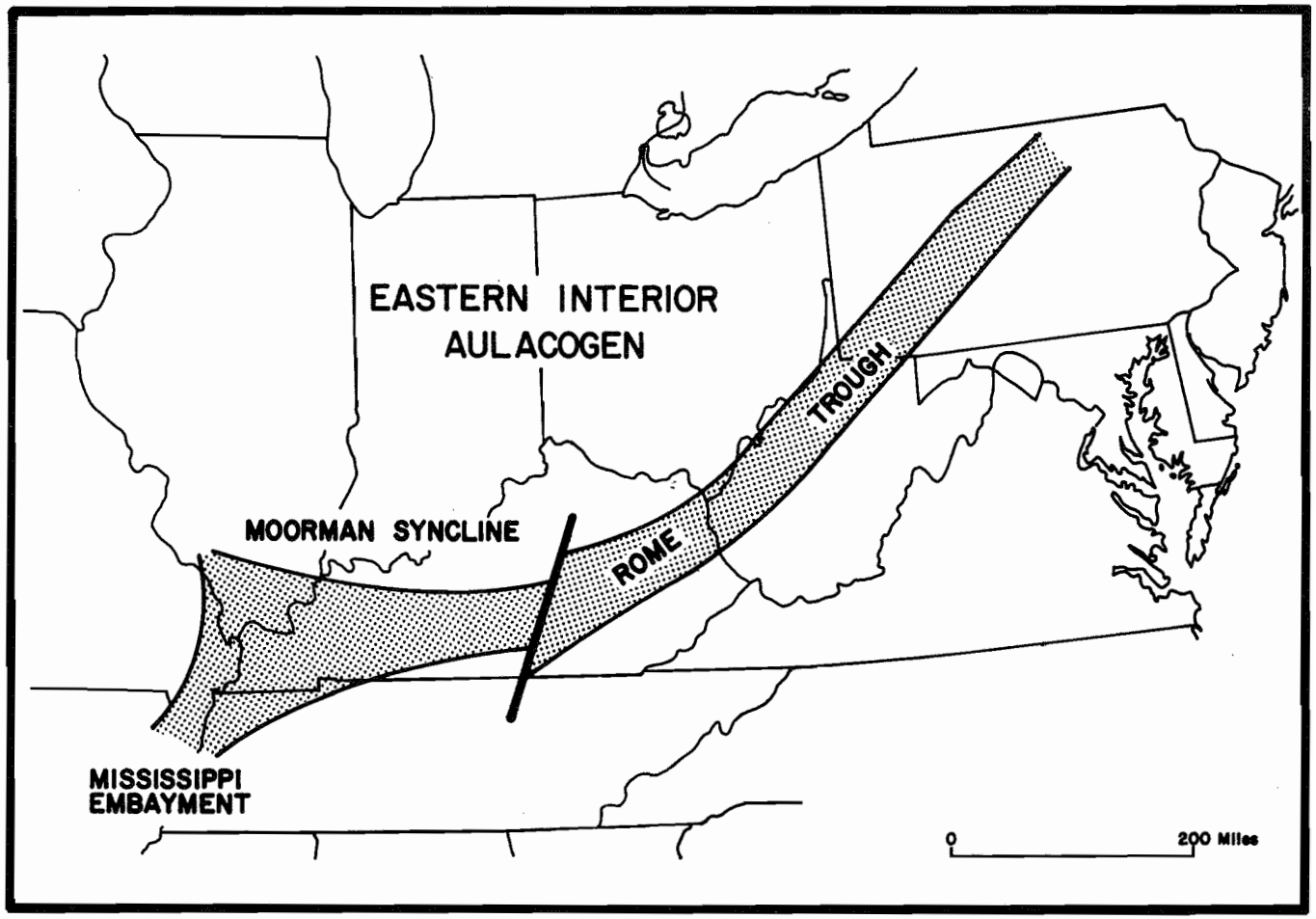


Figure 106 . Projected trend of the Eastern Interior Aulacogen and the component parts. From Harris (1978).

clastics which interfinger with non-marine deposits along the margins of the basins and at the base and top of the sequence. These intercratonic basins were generally kept filled because the sources of sediment could keep pace with the low rate of subsidence (fig. 107). However, periods of sediment starvation or accelerated subsidence may account for the formation of distal basin conditions which allowed for the deposition of organic-rich source beds such as the Antrim and New Albany Shales. Later Paleozoic stages of tectonic activity and sediment-induced subsidence tended to form a series of gentle folds and faults which reflect minor degrees of small-scale deformation as opposed to the more intensely deformed areas of the Appalachian basin.

Vertical Tectonics

As described previously, the plate tectonic theory involves not only large-scale horizontal movement but also a vertical component. Thus, vertical tectonics, in the form of basin subsidence, are essential for the entrapment of sediment and overall evolution of the basin. In addition to basin subsidence, examples of vertical tectonics in the Illinois basin include the Moorman syncline complex and other small, post New Albany Shale anticlinal complexes. In the Michigan basin, examples of structural deformation related to vertical tectonics are restricted to the small-scale anticlines formed in response to decollement tectonics in the Salina salt section. However, since there is no evidence of Antrim/Ellsworth fracturing over these structures, they have not been discussed in this report.

The Moorman syncline is a structural graben which dominates the structure of western Kentucky. The boundaries are delineated by the Rough Creek fault system in the north and the Pennyrile fault system to the south. Variations in shale thickness within the Moorman syncline (Schwalb and Potter, 1978) indicate that the Rough Creek system was tectonically active during deposition of the Devonian New Albany Shale. The thickness variations along the southern boundary are considered to reflect post-depositional faulting and associated fracturing of the overlying New Albany.

In southern Illinois the western portion of the Moorman syncline is known as the Eagle Valley syncline. It parallels the Rough Creek-Shawneetown complex in southern Illinois and terminates in the complex of fault zones associated with the Fluorspar Area fault.

The Rough Creek-Shawneetown fault system is the northern boundary of the Moorman syncline and extends parallel to it in an east-west direction. High-angle normal, reverse, and strike-slip displacements have been mapped along this system, but do not show any consistent direction of dip along the Rough Creek portion of the system (Krauss and Treworgy, 1979). The lack of a consistent direction of throw and the development of grabens and scissor faults without regional displacement suggest the possibility that strike-slip movement developed over a pre-existing fracture zone, possible Precambrian (Heyl, 1972). Local displacements along this fault zone are thought to have been initiated during the Early Paleozoic and continued through the Devonian, similar to the activity associated with the Rome trough in the Appalachian basin. The overall trend produced a sequence of down-to-the-south displacements; later, possibly during the Permian, an overall structural reversal occurred which produced a down-to-the-north direction of throw along the system.

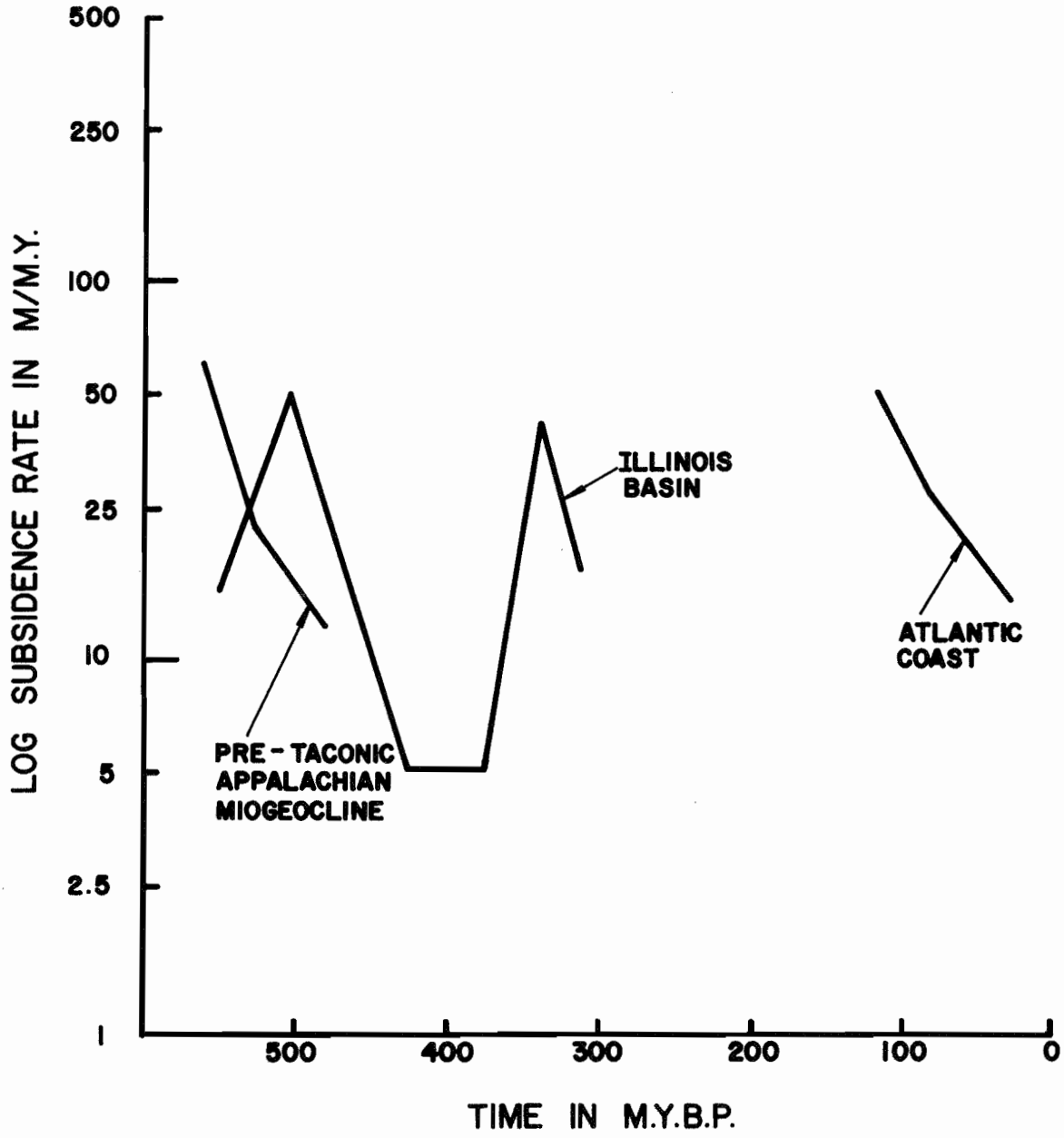


Figure 107. Estimated subsidence rates for the pre-Taconic Appalachian, Illinois basin, and present-day Atlantic Coast. From Dickinson and Yarborough (1976).

The Cottage Grove fault system is an east-west trending system which exhibits a structural style similar to that of the Rough Creek-Shawneetown system; however, it appears to die out as it approaches the Shawneetown fault system and does not become a part of it. The Cottage Grove fault system is considered to have developed in response to right lateral stress field which evolved during the early Permian, contemporaneous with the on-going Allegheny disturbance to the east (Nelson and Krausse, 1981).

Additional examples of vertical tectonics in the Illinois basin include the northeast trending Fluorspar Area fault complex, south of the Rough Creek-Shawneetown zone, and the Wabash Valley fault system, north of the Rough Creek-Shawneetown zone. These fault systems consist primarily of numerous zones of horsts and grabens, but do not appear to represent a continuous, interlinked system. The development of natural fracture systems in the strata adjacent to and immediately overlying these faults is considered likely. Thus, areas overlying these complexes which have favorable geochemical parameters are considered as potential areas for shale gas generation and accumulation.

Occurrence of Shale Gas in Natural Fractures

INTRODUCTION

Production of natural gas from the Devonian shale section is thought to be derived from naturally fractured shales where the fractures provide the increased porosity and permeability necessary for the storage and movement of gas within the reservoir. These fracture systems are essential elements for a commercially productive reservoir in the Devonian Shale.

The reserves locked in the Devonian shales, whether using estimates by the USGS (Charpentier et al., 1982) which tend on the conservative side, or estimates by the Mound Facility (Zielinski and McIver, 1982) on the optimistic side, exceed by several times the current proven gas reserves in the United States. One characteristic of the shale reservoirs is that the organic-rich black shale facies is thought to serve not only as the hydrocarbon source, but also, in areas of intense natural fracturing, as the hydrocarbon reservoir. The fracture systems provide the means by which gas migrates from the source bed(s) into silty zones within the Devonian sequence. Thus, it is evident that natural fracture systems are critical for production in the Devonian black shale and in the thin, tight sand and siltstone bundles associated with the Brallier and Chemung facies. Fractures become increasingly critical basinward because of the decreased matrix porosity and permeability, which is a function of increased overburden. However, in the Appalachian basin the increased overburden pressure is offset somewhat by the increased cleanliness of the reservoirs as one approaches the turbidite source. Predicting where these fracture systems occur, therefore, is considered essential to a successful shale exploration program.

Once drilling or well stimulation procedures have begun, the presence of natural fractures may be determined or inferred by one or more of the following methods:

(1) Lost circulation: where the drilling fluid escapes from the borehole into the shale section, usually indicates that a fractured formation has been penetrated.

(2) Core examination: Natural fractures can be distinguished from coring-induced fractures; poor core recovery may indicate that the shale has been intensely fractured.

(3) Production characteristics: high, "flashy" rates of production which decline rapidly suggest the presence of interconnected natural fracture systems with a small volume of a capacity.

(4) Log analysis: various types of well logs indicate the presence of secondary porosity.

(5) Well stimulation: low fracture gradients during hydrofracturing or other methods of well stimulation (Walker, 1980).

However, fracture detection prior to the drilling operation is important for a successful exploration program. Landsat imagery and aerial photo interpretations, along with fracture trace analyses of photos and topo sheets, are methods by which linear features may be related to natural fracture systems which exhibit surface expression. These processes, information pertaining to local and regional structural features, and the associated fracture patterns allow the geologist to project trends of potential fracturing.

LINEAMENTS AND JOINTS

The detection of fracture systems in the Devonian Shale in areas not associated with known structures is difficult at best. However, various types of remote sensing techniques can be used to identify and project fracture trends. The exploration rationale behind the use of the various remote-sensing techniques is to attempt, through interpretation, to successfully detect areas of higher-than-normal fracture density. The areas with higher-than-normal fracture densities should reflect potential natural fractured reservoirs with the enhanced porosity and permeability necessary for a commercially successful producing well. Research and test data indicate that lineaments and other photolinears can be related to bedrock features and are the surface expressions of vertical or nearly vertical subsurface joint and fault patterns and, therefore, provide a viable tool by which exploration can be conducted (Struble et al., 1980).

Several studies using both landsat imagery and areal photographic interpretation have been conducted throughout the Appalachian basin. Work conducted by the Ohio Geological Survey (Struble et al., 1980) mapped the eastern half of Ohio, showing the photolinear density and trend. The nonfracture-related photolinears were filtered from the raw data and deleted, leaving only those lineaments which were deemed statistically reliable. From this data a series of first- and second-degree trend-surface maps and corresponding residual height maps were constructed showing the anticipated fracture density for eastern Ohio. The second-degree residual-height maps were developed to show the local concentration of photolinears and reflect areas in which the fracture density is higher or lower than the regional average. By using this data, it is then possible to project areas of high fracture density to establish potential trends for the Devonian.

In West Virginia, work by McManus and Metzler (1979), Jones and Rauch (1978), and various other workers has concentrated on lineament and photolinear analysis in conjunc-

tion with existing shale gas fields such as Cottageville and Big Sandy. Lineaments studies over these and other shale gas fields in southwestern West Virginia indicate that fracturing had been controlled to a large degree by recurrent movement along the various faults associated with the Rome trough system.

Two additional geologic features in eastern West Virginia are the Parsons and Petersburg cross-strike structural discontinuities (fig. 108). Recent studies (Sites, 1978; Wheeler, 1980) have demonstrated that these structural lineaments represent zones of increased fracture intensity within the Middle Devonian shales where the lineaments intersect. The presence of more intense jointing in these shales should increase their porosity and permeability, and potential as reservoir for gas.

Landsat imagery over the Cottageville shale gas field revealed several linear trends oriented at N45 to 70E, N35 to 45W, and N80 to 90W crossing the field (McManus and Metzler, 1979). These features were interpreted as being near-vertical extension fractures possibly related to movement along one or more of the fault blocks of the northern limb of the Rome trough. Several of these fractures are postulated as extending through the Devonian section, providing the pathways and reservoir space essential for shale gas production. The fractures commonly occur as sets rather than single features, therefore, the rational for the optimum positioning of a well should be that it penetrate closely-spaced fractures or intersecting fracture systems. Mappling of the Cottageville field by Nuckols (1978) demonstrates the close relationship between structurally-controlled fracture systems and shale gas production.

In southwestern New York linear features were studied using landsat imagery by Van Tyne and Wickerham (1980). The study concluded that the lineaments represent the major joint and fracture trends in the study area. These lineament trends formed two orthogonal sets, one which was structurally controlled, oriented northeast-southwest, and one which reflected the effects of Late Pleistocene glacial activity (north-south and east-west orientations).

In the Michigan and Illlinois basins lineament studies indicate that most linear features are the product of glacial activity and are unrelated to structures in the underlying bedrock (Bergstrom and Shimp, 1980). This observation is due, in part, to the thick glacial drift which blankets both basins. Remote sensing analysis provides the best interpretation in areas where glacial cover is thin and the regional geology is well understood. Therefore, lineament analysis in the glaciated portions of the Michigan and Illinois basins is considered conjectural.

STRESS ORIENTATION

The tectonic episodes of the Acadian and later periods of orogeny imposed a series of fractures and inherent stress patterns on the Devonian Shale sequence. The in-situ stress field of a particular facies may be determined if the principle stresses are resolved. McKetta (1980) cites various studies in which artificially induced hydraulic fractures can be related to the magnitude of the inherent stress patterns. After these values have been determined, the stress can be interpreted to develop a regional stress ratio or fracturing gradient (McKetta, 1980). Figure 109 shows the stress-rated distribution in the

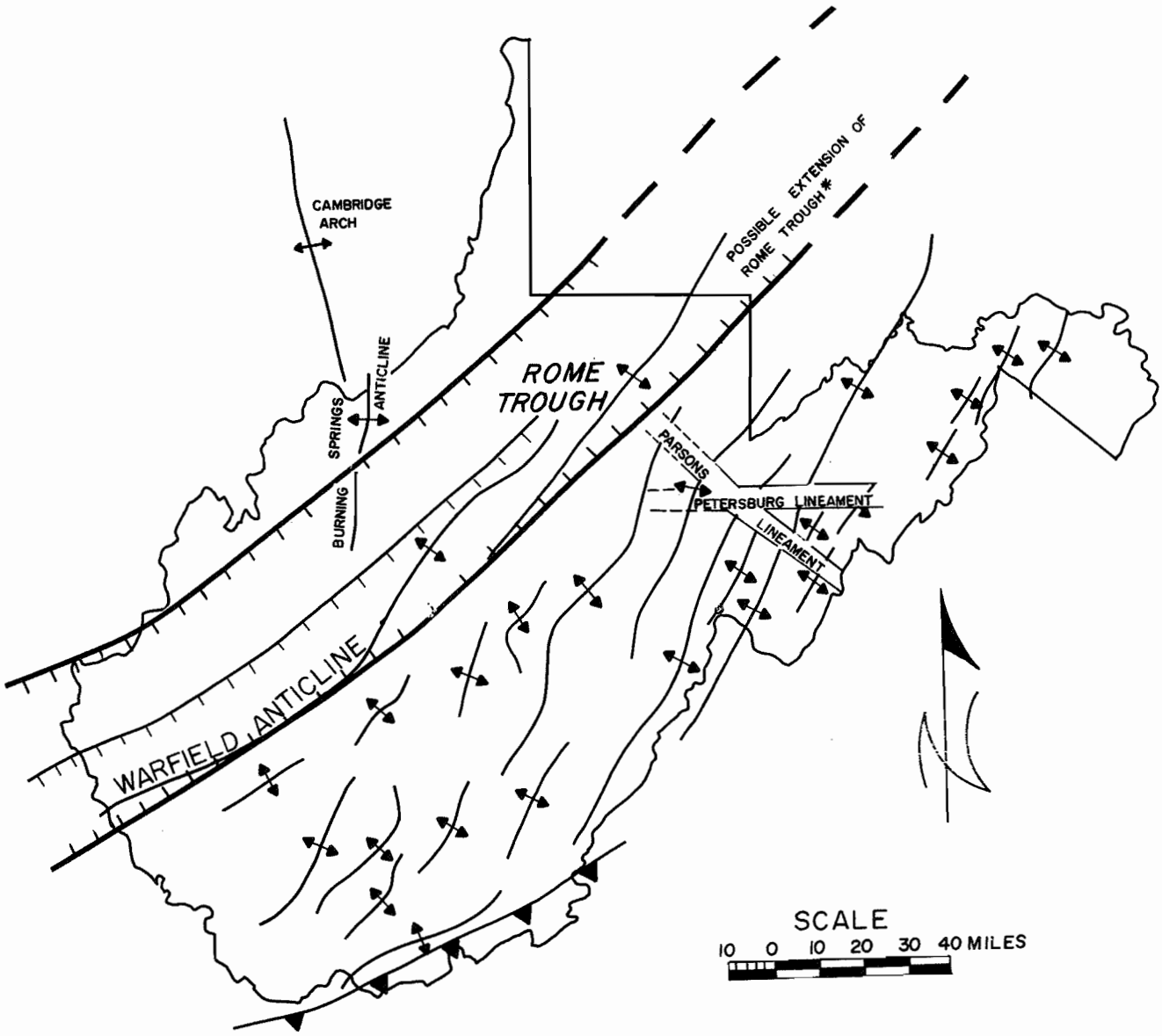


Figure 108. Location of the Parsons and Petersburg lineaments and their relation to other structures in West Virginia. (1) From SAI (1980), (2) *Rome trough extension after Harris (1978).

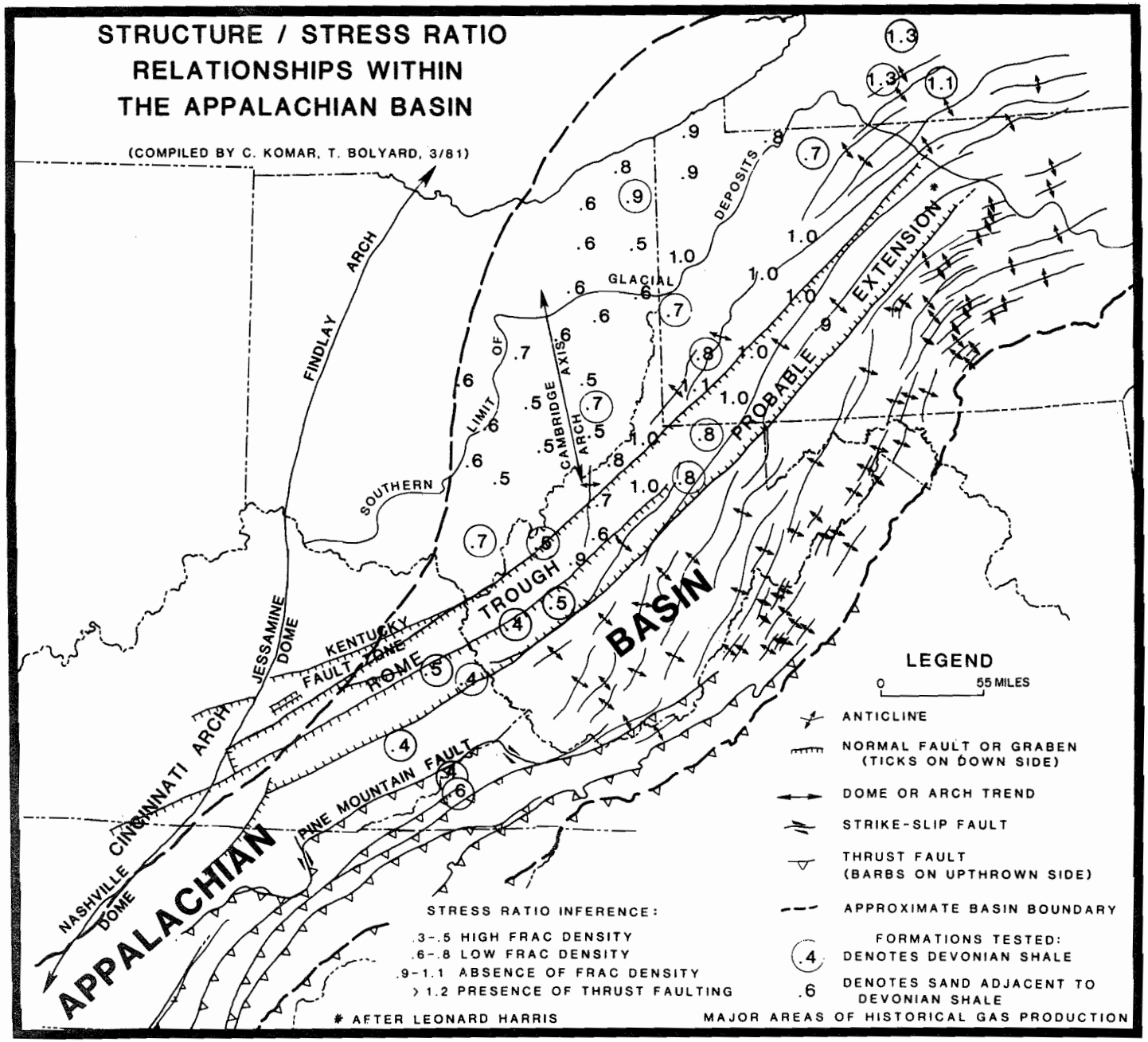


Figure 109. Structure/stress relationships within the Appalachian basin. Compiled by Komar and Bolyard (1981).

Appalachian basin with several of the more prominent structural features overlain. From the computed stress ratios the degree to which natural fracture systems are developed in that area can be inferred.

The prediction and distribution of natural fracture systems was documented, in part, by the analysis of cores taken from the various wells sampled during the Eastern Gas Shales Project (fig. 110). This portion of the project, conducted by Cliffs Minerals, Inc., was concerned with the collection of core sections in and through the Devonian section. Of particular interest was the observation of the density and orientation of fractures contained in the cores. During the coring operation, two distinct types of fractures were noted: natural fractures, which formed in response to the structural history to which the rock had been subject, and induced fractures, which were the result of deformation during the various stages of core acquisition. The induced fractures were generally distinguishable from the natural fractures by their coarse, irregular surfaces which often were curved or spiraling and contained arrest lines, and twist hackles and plumes (Cliffs Minerals, Inc., 1982). The induced fractures never exhibited any mineralization and occurred as several types or combination of types. The induced fractures never exhibited any mineralization and occurred as several types or combination of types. The induced fractures included petal fractures, petal-centerline fractures, torsional fractures, disc fractures, and disc-circular slickensides (fig. 111). The fracture type, fracture strike and dip, and several other data types were collected and cataloged for both the natural and induced fractures. From this data the major and minor fracture axes were presented for each rock group for which data was available. Work by Zielinski and McIver (1982) made use of this data by constructing a series of maps showing the fracture density and orientation for each of the Devonian Shale intervals. Figures 112, 113, and 114 show the observed fractures during Marcellus, Lower Olentangy/Rhinestreet, and early Lower Huron/early Dunkirk time. The orientation of natural fractures varies greatly with each successive rock unit, suggesting a random pattern rather than uniform orientation. As previously stated in other sections of this report, these three horizons are considered to have good source and reservoir potential for shale gas exploration.

Observations of fracture density data from cored wells in the Eastern Gas Shales Project indicates the fractures cannot be correlated regionally to tectonic events but, rather, reflect correlation to local structural features or residual stresses within the rock units themselves. Zielinski and McIver (1982) also point out that the orientation of fractures is of secondary importance when compared to the intensity of fracturing of each core. For a more complete discussion on the Eastern Gas Shales Project investigations of fracture orientations and densities from core samples, the reader is referred to the reports of Cliffs Minerals, Inc. (1982) and Zielinski and McIver (1982).

BASIN SUBSIDENCE FRACTURES

In the Appalachian basin, it is generally accepted that the Devonian Shale sequence was lithified prior to renewed subsidence during the Allegheny orogeny. Hypothetically, then, if the arc of the resultant deep basin is longer than the essentially straight chord of the original shallow plane of Devonian Shale deposition, then below a certain critical depth the individual shale beds would have been subject to tensional stress, and an extension regime produced (fig. 115). However, under compacted sediments such as those formed during periods of rapid sedimentation as dump-in-turbidites, would have been

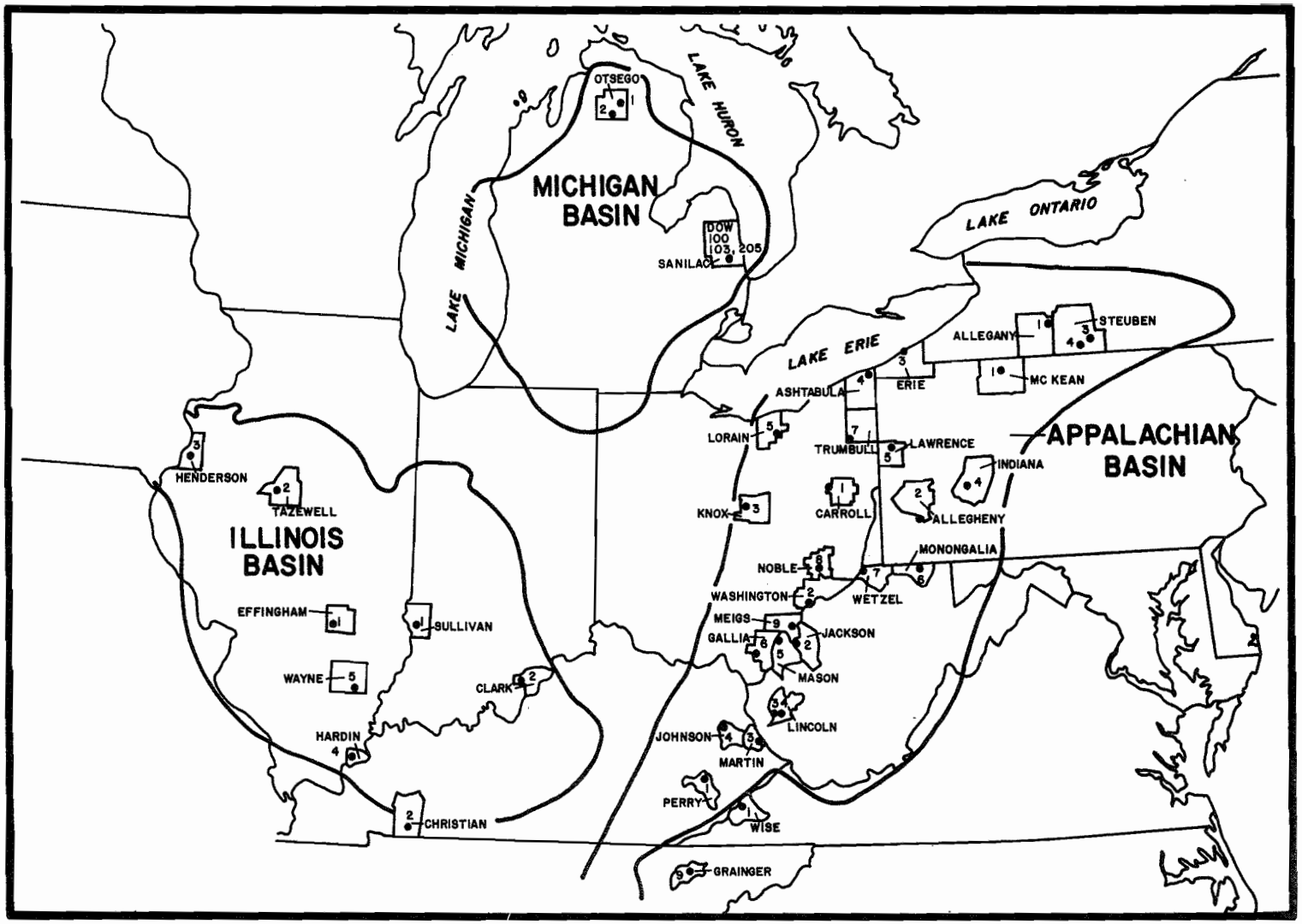


Figure 110. Map showing the locations of EGSP cores in the Appalachian, Michigan and Illinois basins. Modified from Cliffs Minerals, Inc. (1982).

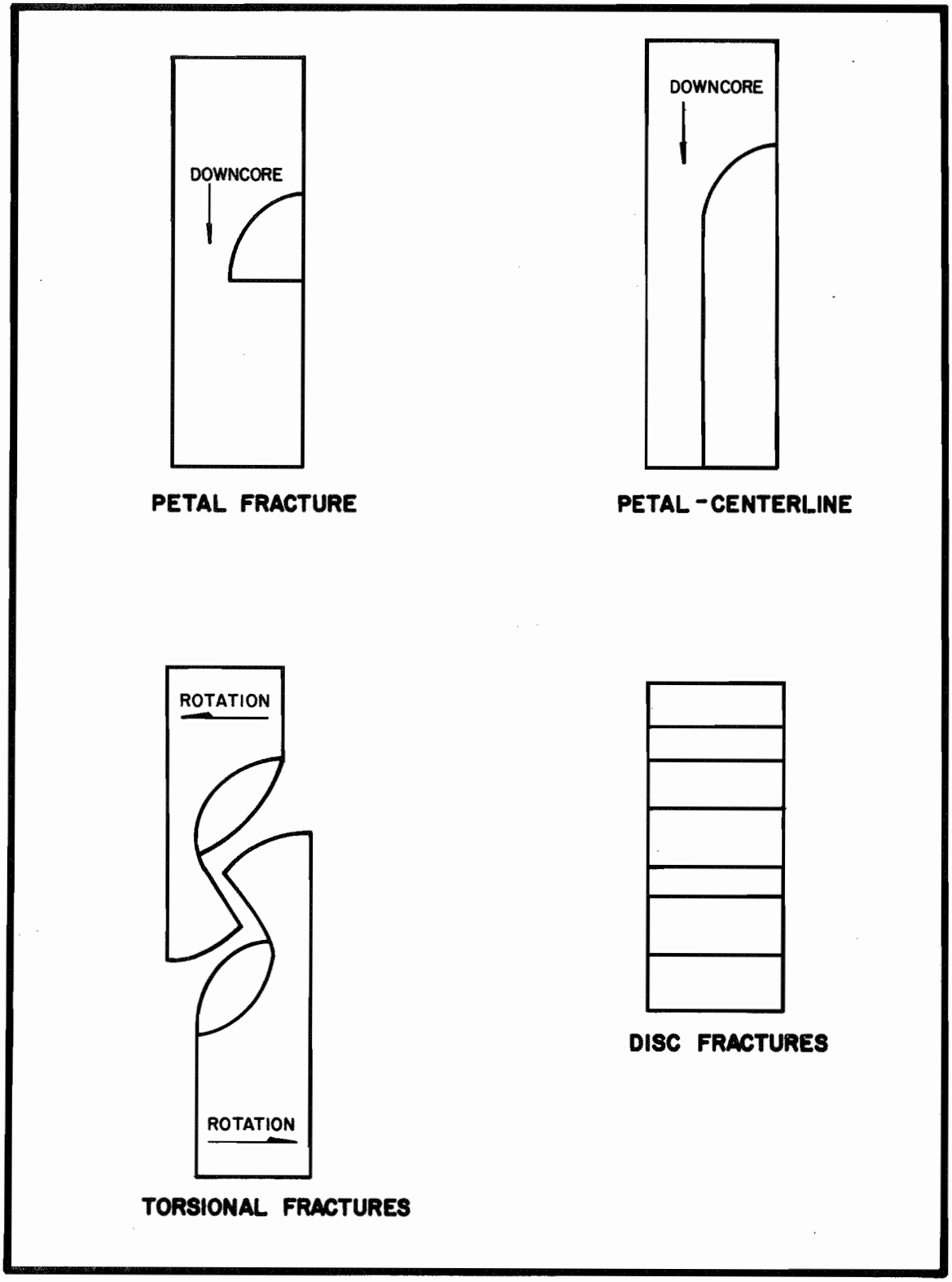


Figure 111. Types of induced fractures detected in the various EGSP cores. From Cliffs Minerals (1982).

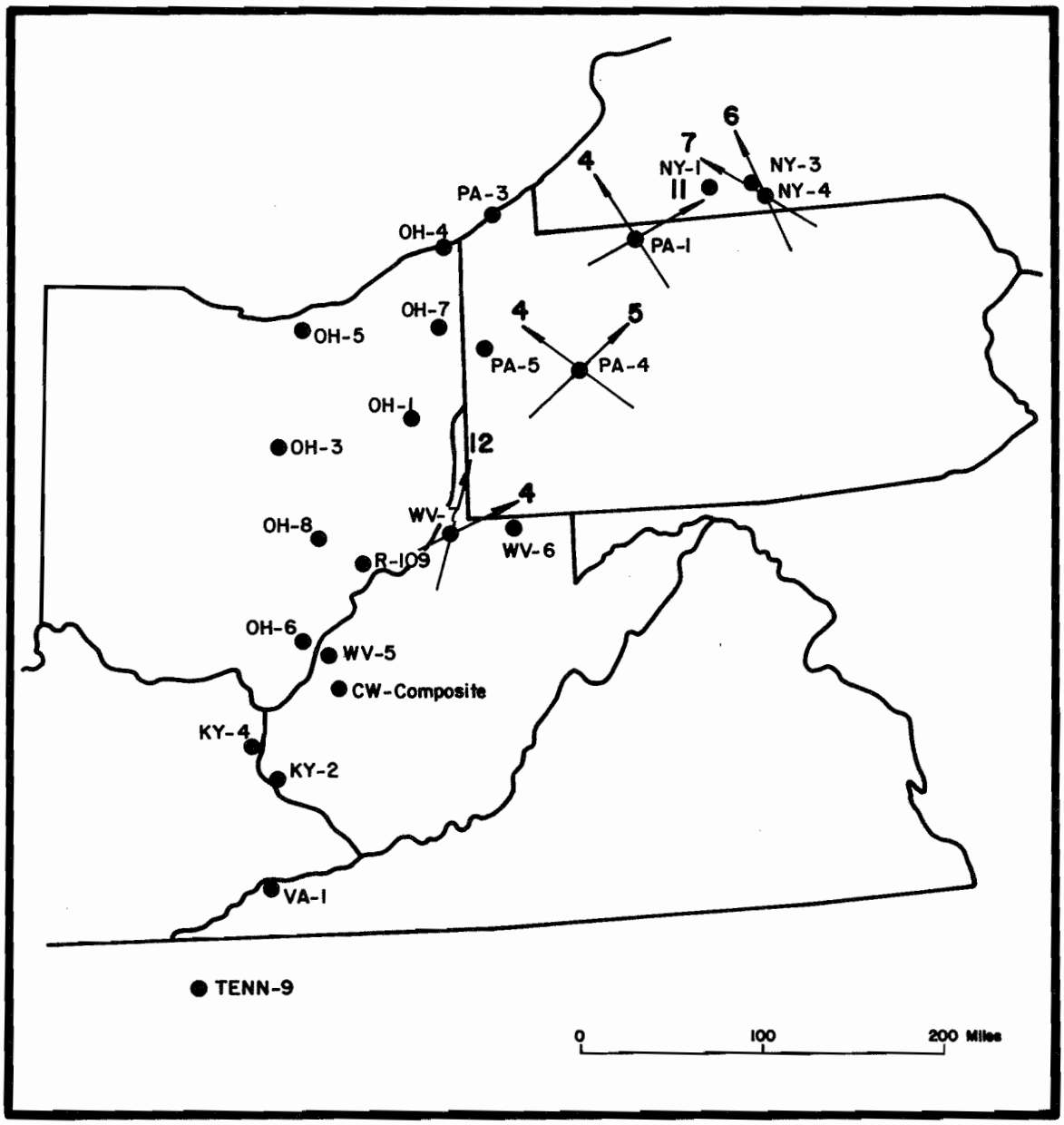


Figure 112 . Map showing fracture orientation and density in rocks deposited during Marcellus time. From Mound Facility (1982).

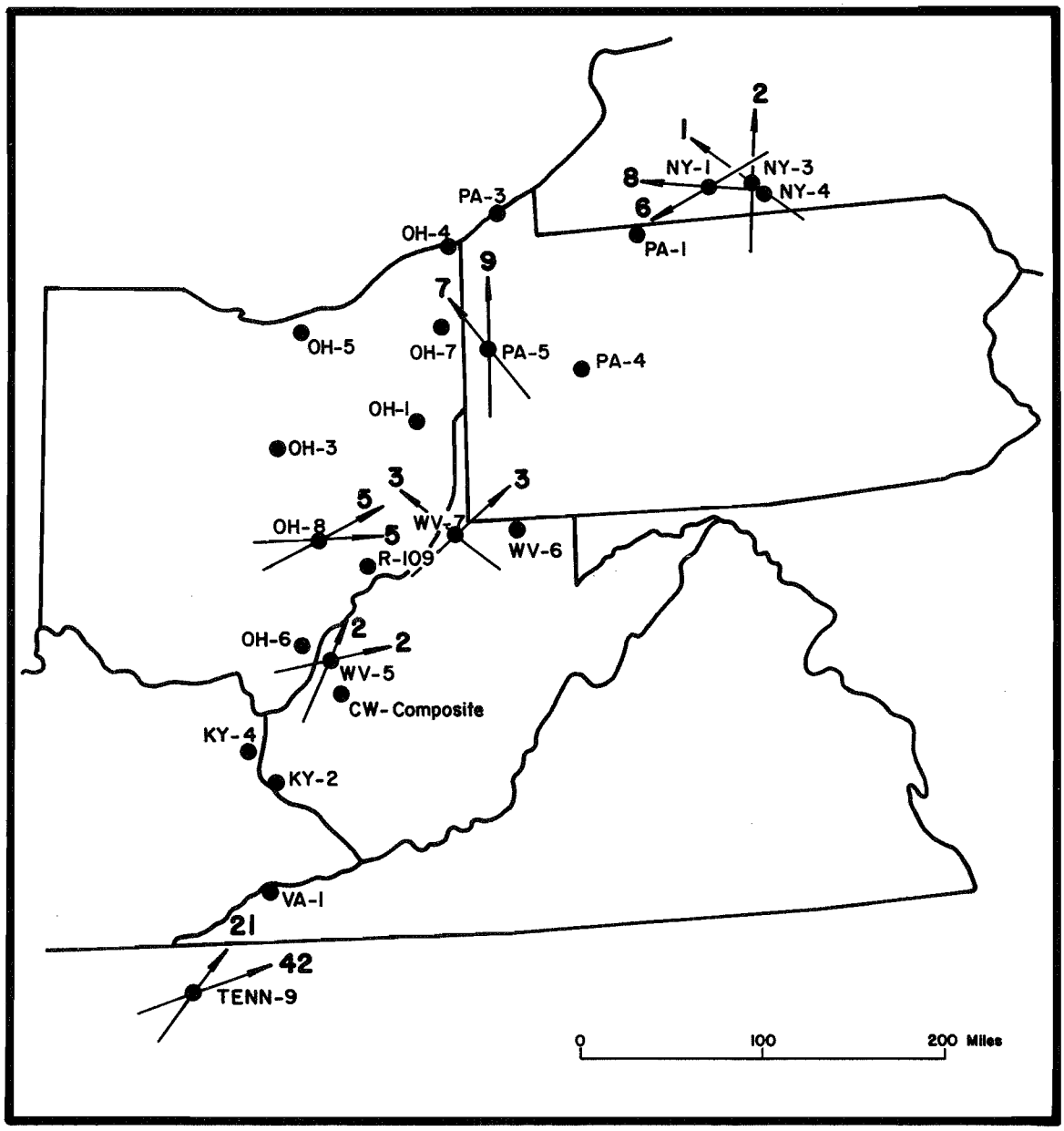


Figure 113. Map showing fracture orientation and density in rocks deposited during Lower Olentangy/Rhinestreet time. From Mound Facility (1982).

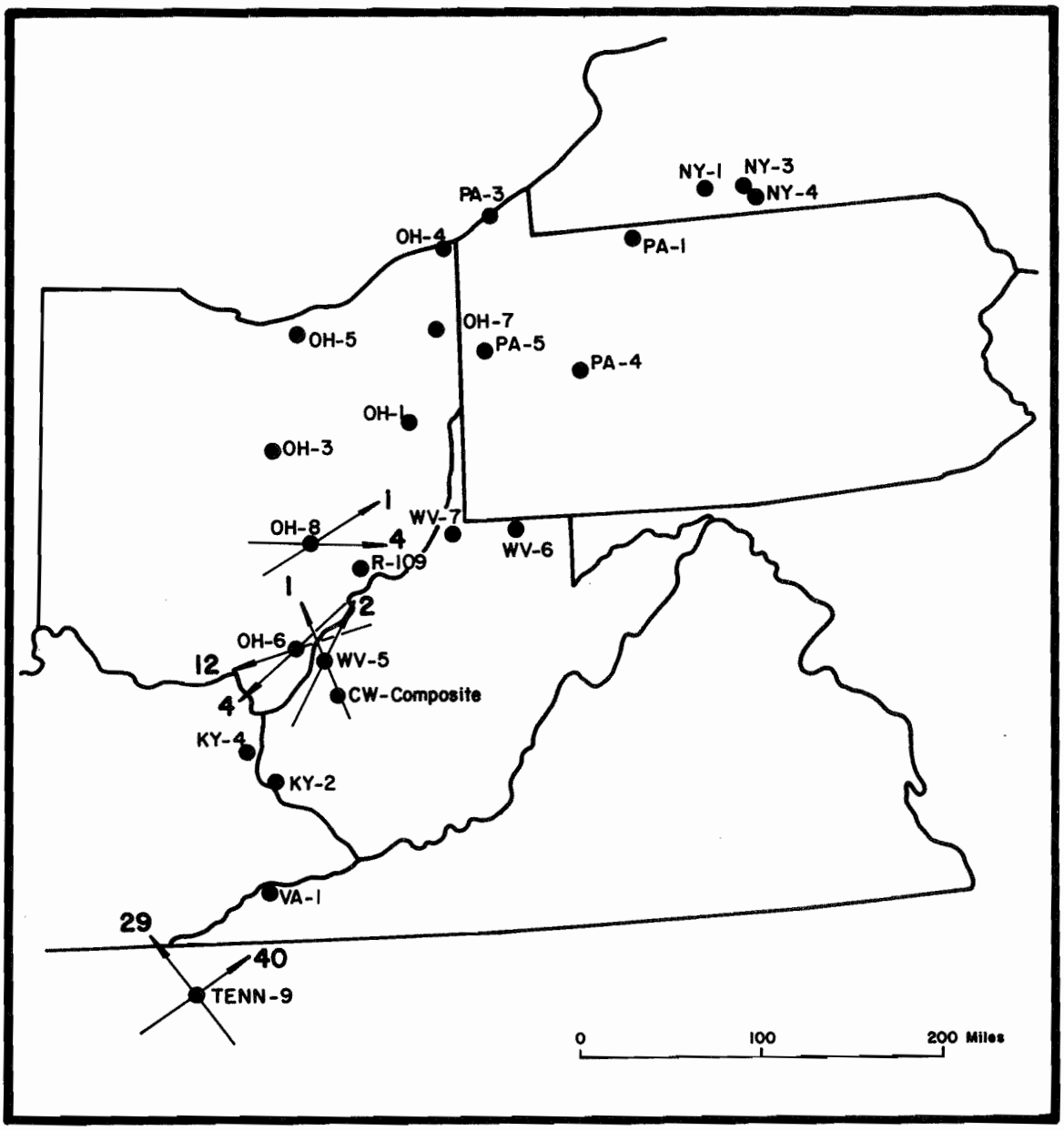


Figure 114 . Map showing fracture orientation and density in rocks deposited during early Lower Huron/early Dunkirk time. From Mound Facility (1982).

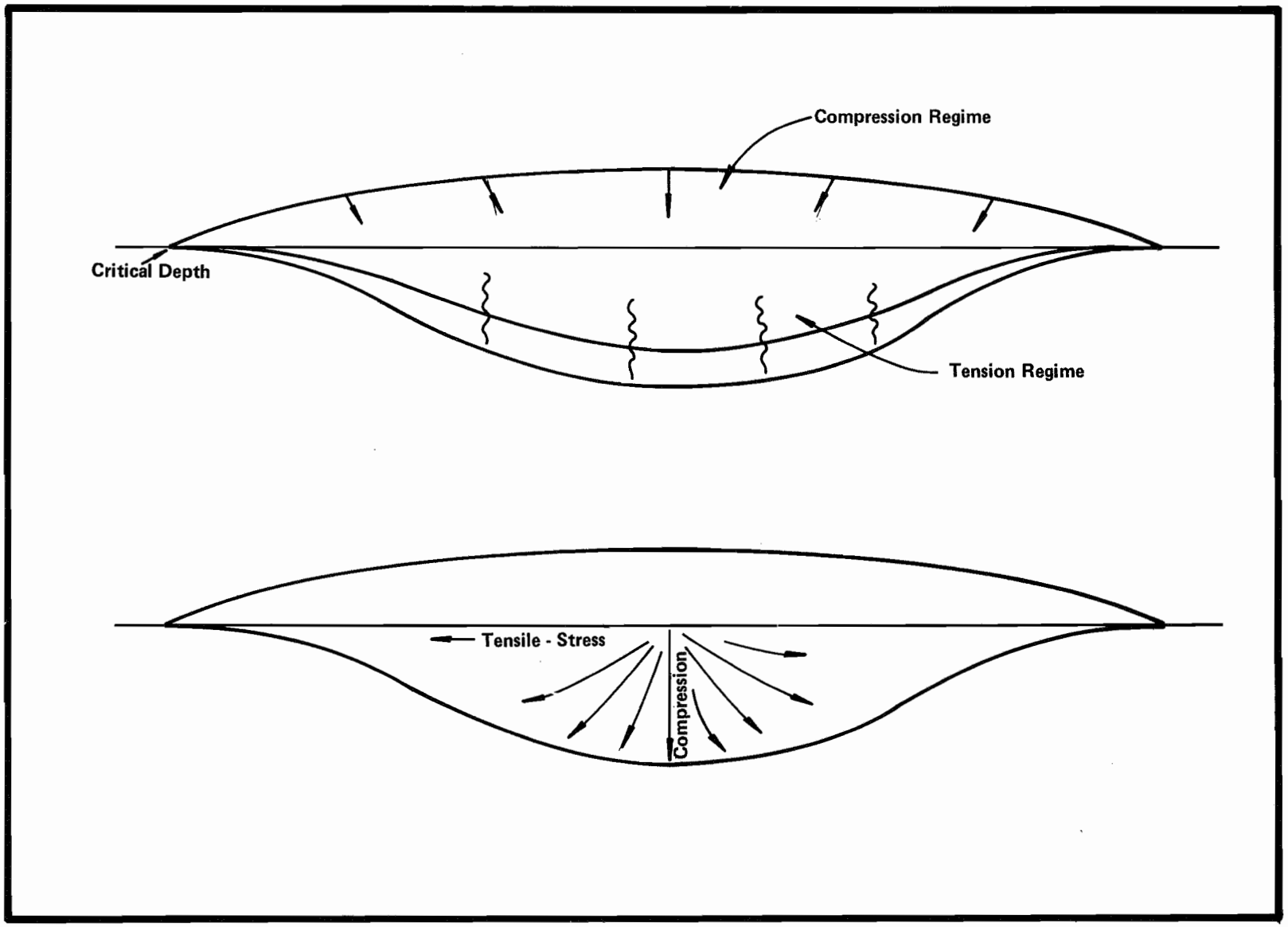


Figure 115 . Schematic diagram showing the evolution of basin subsidence fractures. Modified from Baldwin (1979).

subject to plastic flow since the increasing overburden pressure during subsidence would have been balanced by the hydrostatic pressures of the entrapped formation waters. Possible support for this hypothesis includes the recording of breakdown pressures during frac jobs in the Devonian showing a decrease in pressure with increased depth, indicating that much of the basin is in a state of tension (Baldwin, 1979). Toward the edge of the basin the susceptability of the Devonian section to fracturing is remarkedly reduced, since the shales are still in a state of compression.

ARTIFICIALLY INDUCED FRACTURES

Artificially induced fracture systems in the Devonian Shale through hydraulic fracturing, including the massive hydraulic treatments, or by chemical explosive, do not penetrate far enough into the prospective reservoir to induce significant quantities of shale gas production in the absence of natural fractures. The induced fractures are restricted to a relatively small radius in the vicinity of the well bore and do not provide the radial drainage necessary for a commercial reservoir. In addition, research by Columbia Gas indicates that hydraulic fracture treatments which make use of gelled water and sand are not feasible in the underpressured Devonian shales since the low pressures do not readily expel the injected fracturing fluids, thus creating potential clean-up problems (Smith, 1978). But, recent analysis of foam fracturing techniques in the Devonian Shale suggest that this is a suitable method for treating the low-pressure shale formations (Komar et al., 1980). The average Devonian shale reservoir exhibits an average pressure gradient of 0.152 pounds per square inch (psi) per foot of depth, which is significantly less than the hydrostatic head of water of 0.433 psi per foot of depth (Walker, 1980). Also, the potential exists that the use of water in the fracturing treatment may cause some swelling of clay minerals which form the shale matrix. However, the swelling potential is small since the bulk of the clays in the Devonian shale sequence consist primarily of non-swelling illitic clays.

When artificially induced hydraulic fracturing and other reservoir stimulation methods encounter extensive interconnected natural fracture systems, gas production and deliverability from the Devonian shale reservoirs is greatly enhanced. However, if the extensive natural fractures are not present, man-made fractures in the organic-rich shales may release "matrix gas" in the immediate vicinity of the well bore, but the production volumes are likely to be low and the production declines rapid (Walker, 1980).

GEOCHEMISTRY

Introduction

Petroleum geochemistry applies the principles of geology and analytical chemistry to the study of the origin, migration, accumulation, and the alteration and degradation of petroleum. The science has pioneered the development of new ideas and concepts relating to the origin and migration of hydrocarbons, forcing researchers and explorationists to abandon many of the older hypotheses and concepts advanced to account for the presence of hydrocarbons on the earth. It was not until recently, when the chemistry and physics of the processes of petroleum generation became better understood, that any real progress was made in the understanding of how petroleum is formed. Petroleum geochemistry has provided the oil and gas explorationist with an understanding of the basic requirements necessary for the generation of hydrocarbons and an additional exploration tool for evaluating new areas or previously unexplored horizons. For these reasons, geochemical characterization of the Devonian-age black shales in the Appalachian, Michigan and Illinois basins was given major emphasis in the Eastern Gas Shales Project. The full complement of geochemical methods and technologies was used to evaluate the Devonian-age black shales as a source and reservoir beds for acumulations of natural gas.

Geochemical analyses of the Devonian Shales in the Appalachian basin were conducted by many Eastern Gas Shales Project investigators (Zielinski, 1977; Zielinski et al., 1977; Kalyoncu, 1977; Snyder et al., 1977; Claypool and Threlkeld, 1977; Claypool et al., 1978, 1980; Smith, 1978; Leventhal, 1978, 1979, 1980; McIver and Zielinski, 1978; Zielinski and Nance, 1979; de Wys and Renton, 1979; Chow and Dickerson, 1977; Potter et al., 1980; Hohn et al., 1980; Hohn, 1980; Streib, 1980; Brownell, 1978). Much of the following discussion on the geochemical approach to source bed potential and hydrocarbon assessment of the Devonian Shales within the Appalachian basin is summarized from comprehensive reports of investigations on resource and exploration assessment conducted by the Monsanto Mound Laboratory Facility (Zielinski and McIver, 1982) and by the United States Geological Survey (Charpentier et al., 1982).

The Mound Laboratory Report is a summary of analytical data from chemical analyses performed on more than 2000 core samples and additional drill cuttings from widely spaced wells in the Appalachian basin (fig. 116). The geochemical investigation was directed initially at the hydrocarbon source rock potential of the Devonian shales and was followed by an assessment of the liquid and gaseous hydrocarbon resource within the black shales as determined from geochemical analyses. The United States Geological Survey investigation (Charpentier et al., 1982) approaches the resource assessment from a play-analysis method which partitions the basin into small segments on the basis of stratigraphic, structural and geochemical parameters. The volume of gas within each play area was then calculated by an equation consisting of independent geochemical, physical, structural and geographic variables.

The geochemical characterization and source rock investigations conducted in the Illinois basin (Zielinski and Nance, 1979; Bergstrom et al., 1980; Tetra Tech, 1981), and the Michigan basin (Young, 1978; Mound Facility, 1980; Tetra Tech, 1981) will be the primary references for the discussion of the source rock potential and resource assessment for these two basins.

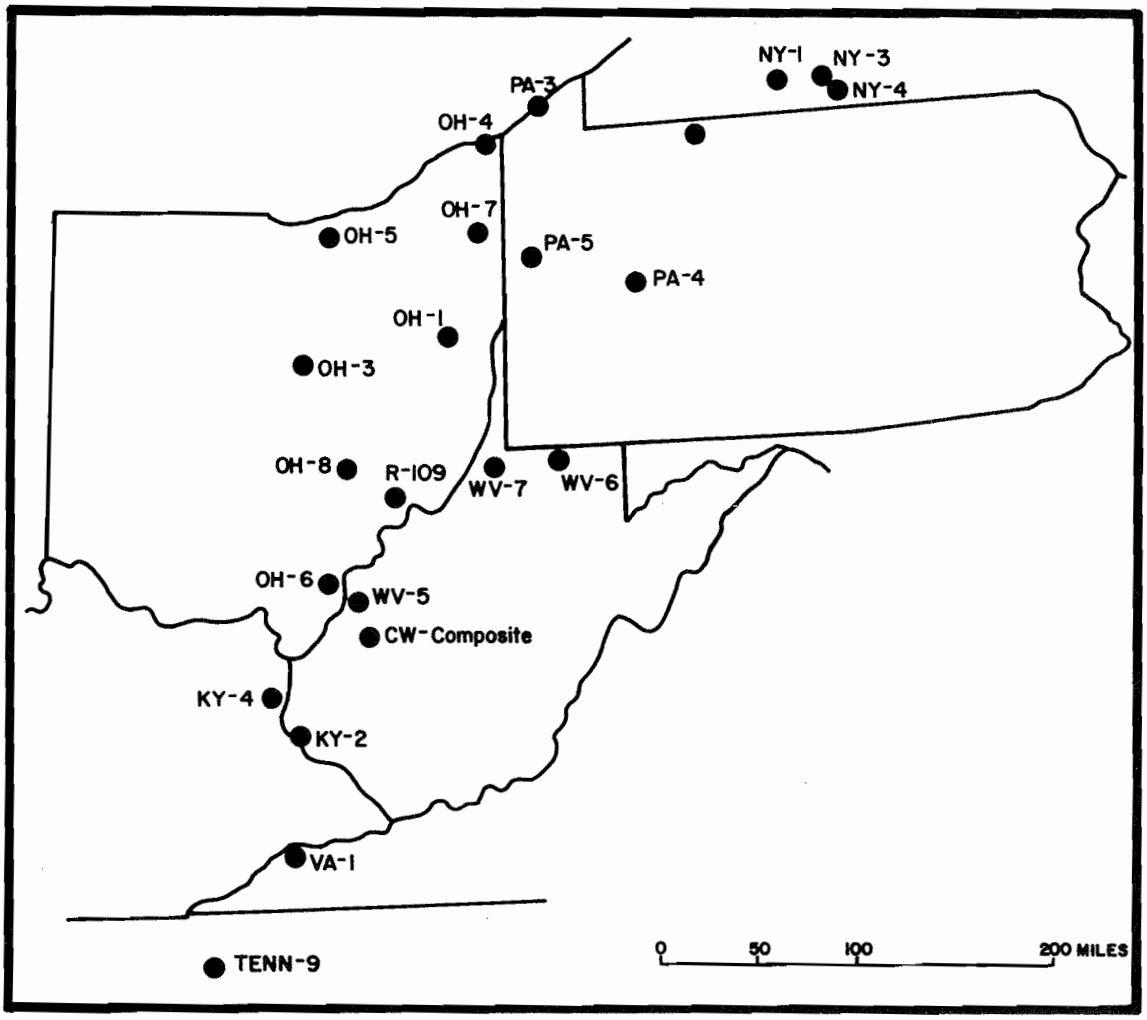


Figure 116 . Map showing locations of wells from which core samples were taken for resource assessment studies. After Zielinski and McIver (1982).

SOURCE BED GEOCHEMISTRY

Hydrocarbon source beds are one of the principal parameters which define the potential of a sedimentary basin as a future natural gas or oil province. Over the last 10 years geochemical analyses of rock samples has been used by geologists to evaluate the hydrocarbon potential of sedimentary basins through identification and analysis of source beds. Early in the history of source bed geochemistry basin-wide projections based upon limited data from a few wells proved unreliable, but recent investigations, using limited geochemical data in combination with paleographic and stratigraphic studies, have proven to be more reliable and an accepted approach to basin-wide assessment of source beds.

Organic Carbon

One important parameter of source-rock geochemistry concerns the quantity of organic matter contained within the rocks. The primary source of organic material in sediments is the remains of living organisms which, after their death, are incorported into the fine-grained rocks during deposition. Except for a minor fraction of this primary source material which is biogenetically converted to gas and expressed from the rock during compaction, the remaining fraction remains incorporated within the matrix of the fine-grained sediment with which it was deposited. The name kerogen has been applied to the dissimilated organic matter in sedimentary rocks which is insoluble in nonoxidizing acids, bases, and organic solvents (Hunt, 1979). In earlier studies the amount of organic material was the parameter used to identify the most favorable source areas within a basin, but more recently the organic carbon content of the sediments has become the accepted reporting parameter (Zielinski and McIver, 1982).

Ronov (1958), the first to map organic content regionally, showed that on the Russian platform accumulations of oil and gas occurred only if the nearby Devonian-age source rocks contained more than 0.5 percent organic carbon. Explorationists using geochemical methods have found that the organic content of rocks must be above a lower threshold of values ranging from 0.4 to 1 percent to be seriously considered as potential source rocks for hydrocarbons. One of the major components of the Mound Facility investigations (Zielinski and McIver, 1982) was an investigation of the vertical and lateral distribution of organic carbon throughout the Devonian Shale sequence. Because of the general westward progradation of lithofacies during Middle and Upper Devonian time, the higher values of organic carbon in the Devonian sequence generally migrate westward in successively higher stratigraphic units. Under conditions of rapidly changing organic carbon values in the vertical direction, attempts to map the total organic carbon to establish regional trends was not feasible. The inorganic carbon determintion from the more than 2000 samples from the Eastern Gas Shales project wells in the Appalachian basin show a range in organic carbon values from 0.10 to more than 27 percent (Zielinski and McIver, 1982). The distribution of the organic carbon in the samples is shown on figure 117. To show the distribution of organic carbon in the Appalachian basin, Zielinski and McIver (1982) subdivided the Devonian sequence into 17 assessment mapping units (fig. 118) and mapped the distribution of organic carbon within each unit. Because of the limited distribution of organic material within each of the mapping untis, the maps are

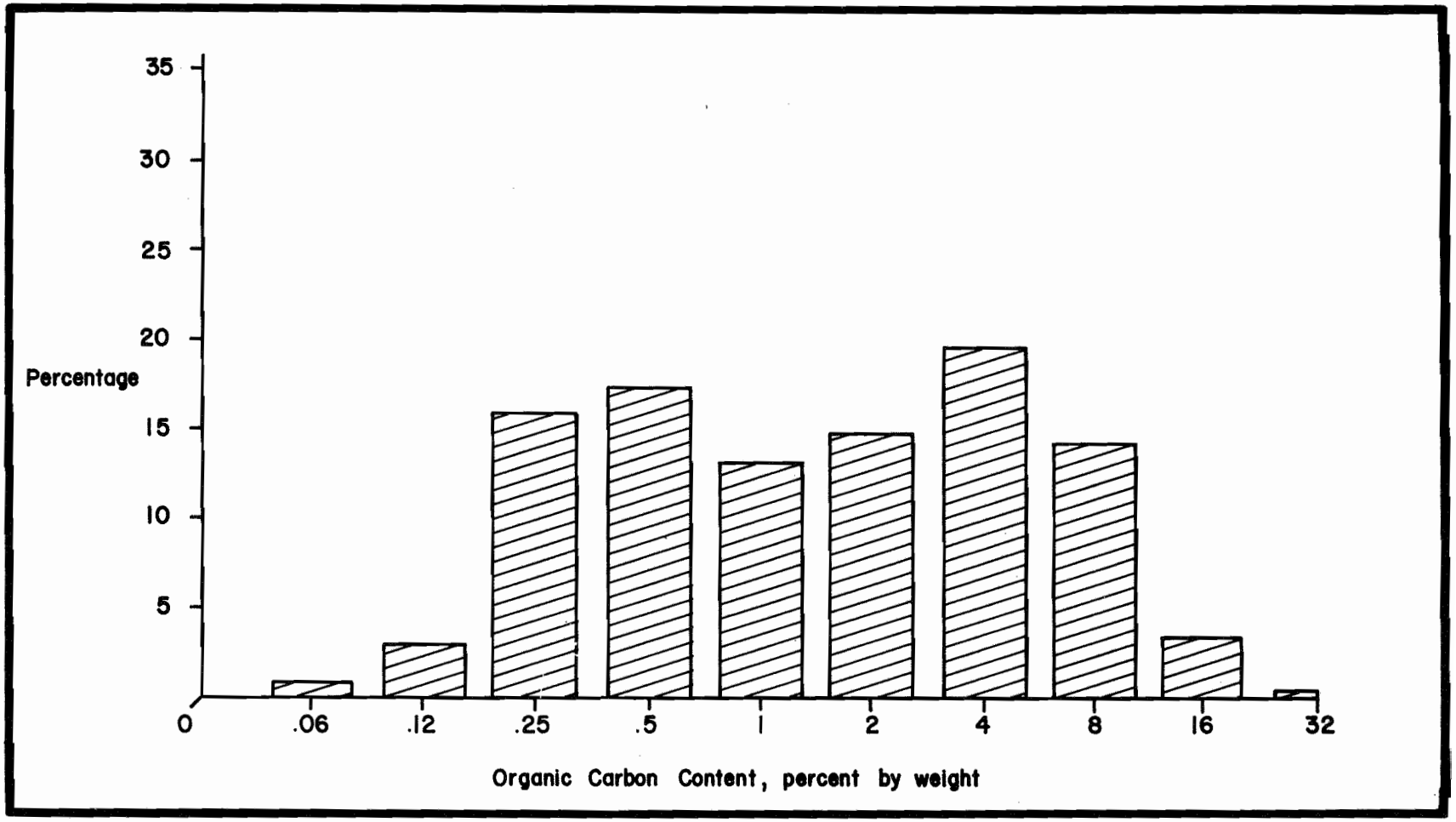


Figure 117. Histogram showing the distribution of organic carbon in more than 2000 samples from the Appalachian basin. Zielinski and McIver (1982).

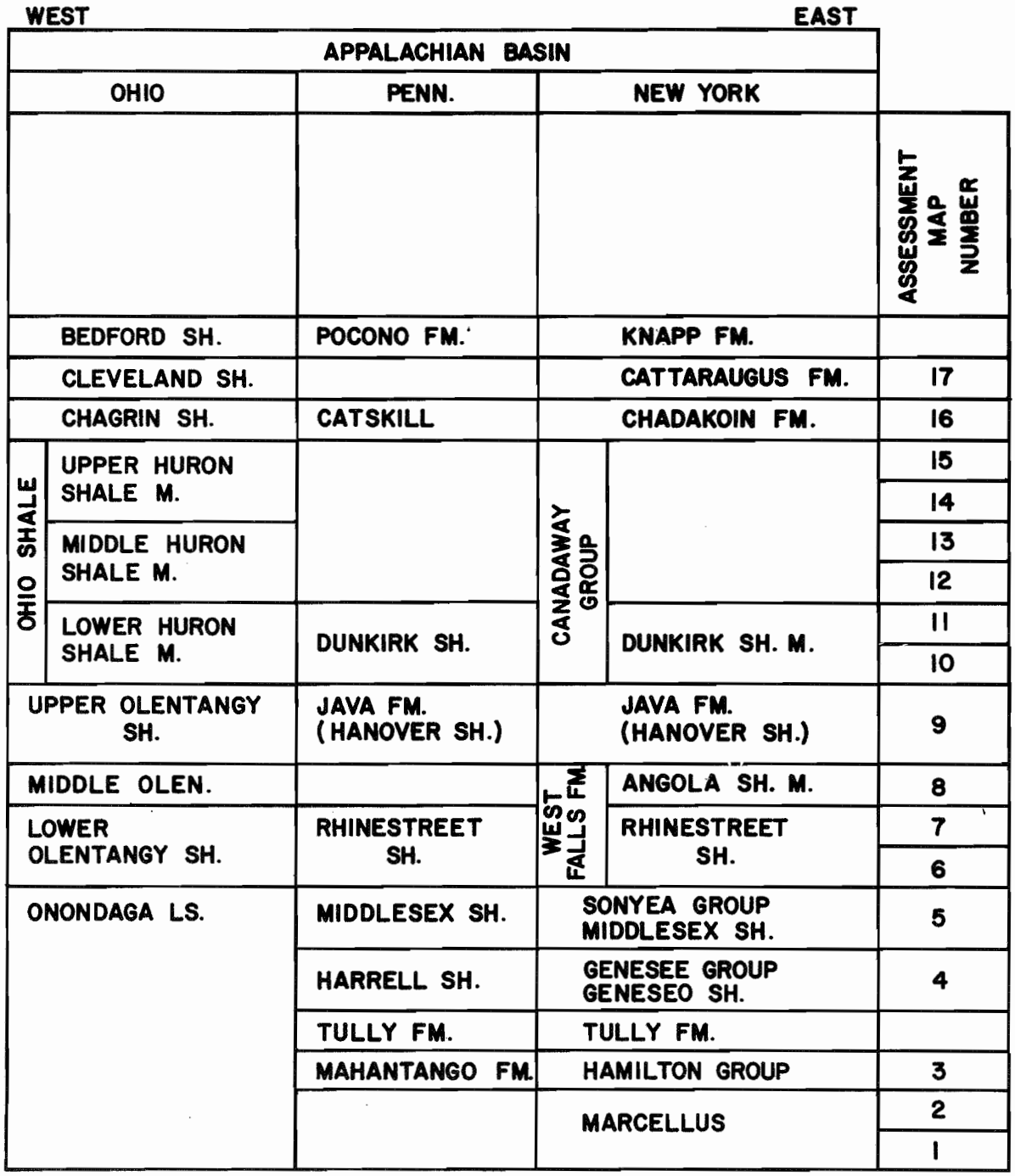


Figure 118. Identification of subdivisions used in organic geochemical assessment mapping. Zielinski and McIver (1982).

not included in this report and interested readers are referenced to figures 8 through 27 of the original report. To supplement this mapping a series of five cross sections (fig. 119) were constructed to show the stratigraphic and regional distributions of the organic carbon along each line of section. The vertical plots of organic carbon values were so variable that detailed correlations of the alternating rich and poor organic carbon zones was impossible, but it was possible to generally identify wedges of organic-rich and very organic-rich potential source rocks within the Devonian shale sequence. The organic-rich wedges shown by the cross sections are generally correlative with the organic-rich, black radioactive shales which have been identified and mapped throughout the Appalachian basin by Eastern Gas Shales Project investigators. Figure 120, an east-west cross section across the northern part of the Appalachian basin, shows the stratigraphic and lithofacies relationships of the organic-rich and organic-poor sediments in the basin. For a more detailed picture of the stratigraphic distribution of organic carbon within the Appalachian basin, refer to figures 5 through 9 of the Mound Facility report (Zielinski and McIver, 1982).

In summary, the range of organic carbon from the samples available for study varied from 0.1 to 27 percent with the mean value being 2.13 percent. This data strongly suggests that the dark, organic-rich Devonian shales must be considered an exceptionally good potential source rock for hydrocarbon generation.

Type of Organic Matter

A second equally important parameter used in evaluating the potential for oil and gas development in a basin is the identification of the type and nature of the organic material incorporated within the sediments. The organic matter in rocks, the kerogen, can be either marine or terrestrial in origin or recycled organic material. Most organic matter can be classified as representing one of two major types, sapropelic or humic. Sapropelic refers to the decomposition and polymerization products of fatty, lipid organic materials such as spores and planktonic algae deposited under oxygen-restricted conditions. This type of organic matter has hydrogen/carbon ratios in the range of 1.3 to 1.7 and, after undergoing maturation, forms boghead coals and oil shales (Hunt, 1979).

The term humic refers mainly to terrestrial materials deposited in swamps in the presence of oxygen (Hunt, 1979). These materials, precursors of peat formation, have hydrogen/carbon ratios approximating 0.9, a value too low to be considered important in the generation of liquid hydrocarbon. When humic materials are swept out into the sea and incorporated into the fine-grained clastic sediments of the depositional basin, they form the humic component of the kerogen. Humic material, spores, pollen or algal material transported into marine environments and the organic material derived from marine organisms all combine to form the kerogen found in marine deposits. Kerogen classifications have been devised by coal petrographers, palynologists and geochemists and the terms from each of the classifications are found interspersed in the geochemical literature. The macerals of coal are defined by coal petrologists as ligtinite (exinite), vitrinite, and inertite; these macerals are identifiable within the kerogen of sedimentary rocks. The terms algal, amorphous, herbaceous, woody, and coaly are used by palynologists to describe the various types of kerogen. Petroleum geologists most often use the classification developed by Tissot et al. (1974) which characterized kerogen as Type I, Type II or Type III depending upon the elemental composition of the kerogen and its evolutional path on a plot of hydrogen/carbon versus oxygen/carbon ratios developed by

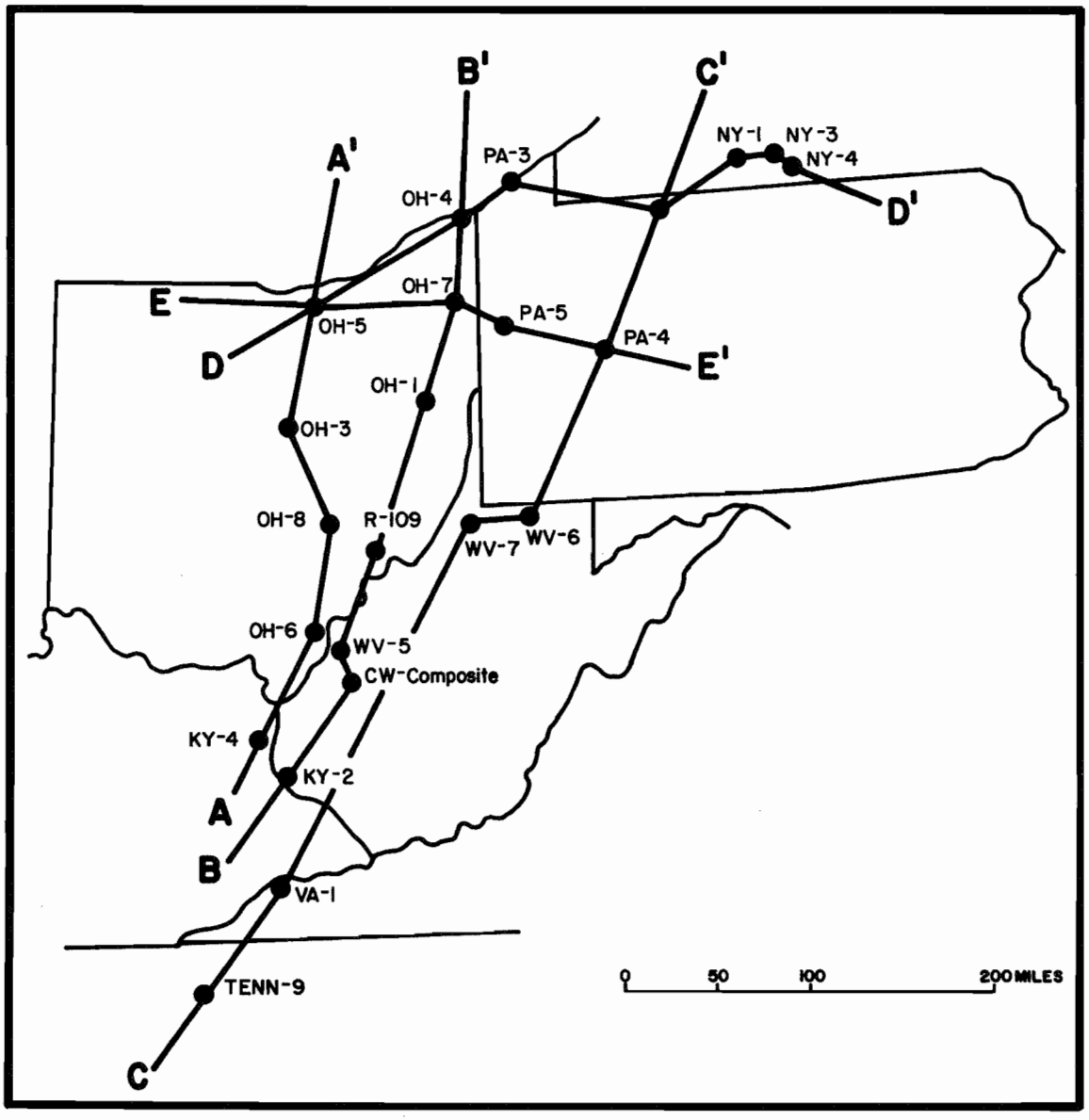


Figure 119. Index map to cross sections showing the stratigraphic distribution of organic carbon within the Appalachian basin. Zielinski and McIver (1982).

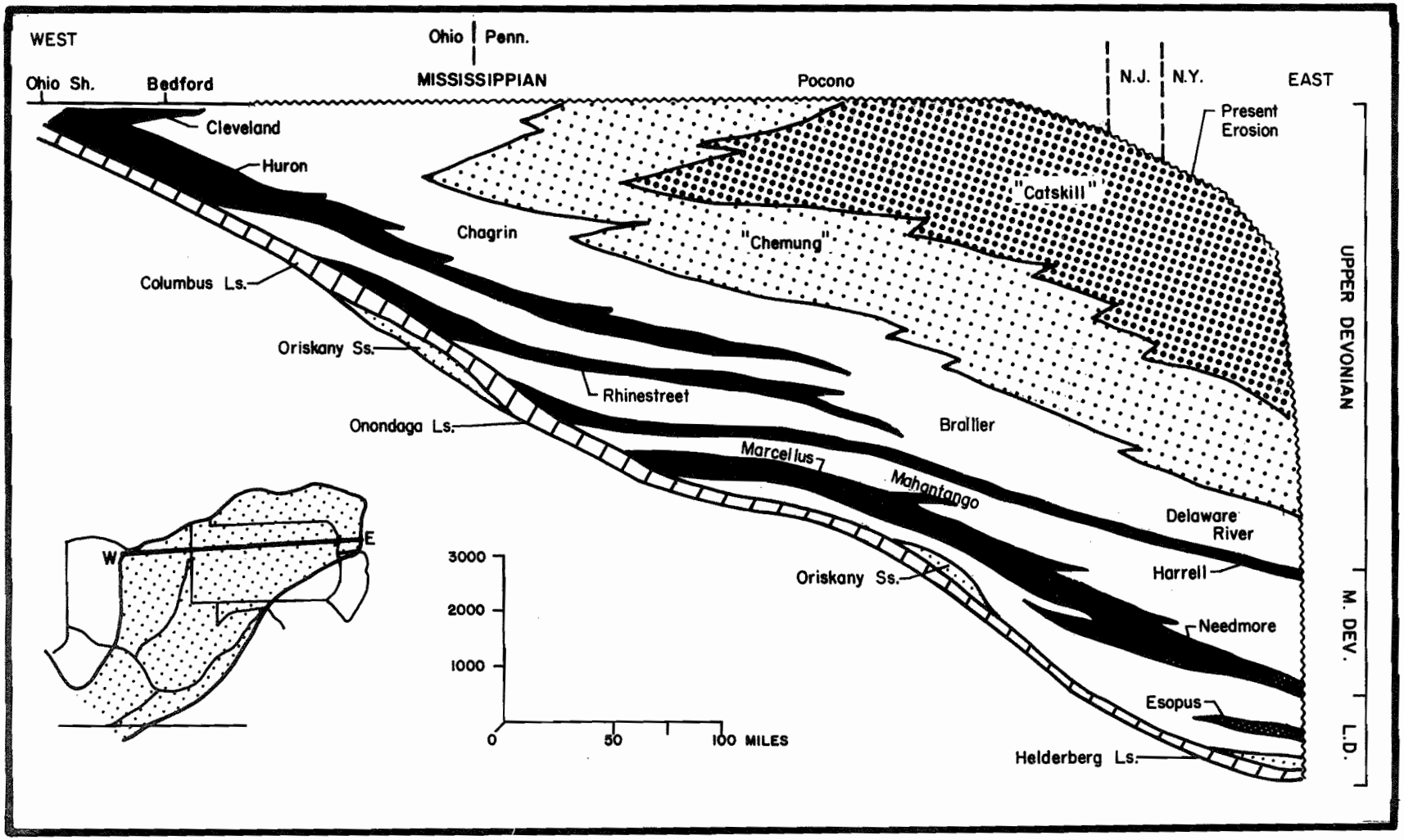


Figure 120. Generalized east-west cross section showing facies relationships between organic-rich and organic-poor lithofacies. Potter et al. (1980).

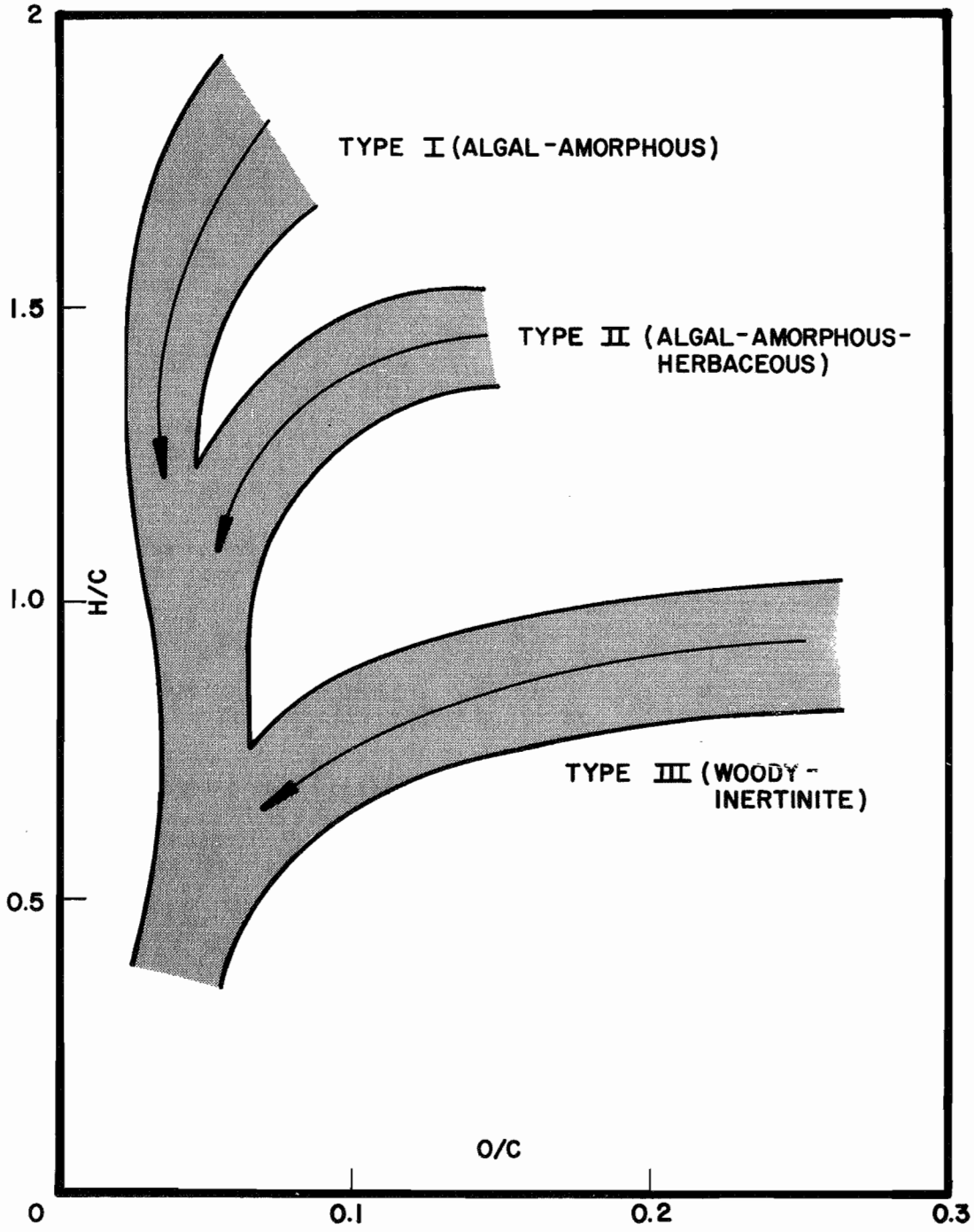


Figure 121. Kerogen classifications dependent upon elemental composition and evolution path on a Van Krevelen plot. Modified from Hunt (1979).

Van Krevelen (1961). Figure 121 illustrates the kerogen types and evolution pathways on the Van Krevelen plot. Type I kerogens are generally comparable to the algal-amorphous types of the palynologists, Type II to the amorphous-herbaceous-woody types, and Type III to the woody-inertite types. Identification and classification of the components of kerogen within a basin of deposition are important because sapropelic (algal-amorphous) organic matter generates oil and gas while humic (woody-coaly) materials yield primarily dry gas.

Elemental analysis is another tool which can be used in distinguishing the origin of the kerogenous materials. Figure 121 shows hydrogen/carbon and oxygen/carbon ratios are indicative of kerogen types. In marine or lacustrine basins, hydrogen/carbon ratio values in the range of 1.6 are characteristic of amorphous kerogens while the hydrogen/carbon ratios for woody-inertinite types range from 0.72 to 0.42 (Hunt, 1979). The type of organic matter found in source rocks not only identifies the type of hydrocarbons (oil or gas) which are likely to be generated from the source rock, but are also an indicator of the potential yield of the hydrocarbon generated. Kerogens of algal and amorphous origins provide greater potential yields of hydrocarbons than kerogens from woody types. Figure 122 is a schematic illustration showing the relative hydrocarbon yields from the range of kerogen types.

In sedimentary basins the organic matter consists of sapropelic and humic kerogens derived from continental and marine sources. The higher content of humic kerogens are found in nearshore marine clays, shales, siltstones, and sandstones while sapropelic types are dominant in deeper water, low energy depositional environments which formed under anoxic conditions.

Another geochemical method which aids in distinguishing the type of organic matter in the sediments is the determination of the carbon isotope ratios from samples of the source rock. The carbon isotope composition of terrestrial organic matter is quite different from that of marine. Potter et al. (1980) in their study of carbon isotopes from samples in the Appalachian basin suggest that two important sources of carbon existed in the basin, a marine source (C^{13} -26) and a non-marine source (C^{13} -32) and that the carbon isotope ratios reflect the relative proportion of marine and non-marine kerogen in the sample. The greenish-gray shales (nearshore facies) deposited in the Appalachian basin during the Devonian exhibit, in most cases, a higher percentage of terrestrial values than the dark brown or black shale distal basin facies.

Zielinski and McIver (1982) included in their investigation a comprehensive study of the biomass which was the source of the organic matter incorporated in the Devonian sediments of the Appalachian basin. Data for the biomass analysis came from the study of the over 2000 core and drill cutting samples. Their study found that west of the axis of the Appalachian basin the kerogen composition was more of the algal form and to the east of the axis the more woody-coaly types dominated. The relative quantities of kerogen types were so variable, both vertically and laterally within the same stratigraphic unit, that an average composition value for a thick sequence of rock was not a meaningful value for showing the areal or vertical contrasts in organic content. Palynological investigation was the analytical technique used by Zielinski and McIver (1982) to show the areal and stratigraphic contrast of the organic matter in the Appalachian basin. The dominant biomass facies which was recognized by the palynologic investigation was labeled "Tasmanites." The facies is characterized by very large occurrences of the green algal, Tasmanites, to the exclusion, in many cases, of all other marine forms such as

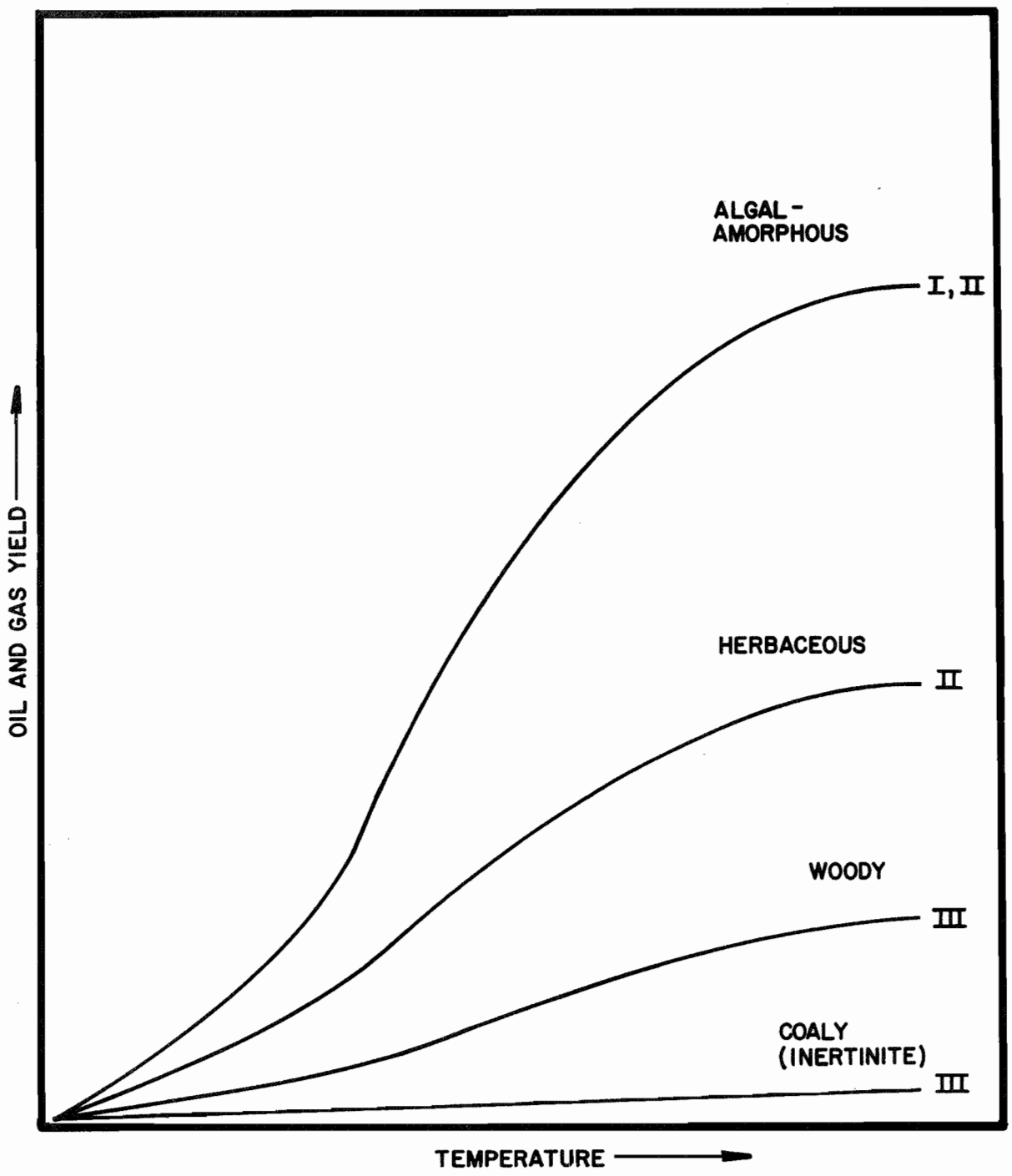


Figure 122. Schematic diagram showing relative hydrocarbon yields from the range of kerogen types and an increase in temperature. Hunt (1979).

acritarchs, scolecodonts, and chitinozoans. Tasmanites is considered to be marine in origin and, in the Appalachian basin during Devonian times, is thought to have flourished to such an extent that other forms of marine algae could not grow. One possible explanation forthis phenomenon was that the metabolism of Tasmanites produced toxic by-products which were lethal to other forms of marine life (Zielinski and McIver, 1982). Incorporated with the Tasmanites in this facies are spores which were transported by the winds to the marine depositional sites where they were incorporated in the sediment. A second marine facies recognized by Zielinski and McIver (1982) was called the "marine" facies. This facies contains the normal assemblage of Devonian marine microfossils. Forms reported in this facies in the Devonian shales of the Appalachian basin are chitinozoans, acritarchs, scolecodonts, leisosheres, a few Tasmanites and some herbaceous materials. Terrestrial kerogen, consisting of fresh woody debris and oxidized and reworked woody materials, was the major component of a third biomass facies designated "terrestrial" by Zielinski and McIver (1982). Incorporated within this facies, along with the predominance of non-marine terrestrial kerogen, were minor amounts of marine palynomorphs and herbaceous kerogen.

Palynological evidence indicates that much of the Middle and Upper Devonian sequence in the Appalachian basin was deposited within the framework of a subsiding marine basin. Within the depositional basin the organic matter incorporated in the sediments varied in both biological and geographical origin (Zielinski and McIver, 1982). As mentioned previously, west of the axis of the Appalachian basin, during periods of the Middle and Upper Devonian, the green algae, Tasmanites, flourished to such an extent that other marine forms could not coexist in the basin. Similar conditions existed to the east of the axis of the basin where woody and coaly types of organic material accumulated in such large volumes that once again normal marine forms and the "Tasmanites" facies were completely overshadowed. Throughout the basin, because of the mode of transportation, herbaceous organic matter, in the form of saccate and zonate spores, is found incorporated in the sediments along with the other principal biomass facies. Because of the rapid and vertical changes in the biomass facies within individual units of the Devonian shales sequence, Zielinski and McIver (1982) elected to show the distribution of the biomass facies both stratigraphically and areally. Biomass facies definition for each sample was dependent on the location of a point within a triangular diagram corresponding to the relative percentages of the major biomass facies in the sample (fig. 123).

The stratigraphic distribution of the biomass facies in the Appalachian basin was shown on the same series of five cross sections used to shown the stratigraphic distribution of organic carbon in the basin (fig. 119, page 218). Cross sections A-A' and B-B' are north-south transects located west of the axis of the Appalachian basin. In a north-south belt of Middle and Upper Devonian rocks shown within cross sections A-A' and B-B' Tasmanites flourished during intervals of Middle and Upper Devonian time, but the distribution was not a blanket type of occurrence where the Tasmanites were present over wide areas within specific stratigraphic horizons. Conversely, the "Tasmanites" facies occured at different stratigraphic positions in different wells in the sections. In the belt of rock extending from northern Kentucky to northern Ohio, Tasmanites were abundant in portions of the Marcellus, Lower and Middle Olentangy, Rhinestreet, Middle Huron-Dunkirk, and the Cleveland Shales. Because of the dominance of the "Tasmanites" facies in the belt of rocks within the stratigraphic framework of cross sections A-A' and B-B,' this sequence of rocks possesses great potential for yielding hydrocarbons where thermal maturation has reached suitable levels. Cross section C-C' has a much more limited potential for hydrocarbon generation because of the abundance of terrestrial organic

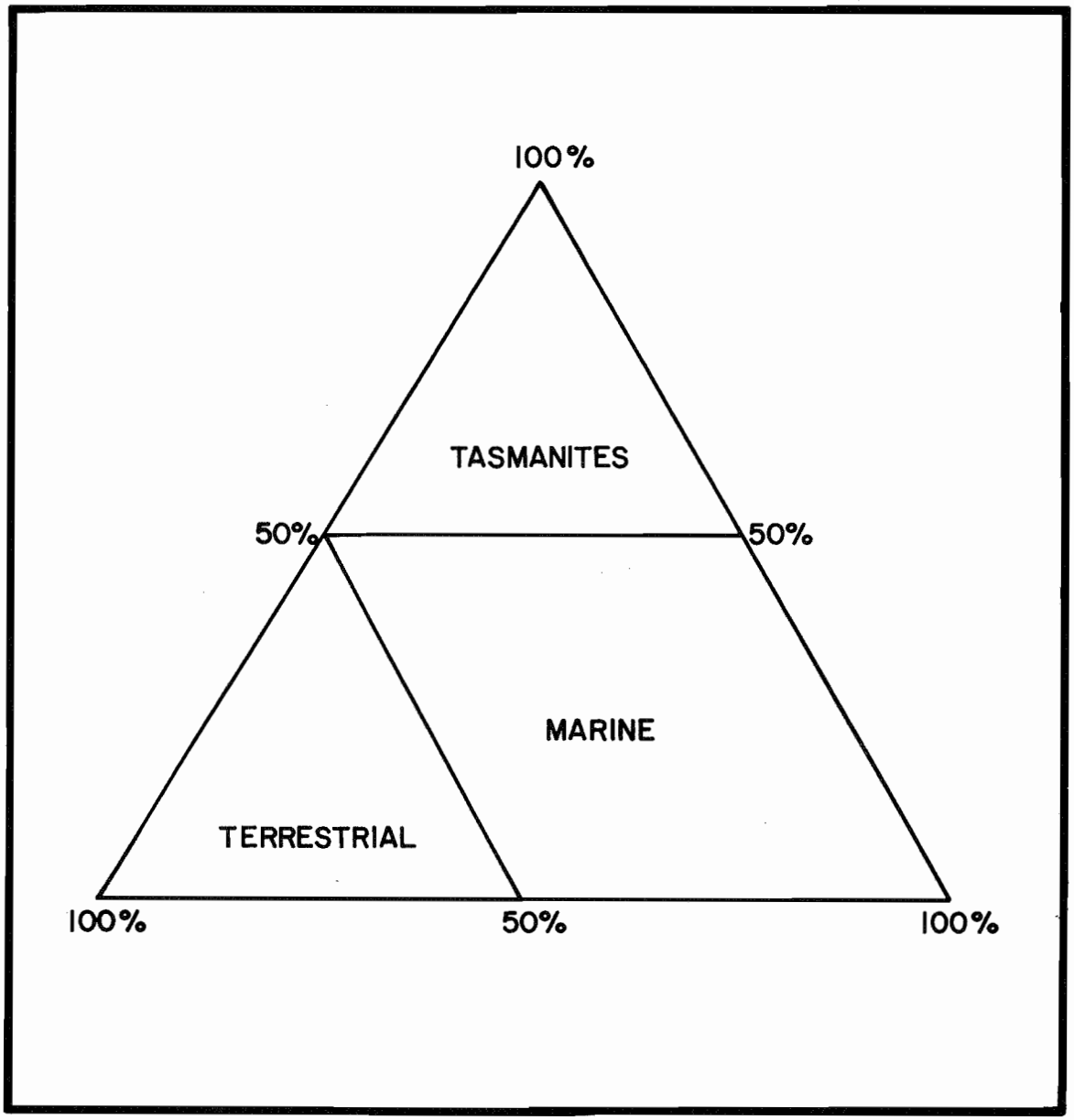


Figure 123. Triangular diagram used for the identification of the major biomass facies in the Appalachian basin. After Zielinski and McIver (1982).

matter incorporated within the rocks. Palynologic evidence from samples from wells along Section C-C' indicates an eastern source for the terrestrial organic materials; a major river system in the vicinity of Pennsylvania and West Virginia has been postulated as the transporting agent in the terrestrial materials into the Appalachian basin. The east-west cross sections, D-D' and EE', strengthen the concept of an eastern source for the "terrestrial" facies in an eastward direction along the sectin. For a more detailed discussion of the stratigraphic distribution of the biomass facies, refer to figures 29 through 33 and the accompanying text in Zielinski and McIver (1982).

To map the areal extent of the biomass data, Zielinski and McIver (1982) elected the same stratigraphic intervals used to show the distribution of the organic matter in the basin (fig. 188, page 216). The Tasmanites blooms, which flourished and then died out throughout intervals of Middle and Upper Devonian period, are believed by Zielinski and McIver (1982) to be the major contributors of marine organic matter into the sediments of the Appalachian basin. The Tasmanites blooms, exhibiting the widest lateral distribution in the Appalachian basin, occurred during the Lower Marcellus, Lower Olentangy/Rhinestreet and the Lower Huron/Dunkirk stratigraphic intervals. The distribution of the blooms during these prolific times of Tasmanites growth are shown on figures 124 through 126. Periods of great influxes of terrestrial organic matter from sources to the northeast and southeast coincide with Tasmanites die-outs and periods of limited areal Tasmanites distribution. For a detailed discussion of the areal distribution of the biomass in the Appalachian basin, the reader is referred to figures 34 to 50 and accompanying text from Zielinski and McIver (1982).

Thermal Maturation

Most geologists and geochemists now believe that petroleum is derived by the action of temperature on organic matter incorporated within organic-rich source rocks. Only in recent years, through the investigations of palynologists, geochemists and refinery technologists, has the importance of temperature been considered in the process of hydrocarbon generation. This process has been summarized by Hunt (1979) as: "The transformation of the simple molecular hydrocarbon spectrum of living organism to the complex spectrum of petroleum through the diagenetic formation of a wider group of hydrocarbon derivatives from the original organic molecules." Through the subsequent processes of thermal alteration of the deeply buried organic matter, large quantities of hydrocarbons are formed. Under optimum thermal conditions the organic materials preserved in organic-rich sedimentary rocks have the potential for converting up to 35 percent of their original mass to petroleum hydrocarbons.

Diagenesis is the initial process in the alteration of organic materials incorporated in sediments prior to any exposure to the pronounced effects of temperature. It consists primarily of biological, physical, and chemical changes in sediments during the rock-forming processes. In sedimentary basins the diagenesis results principally from the burial of older sediments by younger in areas of active deposition. The original organic materials within the sediments consist primarily of biopolymers such as carbohydrates, proteins, lipids, lignins, chitins, waxes, resins, fat, oils, etc. If not consumed by living organisms the biopolymers undergo degradation to form complex high-molecular-weight geopolymers that are the precursors of kerogen (Hunt, 1979). During diagenesis, the altered organic matter undergoes a series of low temperature biological, physical and chemical reactions which result in the formation of biogenic hydrocarbons and hycrocar-

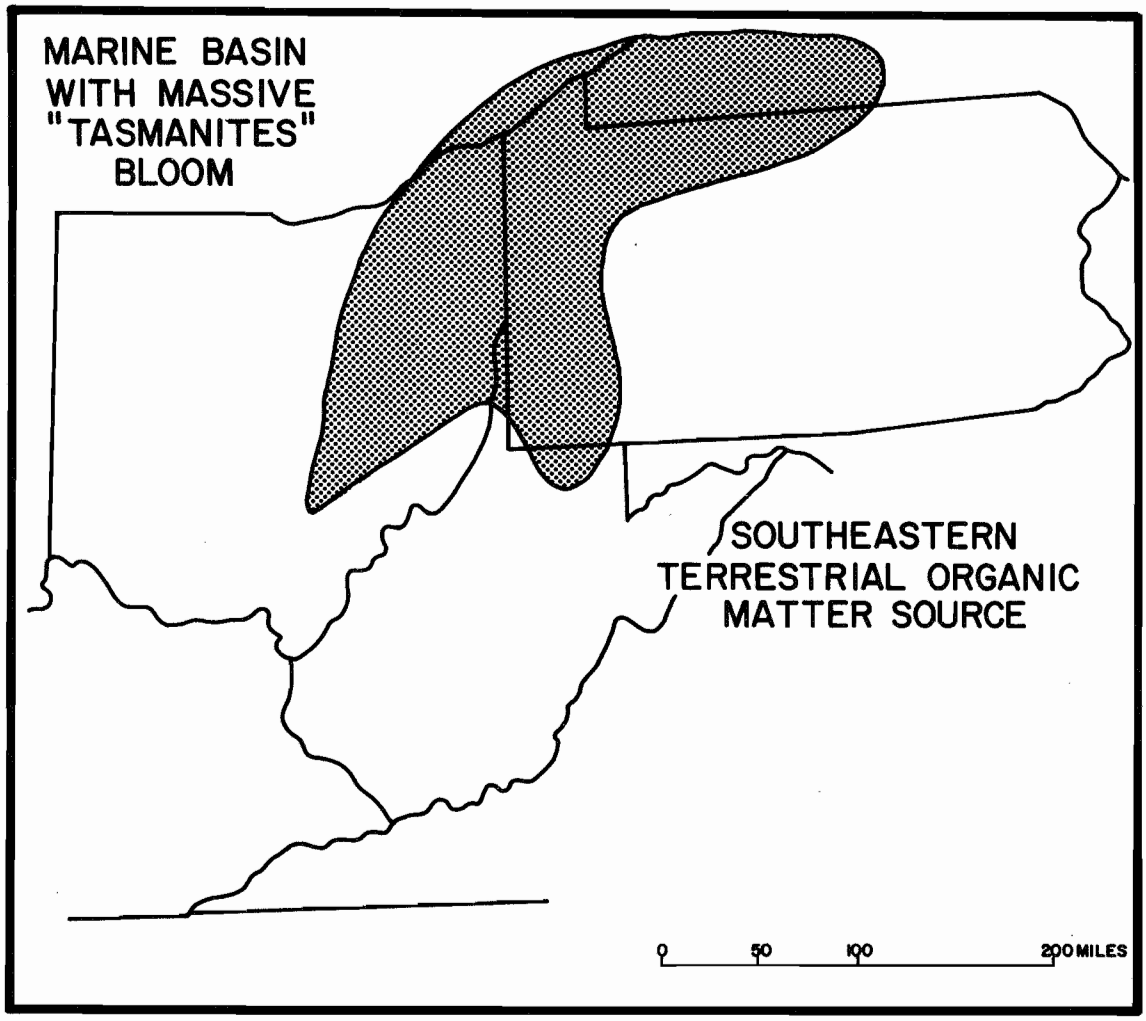


Figure 124. Distribution of Tasmanites bloom in early Marcellus. After Zielinski and McIver (1982).

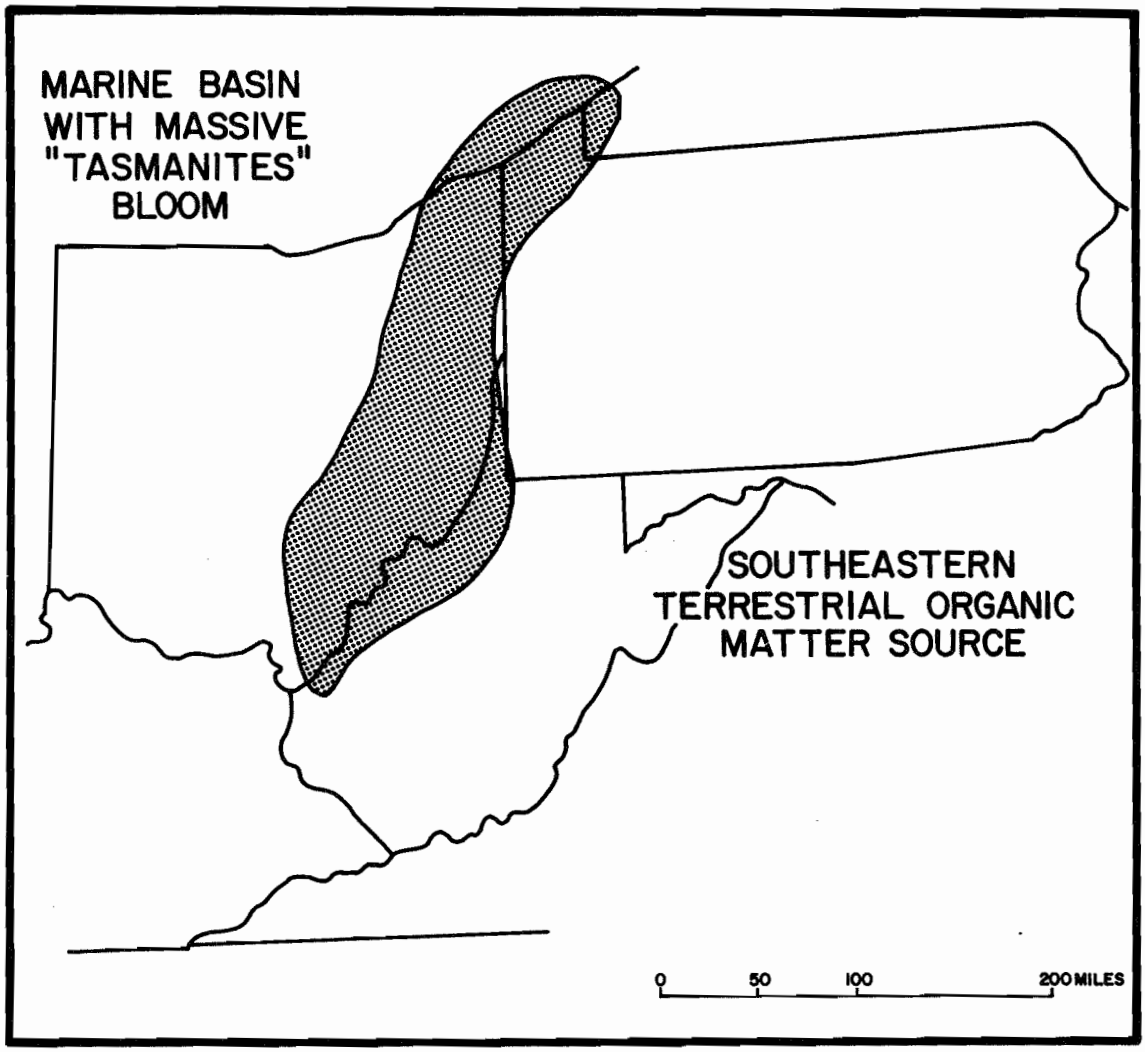


Figure 125. Distribution of Tasmanites bloom, Early Lower Olentangy/Early Rhinestreet. After Zielinski and McIver (1982).

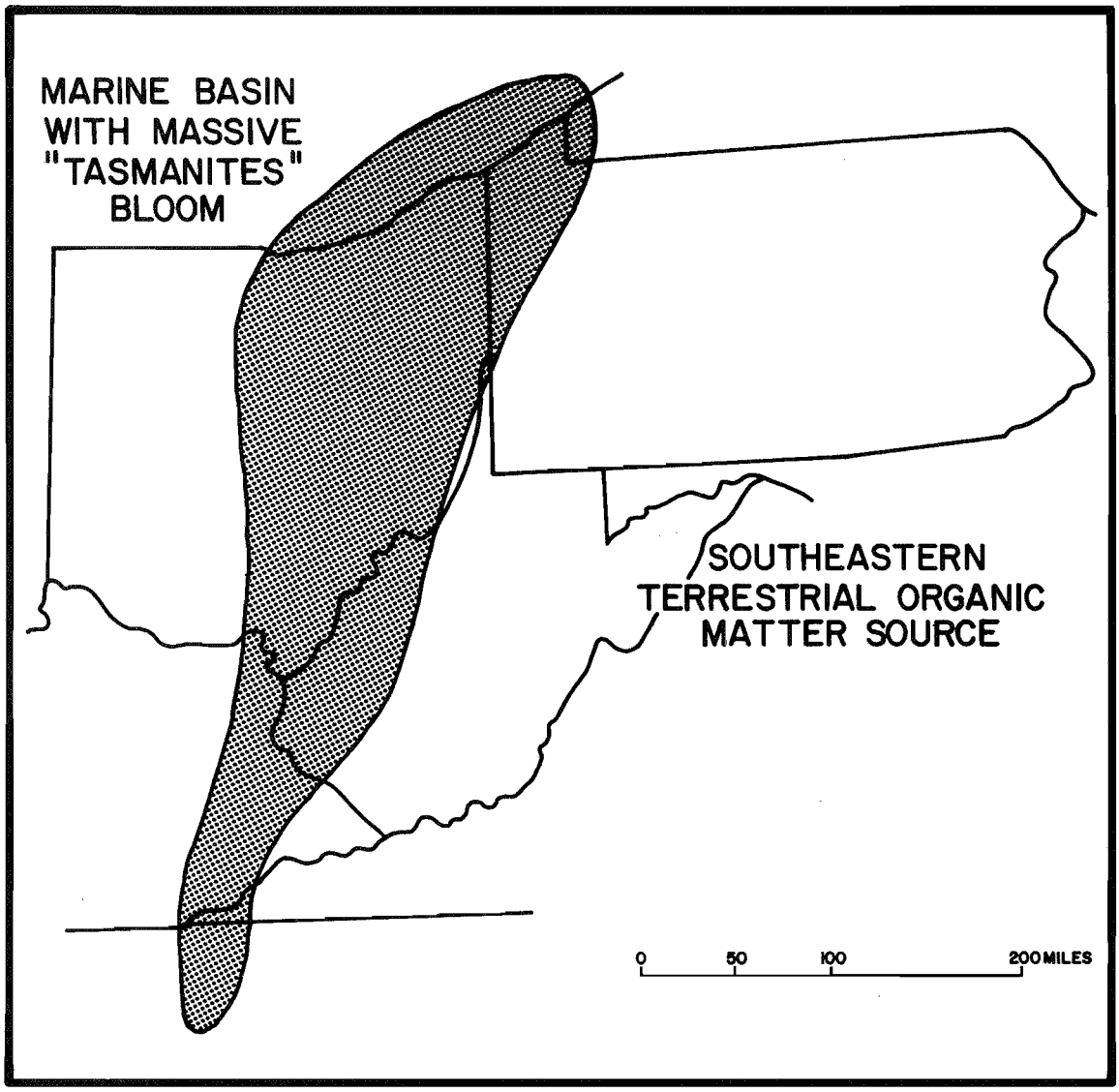


Figure 126. Distribution of Tasmanites bloom, Early Lower Huron/Early Dunkirk. After Zielinski and McIver (1982).

bon-like materials. Biogenic gas, which is identifiable by its preferential enrichment of the light carbon isotope C^{12}, is estimated to contribute approximately 20% to the world's reserve base of natural gas. Diagenesis, as generally defined, is limited to temperatures ranging from ambient surface temperature up to approximately 50°C (122°F).

As sediments accumulate in depositional basins, they are subject to increasing depths of burial as sedimentation continues and the basin subsides due to the increased load. Compaction of the sediments due to increased depth of burial subjects the organic matter contained within the sediments to increasingly higher temperatures. In a reducing environment the temperature increase promotes the thermal degradation of the organic matter and subsequent formation of petroleum-range hydrocarbons. These processes have been demonstrated in the laboratory over the years by petroleum geochemists and refinery chemists and technicians. The temperature constraints for petroleum generation from organic matter range from a low temperature of 50°C (122°F) to an upper range in the vicinity of 200°C (392°F) (fig. 127). The thermal alteration of organic materials within the 50°C to 200°C range is called catagenesis. Field and laboratory investigations from throughout the world have shown that the greatest quantity of petroleum hydrocarbon is formed from organic matter subjected to alteration temperatures ranging between 60°C (140°F) and 150°C (302°F) (Hunt, 1979).

The term metamorphic is used to describe thermal alteration of organic materials at temperatures above 200°C (392°F). Generally speaking, fine-grained organic-rich rocks heated to temperatures above 200°C are capable of producing only small amounts of methane (fig. 128).

Since temperature is such an important parameter in the transformation of organic matter found in source rocks to hydrocarbons, it is essential that the thermal history of source beds be determined in order to evaluate the potential of the beds to generate oil or gas. Geochemists and palynologists, over the years, have developed techniques for the evaluation of kerogen maturation. Current techniques have reached a degree of sophistication which enables investigators to not only determine maturation but also the provenance of sediments, the depositional environments, and the tectonic history of basin areas (Hunt, 1979).

Eastern Gas Shales Project investigators have used several techniques over the length of the project to determine the thermal history of the Devonian-age shales in the Appalachian, Michigan and Illinois basins. Most investigators used more than one method for determining the thermal history and then compared the results of the various methods. The most widely used methods were kerogen coloration, conodont coloration, and vitrinite reflectance. In the kerogen coloration method, microscopy under transmitted light is used to observe changes in the colorations of organic matter, mainly spores, pollen, and plant cuticle. As the spores are subjected to increases in temperature and pressure, the color changes from a light yellow to black over the immature, mature, and metamorphosed levels of kerogen alteration. This technique works when the observed color alterations are restricted to the observation of a single species because maturation rates can vary within different species. The degree of thermal alteration is identified by the Thermal Alteration Index (TAI) which consists of five color partitions over a temperature range of 20°C to 266C (fig. 129). The color alteration ranges from light yellow (unaltered kerogen, TAI=1) to black (severely altered kerogen, TAI=5). Oil and gas generation stages are correlated best with the moderately mature to mature kerogens which are yellow-orange to light brown, TAI=2 and 3, which, more or less, correspond to the catagenic stage of oil generation.

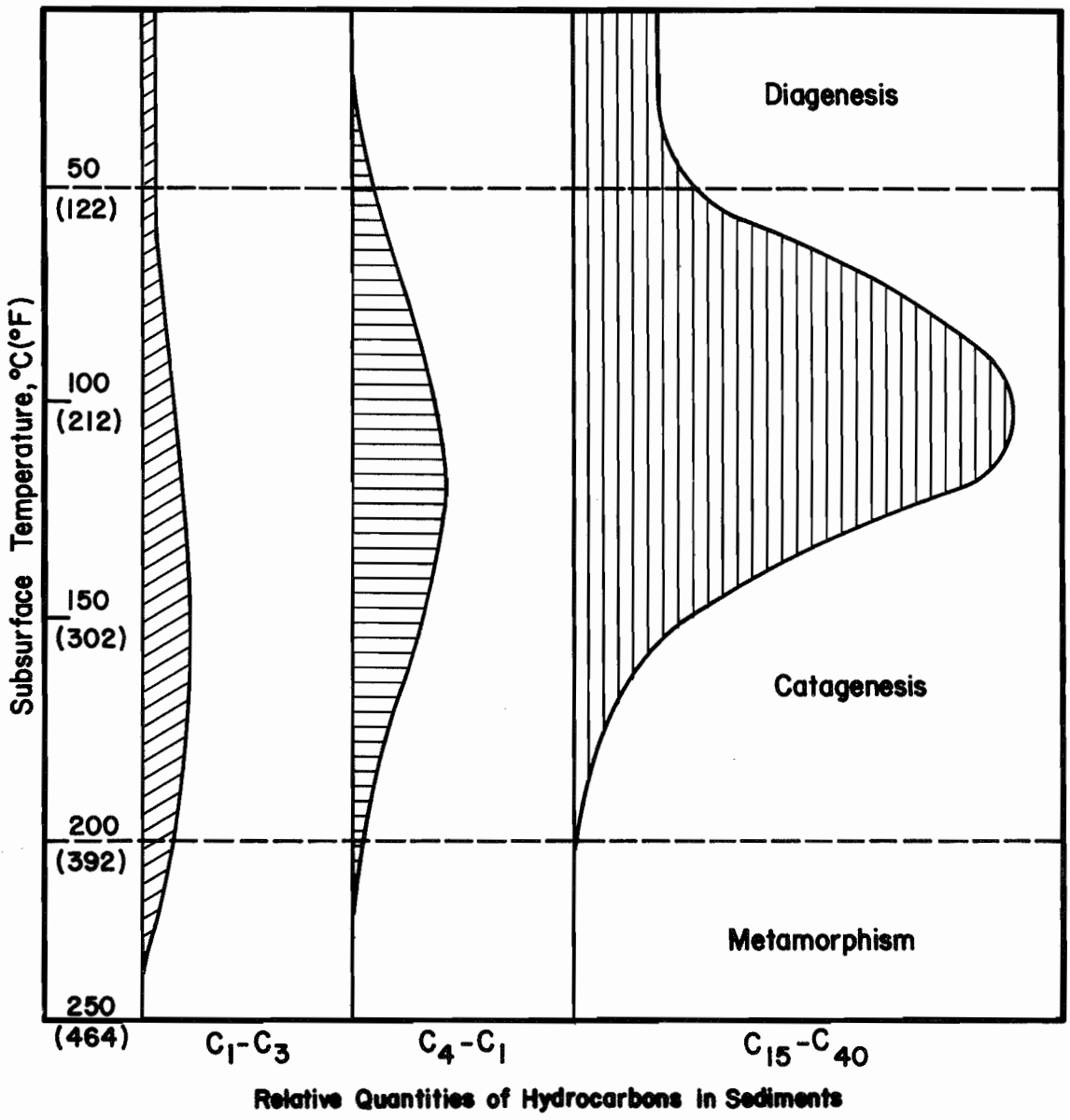


Figure 127. Relative quantities of hydrocarbons in fine-grained nonreservoir rocks. Modified from Hunt (1977).

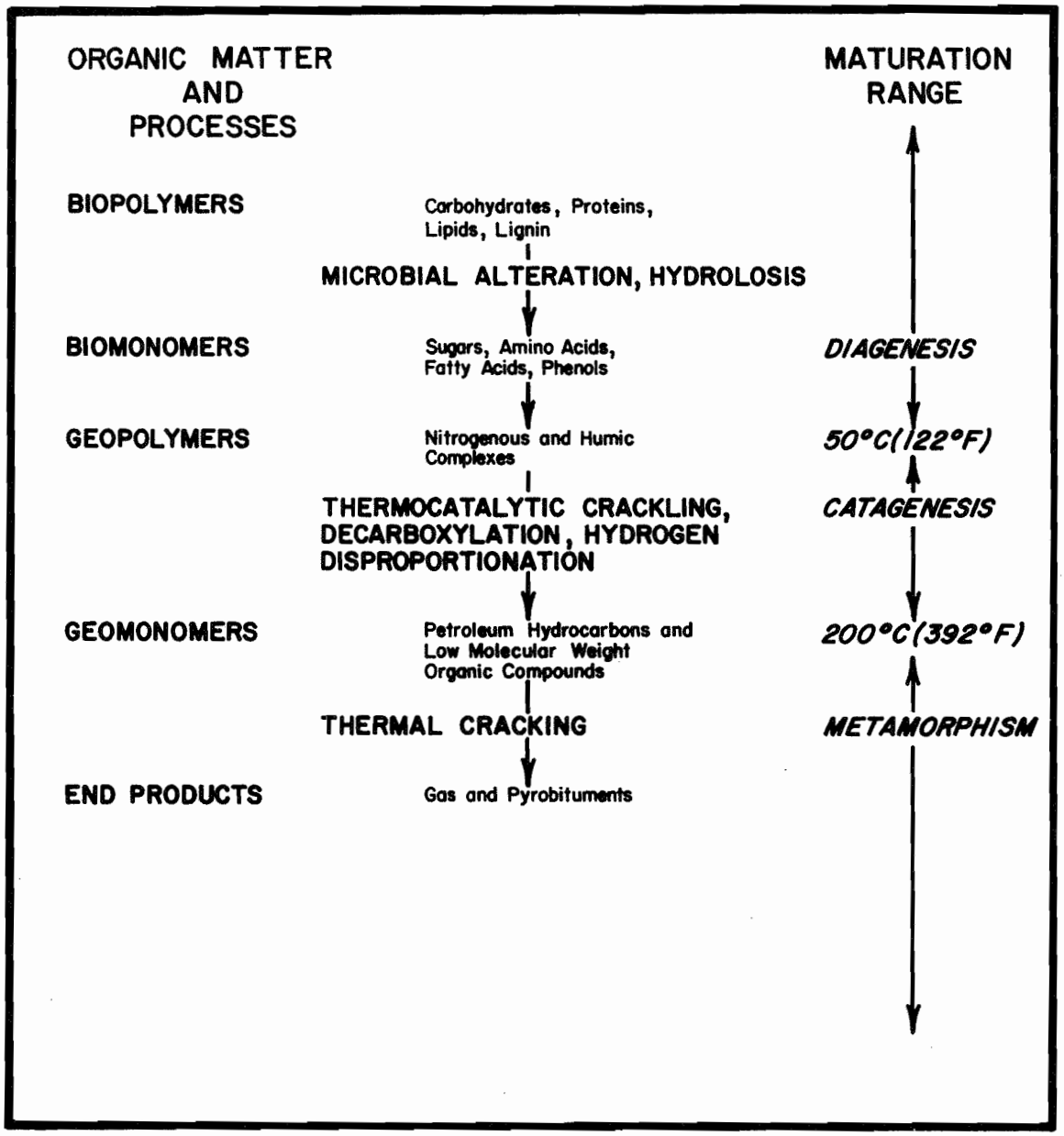


Figure 128. The transformation of organic matter in nature. After Hunt (1979).

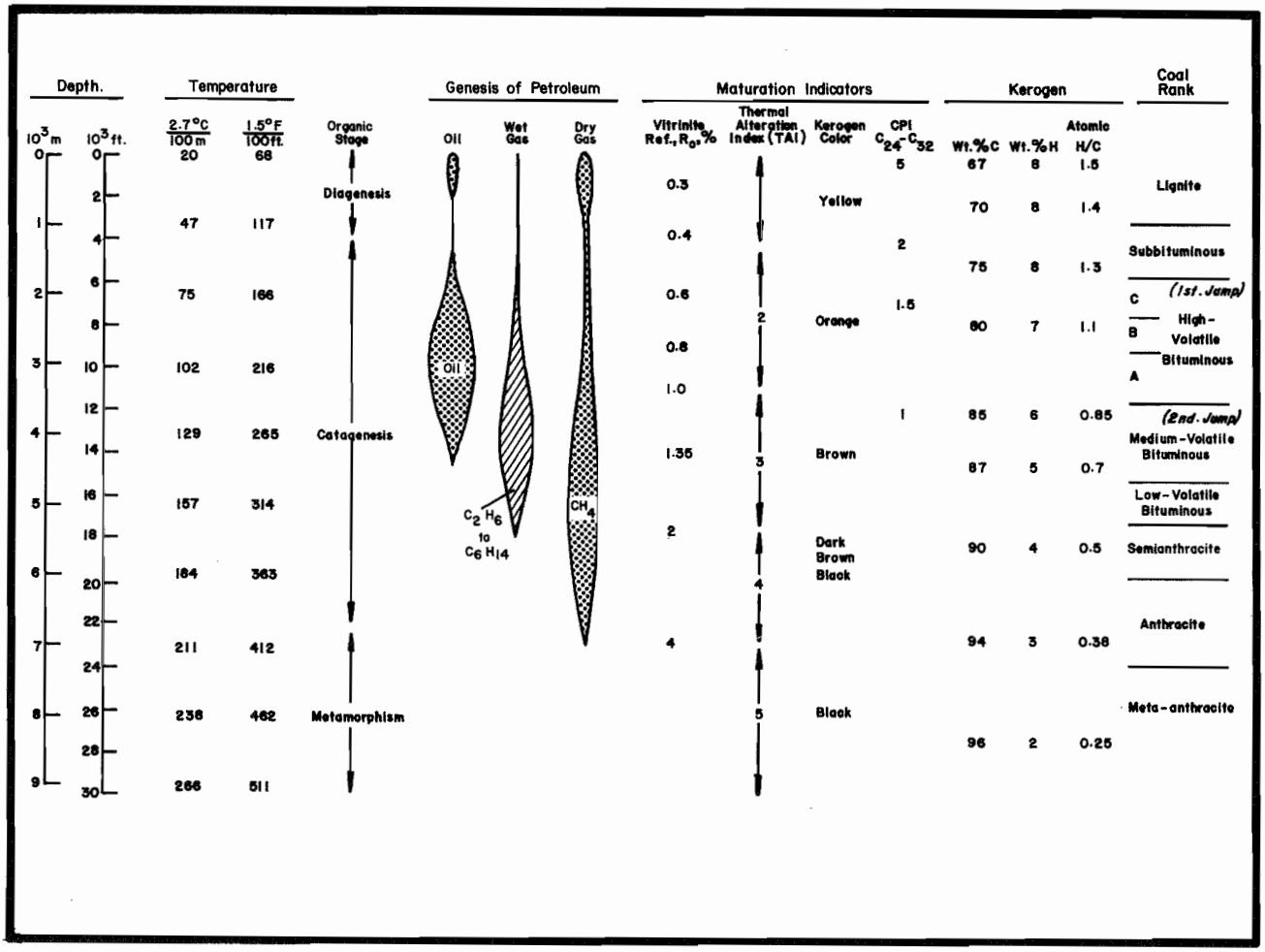


Figure 129. Summary of the maturation of organic matter in fine-grained sedimentary rocks. Modified from Hunt (1979).

Vitrinite reflectance (R^o) was used by most Eastern Gas Shales Project investigators as the means for determining the thermal maturation of potential source beds. In this method the reflectivity of the vitrinite macerals incorporated in the organic matter (kerogen) of sediments provides a means for determining the thermal alteration and maturity of the sediments. R^o values within the range of 0.5 to 3.0 indicate sufficient thermal history to generate oil and wet gas. R^o values greater than 3.0 indicate only a capacity for the generation of dry gas. Immature stages of thermal maturation are indicated by R^o values of less than 0.5 and reflect the potential for only biogenic gas and heavy oil generation. The distribution of Vitrinite Reflectance values for the Appalachian basin are shown on figure 130.

A third method for determining thermal maturation of source beds was introduced by Harris (1978) and deals with coloration changes in conodonts incorporated in sediments through a range of temperatures from 0^oC to 500^oC. In investigations in the Appalachian basin, Harris (1978) has correlated the Conodont Alteration Index (CAI) values of 1 to 5 with temperature ranges, overburden thickness, weight percent of carbon, vitrinite reflectance values and percent fixed carbon (fig. 131). CAI values 1 and 2 are correlated well with the other parameters which indicate temperature conditions favorable for generation of oil. The CAI isograd shown on figure 132 (A) correlates well with the eastern limit of oil production from Devonian sediments in the Appalachian basin. The eastern limit of Devonian gas production in the Appalachian basin generally conforms with the CAI isograd value of 4 (fig. 132 (B)).

For the Appalachian basin geochemical analyses and subsequent oil and gas assessment calculations, Zielinski and McIver (1982) used the Thermal Alteration Index (TAI) method for assessing the degree of thermal maturation of the Devonian shales. They found the TAI values more useful for purposes of assessment than vitrinite reflectance measurements. The TAI data more closely paralleled the geology of the basin and showed variations between samples from the upper and lower intervals in wells while vitrinite reflectance data remained generally uniform in samples from the upper and lower parts of wells. To show regional variations in maturity throughout the Appalachian basin, TAI values were plotted on the same 17 base maps used to show the lateral distribution of organic carbon and the biomass facies. Where values on the 17 interval maps were similar, the units were combined. Five maps were used by Zielinski and McIver (1982) to show the changes in maturation levels within the basin. Figures 133, 134, and 135 show the lateral changes in maturation within the three intervals which exhibited the widest lateral variation of the "Tasmanites" facies in the basin (figures 124, 125, and 126, pages 226, 227 and 228. For the Early Marcellus through Geneseo interval, TAI values increase in magnitude in a west to east direction from less than 2 in northeastern Ohio to a maximum of 4 in north-central Pennsylvania. Maturation levels for the Lower Olentangy through the Hanover Shale interval show an eastward ncrease in values from less than 2 in northeastern Ohio to values greater than 3 in southeastern Ohio and northern West Virginia, while TAI values for Lower and Middle Huron intervals range from just over 1 in northeastern Ohio to greater than 3 in southeastern Ohio and western West Virginia. The mapping of thermal alteration indices permits the partitioning of the basin into areas which show a greater potential for hydrocarbon generation than others. The Zielinski and McIver (1982) investigation suggests that the Devonian shales in the extreme northwest and western portions of the basin, with TAI values less than 2, are too immature to have undergone sufficient cracking to generate even a small percentage of their hydrocarbon potential and propose that the major portion of gas formed in these

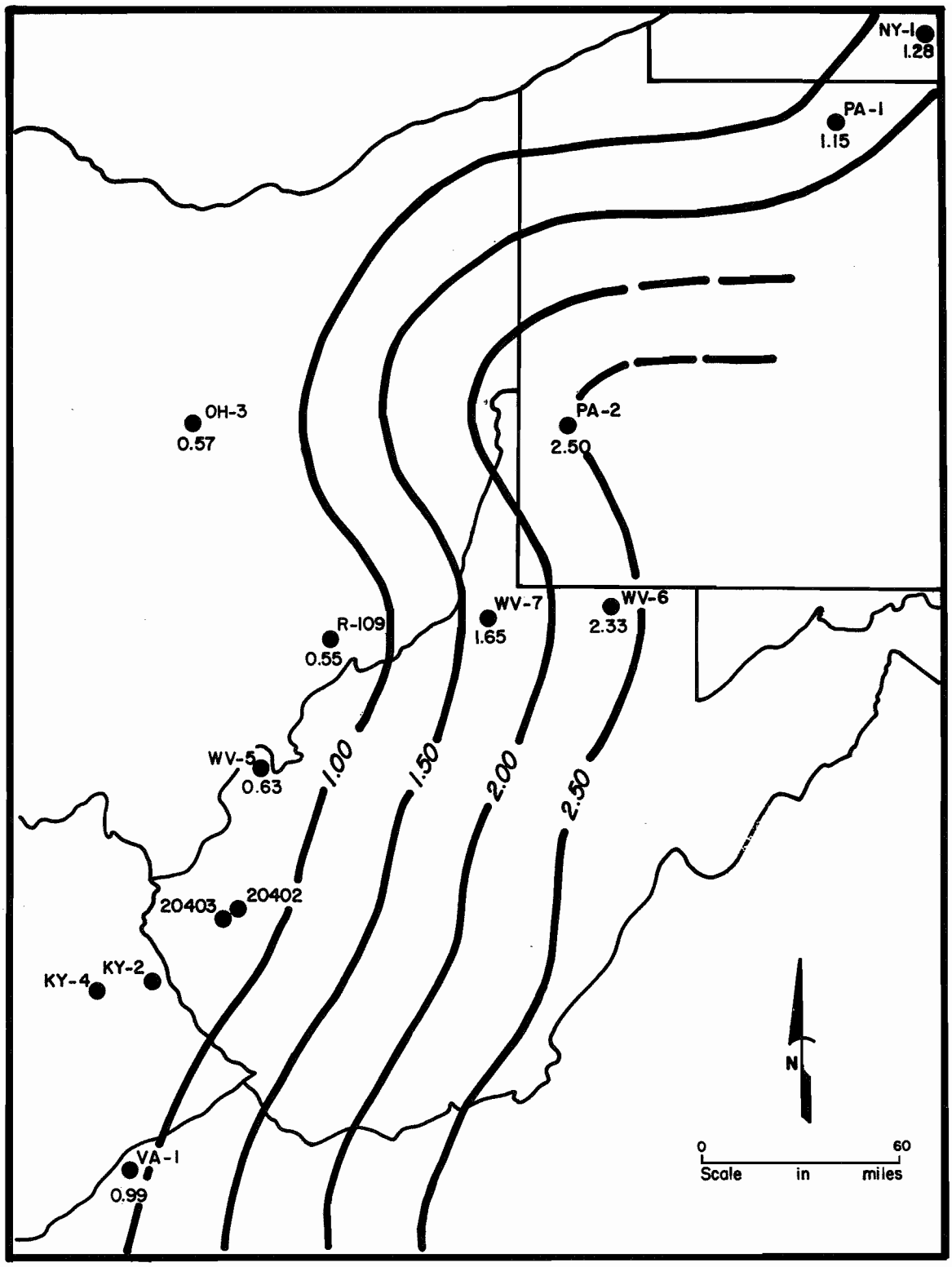


Figure 130. Distribution of vitrinite reflectance (R_o) for the Devonian shales in Ohio, Pennsylvania, and West Virginia. From SAI (1980), after Mound (1980).

	CONODONTS		PALYNOMORPHS[1]	VITRINITE[1]	PERCENT FIXED CARBON
CAI[2]	Temperature	Approx. overburden, in ft. (m) (values for Ordovician rocks in Appalachian basin)[4]	Weight percent carbon in kerogen	Reflectance	
1	<50-80	<4,000 (<1,220)	<82	<0.8	<60
1½	50-90	4,000-8,000 (1,220-2,440)	81-84	0.7-0.85	60-65
2	60-140	8,000-12,000 (2,440-3,660)	81-87	0.85-1.3	65-73
3	110-200	12,000-18,000 (3,660-5,490)	83-89	1.4-1.95	74-84
4	190-300	18,000-26,000 (5,490-7,930)	84-89	1.95-3.6	84-95
5	300-400	begins at 26,000-30,000 (7,930-9,150)	+90	+3.6	+95

Figure 131. Comparison of conodont alteration index (CAI) with temperature ranges, overburden thickness, weight percent of carbon, vitrinite reflectance and percent fixed carbon. After Harris (1978).

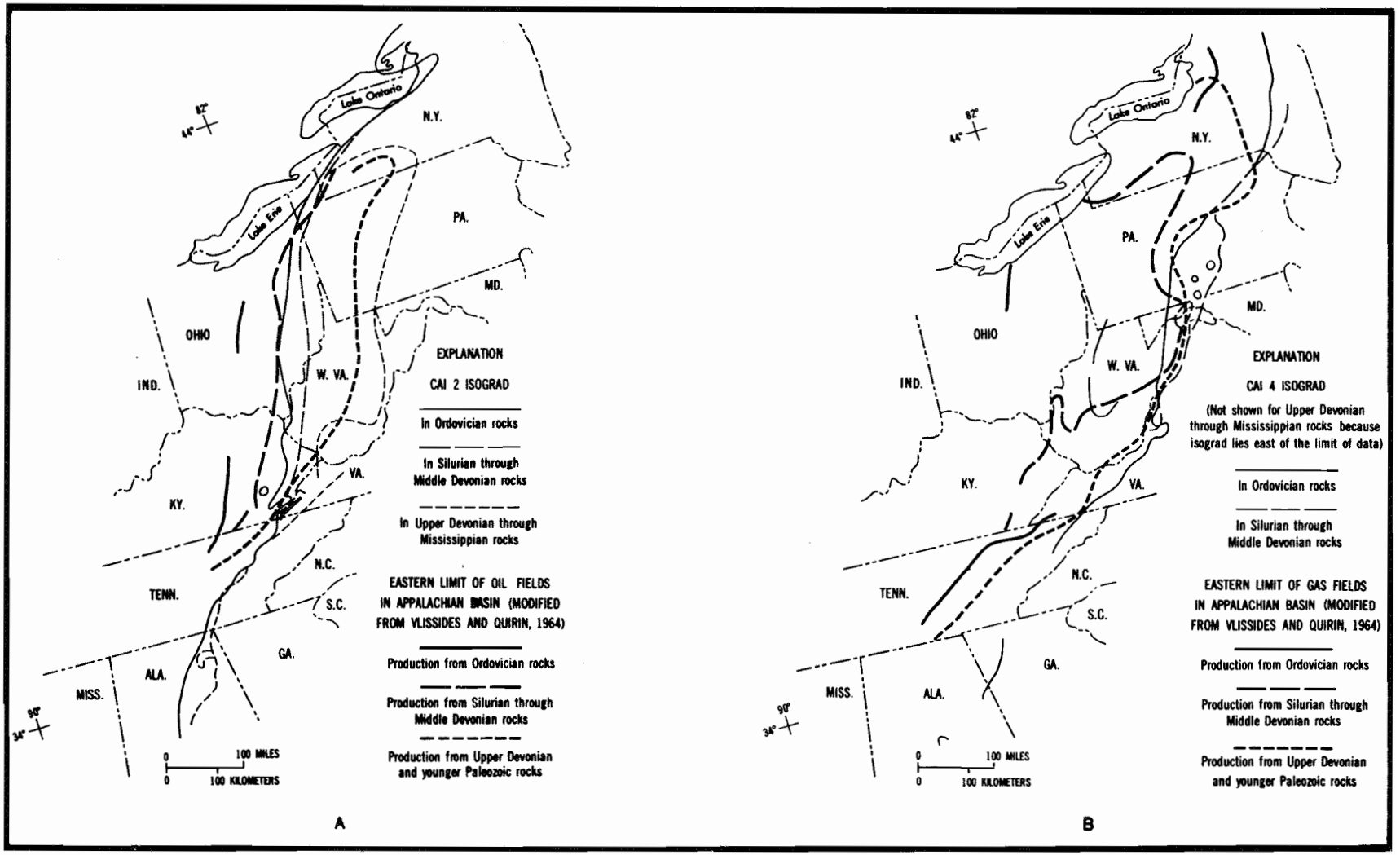


Figure 132. Maps showing the eastern limit of oil (A) and gas (B) production for three stratigraphic intervals in the Appalachian basin. After Harris (1977).

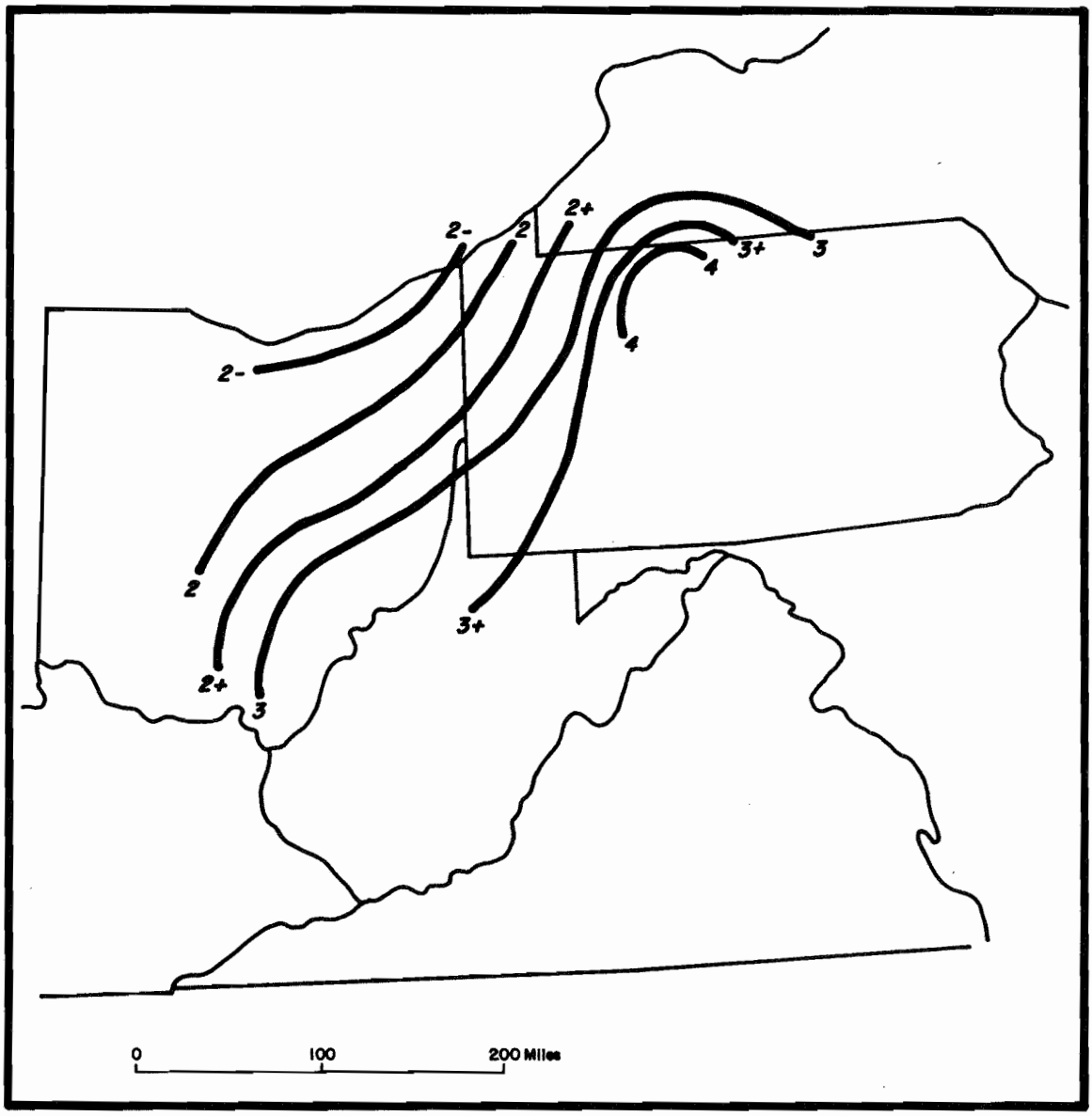


Figure 133. Lateral distribution of thermal alteration index (TAI), Early Marcellus through Genesee/Geneseo. After Zielinski and McIver (1982).

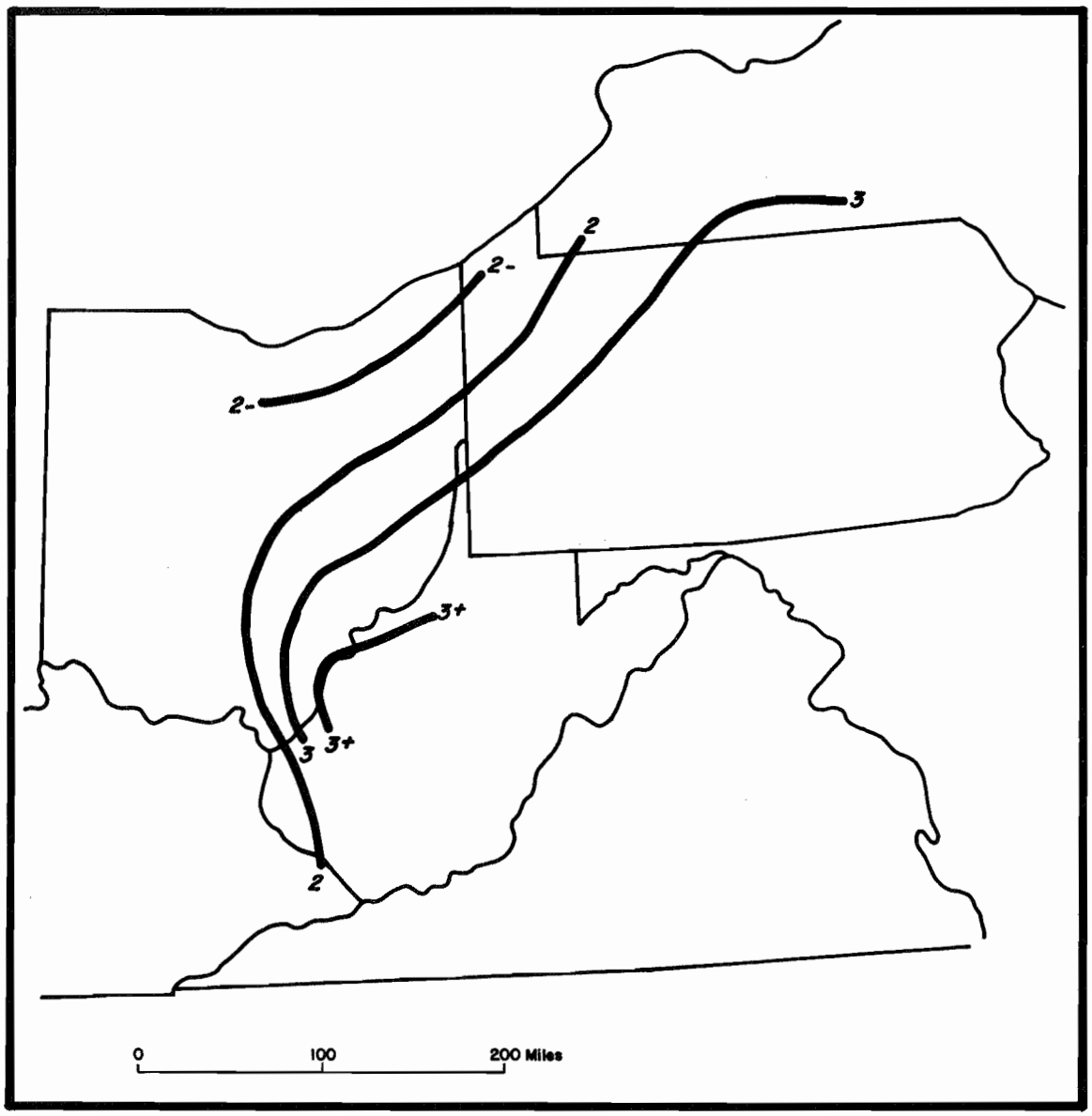


Figure 134. Lateral distribution of thermal alteration index (TAI), Early Upper Huron through Cleveland. After Zielinski and McIver (1982).

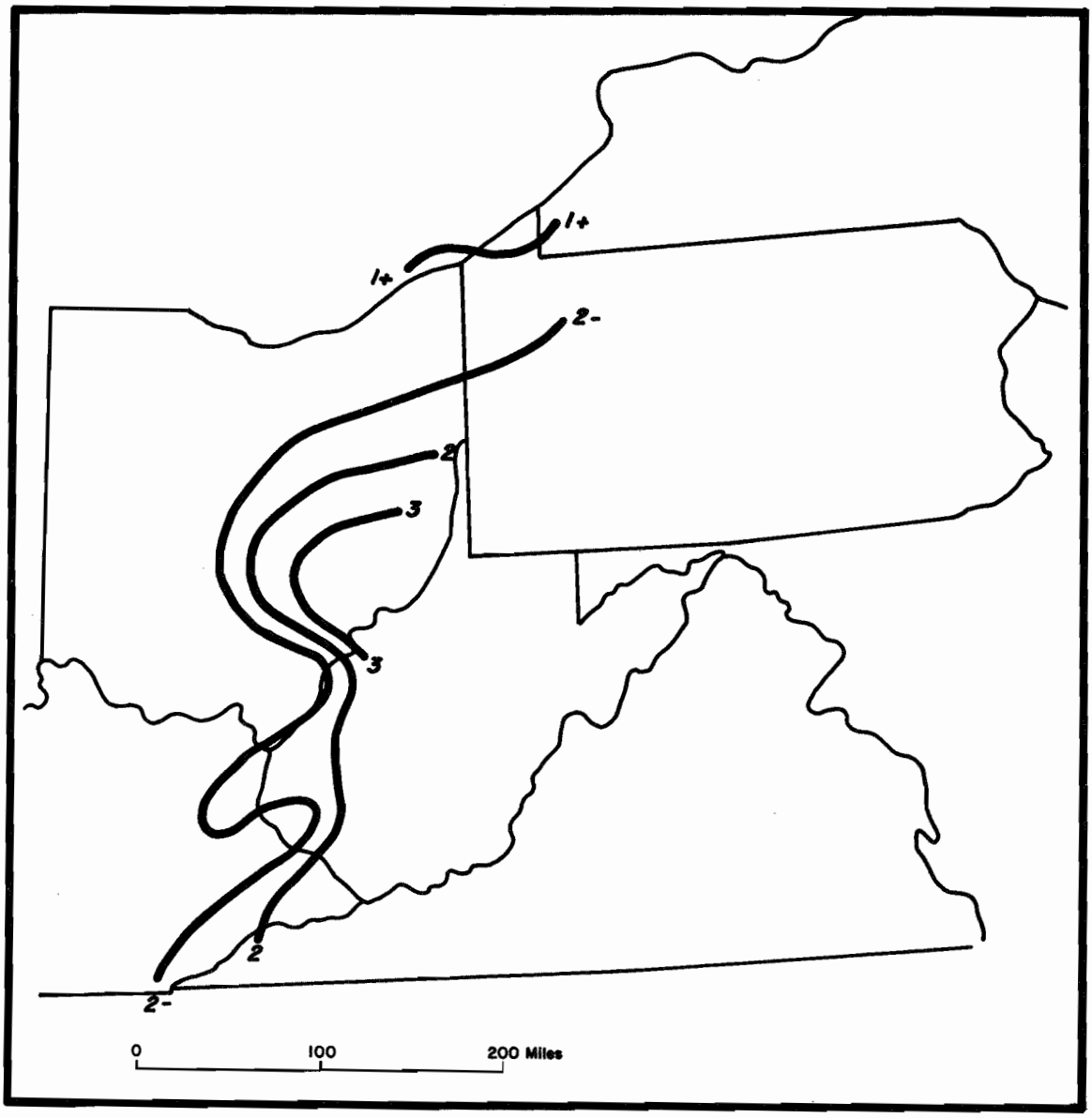


Figure 135. Lateral variations in thermal alteration Indiana during Early Lower Huron through Lower Huron through Late Middle Huron time. Zielinski and McIver (1982).

areas is biogenic gas. Likewise, the Devonian shales in the eastern portion of the basin with TAI values above 3+ are too mature to be good sources for oil and gas because they have been exposed to temperatures which have destroyed nearly all of the potential hydrocarbons. As a subsequent step in geochemical evaluation of the oil and gas resources in the Appalachian basin, Zielinski and McIver (1982) combined the data on organic carbon content, biofacies type and thermal alteration into a rating system that showed the source characteristic for the 17 study intervals and for the Appalachian basin as a whole. The rating system, based upon variations in the combinations of organic contents and thermal alteration indices, is shown on figure 136. The values presented are based upon petroleum geochemical considerations which are somewhat biased by observations of the investigators. These observations indicate that, because of the low permeability of the Devonian shales in the Appalachian basin, the shales retain most of the gas they generate; therefore, maximum generation of hydrocarbons, particularly liquid hydrocarbons (oil), is held back until higher temperatures are reached at higher alteration indices (Zielinski and McIver, 1982). For detailed assessment of the oil and gas source rock potential, the reader is referred to figures 56 through 72 and the accompanying text from the original Mound Facility Report (Zielinski and McIver, 1982). Figure 137, showing the gas source rock potential for the Appalachian basin, indicates that the most promising source rock areas are concentrated in southwestern Ohio, southwestern Pennsylvania, northwestern West Virginia and northeastern Tennessee. The overall oil source quality map (fig. 138) shows that potential oil source areas are concentrated in southeastern Ohio, southwestern Pennsylvania and northwestern West Virginia.

The final step in the geochemical resource assessment study by Zielinski and McIver (1982) was the integrating of the source rock potential data with the thickness data for each of the 17 selected intervals being investigated (figures 72 through 81 of the original Mound Facility Report by Zielinski and McIver, 1982). The combined data were used to develop a series of maps showing the relative gas source and oil source potential. The relative oil and gas source potential maps, figures 92 through 119 of the Mound Facility Report (Zielinski and McIver, 1982) show a wide range of values. The contour values on the relative oil and gas potential maps, figures 137 and 138, pages 242 and 243, are the product of the source quality values, figure 136, page 241, and the thickness of the interval for each of the 17 separate units. The relative potential values range from less than 100 to more than 2000 and show by the variations in magnitued of the values the relative potential of each of the units for generating hydrocarbons.

In addition to the cited geochemical exploration parameters, organic carbon, organic matter type, thermal alteration index, and gas content (controlled out-gassing investigations), Eastern Gas Shales Project investigators conducted other detailed geochemical analyses to characterize the Devonian shales and incorporated organic matter. Included in the suite of geochemical analyses undertaken to characterize the Devonian shales were elemental analysis, carbon isotope studies, pyrolysis and gas chromatograph analyses, and C_{15} hydrocarbon extractions. Interested readers are referred to the Unconventional Gas Resource bibliography for reference to these studies.

In summary, three of the four parameters deemed critical for evaluating the oil and gas potential of the Appalachian basin (total organic carbon, biofacies type, and thermal alteration) provide an excellent overall appraisal of the source and reservoir potential of the rocks if porosity is available to accumulate the indigenous hydrocarbons (Zielinski and McIver, 1982).

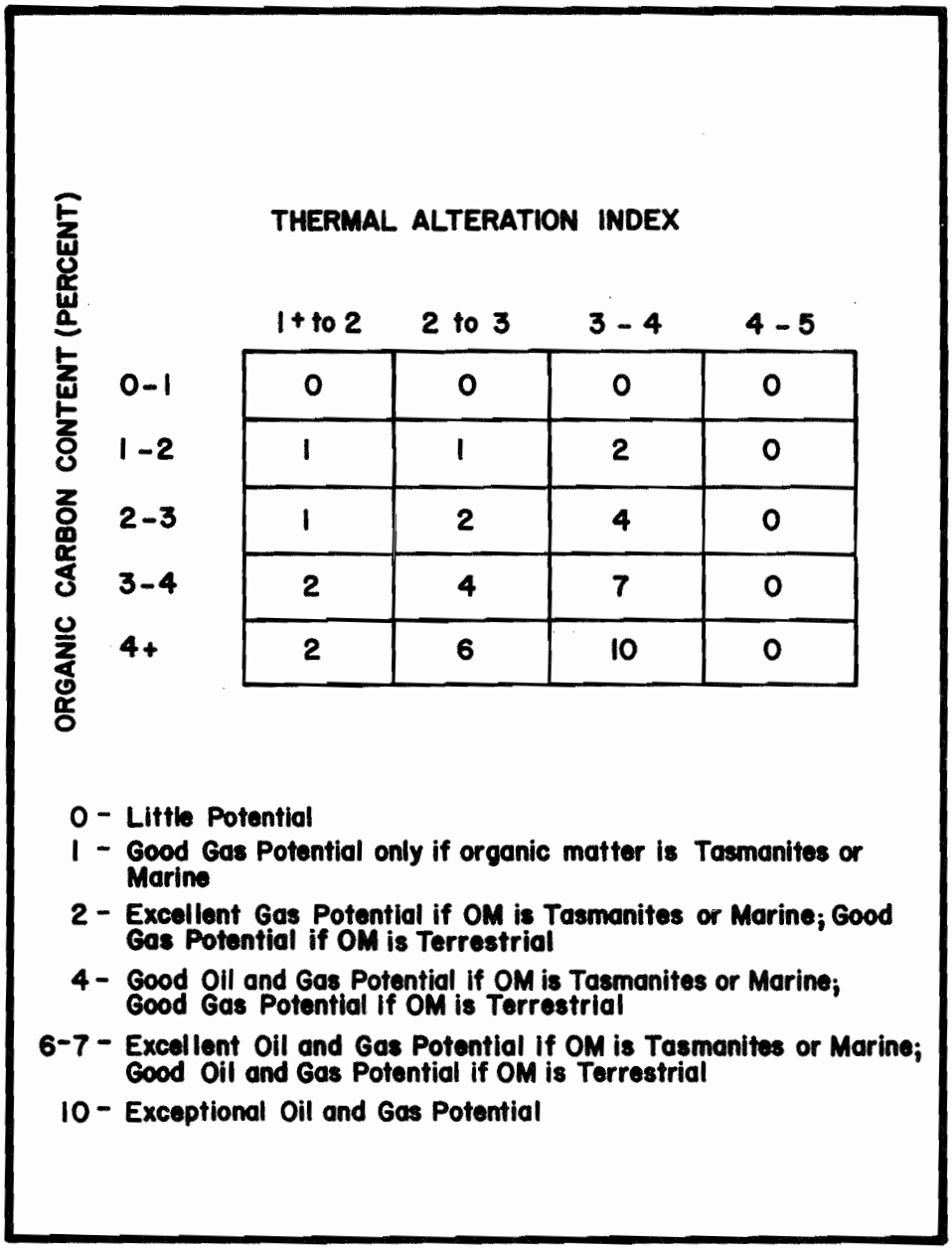


Figure 136. Relative source rock rating system for the Devonian shales in the Appalachian basin. After Zielinski and McIver (1982).

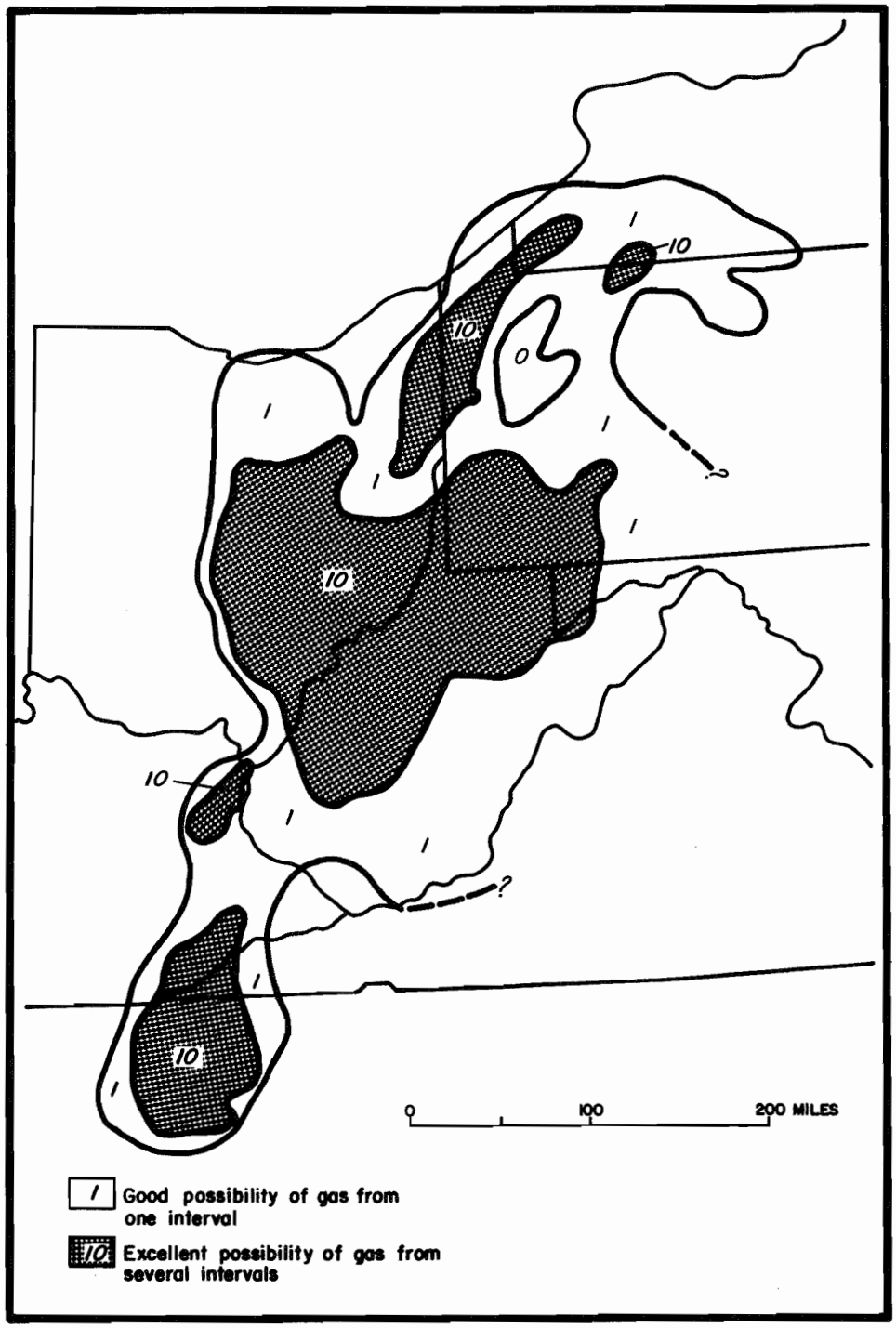


Figure 137. Index map showing the overall gas source rock potential of the Devonian shales in the Appalachian basin. After Zielinski and McIver (1982).

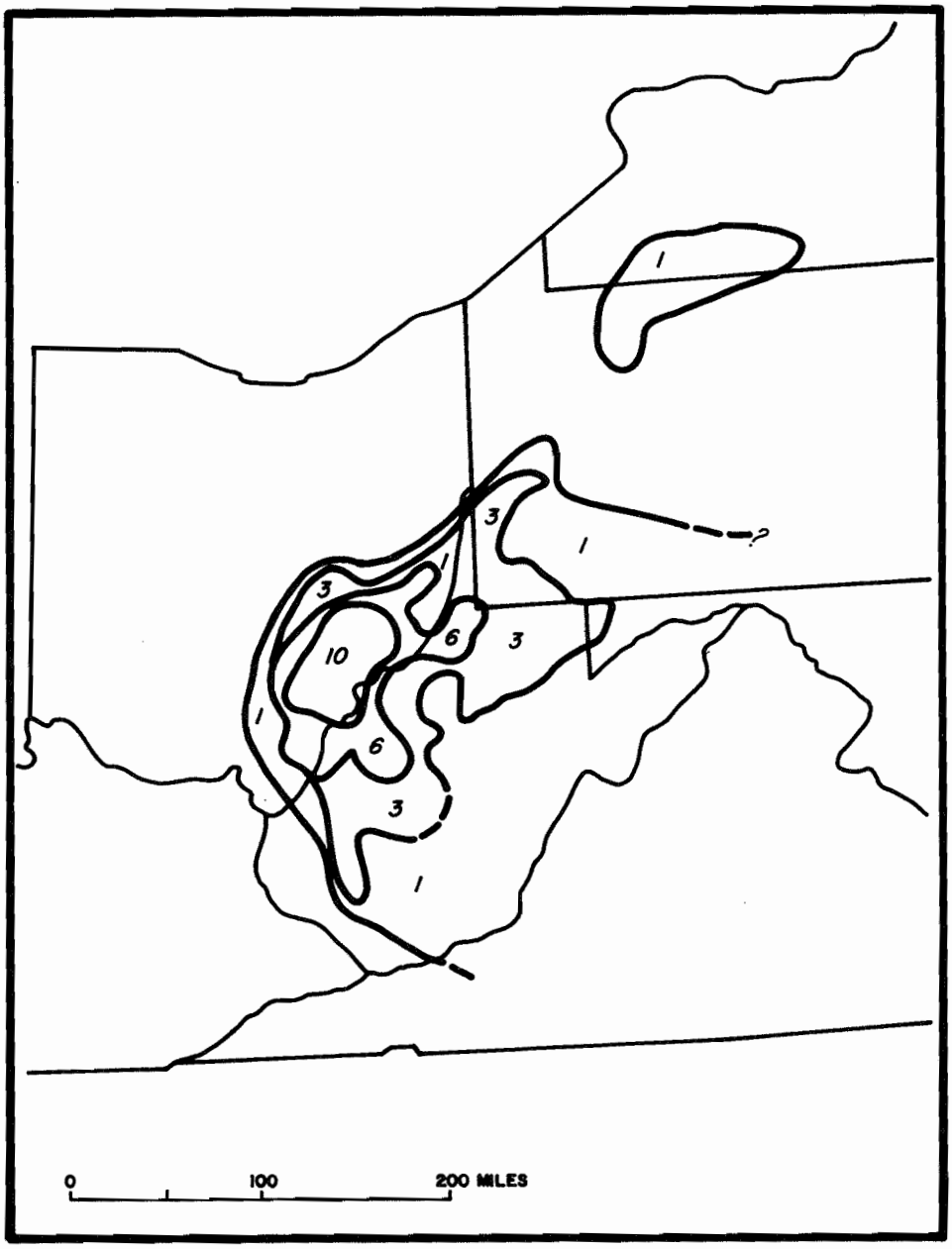


Figure 138. Index map showing the overall oil source rock potential of the Devonian shales in the Appalachian basin. After Zielinski and McIver (1982).

Illinois Basin

Geochemical investigations in the Illinois basin closely paralleled the investigations in the Appalachian basin. Initially, the Illinois basin investigators proposed utilizing almost the entire suite of petroleum geochemical analyses and techniques to characterize the Devonian shales and evaluate the potential of the shales as source rocks and unconventional reservoirs for natural gas. Included in the detailed geochemical investigations were the following analytical investigations: (1) major, minor, and trace element analyses; (2) organic carbon determinations; (3) type and characterization analyses of organic matter; (4) carbon isotope analyese; (5) hydrocarbon content and composition analyses; (6) outgassing investigations; (7) thermal maturation investigations, and (8) additional supplementary analyses. It became apparent after a short period that certain physical and petroleum geochemical parameters provided the best data for evaluating the natural gas potential of the Devonian New Albany Shale as both a source rock and reservoir in the Illinois basin. The criteria found most useful in the Illinois basin closely parallel the parameters used in the Appalachian basin for assessing the natural gas potential of the Devonian shales. For the Illinois basin the potential natural gas resources of the Devonian shales is related to the following five key elements: (1) relative organic content of the shale; (2) relative thickness of the organic-rich shales; (3) type of organic matter; (4) thermal maturity as related to depth of burial, and (5) the presence of natural fractures (Tetra Tech, 1981). The majority of subsurface physical and analytical data came from samples from Department of Energy Eastern Gas Shales Project-sponsored cores in Illinois (5), Indiana (1) and Kentucky (2). These data were supplemented by samples from cores and drill cuttings in repositories of the Illinois, Indiana and Kentucky geological surveys. The following discussion is summarized from the Illinois basin screening report (Tetra Tech, 1982, DOE/METC 124), the geologic and geochemical investigations of the New Albany Shale in Illinois (Bergstrom et al., 1980), the final report on the Devonian shale in Kentucky (Blackburn, 1980), and shorter contributions from papers published in the Proceedings of USDOE/METC symposiums (DOE/METC/SP-77, -78, and -79).

The organic-rich New Albany shale ranges in thickness from a few feet along the outcrop to more than 400 feet at the depocenter near the common boundary between Illinois, Indiana and Kentucky (fig. 139). Previous studies of gas-bearing shales in other basins have shown a close correlation between areas of thick sequences of organic-rich shales and gas production and that the best gas-producing areas occurred where the black, organic-rich shales exceeded 150 meters in thickness (Harris, de Witt and Colton, 1978). Accordingly, since the entire New Albany sequence in the Illinois basin only attains a maximum thickness of 470 feet, the black organic-rich facies falls short of the 150 meters considered essential for commercial gas production. The cumulative thickness and distribution of the radioactive black shales in the basin (fig. 140) shows the maximum development of organic-rich shale occurs near the center of the basin at the approximate position of maximum New Albany Shale development. On the basis of thickness of organic-rich shale only, the area within the basin most favorable for exploration of natural gas would occur within the 150-foot contour line of figure 139, page 245.

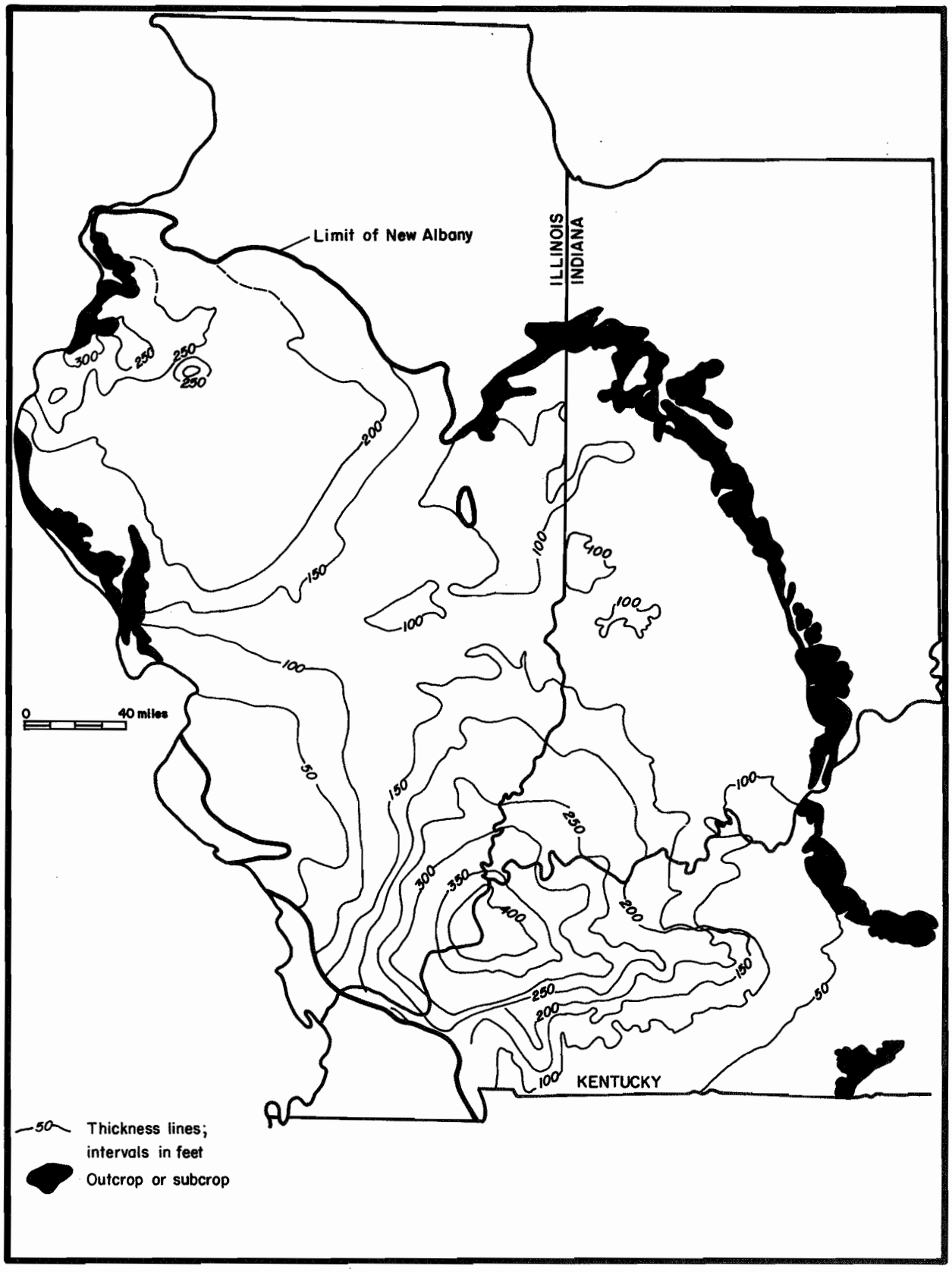


Figure 139. Thickness of the New Albany Shale Group in the Illinois basin. From Illinois State Geol. Survey, Lineback (1980), after Reinbold (1978); Bassett and Hasenmueller (1978); and Schwalb and Potter (1978).

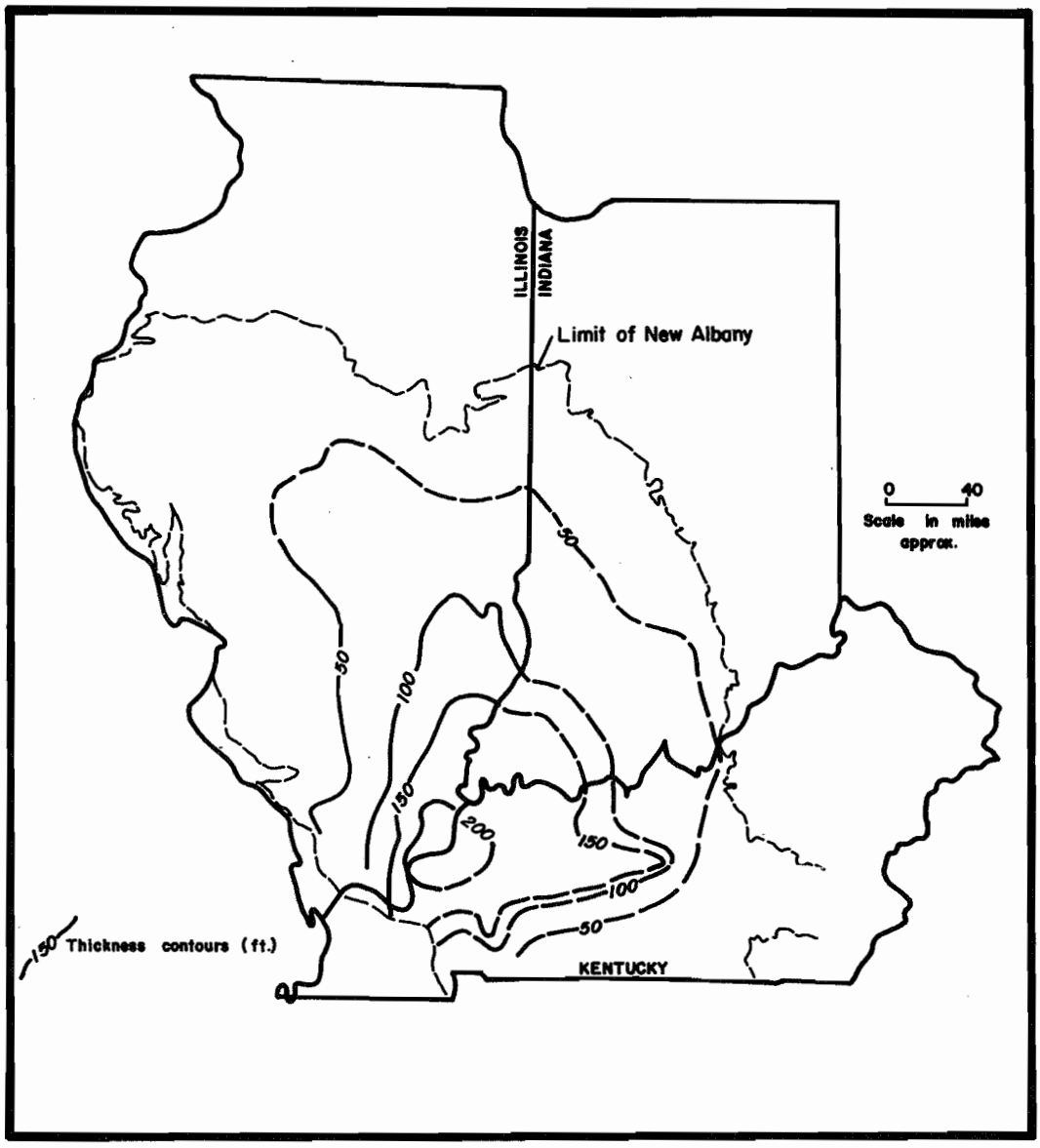


Figure 140. Cumulative thickness of "radioactive" black shale (gamma-ray log values more than 60 API units above a normal shale baseline value) in the New Albany Shale Group of the Illinois basin. Contours in northern Illinois, Indiana, and Kentucky are based on comparative thickness of units and are only approximate, due to paucity of gamma-ray log control. From Illinois State Geol. Survey, Lineback (1980).

A first approach at determining the potential of the New Albany Shale as a potential source rock was the determination of the quantity of the organic matter incorporated in the shales. As pointed out in geochemical discussions of the Appalachian basin, the determination of percent-by-weight of organic carbon found in the shale is an accepted technique for estimating the quantity of organic matter in the samples. Stevenson and Dickerson (1969) determined the quantity of organic matter in the New Albany shale by analyzing for percent-by-weight of organic carbon from core samples and drill cuttings from 350 wells in Illinois. Their study showed organic carbon content in the bottom 15 meters of the organic-rich New Albany ranged from just less than 1.0 percent to greater than 9.0 percent in the basin (fig. 141). Lineback (1970) reports organic carbon contents of as high as 20 percent in the Indiana portion of the Illinois basin. The generally accepted lower limit of organic carbon content required to generate significant quantities of petroleum hydrocarbons lies somewhere between 0.5 and 1.0 percent (Tissot and Welte, 1978). Since most of the samples from the New Albany in Illinois ranged above 1.0 percent, the shale must be considered as a potential source rock throughout its area extent.

In conjunction with quantity, the type of organic matter is important in evaluating source rock potential and the type of hydrocarbon capable of being generated. In the Illinois basin the occurrence and type of organic matter are facies-dependent. The organic matter associated with the greenish-gray shale facies of the New Albany is sparse and, where observed, consists primarily of the humic type macerals, vitrinite and intertinite, with some isolated organic types. The composition of the organic matter in the greenish-gray shales correlated well with the Type III kerogens of Tissot and Welte (1978). In contrast, the brownish-black and black shale facies contain 90 to 95 percent of amorphous organic matter; the remaining 5 to 10 percent of organic matter being of the humic type (liptinite, vitrinite, and intertinite). The amorphous types of organic matter are interpreted as the decomposition products of marine algae. Tasmanites is the most commonly recognized variety and appears to randomly vary in abundance, both stratigraphically and areally, throughout the basin. Mixed assemblages of predominantly marine organic with minor amounts of terrestrial materials compare closely with the composition of Type II kerogens as defined by Tissot and Welte (1978). In the Illinois basin the mixed assemblage of prediminately marine organic matter with secondary terrestrial organics (Type II) occurs in the southeastern portion of the basin (fig. 142). The Type II distribution corresponds well with the area of maximum thickness of New Albany Shale and greatest thickness of radioactive organic-rich black shale (fig. 140, page 246.

The high percentage of organic carbon, derived from Type II kerogens in southeastern Illinois and the deeper portion of the Illinois bsin, strongly suggests that the New Albany Shale in the Illinois basin would have excellent potential as a source rock for oil and natural gas if favorable thermal conditions had existed during the historic development of the basin.

The vitrinite reflectance method was used by Illinois basin investigators to obtain the relative thermal maturity of the Devonian shales throughout the basin. The level of reflectance of the vitrinite macerals incorporated in the shales is a measure of the thermal history and thermal maturity of rocks. Vitrinite reflectance values obtained from samples from over 100 wells in the Illinois basin range from less than 0.5 percent R^o to greater than 1.0 percent R^o (fig. 143). The maximum thermal maturity values occur in the area of the Illinois basin depocenter where thickness of sediment and depth of burial reach the maximum. Vitrinite reflectance indicates the shales in some areas of the basin

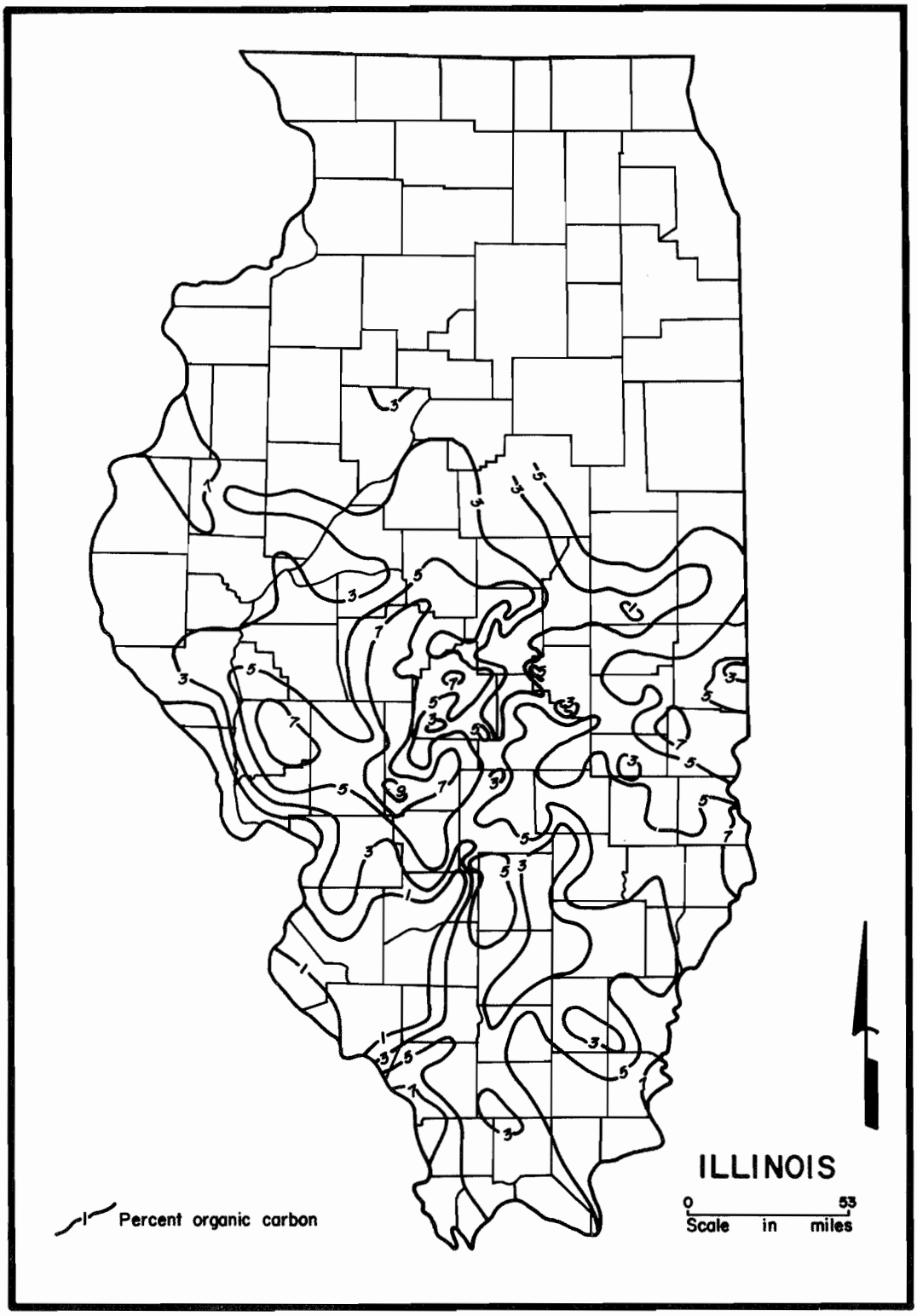


Figure 141. Percent organic carbon in bottom 15 meter of New Albany Shales in Illinois. From Stevenson and Dickerson (1969).

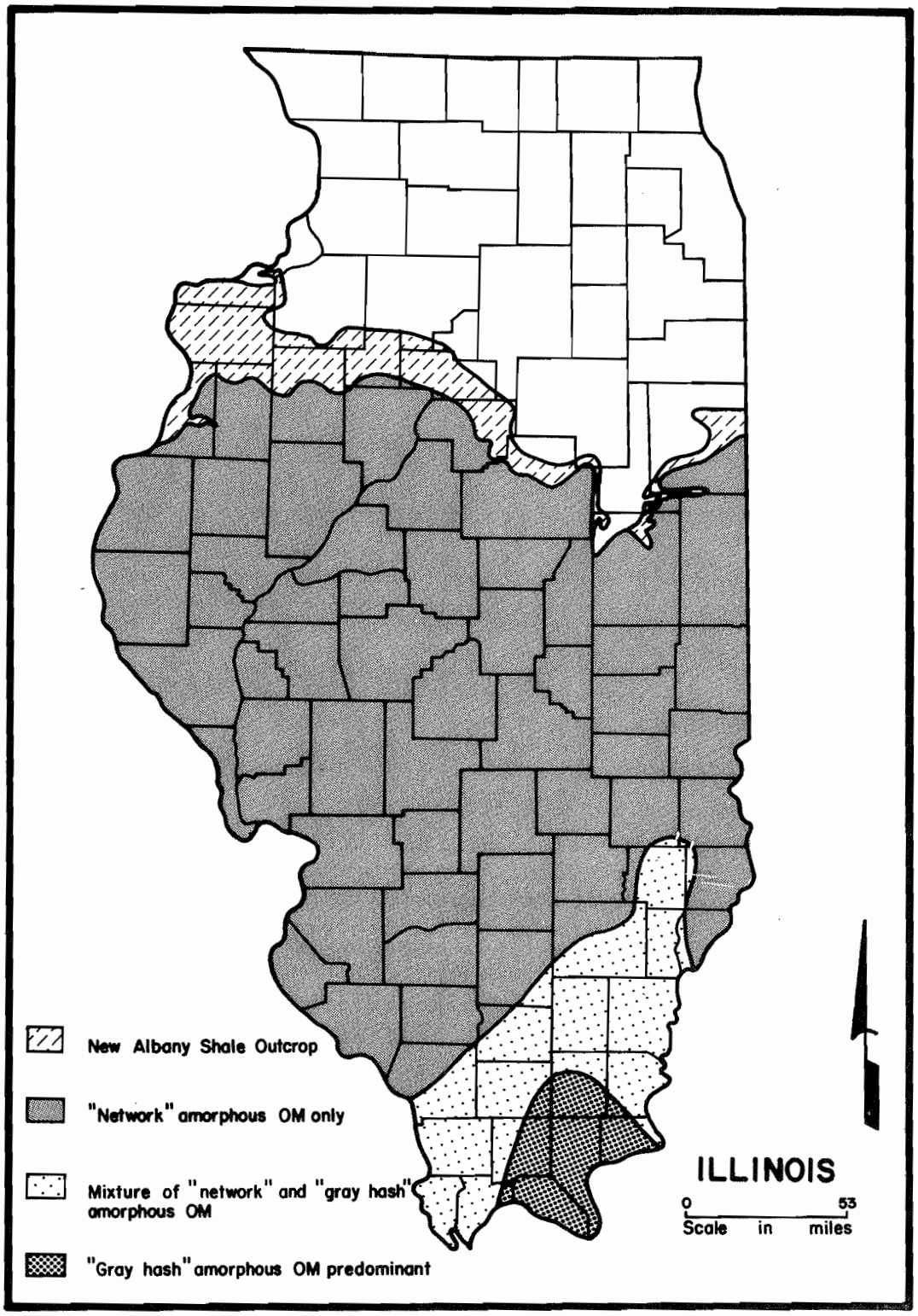


Figure 142. Distribution of kerogens types in the New Albany Shale in Illinois. After Bergrstrom et al. (1980).

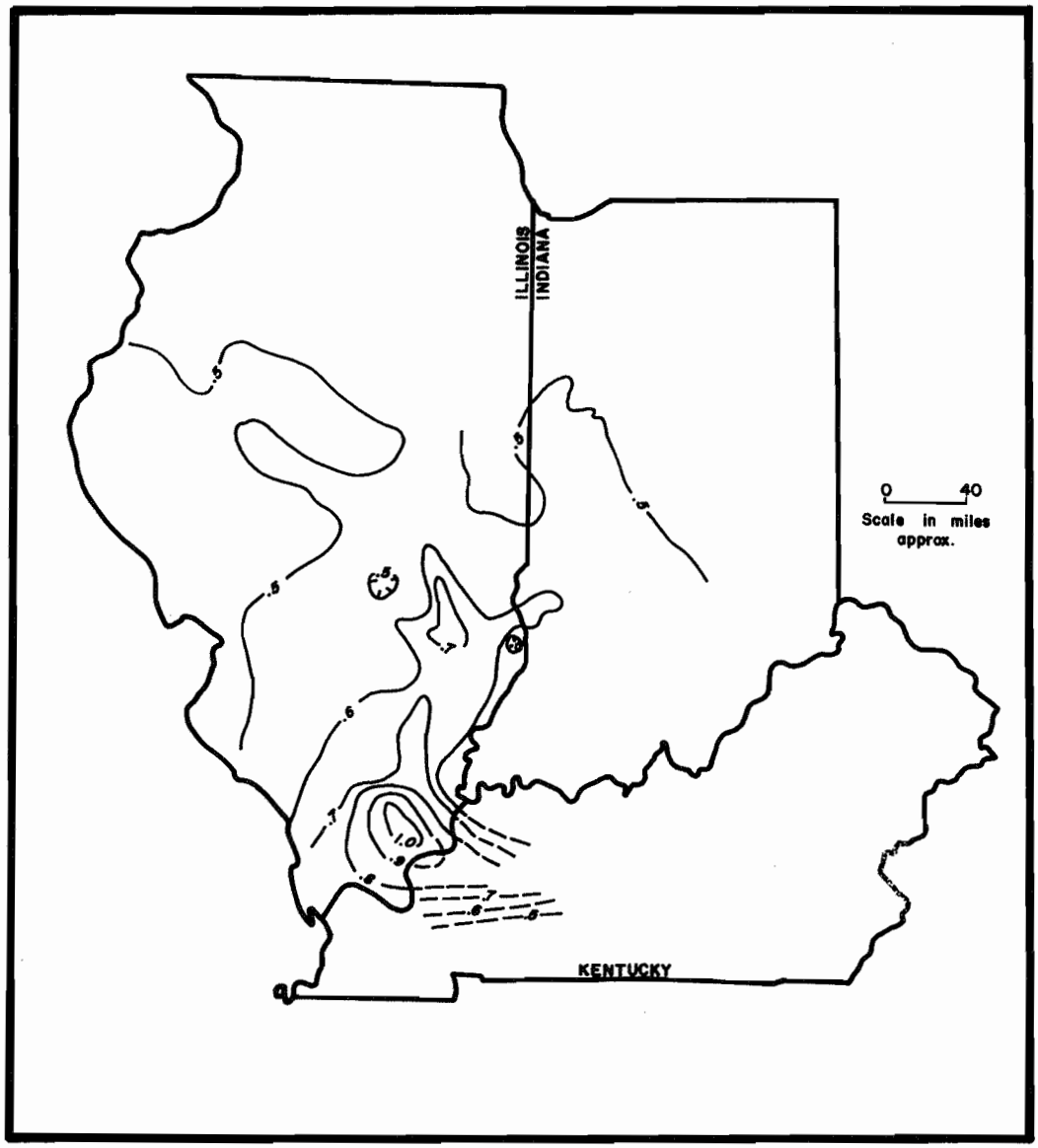


Figure 143. Mean random vitrinite reflectance in the New Albany Shale, Contom interval in R_o percent. From Barrows et al. (1979).

are in the immature stage of thermal maturity (R^o less than 0.5 percent). Those areas with maturation levels between 0.5 percent R^o and 0.7 percent R^o are within the earliest stages of oil generation for Type II kerogens. In these areas the question remains as to whether oil generation was ever initiated or whether the volume of oil generated was sufficient for explusion of the oil from the source rock (Bergstrom et al., 1980). Oil generation and expulsion are most likely in the area of the basin where the reflectance values exceed 0.7 percent R^o. Maturation levels corresponding to the major gas generation window (greater than 1.3 percent R^o) have not been recognized in the Devonian shale sequence in the Illinois basin.

To partition the Illinois basin into areas of relative natural gas potential, two additional parameters were evaluated by Eastern Gas Shales Project investigators. Historical Devonian gas production, "shows," and structure were used as weighting factors prior to the final designation as to the relative potential for natural gas production. The gas-producing areas of the basin are shown on figure 144, and the major structural features are shown on figure 145. The structural data is important because the Eastern Gas Shale Project investigations and production characteristics strongly indicate that the natural gas reservoirs within the Devonian shale are in secondary fracture porosity zones associated with structural elements. The stratigraphic data, source bed geochemical data, core outgassing data, structural data in combination with historical production and shows were used to partition the Illinois basin into areas of relative natural gas potential (fig. 146).

In summary, the relative potential for natural gas in areas within the Illinois basin has been defined on five key geological and geochemical elements: (1) relative organic content of the shale; (2) relative thickness of the organic-rich shale; (3) type of organic matter; (4) thermal maturity, and (5) presence of natural fractures and production or shows of gas. The radioactive Devonian shales in the Illinois basin have maximum thickness and maximum organic content in the southeastern portion of Illinois and adjoining areas of Kentucky and Indiana. The shales in this area, approximately 400 feet thick, are deeply buried by younger rocks and the organic matter shows the highest level of maturity. The area also has potential for secondary fracture porosity reservoirs because of the proximity and orientation of major faults along the Rough Creek lineament, the Wabash Valley fault system and the Moorman syncline. This area, identified on figure 105, page 195, has the greatest potential for natural gas resources in the Illinois basin. The eastern portion of the basin, where the organic-rich shales are thinner, has been assigned a poor to moderate potential for additional discoveries of small gas fields while the western and northern portions of the basin have low potential for natural gas resources because of the low organic content and thermal immaturity of the shales.

Michigan Basin

In the Michigan basin four key factors were used to characterize the potential natural gas resource of the organic-rich Antrim Shales. These factors, both geologic and geochemical are: organic carbon content; thickness of the radioactive organic-rich shales; the presence of natural fractures, and the presence of gas production indicators (historic production or hydrocarbon "shows"). The principal sources of data incorporated into the following discussion are from the final Michigan basin screening report (Tetra

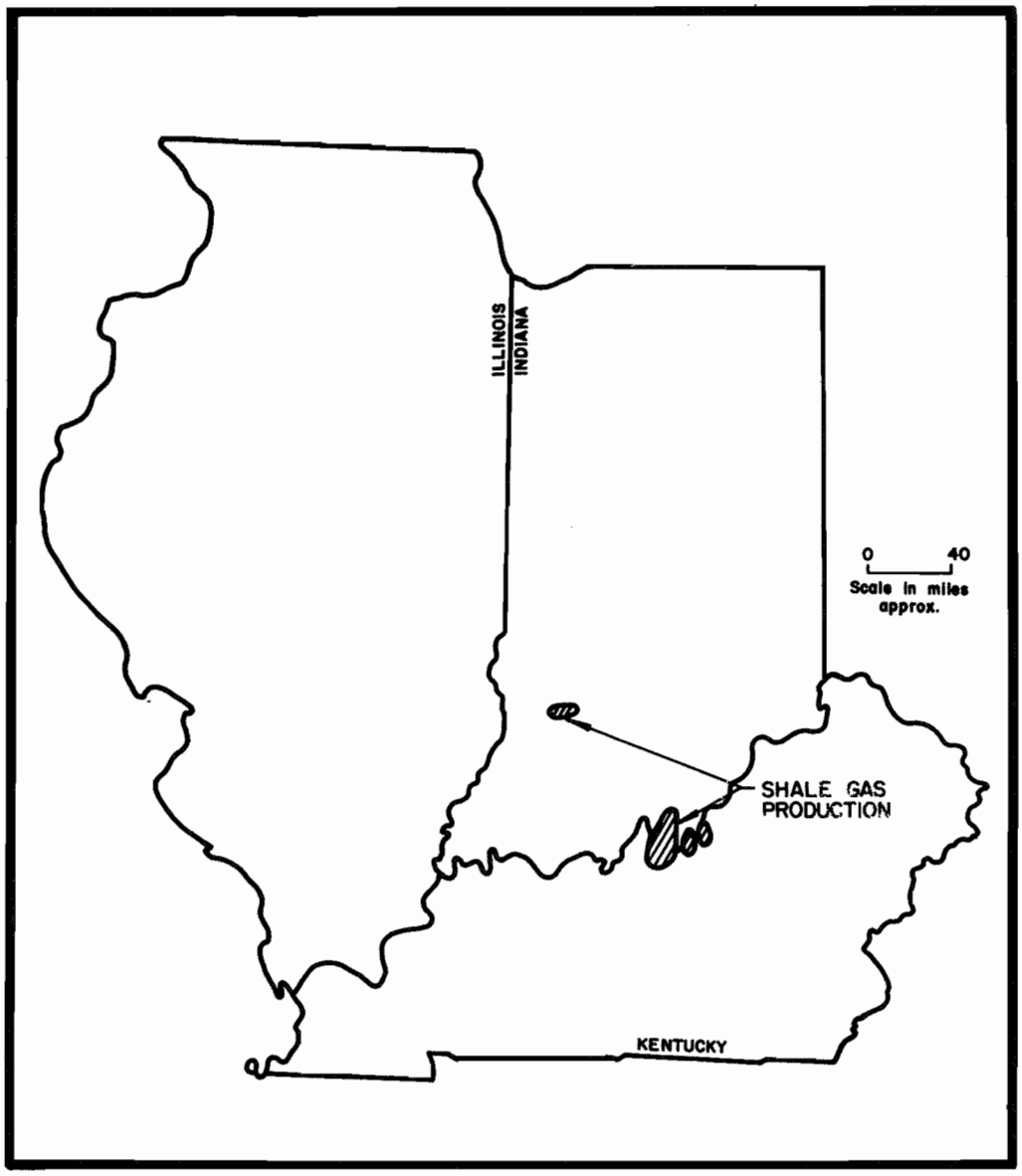


Figure 144. Index map of shale-gas production in the Illinois basin . Redrawn from Komar (1981).

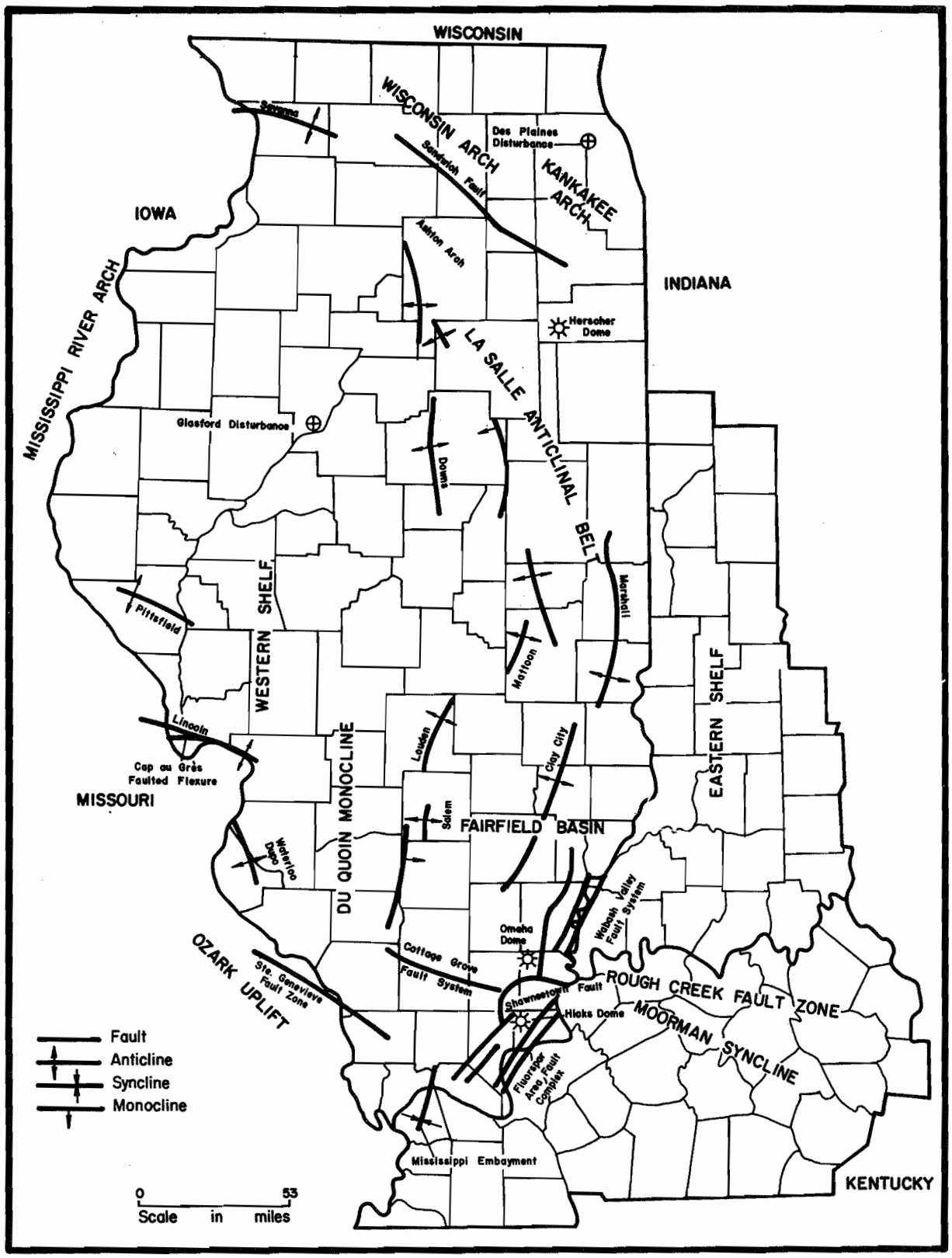


Figure 145. Major structural features of the Illinois basin. After figure 12, Illinois Geological Survey Bulletin 95.

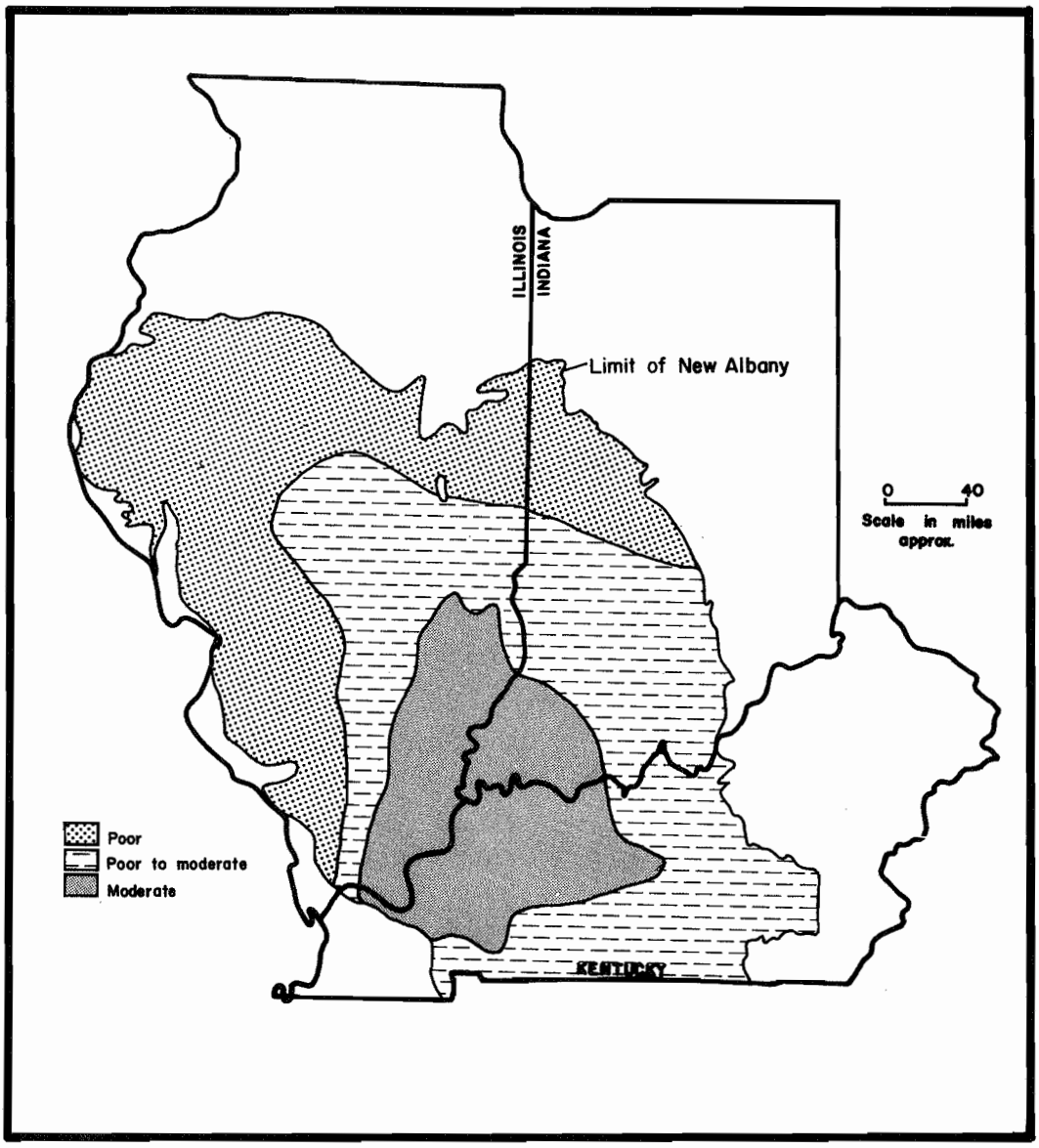


Figure 146. Natural gas potential of the New Albany Shale Group in Illinois basin. From Illinois State Geol. Survey, Lineback (1980).

Tech, Inc, 1981, DOE/METC-123) and the interim statewide Devonian shale exploration screening report for Michigan (McIver and Zielinski, 1980). Other contributions to the understanding of the geochemical characterization of the Antrim Shales in the Michigan basin can be found in reports by Young (1978), Leventhal (1980), and Snyder and Maness (1980). The primary geochemical methods used in the assessment and evaluation of the natural gas resource potential of the Antrim Shale were the determination of organic compound content (McIver and Zielinski, 1980) and the pyrochromatic analyses to determine residual hydrocarbon components remaining in drill cuttings or core samples (Snyder and Maness, 1980).

Organic carbon determinations were made from analyses of 280 Antrim shale samples from wells in the Michigan basin. The analyses showed the organic carbon content to be very high for the Antrim Shale. The values obtained in the analyses were plotted on a histogram which shows that approximately 80 percent of the samples analyzed had organic carbon contents in excess of 2 percent. The mean range in values over the basin was between 0.09 percent and 24 percent. The atypical organic richness of the Antrim shale is apparent when compared to a histogram plot of organic carbon contents for 1066 shales from around the world (fig. 147a). Figure 147(b) indicates that over 80 percent of the 281 samples analyzed from the Michigan basin can be interpreted to possess very good to excellent hydrocarbon source potential with respect to only organic carbon content. Comparison of the histograms indicated that, on the average, the Antrim Shale is three to four times richer in organic carbon than the hydrocarbon sources shown on figure 147(b) and approximately twice as rich in organic content as samples analyzed from the Rhinestreet and Dunkirk stratigraphic equivalents in northeastern Ohio. On the basis of organic carbon content alone, the gas-generating capacity of the Antrim Shale is interpreted as excellent. However, because only a limited number of off-gassing tests were conducted on cores of Antrim Shale throughout the basin, an estimate of the gas-generating capacity of the Antrim Shale in the Michigan basin at this time is only conjectural. Thermal maturation investigations and determinations of the types of organic matter, two parameters considered essential in the assessment of source and production potential in the Appalachian basin, were not available for inclusion in the Michigan basin screening reports (Tetra Tech, 1981, DOE/METC 123; McIver and Zielinski, 1980). However, the occurrence of oil and gas above and below the Antrim Shale indicates a maturation level equivalent to a Color Alteration Index range of between 2 and 3 (vitrinite reflectance 0.6 - 1.5 percent R^o) for the entire basin (McIver and Zielinski, 1980). Maturity levels in this range, in conjunction with the high organic carbon contents and moderately thick radioactive organic-rich shales, indicate a high producing potential for fractured Antrim Shale. The few fish scales and conodonts described by Leventhal (1980) in conjunction with pyrochromatographic analyses showing both oil and gas residues in samples suggest marine environmental conditions and marine organisms favorable for the formation of Type I and II kerogens.

Pyrochromatographic analyses (Snyder and Maness, 1980) of the residual hydrocarbon contents were run on 114 core samples and 549 drill cutting samples from 35 wells in the Michigan basin. The objective of the analysis was to determine the types of hydrocarbons which could be generated from the Antrim and the relative permeability of the shales. Hydrocarbons detected in the analyses were grouped by carbon numbers from C_5 to C_{30} and the percent hydrocarbon component versus total hydrocarbon count was calculated. Data plotted as cumulative percent of each hydrocarbon component were used to determine the type of hydrocarbon, oil or gas, most likely to be produced from the shales. Idealized cumulative plots showing the relationship between hydrocarbon compo-

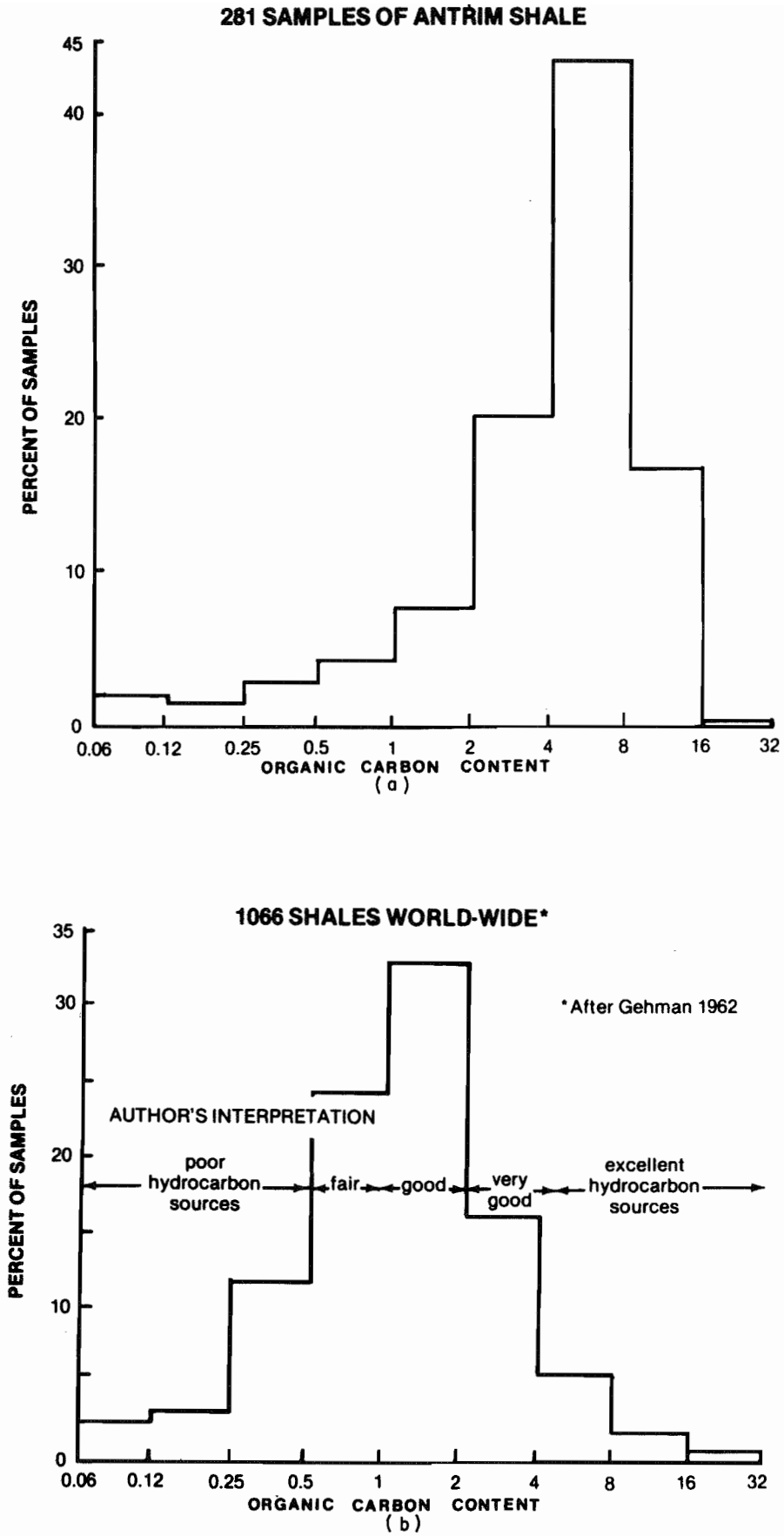


Figure 147. Organic carbon content of Michigan basin Antrim Shales compared with other shales. Mound Facility (1980).

nents, total hydrocarbon and productive type of hydrocarbons for the Antrim Shalein the Michigan basin are shown in figure 148. The analyses indicate that not only could the Antrim Shale be gas-productive in the Michigan basin, but that it also has excellent source rock potential. The pyrochromatographic analyses were also used as a tool to infer the permeability of the formation--low permeability is reflected by a high concentration of light components along with a wide range of other components; conversely, a low concentration of lighter components along with high concentrations of heavier components indicates the escape of lighter components because of higher permeabilities. The study also showed good correlation between high concentrations of measurable hydrocarbons and highly radioactive organic-rich black shales.

Two additional parameters used in the evaluation of the production potential of the Antrim Shale were the thickness of the organic-rich shales and producibility indicators (production and shows). The thickness of the radioactive organic-rich Antrim Shales ranges from a minimum of 70 feet in extreme southwestern Michigan to greater than 400 feet northwest of Saginaw Bay (fig. 149). McIver and Zielinski (1980) defined a new parameter "Target Quality Index" to identify geographic areas within the basin with the best combinations of shale thickness and gas-prone organic matter. The "Target Quality Index" value, read from the gamma-ray log, is the standard API unit reading greater than 20 API units above the shale baseline summed over the thickness of the shale interval. The map of "Target Quality Index" values (fig. 150) is similar in appearance to the isopach map of radioactive shale, except the "Target Quality Index" map shows a slight southeastward shift in maximum values in the Saginaw Bay area.

On the basis of geochemical and shale thickness data plus additional data from historical production and shows, the geographic area outlined on figure 151 appears to offer the greatest potential within the Michigan basin for the exploration and production of natural gas from the Antrim Shale.

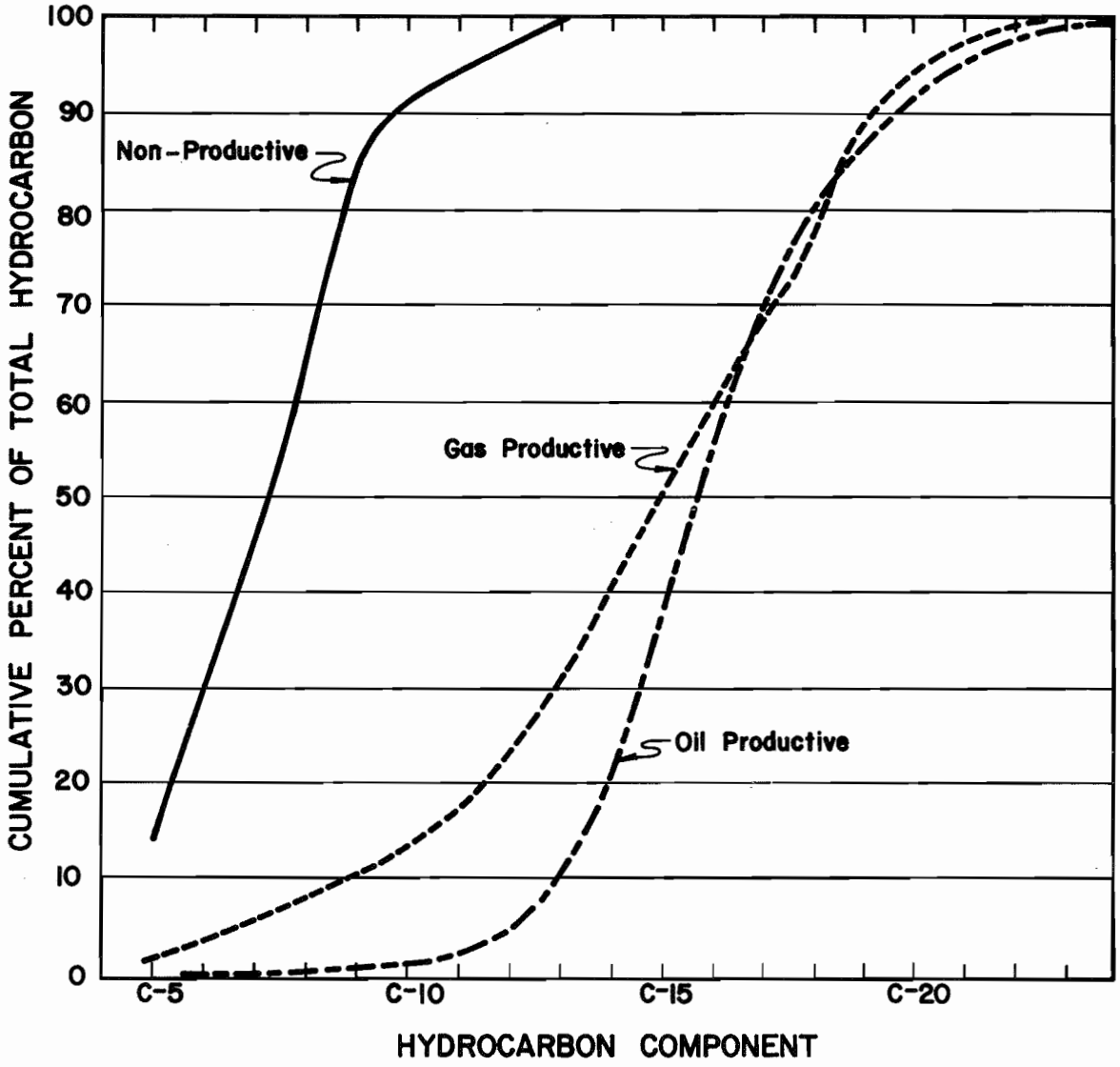


Figure 148. Idealized cumulative frequency of hydrocarbon components - Antrim Shale - Michigan basin. After Snyder and Maness (1980).

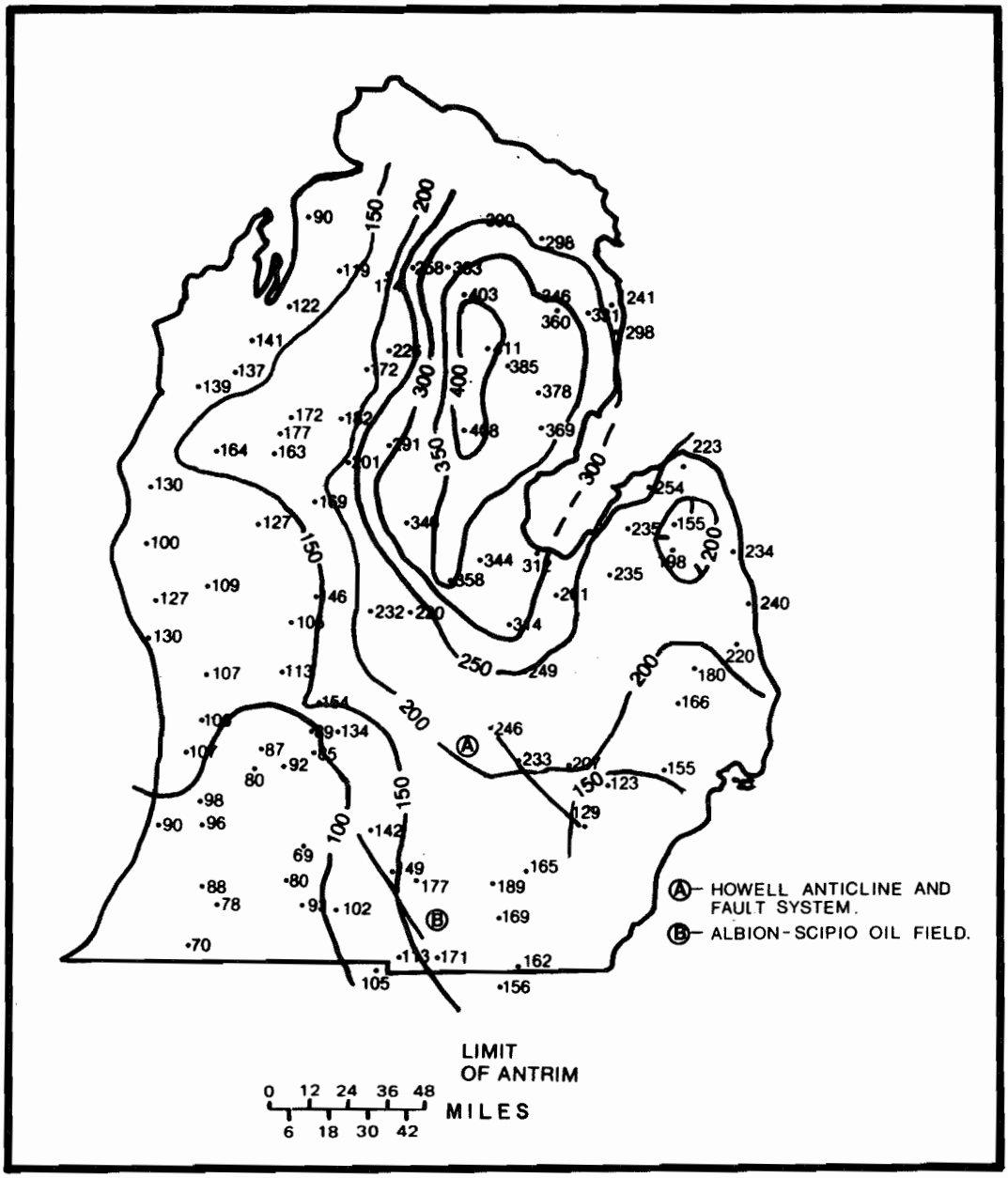


Figure 149. Isopach map of net radioactive shale in the Bedford/Antrim or Ellsworth/Antrim Shales. Contours in feet. Mound Facility (1980).

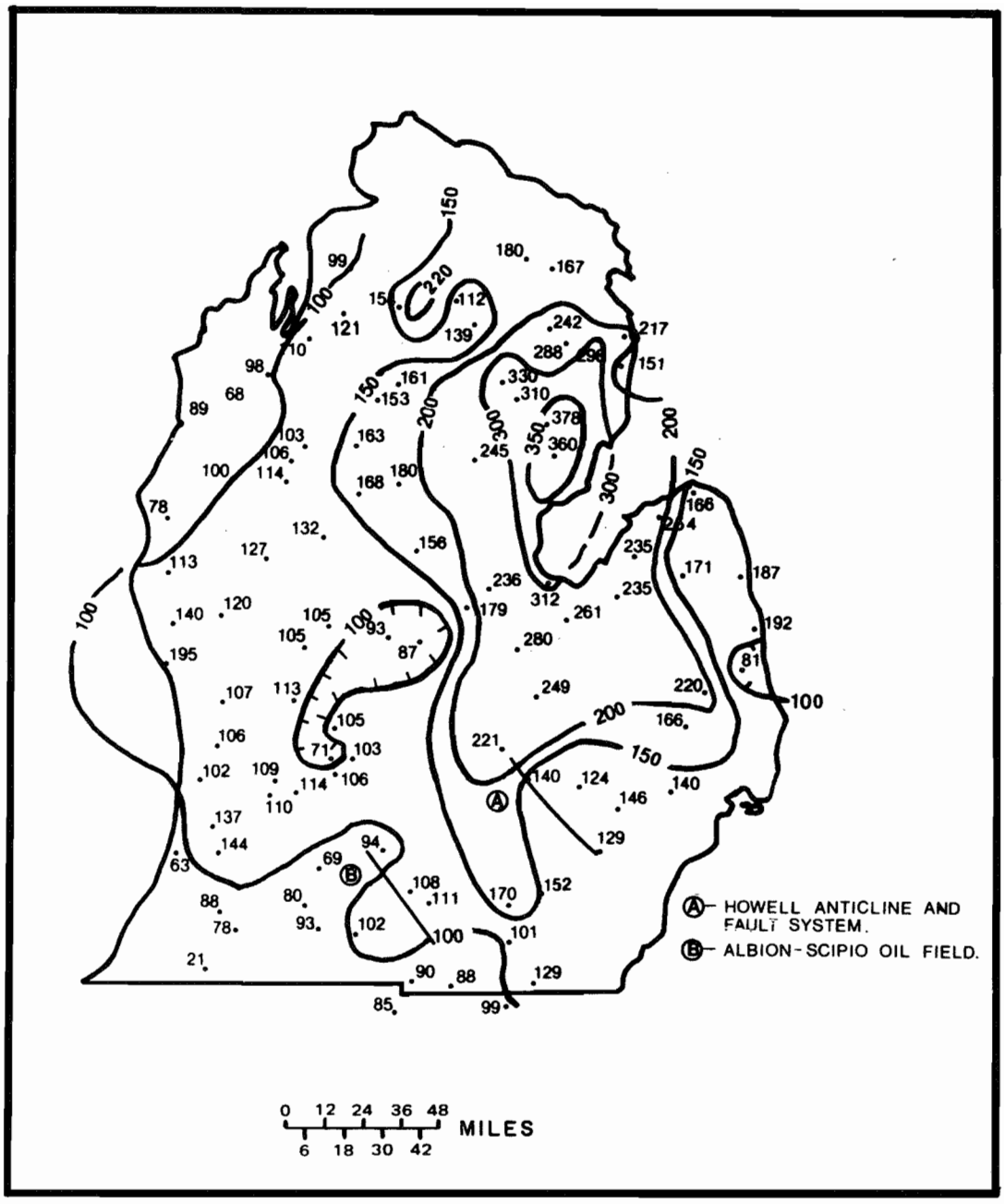


Figure 150. Index map showing radioactive shale target quality. Contours in 100 API unit feet. Mound Facility (1980).

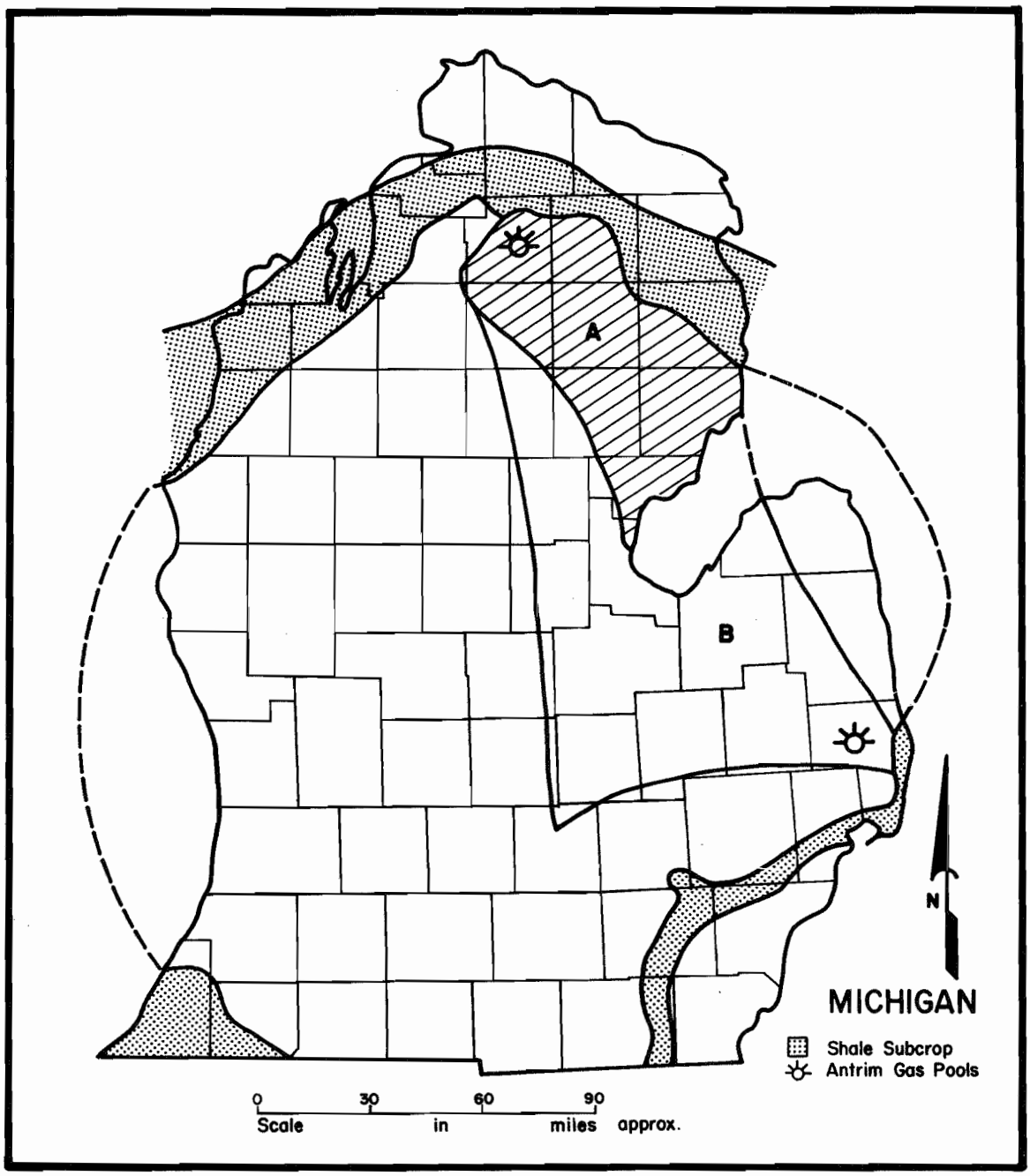


Figure 151. Areas of Michigan with greatest potential for gas production from Antrim Shale. A = good potential, B = moderate potential. After Mound Facility (1980).

BASIN ANALYSIS

Introduction

The following basin analyses of the Appalachian, Michigan and Illinois basins is a summary of information gathered by various Eastern Gas Shales Project investigators and from open file reports. In particular, this section draws heavily upon work by Schwietering (1977), Potter et al. (1980), Ettensohn and Barron (1981), and Zielinski and McIver (1982). The cross sections included in this report (plates 2-11) and those constructed by other workers support the deltaic sedimentation model presented in this report.

The Appalachian structural basin owes its present form to the Allegheny orogeny which culminated near the close of the Paleozoic Period. The basin, elongate and narrow in shape, trends southwestward from south-central New York through western Pennsylvania, eastern Ohio, West Virginia, western Virginia, east-central Kentucky and Tennessee and terminates just south of the common corner of northwestern Georgia and northeastern Alabama. The Alleghany Structural Front marks the eastern limit of the Appalachian basin. The western boundary is not as well defined and is considered to follow the trend of the Findlay arch in northwestern Ohio and the Cincinnati arch through western Ohio and northern Kentucky. Through southern Kentucky and Tennessee the western boundary follows the trend of the Nashville dome and its northern projection. From New York southward to northern Alabama, Middle and Upper Devonian rocks underlie an area of approximately 100,000 square miles in the Appalachian basin.

The Appalachian basin is a very complex geologic province. The Middle and Upper Devonian shale stratigraphy in the northern and eastern part of the Appalachian basin falls within the complex stratigraphic and depositional framework of the westward prograding Catskill delta. The Middle and Upper Devonian shale interval is characterized by rapidly changing facies from coarse clastics in the northeast and central part of the basin to fine clastics along the southern and western margins. These clastics reflect the depositional character of the many facies within the framework of the prograding delta. Further complicating the geologic picture are the tight folds and faults along the eastern margin of the basin.

In New York state, the outcrop belt of Devonian rocks has been designated the standard reference section for the eastern North American Devonian System because it is the most complete sequence of Devonian rocks in the eastern United States. However, the Devonian Shales, which constitute an unconventional gas reservoir, occupy only the interval between the Middle Devonian Onondaga Limestone and the top of the Upper Devonian Perrysburg formation in New York. The post-Perrysburg Devonian facies in New York is characterized by sandstone and siltstones of the near shore, slope and diverse subtidal depositional facies. This stratigraphic interval in the western and southern part of the Appalachian basin is composed of black, brittle, highly organic shale of the distal basin facies. Because of the complex stratigraphic relationships resulting from the westward progradation of the Catskill delta during Upper Devonian time, Eastern Gas Shales Project stratigraphers used the New York stratigraphic nomenclature for the interval between the top of the Onondaga Limestone and the tops of the Perrysburg

formation. In this report, the stratigraphic nomenclature as used in Ohio was adopted for the post-Perrysburg Upper Devonian stratigraphy.

Geographically, the Michigan basin includes the area of the Southern Peninsula, the eastern part of the Northern Peninsula, eastern Wisconsin, northeastern Illinois, northern Indiana, northwestern Ohio and western Ontario. The area of the basin, including those areas covered by Lake Michigan, Lake Huron and Lake St. Clair, is approximately 122,000 square miles. A framework of surrounding basement and structural features define the basin. The western limit of the basin in central and northern Wisconsin is defined by the position of the Wisconsin arch. The Canadian Shield serves as the boundary in northern and northeastern Michigan. The Algonquin arch in Ontario and the Findlay arch in northwestern Ohio mark the eastward and southeastward limits of the basin. In northern Indiana and northeastern Illinois the southern and southwestern boundaries of the Michigan basin is defined by the Kankakee arch. The Middle Devonian sequence in the Michigan basin is composed primarily of carbonate rocks of the Traverse Group which reflect a shallow marine, subtidal depositional environment. The Upper Devonian sequence is dominated by dark-gray to brown to black organic shales of the Antrim/Ellsworth sequence. The character of the Antrim/Ellsworth sequence suggests a distal basin environment of deposition.

The Illinois basin, located in the east-central United States, is elliptical in shape with the major axis trending northwest-southeast. Geographically, the basin is centered in southeastern Illinois and covers most of west-central and southern Illinois, the southwest part of Indiana and western Kentucky. The basin is a structural depression surrounded on all sides by a framework of positive structural elements. To the southeast and east the basin is separated from the Appalachian basin by the Nashville dome and the Cincinnati arch. To the north, separating the basin from the Michigan basin, are the Kankakee and Wisconsin arches. The western and southwestern limits of the basin are defined by the Mississippi arch, the Ozark dome, and the Pascola arch. The area within the structural framework is approximately 50,000 square miles.

The Middle Devonian sequence in the Illinois basin is composed of carbonate rocks of a shallow marine, subtidal, depositional environment. The Upper Devonian rocks are dominated by the New Albany black shales, characteristic of deposition in a distal basin environment.

Stratigraphic Cross Sections

LOCATION AND CONSTRUCTION

Ten regional stratigraphic cross sections were constructed parallel to and perpendicular to strike using available gamma-ray logs and pre-existing cross sections constructed by various state geological surveys and by the United States Geological Survey. Six cross sections are located in the Appalachian basin and two each in the Michigan and Illinois basins (fig. 85, page 160). The cross section were constructed using sea level for the data so that they would reflect the present configuration and subsurface conditions of the respective basins. In the Appalachian basin, cross sections A, B, and C (plates 2, 3, and 4) were constructed perpendicular to strike to show both the structural dip and the

westward progradation of the various deltaic facies. Cross section D was constructed approximately parallel to the advancing delta front in the northern and central Appalachians (plate 5). Cross sections E and F (plates 6 and 7) show the stratigraphic and structural relationship in the southern portion of the Appalachian basin.

The cross sections in the Michigan and Illinois basins (plates 8 through 11) form a pair of criss-crossing patterns which exhibit the circular nature of these infracratonic basins. These sections were modified from existing state geologic survey cross sections and were constructed using sea level as the datum.

The cross section in all three basins were constructed to show the sequence between the approximate Mississippian-Devonian boundary and the top of the Middle Devonian Onesquathaw Stage carbonates. These sections were all constructed as close as possible to a straight line to eliminate false or apparent changes in structural or stratigraphic attitude. Therefore, any reversals in dip or anamolous thickening of individual strata may be considered indicative of potential structural influence. The stratigraphic terminology used for the Appalachian basin correlations is a composite of the New York and Ohio nomenclature, as recommended by the Eastern Gas Shales Project. The stratigraphic nomenclature used in the construction of the Michigan and Illinois basin cross sections is a composite of currently accepted terminology used by the Michigan and Illinois state geological surveys. In areas on the cross sections where the Upper Devonian coarse clastic sandstones and turbidites are identified, local State names have been applied, which may lead to some confusion when state boundaries are crossed.

The gamma ray logs were included in the cross section to give the reader a better understanding of why a particular correlation was made. The correlations made by the various surveys and the United States Geological Survey were generally accepted, but in logs in which some confusion arose (in cases where the same log was used, but different points were picked) the correlation which best fit the cross section interpretation was chosen. In logs added to complete or straighten the existing cross sections, correlations were made entirely on the basis of the gamma ray character and may be open to differing interpretations.

INTERPRETATION

The cross sections for each of the three basins indicate that structural control during Devonian-aged sedimentation exerted a subtle, but important, influence on the stratigraphic distribution of the various facies. The spasmodic episodes of plate interaction which, in turn, produced the rising highlands along the eastern margin of the actively subsiding basin had probably the greatest structural and stratigraphic influence on the Appalachian basin. These uplifted areas served as the sediment source areas for the westward-prograding Catskill delta system. In addition, structures of limited areal extent served to deflect or accumulate sediments, producing areas of local thins and thicks. These structures tend to have a low, broad relief which, given the spacing of control wells used in the cross sections, makes detection of these features difficult. However, areas which exhibit a thicker or thinner than anticipated stratigraphic section indicate the possibility of some structural control.

Post-deposition tectonic deformation, such as movement along the Rome trough, may be inferred from the cross sections (plates 3 through 6) which exhibit a sharp increase

in the rate of dip in local areas. However, as previously mentioned, given the cross section well spacing, the location of these structures may only be approximated.

A second observation pertains to the influence of the Cincinnati arch on the western portion of the basin. Evidence that the arch complex acted as a positive element during deposition of the Devonian shales has been documented by numerous investigators (Janssens, 1967; Schwietering, 1970 and 1977; Potter et al., 1980), but the present structural setting has most likely been the result of continued post-Devonian subsidence. The relationship of the arch to sediment deposition may be seen by the westward-transgression of the updip limits of the individual Upper Devonian formations as they lap onto the arch (fig. 87, page 164, and plates 2, 3, and 4). The westward progradation of the delta system can be discerned from the progressive westward migration of the distal basin black shale facies. An example of this westward progradation can be seen on cross section A-A' (plate 2) which shows the westward shift of black shale depocenters from Rhinestreet time to Dunkirk/Lower Huron time. This westward migration of the distal basin facies can be observed on isopach maps and cross sections in western New York (Van Tyne and Peterson, 1978; Rickard, 1975).

West of the Devonian outcrop, erosion has removed the shale along the crest of the arch, except for scattered remnants such as the Bellefontaine outlier. Thus, determination of when the delta facies topped the Cincinnati arch remains a matter of conjecture.

Cross sections in the Michigan and Illinois basins (plates 8, 9 and 10, 11, respectively) exhibit a greater structural simplicity than those of the Appalachian basin. The most obvious structures are the stable arch complexes that surround both basins. These basins are also stratigraphically less complex, consisting primarily of fine-grained clastic and carbonate sequences. In both the Michigan and Illinois basins fine-grained clastic sedimentation did not begin until the Senecan Series of the Upper Devonian. During the Middle Devonian, carbonate sequences were deposited exclusively in the Michigan basin and were dominant in the Illinois basin while fine-grained distal basin clastics were being deposited in the western portion of the Appalachian basin simultaneous with the deposition of delta front sandstones and turbidite bundles in the eastern portion of the basin.

The stratigraphic character and framework of the northeast-southeast and northwest-southeast cross sections in both basins indicate deposition in relatively shallow basins which subsided evenly. Both basins are slightly elliptical with the deepest portions located in the approximate center of the basin.

Facies Distribution

The facies distribution in the Appalachian basin has a systemic arrangement, progressing in a westward direction from non-marine clastics through shelf, delta front, delta slope, and distal basin environments (Potter et al., 1980). Deposition resulting from episodes of deltaic progradation into the cratonic Appalachian seaway is generally the accepted model; however, a number of other models have been invoked to account for the origin of the black shale facies. Most of these interpretations have concentrated upon the depositional regime of the distal basin black shales as being either shallow-water or deep-water deposits. The water depth may have varied from 500 to 2500 feet in the basin

center, but was negligible near the delta and possibly only a few hundred feet in depth along the interior craton (Potter et al., 1980). Ettensohn and Barron (1981) speculate that whatever model is finally accepted, it will be somewhere between these extremes to satisfy all of the seemingly contradictory evidence. Their approach was to analyze all of the stratigraphic, structural, and geochemical data as interrelated elements rather than concentrating on a specific depositional environment for the black shales. The plate tectonic model that Ettensohn and Barron settled on is shown on figure 152.

The distribution of the distal basin and various interrelated deltaic facies in the Appalachian basin are shown on figure 153. As previously discussed, the Michigan and Illinois basin exhibit a much more uniform distribution, suggesting that these basins were further from the source(s) and not subject to the rapid sedimentation associated with deltaic advance.

DISTAL BASIN FACIES

The distribution of the black, organic-rich shales associated with the distal basin facies (Marcellus type of Rickard) is widespread. In the Appalachian basin the Middle Devonian black shales, primarily the Marcellus, attain their maximum thickness in the eastern portion of the basin, but are present throughout most of the basin. During the Upper Devonian the depocenters of the black shales exhibit a westward migration from Rhinestreet time through Dunkirk/Lower Huron, and Cleveland time (figures 154, 155 and 156).

The distal basin facies is characteristically comprised of black and dark greenish-gray, fissile shales. The black color reflects the high organic content of this facies and is considered to be the result of anoxic bottom conditions. The anoxic environment restricted the development of bottom-dwelling organisms, thus allowing the organic material to accumulate (Potter et al., 1980). Thus, the black shales are relatively unfossiliferous, and those pelagic forms present exhibit a low diversity. Potter et al. (1980) note that the basal contact between the black shale facies and underlying rock is almost always sharp and that they grade both laterally and vertically into gray, organic-lean shales.

The organic material contained in the distal basin facies includes both marine pelagic matter and terrestrially derived organic matter. The source and the character of the organics were discussed in the geochemistry section of the report and will not be repeated here. For more information, the reader is referred to the report by Zielinski and McIver (1982).

Deposition in the distal basin is considered to represent low rates of sedimentation away from the clastic influx of the prograding delta wedge. The sedimentation rate and the development of anoxic conditions favored the accumulation of the black, organic-rich shales. The black shales in the Appalachian basin are thought to have been deposited primarily during periods when the relatively shallow intracratonic sea transgressed onto the stable interior craton (Ettensohn and Barren, 1981). As discussed in the plate tectonics section, these transgressive events correspond to rises in sea level which, in

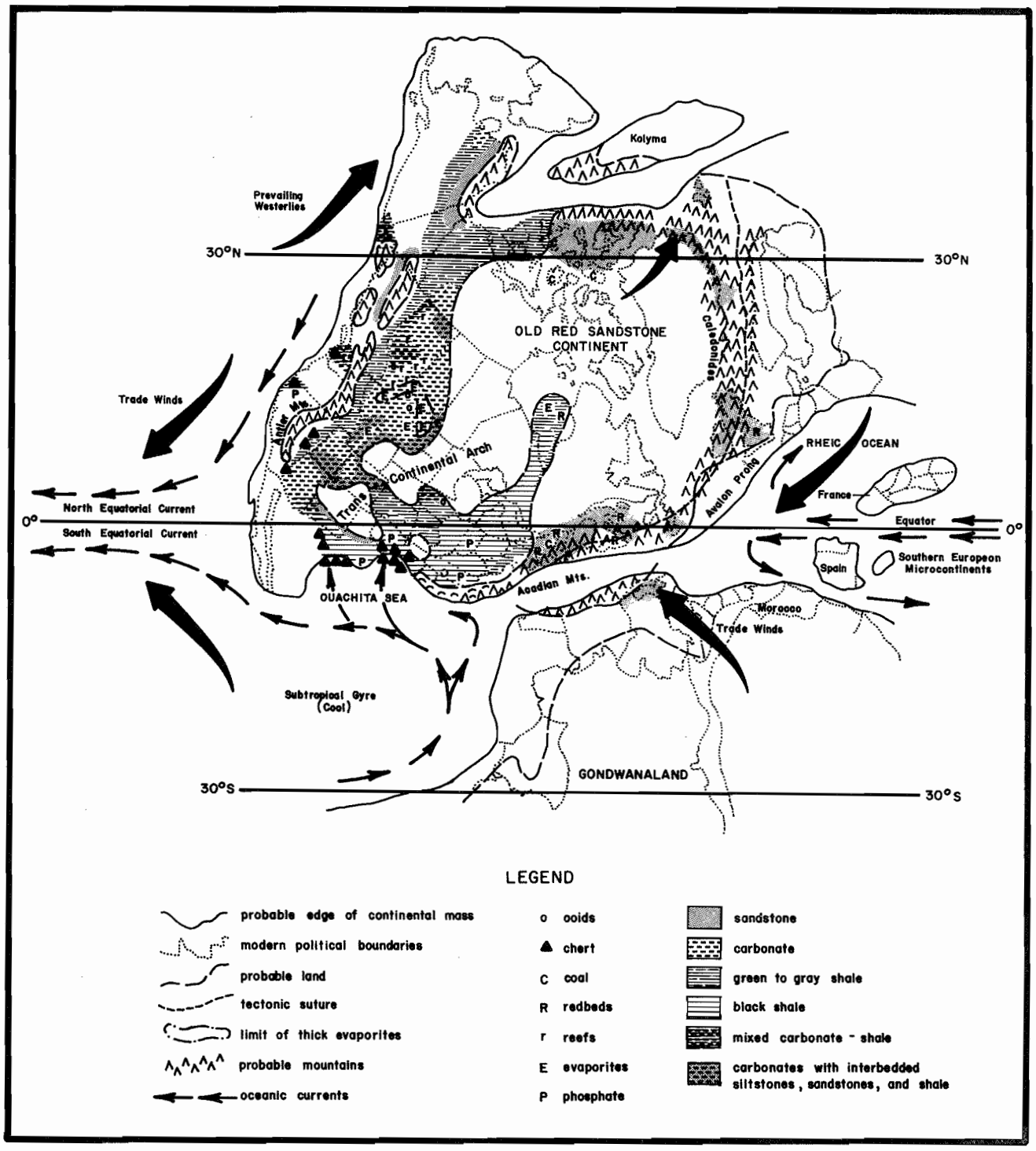


Figure 152. Generalized paleogeography and lithofacies during the Upper Devonian for the North American plate. From Ettensohn and Barron (1981). Paleogeography summarized from McKerrow and Ziegler (1972), Seyfert and Seren (1973), Badham and Halls (1975), and Heckel and Witzke (1980); lithofacies from Heckel and Witzke (1980).

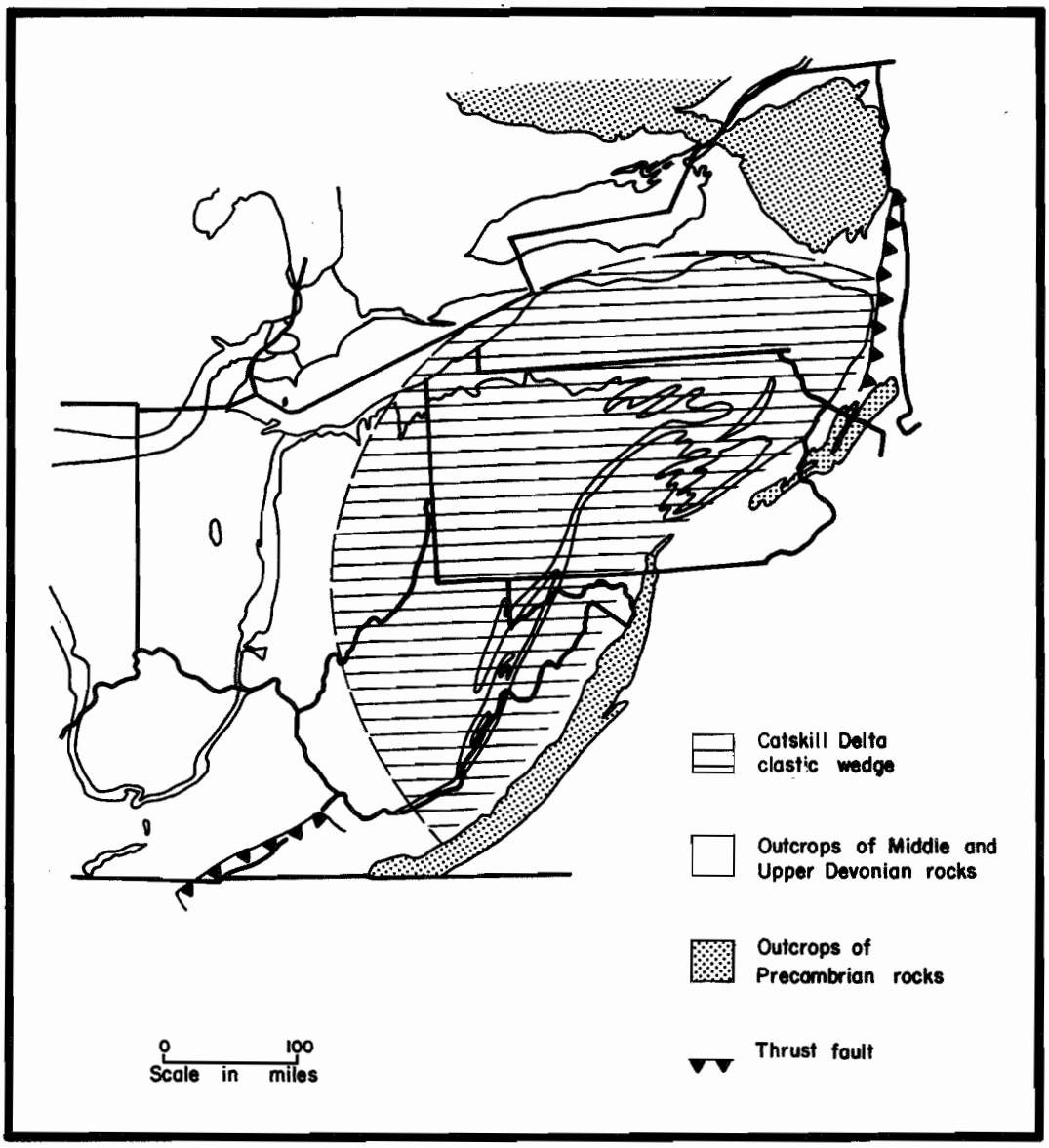


Figure 153. Map showing the distribution of Middle and Upper Devonian Catskill delta clastic sediments in the Appalachian basin. From Schwietering (1977). Location of the Catskill delta clastic wedge from King (1959); stratigraphic data from Dennison (1961, 1963, 1970, and 1971), Dennison and Naegele (1963), and Woodward (1943).

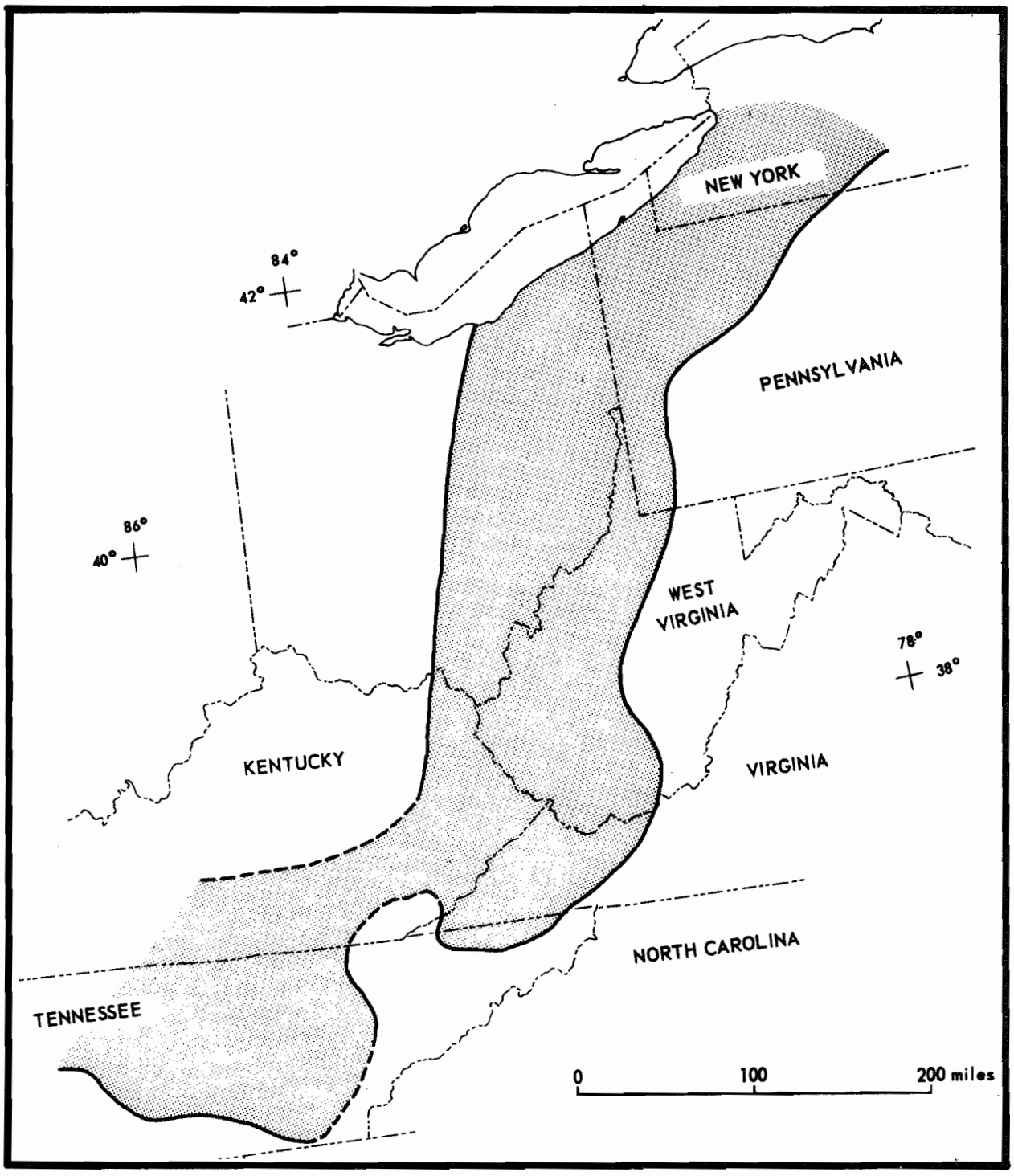


Figure 154. Map showing areal extent of the Rhinestreet Shale and its equivalents. After Roen (1980).

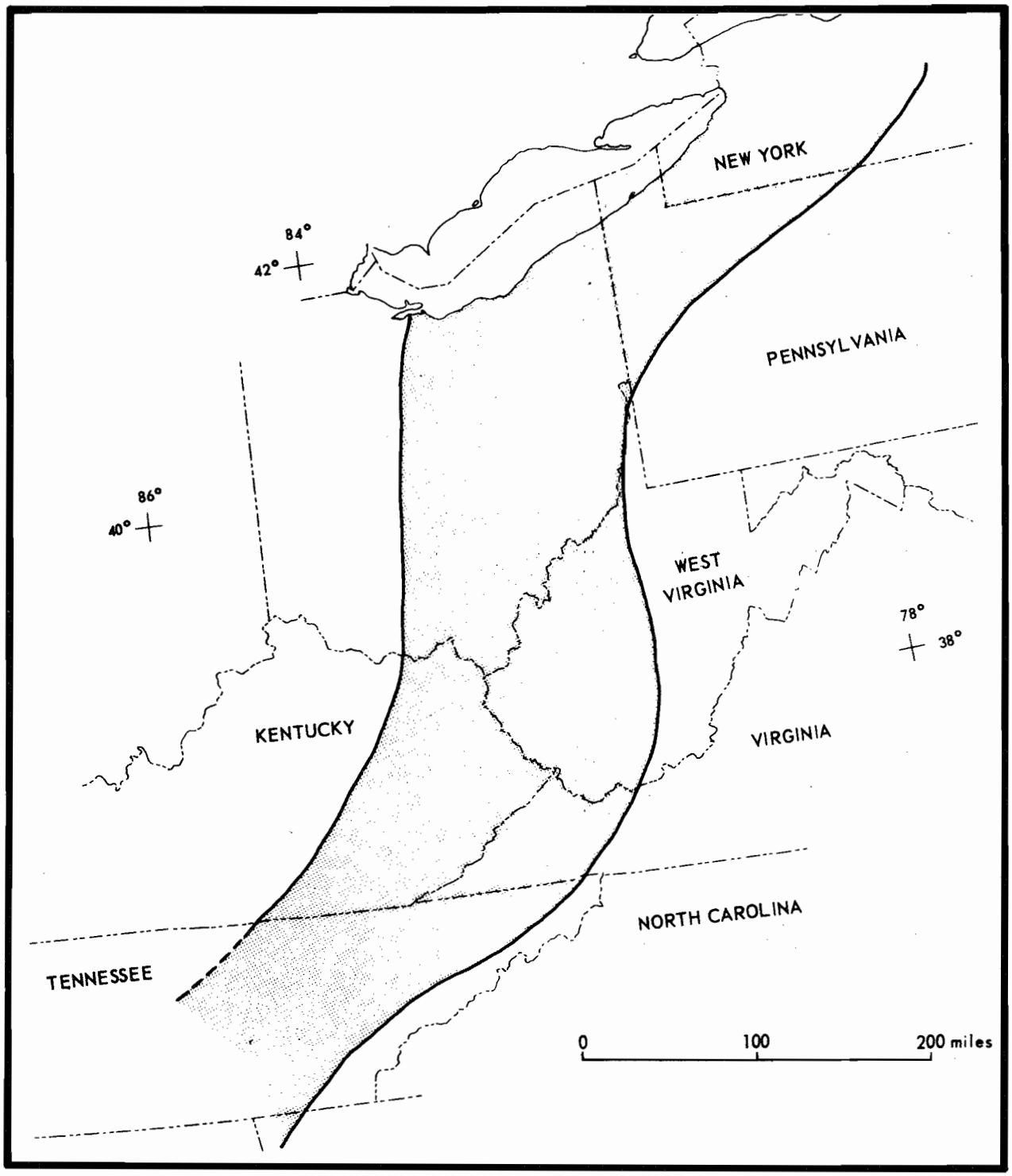


Figure 155. Map showing areal extent of the Dunkirk Shale and its equivalents. After Roen (1980).

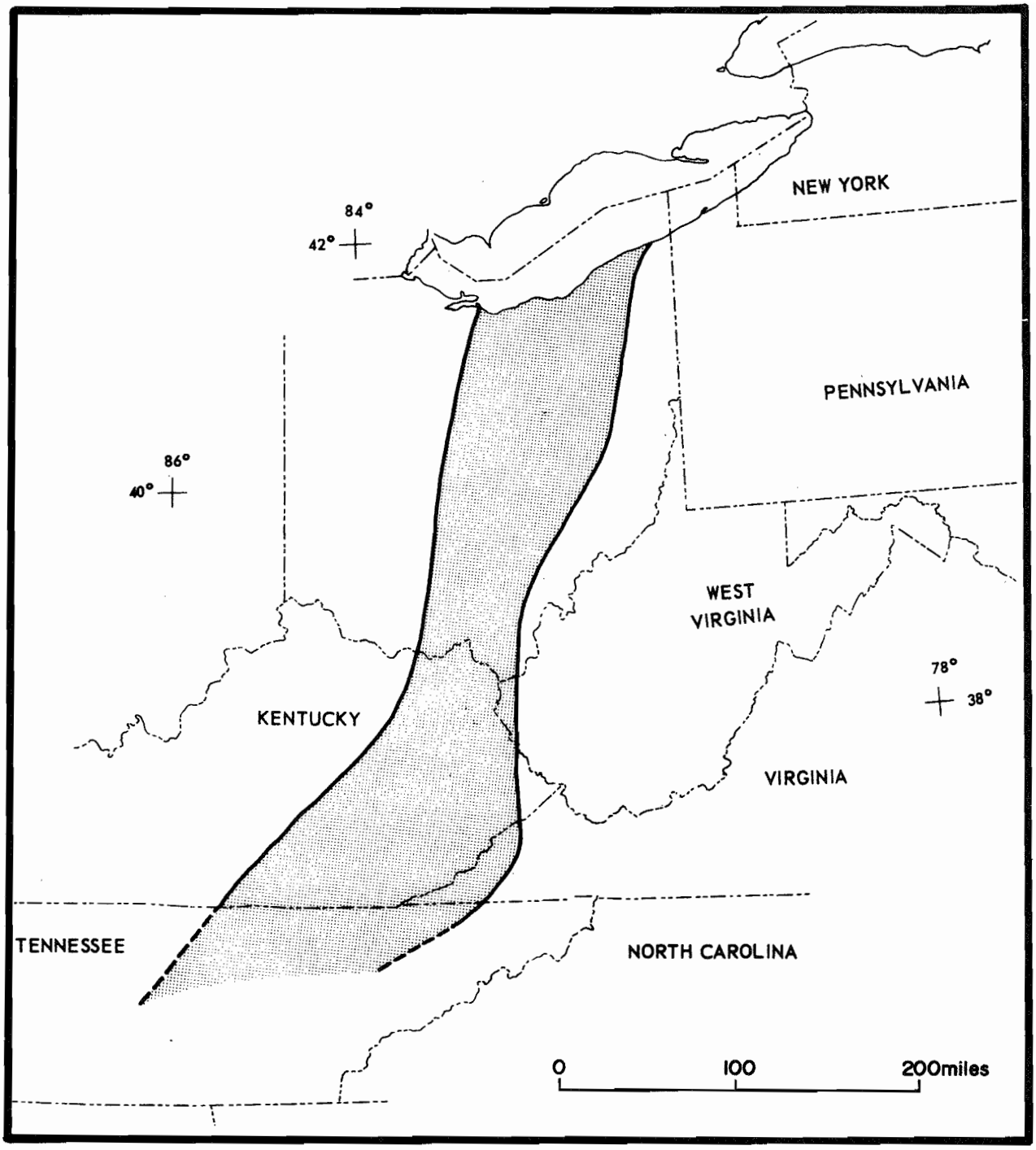


Figure 156 . Map showing areal extent of the Cleveland Shale and its equivalents. After Roen (1980).

turn, are related to periods of plate spreading and subduction that produced orogenic activity along the continental margin. Figure 157 is a diagrammatic illustration showing stages of lateral progression of deltaic facies during a transgression by an epicontinental sea (Schwietering, 1977). The illustration shows the westward progression and overlap of the craton by the black shale facies and simultaneous overlapping of the deeper marine black shale and pro-delta facies by the less marine deltaic facies which resulted from a sea-level rise associated with uplift. A drop in sea level would produce the reverse effect with an eastward progradation and the overlapping of nearshore marine and continental facies by deeper distal basin facies.

The paleogeographic and paleoclimatic controls governing the black shale deposition have been discussed in detail by Ettensohn and Barron (1981) and the interested reader is referred to their paper for an in-depth discussion of these subjects.

The Upper Devonian Shales in the Michigan basin comprise approximately one-third of the Devonian sequence. The predominant lithofacies are normal marine gray shales and siltstones (Ellsworth Formation) and brown or black organic-rich shales with minor amounts of limestone and dolomites (Antrim). The distribution of these lithofacies is shown on figure 158. The protoquartzite lithofacies shown on the figure corresponds to the distribution of the Berea Sandstone which was tentatively placed in the Upper Devonian on the basis of spores identified from drill cuttings (Sanford, 1967). The Antrim lithofacies, with a maximum thickness of approximately 650 feet near Saginaw Bay, thins in a westward direction across the state where it intertongues in the upper part with the normal marine gray shales of the Ellsworth lithofacies. The thicker black shales of the Antrim reflect deposition and subsequent burial of organic materials near the depocenter of a deep anoxic basin. The organic-poor shales of the Ellsworth sequence are characteristics of normal marine sediments deposited upon a stable shelf in moderate depths of water.

A description of the character of the Middle and Upper Devonian sequence in the Michigan basin and the effect of structure on the distribution of the predominant lithofacies has been described previously in the stratigraphic, geochemistry and tectonic sections of the report.

Petrographic and stratigraphic studies of the New Albany Shale Group by the Illinois State Geological Survey (Bergstrom et al., 1980) have identified and characterized five lithofacies: (1) limestones and dolomites; (2) highly bioturbated mudstones; (3) indistinctly bedded shale; (4) thickly laminated shales; and (5) finely laminated shales. The distribution of these lithofacies reflects the environment of deposition for the shale, the wave energy, the bottom oxygenation and the bottom topography of the basin. The following discussion is summarized from Bergstrom et al. (1980) and the reader is referred to the original report for a more detailed treatment of the subject.

Anaerobic conditions prevailed during most of New Albany time in the deepest areas of the basin, and the thickly to finely laminated, black organic-rich shales were deposited. Figure 159 shows the paleogeography of the New Albany sea in the Illinois portion of the Illinois basin. The black shale lithofacies attains maximum development and thickness near the center of the Illinois basin but thins by interfingering relationship with the bioturbated mudstones and indistinctly bedded shale lithofacies of the basin slope and shelf margin depositional areas.

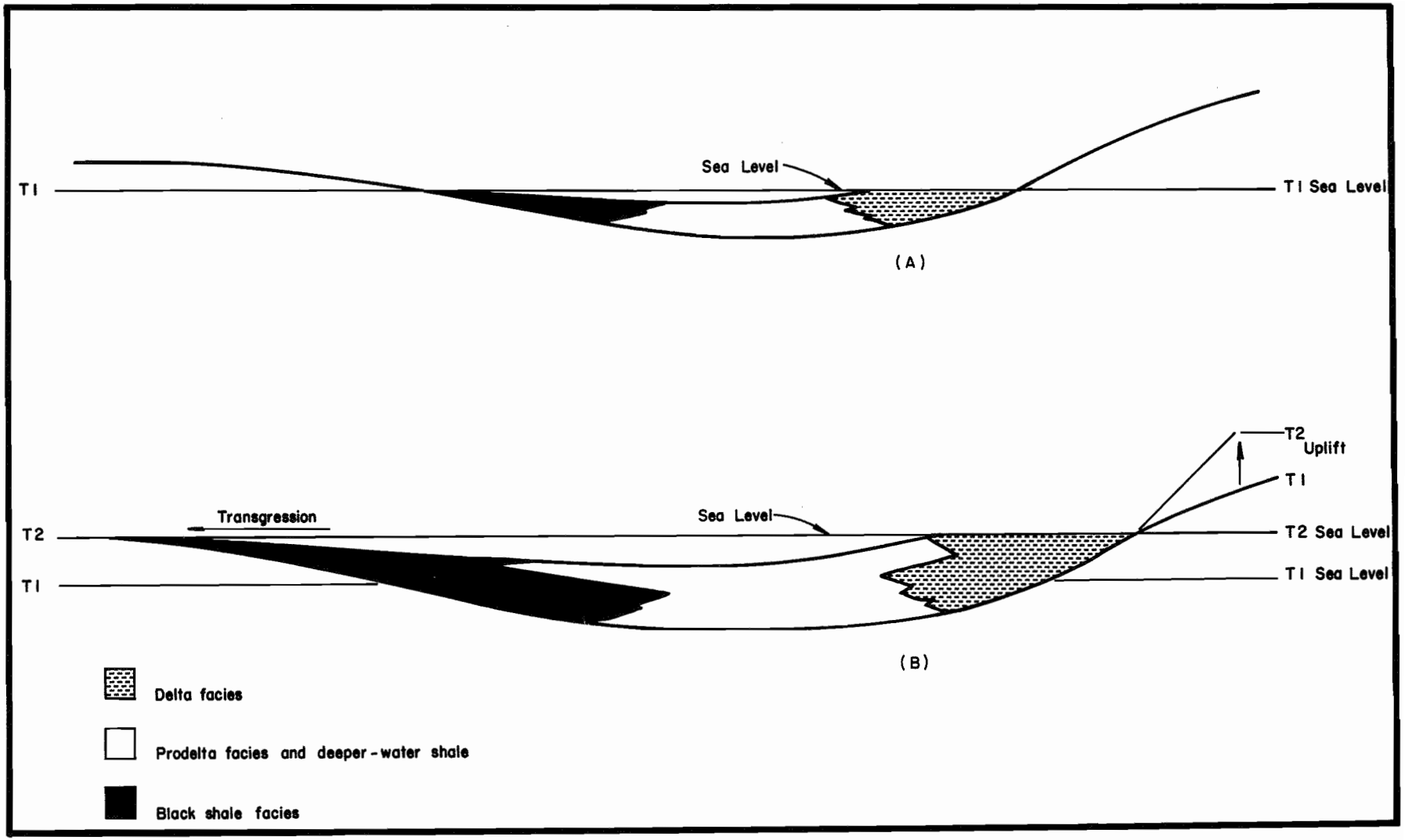


Figure 157. Schematic diagram showing the lateral movement of the delta facies during a transgression of an epicontinental sea. From Schwietering (1977).

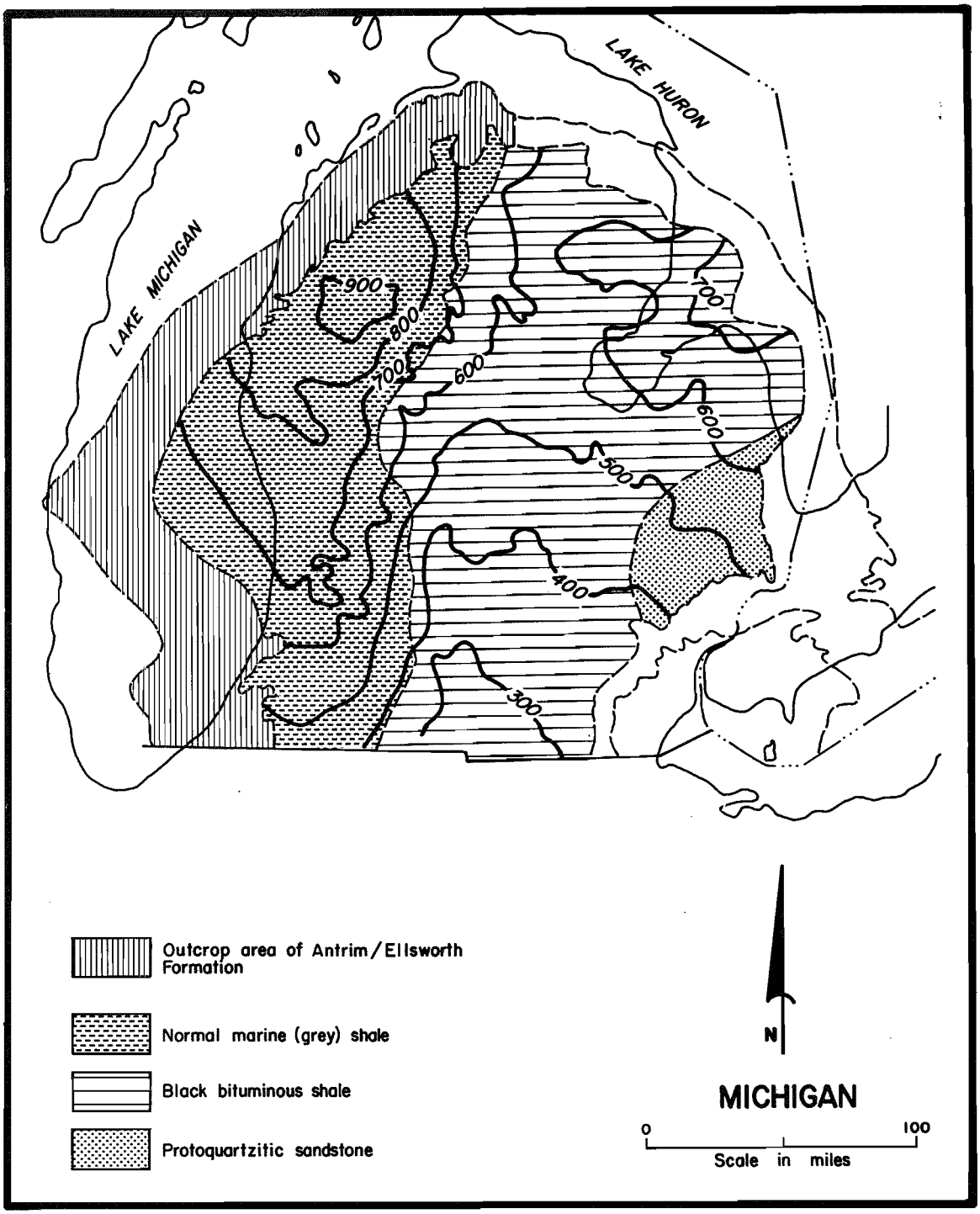


Figure 158. Facies and isopachous map of Upper Devonian rocks - Ontario and Michigan. Contours in feet. After Sanford (1967).

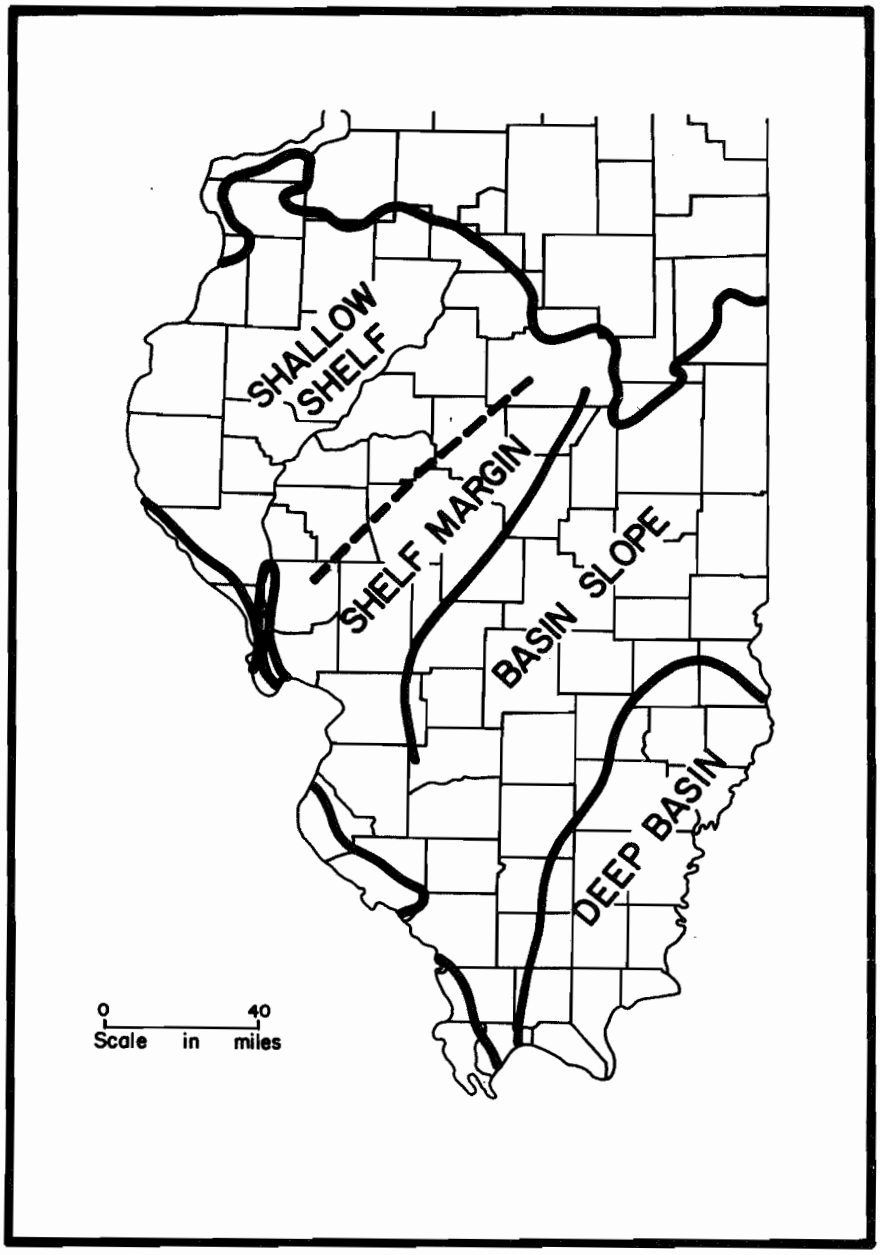


Figure 159. Paleography of the New Albany Sea in Illinois. After Bergstrom et al. (1980).

The intertonguing and gradational relationships of the lithofacies in the New Albany shale indicates that depositional conditions were not static throughout the Upper Devonian but fluctuated on both a regional and local scale. The regional intertonguing of the gray and black shales in the Illinois basin is interpreted as the result of major fluctuations in the position of the anaerobic/dysaerobic boundary caused by fluctuations in sea level. During most of the Upper Devonian the fluctuations in oxygenation conditions were restricted to the deep-basin area of deposition while most of the prominent facies changes occur in the basin slope and shelf margin areas.

The effects of structure on the deposition of the New Albany Shale and the distribution of the prominent lithofacies has been discussed in detail in the tectonic, geochemistry and stratigraphic sections of the report.

SLOPE AND PRO-DELTA FACIES

The slope and pro-delta facies associated with the westward prograding delta complex attain their maximum thickness in the eastern and east-central portions of the Appalachian basin. Lithologically these facies consist primarily of interbedded black and dark-medium greenish-gray shales, gray shales, siltstones, and a few fine-grained sandstones. This stratigraphic sequence includes the Portage and part of the Chemung type facies of Rickard (1975), but are generally referred to as the "Brallier" facies, after the West Virginia usage. These sediments, which show a low fossil density, are interpreted to have been deposited well below the wave base of the Appalachian seaway in slope and pro-delta depositional environments. The fossil assemblages present include a mixed benthic and pelagic fauna but exhibit little diversity (Rickard, 1975). Sedimentary structures commonly observed along the outcrop in these facies include cross-lamination, current ripples, convoluted bedding and bioturbation.

The most promising lithofacies in the "Brallier," as far as hydrocarbon exploration is concerned, are the siltstone and turbidite bundles contained in the fine-grained clastics of the slope and pro-delta environments. Paleocurrent analysis studies of the turbidites were conducted by Potter et al. (1980), indicating that these sequences were deposited at approximate right angles to the basin axis (fig. 160). This sedimentary sequence was deposited in the relative calm water between the distal basin and the delta front and was determined to be lithogenetically related to both the distal basin and overlying shelf-delta front facies (Lundegard and Samuels, 1978). It is the general consensus that paleocurrent direction and facies distribution indicate that the delta complex prograded westward in a uniform manner. Deposition of the Devonian-aged turbidite sequence did not occur in the submarine channels and fans characteristically associated with present-day turbidites. Rather, the turbidites exhibit a finer, more uniform grain size which suggests a series of relatively small, short-lived, low-density turbidity currents which formed from multiple points of origin. Lundegard and Samuels (1978) theorized that these multi-sourced, low-density turbidity currents formed in response to some combination of storm agitation of the unconsolidated outer shelf sediments and abnormally high river discharge which created plumes of suspended sediment. Repetition of this sequence of events produced numerous low-density submarine flows that eventually coalesced to form a laterally extensive turbidite wedge immediately in front of the prograding delta.

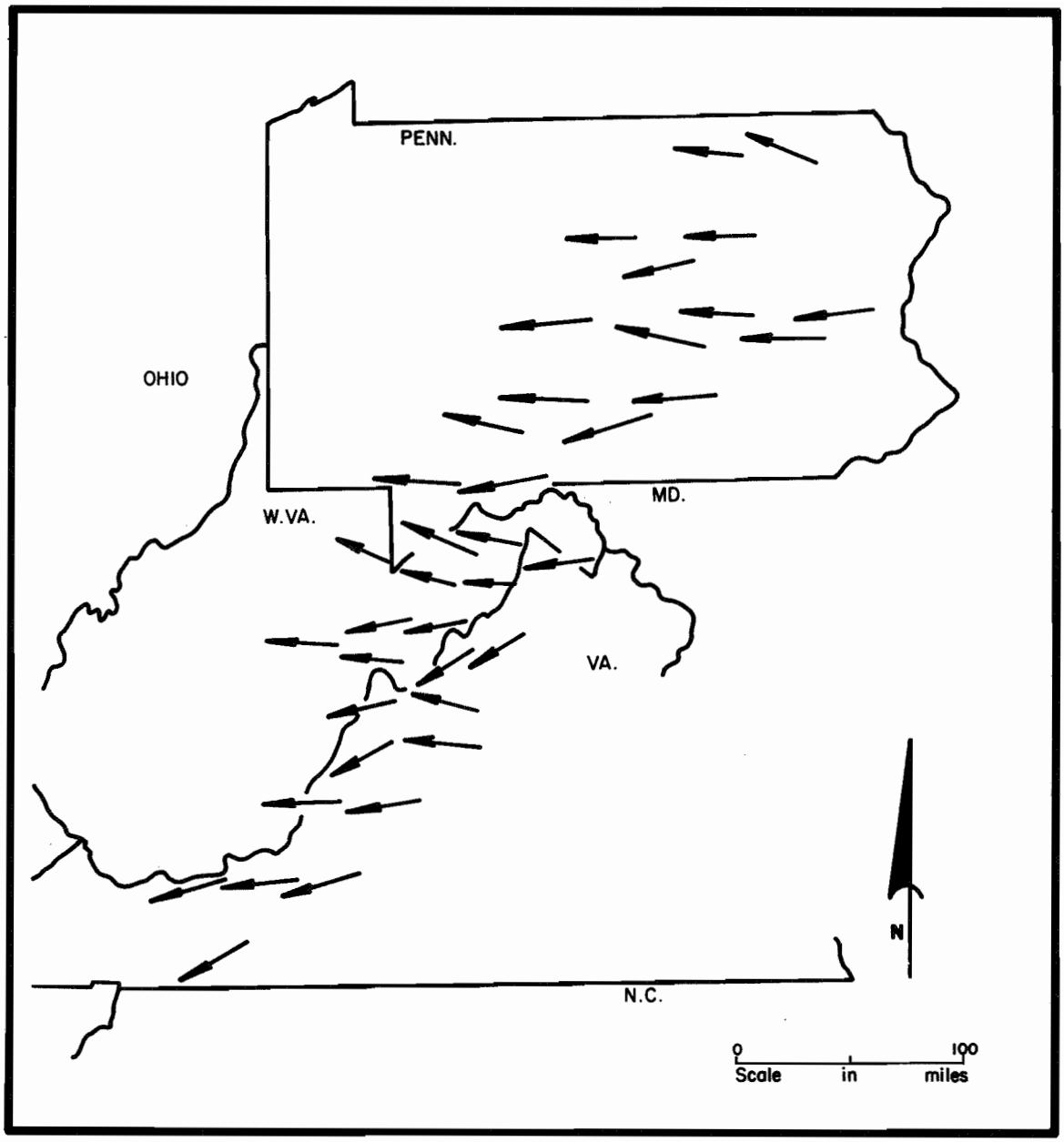


Figure 160 . Paleocurrent map of Upper Devonian turbidites in the Appalachian basin. Data in Virginia and West Virginia is from the Brallier Formation and lower "Chemung" Formation. Data in Pennsylvania is from McIver. Arrows represent vector means of 30-minute quadrangles. After Lundegard and Samuels (1978).

The "Brallier" type facies was deposited in a systemic relationship with the westward migrating distal basin facies and the prograding delta front complex. Thus, as the delta complex advanced and retreated through time, a steady westward progression may be observed in the successive vertical sequences. This facies is spread over much of the basin but attains its maximum thickness in the eastern half of the Appalachian basin. Because the Michigan and Illinois basins are considered to have been more distant from the sediment source(s) and formed in structurally less active settings, it is not surprising that these basins did not develop the rapid, dump-in turbidite sequences which interfinger with the distal basin sediments. Rocks reflecting deposition in the slope areas of the Illinois basin are characterized by olive-gray to black, weakly bioturbated shale which commonly are interbedded with thickly laminated black shales. The distribution of this lithofacies in Illinois is shown on the Upper Devonian paleogeographic map (fig. 159, page 275).

DELTA FRONT, SHELF, AND NEARSHORE FACIES

The subtidal shelf facies, including the delta front sandstones and delta platform sequence, and the nearshore facies, including the various subaerial environments characteristic of a delta distributary system, constitute the coarse clastic sequences normally associated with deltaic deposition (Chemung and Hamilton type facies of Rickard, 1975). These facies exhibit a high degree of lateral and vertical variability, interfingering horizontally with one another and changing vertically by gradation. The facies include gray and green shales, siltstones, fine- to medium-grained sandstones, and conglomerates. Common sedimentary structures observed in these facies in the outcrop include cross-bedding, wave and current ripples, flute and groove casts, and ball and pillow structures (Rickard, 1975). But, except for the following brief discussion, they are not treated in the framework of this report.

The coarse deltaic facies are concentrated in the eastern portion of the Appalachian basin, forming many of the traditional Upper Devonian sandstone reservoirs of north-central and northern Pennsylvania and southern New York. Cross sections A-A' and D-D', plates 2 and 5, respectively, show the lateral distribution and westward progradation of the various components of the subtidal shelf and nearshore facies. These facies are not recognized in the Upper Devonian sequences of either the Michigan or Illinois basins, indicating that these basins were not directly affected by deltaic advancement (plates 2 through 7). In the Illinois basin shelf and nearshore facies reflect high energy, very shallow conditions which are recorded by oolitic-skeletal grainstones and packstones with abundant calcified marine invertebrate fossils. Further offshore, less agitated areas are represented by highly bioturbated carbonate wackestone, argillaceous quartz siltstone and greenish-gray mudstone lithofacies. These lithofacies occur within the shallow shelf and shelf margin areas shown on the Upper Devonian paleogeograhic map of Illinois (fig. 159, page 275).

The peritidal, alluvial flood plain and piedmont sequences (Cattaraugus and Catskill type facies of Rickard, 1975) are present in extreme southeastern New York and northeastern Pennsylvania. The subaerial sequences represent the final stage of deltaic deposition, but other than noting their occurrence, are not considered further in this report.

Sedimentary Model

The stratigraphic framework, the lateral and vertical distribution of the lithofacies, primary depositional structures and paleontologic evidence of the Middle and Upper Devonian rocks of the Appalachian basin fit best within the framework of a deltaic model of deposition. Historically, this westward-thinning clastic wedge has been referred to as the Catskill delta because of its geographic location. A generalized east-west cross section of the delta is shown in figure 161. The clastic wedge which covers southern New York, most of Pennsylvania and West Virginia, western Maryland, eastern Ohio and northwestern Virginia occupies approximately 100,000 square miles within the central Appalachian basin (fig. 153, page 268). The wedge attains a maximum thickness of approximately 12,000 feet in south-central Pennsylvania. The rapid lateral changes in facies within the clastic wedge reflect deposition within the varied sedimentary environments associated with modern and ancient deltas. The subaerial alluvial and fluvial environments are characterized by red and green sandstones and shales. Gray sandstones, the predominant lithology of the delta front and shelf environment, represent beaches, off-shore bars, distributary channel and distributary mouth bar deposits. Gray shales and siltstones occur primarily as slope and basin deposits, mostly of turbidite origin, while the brown and black organic-rich shales of the Devonian sequence reflect deposition in the distal margins of the basin. A limestone lithofacies of limited extent occurs with the predominantly clastic sequence of the Middle Devonian. This lithofacies is represented by the Tully Limestone and other thin limestone units of the Hamilton Formation. The limestone lithofacies is of local extent and limited primarily to areas of New York, Pennsylvania, and West Virginia. The character and fauna of the limestone indicate a shallow marine shelf environment of deposition but because of its stratigraphic relationship with distal basin black shales, some investigators have proposed a clastic limestone origin for this lithofacies. Figure 162 shows the distribution of the Tully Limestone in the Appalachian basin and its lateral relationship with equivalent clastic lithofacies. Regionally, the depositional strike is north-south, but local variations are numerous due to the rapidly changing configurations of the delta with time. The paleoslope during the Middle and Upper Devonian was down to the west from an eastern bordering highland. Paleocurrent interpretation from outcrop data and seven oriented cores is shown on figure 163 (Potter et al., 1980). The paleocurrent directions verify the generally north-south depositional strike and the derivation of the sediment from the east.

The influence of structure on the deposition and character of the Middle and Upper Devonian sediment has been discussed in detail in the tectonic section of this report. Isopach mapping of the Devonian shale units and the total Devonian sequence shows that certain structures were positive or mobile features during Devonian shale deposition. The most notable features--the Cincinnati arch, the Rome trough, and the Central West Virginia arch--all appear to have been active during the Middle and Upper Devonian and had an influence on the depositional character and thickness of the sediments.

The distribution of organic materials within the Appalachian basin has been discussed in detail in the geochemical section of the report; lateral and vertical facies changes within the Devonian sequence have been covered in detail in the stratigraphic discussion.

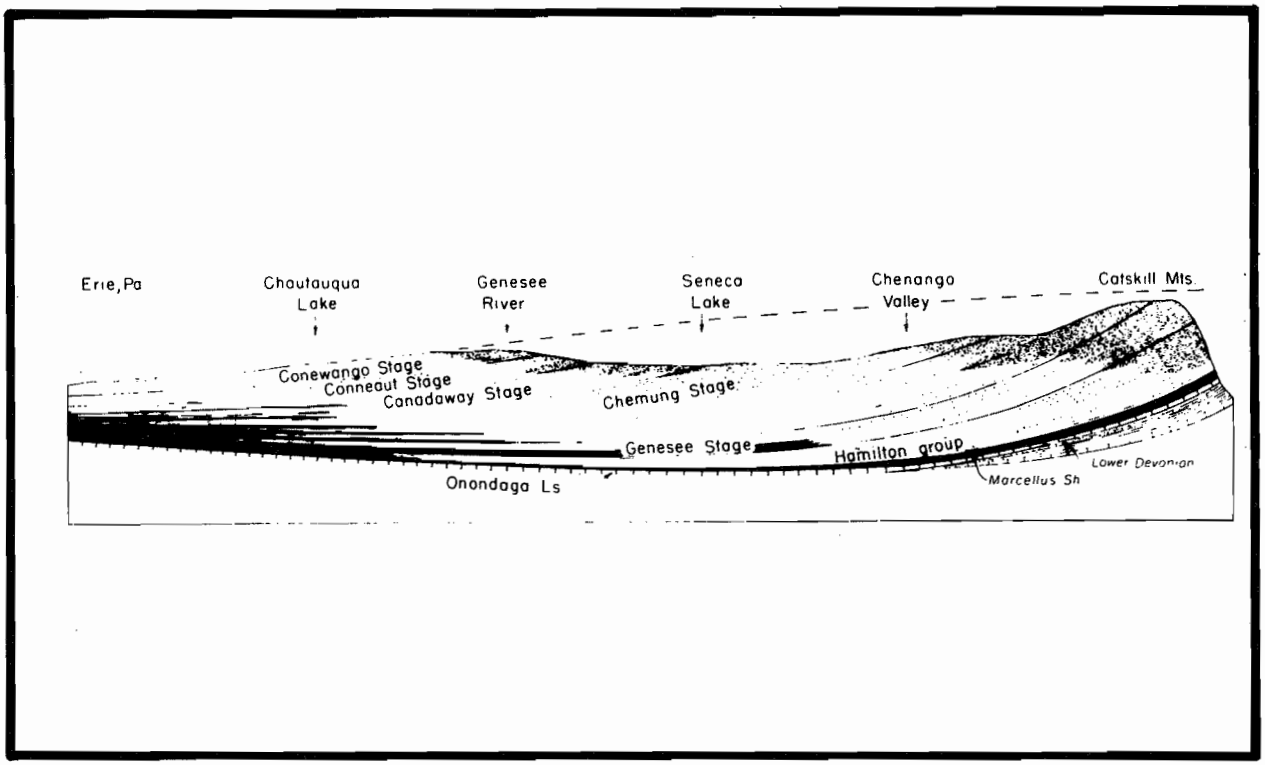


Figure 161. Cross section of the Catskill delta from the Hudson Valley to Erie, Pennsylvania. From Dunbar and Waage (1969).

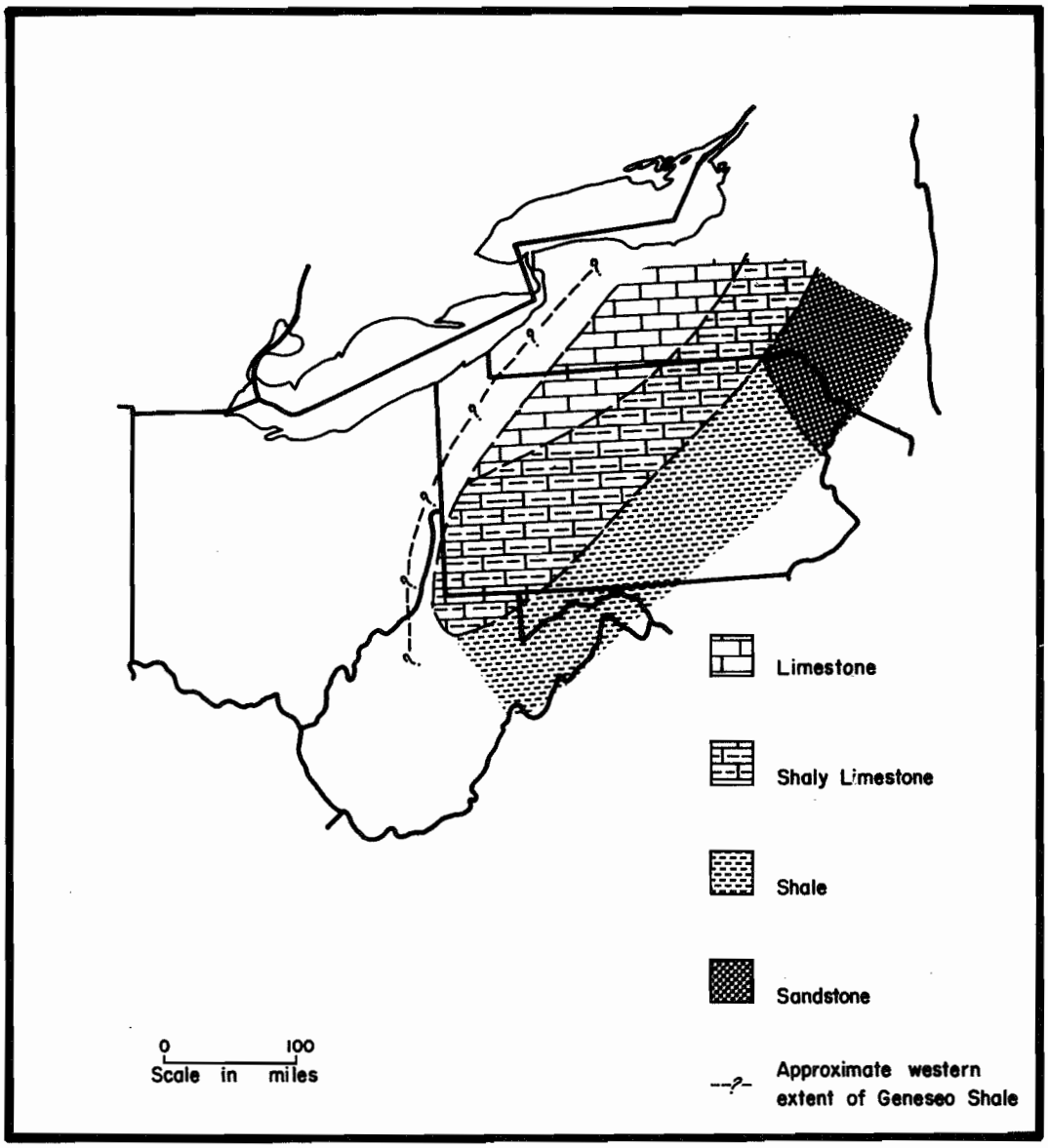


Figure 162. Map showing the distribution of facies in the Tully Limestone and its clastic equivalents and the approximate western extent of the Geneseo Shale and its equivalents. From Schwietering (1977); Tully Limestone distribution modified from Heckel (1969).

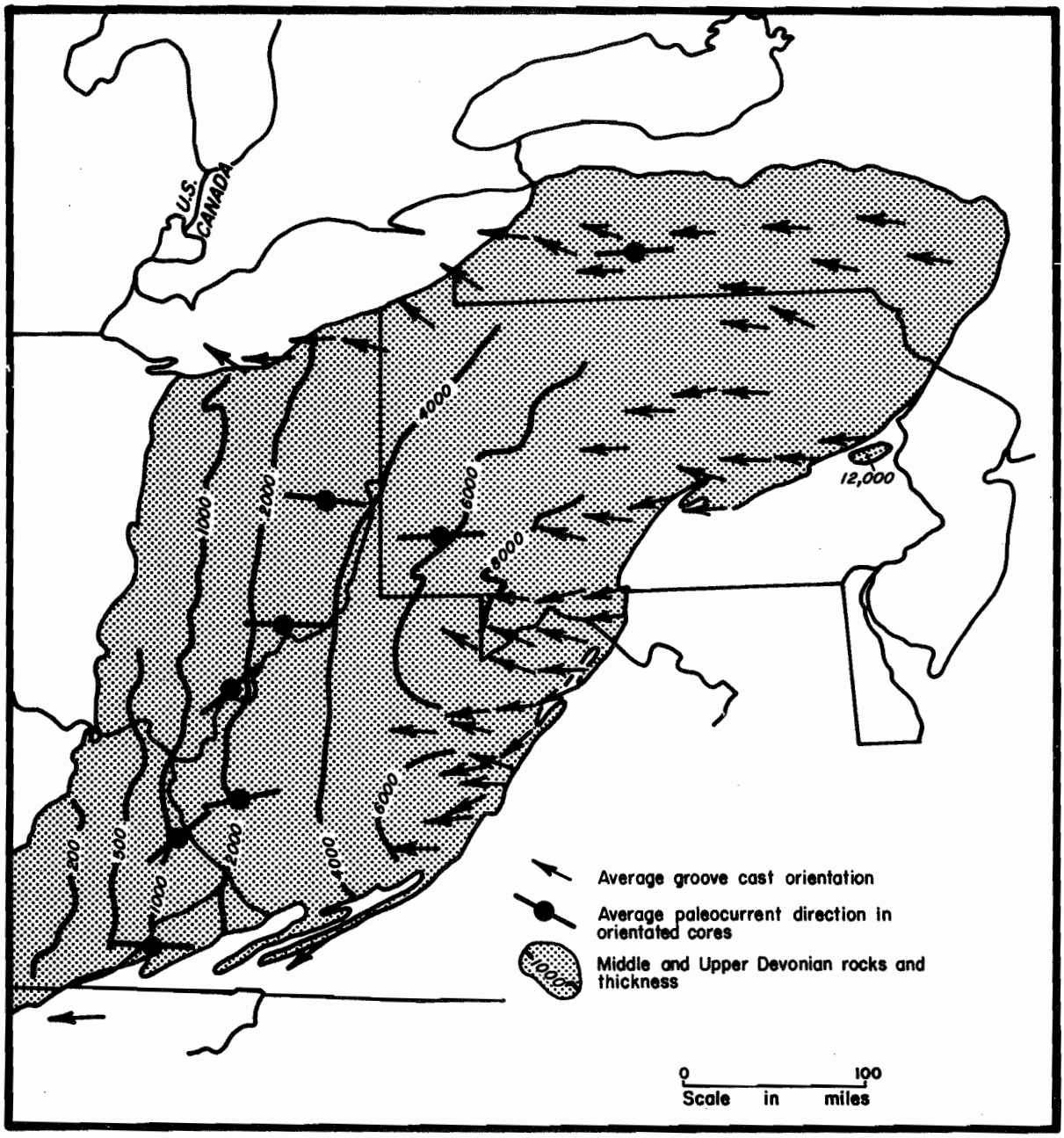


Figure 163 . Generalized paleocurrent map of Devonian sediments in Appalachian Basin. Note uniformity of flow. After Potter et al. (1980).

EXPLORATION PARAMETERS ESTABLISHING SITE SPECIFIC AREAS FOR DEVONIAN SHALE TARGETS IN THE EASTERN UNITED STATES

Introduction

Recent studies conducted by investigators for the Eastern Gas Shales Project have demonstrated that the highly organic Devonian-age shales are potential targets for natural gas exploration in the eastern United States. Historically, production from Devonian shale reservoirs has been low-pressure, low-volume flows with a low rate of decline except in those local areas where permeability is enhanced by siltstone lenses or natural fracture systems. The low-pressure, low-volume character of the earlier production is based upon performance of wells drilled prior to the advent of the Department of Energy's Eastern Gas Shales Project. Under sponsorship and coordination of the Eastern Gas Shales Project, a major research effort was directed at determining new exploration parameters and stimulation designs which would increase the daily production rate and raise the recoverable reserves per well to volumes considered commercial at current wellhead prices. Conclusions obtained from Eastern Gas Shales Project studies have provided exploration parameters which enhance the prospect of drilling commercially-productive natural gas wells from Devonian shales in the eastern United States.

The search for gas in the unconventional Devonian Shale reservoirs of the Appalachian, Michigan and Illinois basins should be based upon a sound exploration rationale in order to avoid economic and temporal waste. Basically, the search is to find a reservoir with sufficient porosity and permeability, either primary or secondary in nature, that contains sufficient hydrocarbon reserves. In the past, in most instances, if a suitable trapping mechanism could be demonstrated, the prospect would generally have been drilled, oftentimes with success but just as often without.

To increase the chance of successfully drilling in the Devonian shale, a prospect evaluation should indicate more than just the thickness of the radioactive black shales and/or turbidites in the prospect area. Principally, a prospect evaluation should take into consideration, in addition to thickness, the following parameters:

1) The amount of organic carbon.
2) The type of organic material from which the kerogen was derived.
3) The thermal maturity of the kerogen.
4) The potential for secondary fracture porosity.
5) The potential for interbeds of siltstone and fine sandstone.
6) The trapping mechanism.

Data on all of the above evaluation parameters is seldom available for every specific site, but the assessment of the potential of the site is strengthened when data is available as the majority of the parameters.

In the selection of potential drilling locations in areas of the Appalachian, Michigan, and Illinois basins as many of the aforementioned criteria were addressed as feasible. To properly address the exploration parameters, it becomes incumbent for the exploration program to rely upon published literature and a careful analysis of the available data. By making use of data generated by the various Eastern Gas Shales Project investigators, it was possible to determine the shale thickness, type of organic matter present regionally, the percent of organic carbon in the various black shale facies, the thermal maturity of the source rock, and to estimate the presence and development of natural fracture systems. The reservoir parameters generally apply over the entire region for which they were developed, but the trapping mechanism varies from state or region depending upon the local structural and tectonic history of the region.

Exploration rationales and resource appraisals for the Michigan, Illinois and Appalachian basins had been prepared earlier in screening reports published by the Department of Energy, Morgantown Technology Center, DOE/METC Reports 118-124 (Tetra Tech, 1981). Data from these reports, in conjunction with recently acquired data, is being used to develop a rationale for selection of potential exploration areas and specific drilling locations for states in the Appalachian basin (New York, Pennsylvania, Ohio, and for the Illinois and Michigan basins). The discussion of the parameters used in the selection of potential resource areas and drilling sites will include consideratoin of the geology, petroleum geochemistry, tectonics and production history of the region and a general prognosis workup for each specified well location. Other maps prepared by Tetra Tech, Inc. and other investigators were used extensively to provide a regional overview of the stratigraphy, structure, tectonics and historic production. These maps (plates 14 through 19) were integral to the evaluation of the source potential and selected drilling sites.

Exploration Parameters Establishing Site Specific Areas for Devonian Shale Targets in New York

INTRODUCTION

Oil and gas operators have been aware for more than a century that thick deposits of black petroliferous shales were present in the Devonian outcrop belt and in the subsurface of western and south-central New York. Natural gas was produced for domestic and small industry use as early as 1821. The low-pressure, low-volume character of the Devonian shale production did not encourage continued shale exploration because operators were more interested in conventional sandstones and carbonate reservoirs which exhibited greater reserves and larger rates of flow. Natural gas shortages resulting from declining reserves in the United States and some extremely cold weather in the northeastern part of the nation led the U.S. Department of Energy to initiate a comprehensive research investigation of the Devonian shales in the eastern United States to evaluate its potential as a natural gas resource. This study included both resource assessment and facies characterization of the Devonian shales in New York.

The Devonian shale sequence of New York is considered to occupy the interval from the top of the Onondaga Limestone to the top of the Perrysburg Formation. The stratigraphic framework of the Devonian rocks of New York is shown on figure 164.

The Middle and Upper Devonian shale sequence is part of a clastic wedge which occupies over 100,000 square miles in the northern part of the Appalachian basin. The shale sequence is several hundred feet thick in the east and thins towards the western and southern margins of the basin. In New York, the Devonian shale sequence is cyclic in nature, and begins with a black shale facies that intertongues with and is overlain by lighter colored shales, mudstones, and siltstones. These lithologies (facies) are characteristic of depositional environments found within the framework of the prograding Catskill delta. The black shales of the distal basin facies coalesce towards the west and are thickest in central and west-central New York. The cyclic nature of the Devonian shale stratigraphic and depositional framework in New York is shown on figure 165.

PRODUCTION POTENTIAL INDICATORS

An outgrowth of the Eastern Gas Shales Project investigations was the recognition of certain shale characterization parameters which enhance the potential for finding commercial production of natural gas from the Devonian shale basins in the eastern United States. These characterization parameters are (1) thickness of black shale facies, (2) type of organic matter, (3) percent organic carbon and (4) thermal maturation. It was also found that these parameters, when associated with natural fracture systems, as well as close proximity to Devonian shale production or "shows," can be used to define areas in New York which are the most favorable for exploration. An indirect method for estimating the fracture density of an area is obtained through the calculation of stress ratios: the ratio of the minimum horizontal stress and overburden thickness. The stress ratio data for western New York is not very encouraging with respect to the fracture densities, but does indicate potential for thrust faulting. The structural/stress ratio relationships within the basin are shown on figure 109, page 203.

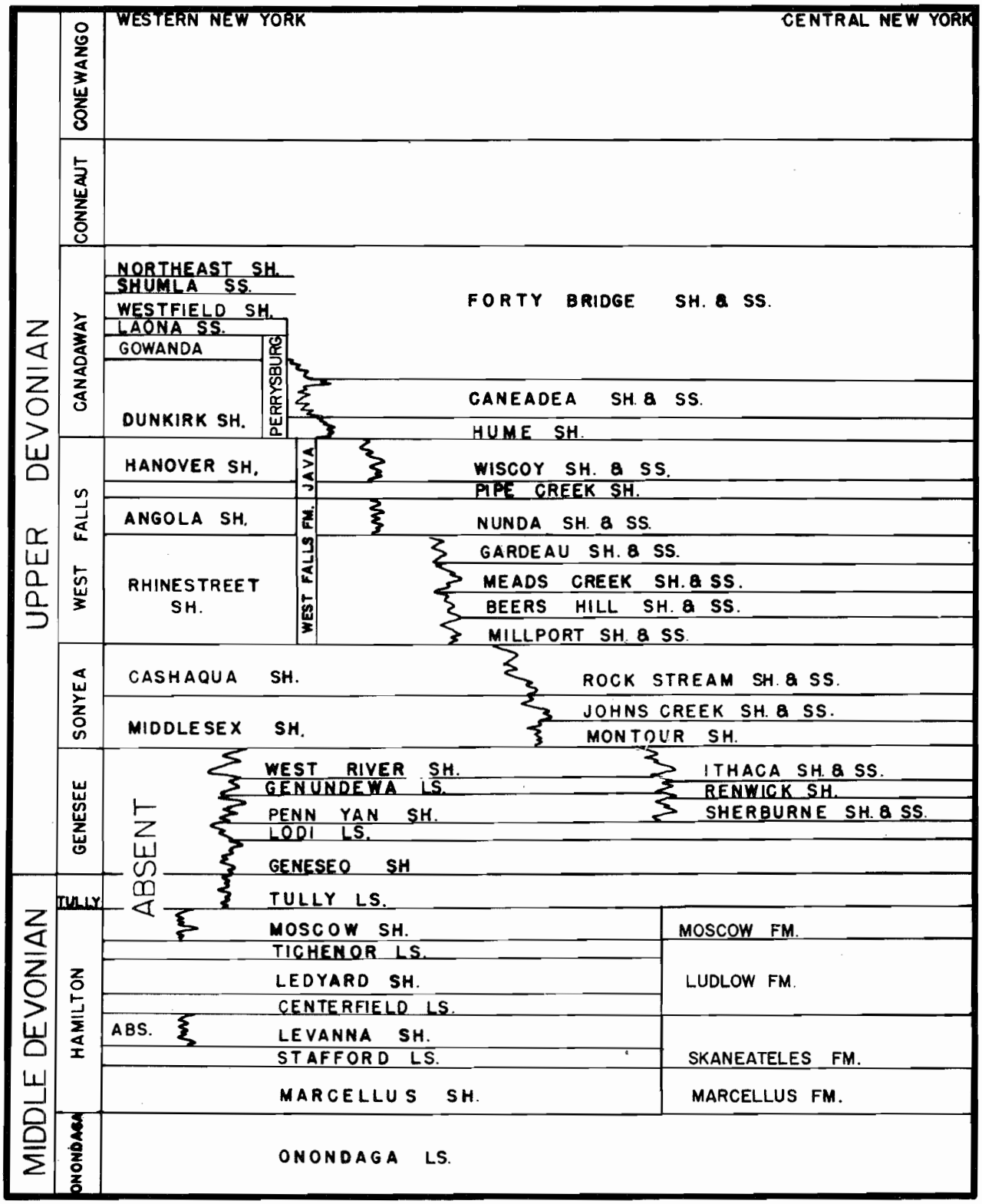


Figure 164 . Generalized time-stratigraphic correlation chart of the Middle and Upper Devonian Systems of western and central New York. Modified from Van Tyne and Peterson (1978).

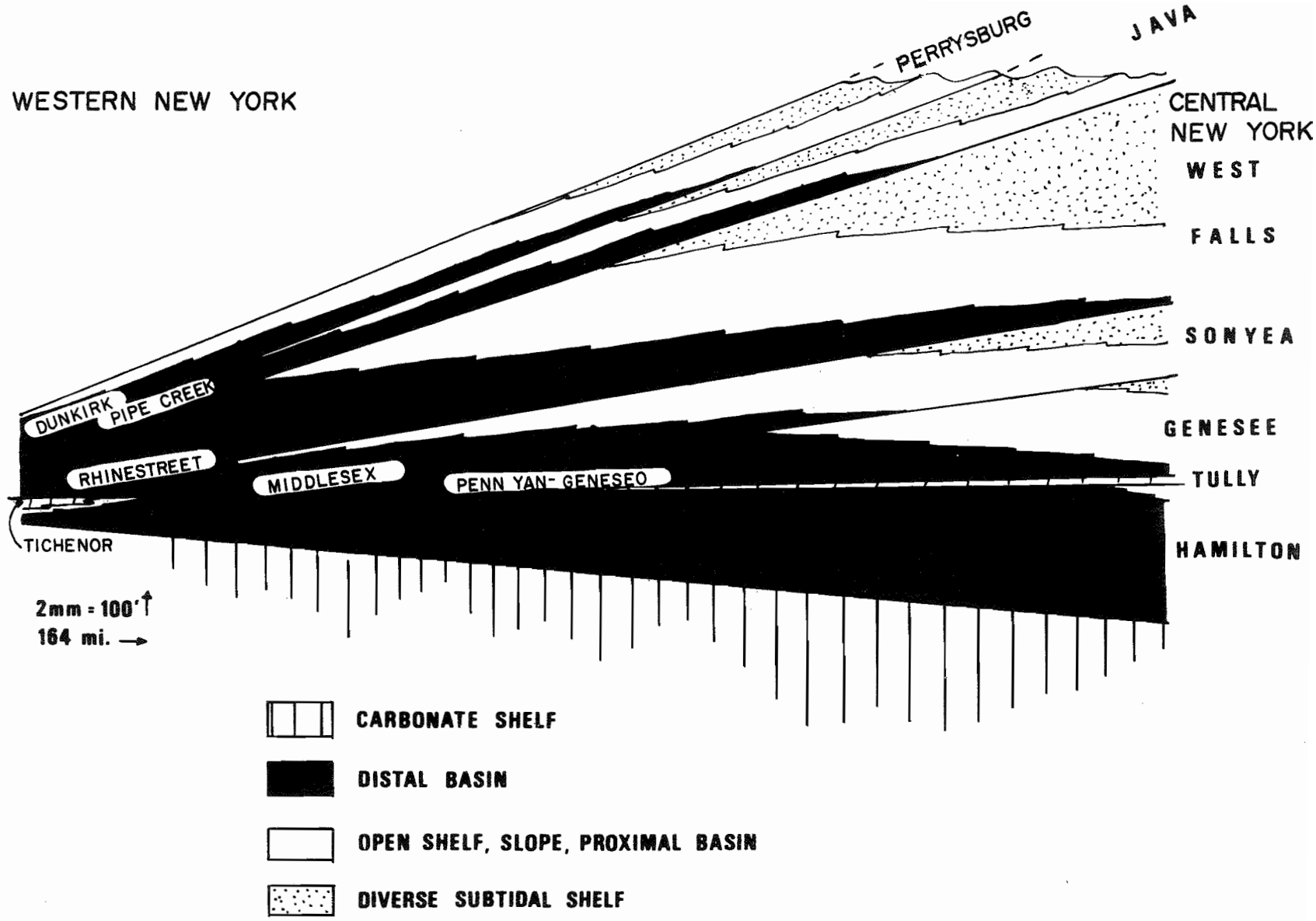


Figure 165. Facies of the Middle and Upper Devonian of New York. After Van Tyne and Peterson (1978), facies after Rickard (1975).

Based upon the above exploration parameters, the most attractive areas for exploration of natural gas from the Devonian shale in New York is a rectangular area bounded by parallels of latitude 42° and 43° M/ and meridians of longitude between 76°30' and 78°30' W. Another area is prismatic in shape and parallels the New York shoreline of Lake Erie from the Pennsylvania state line to the eastern boundary of Erie County, New York. The areas with the greatest potential for finding commercial production in New York are shown on figure 166.

GEOLOGIC RATIONAL FOR SELECTION OF DRILLING SITES

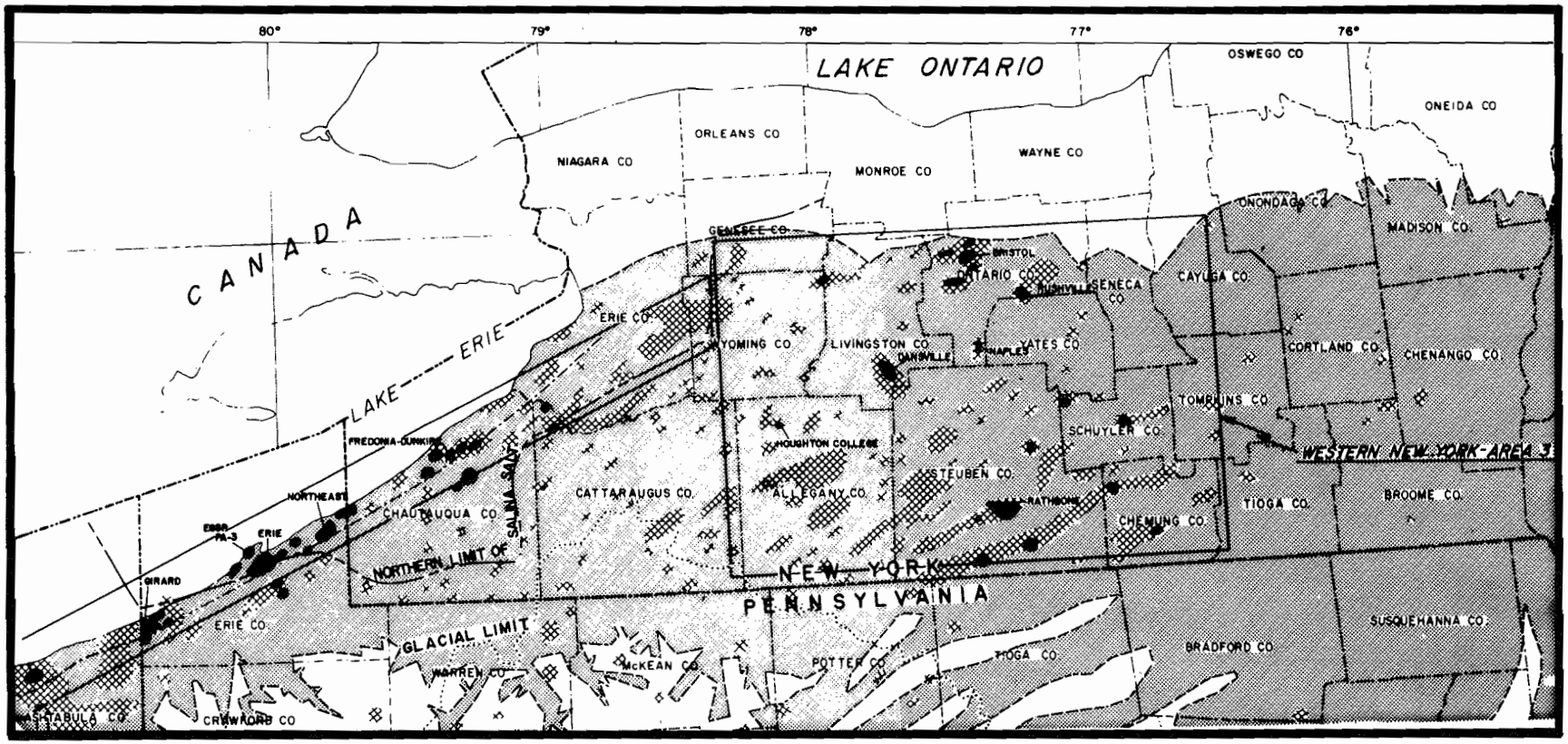
The Devonian shale drilling program in New York was a cooperative program between the New York State Energy Research and Development Authority, and the United States Department of Energy. Five wells were drilled by the New York State Energy Research and Development Authority on high school and university properties to develop sources of low-cost, self-help gas from the Devonian shale reservoir. After the wells were drilled and cased, the U.S. Department of Energy, through Gruy Federal, proceeded with the stimulation, testing, and completion of the wells.

The primary rationale for drill site selection was that the wells be located on school properties within areas where characterization and structural exploration parameters indicated the greatest potential for production. However, it appears that the selection of specific sites in New York departed from the geologic rationale and was dependent more on the location of available school properties rather than on the shale characterization properties and geologic parameters.

Location 1 (Houghton College), location 3 (Allegany County BOCES), and locations 5 and 6 (Alfred University) were within the boundary of potentially attractive Area II. Location 2 (Portville Central School), location 4 (Franklinville Central School) and location 7 (St. Bonaventure) fell just outside the western boundary of Area II. The location of the 7 well sites are shown on figure 167.

Area II, which contains a thick, organic-rich shale section exhibiting thermal maturity indices for the generation of natural gas, was subject locally to extensive natural fracturing and has a history of natural gas "shows" and gas production from Devonian shales.

All locations were in close proximity to "shows" of gas from the Devonian or appeared to lie along projections from, or trends between, historic or currently producing Devonian shale gas fields. Potentials for secondary porosity from natural fractures were evaluated to be the greatest at location 7 (St. Bonaventure) located along the trace of a downthrown fault block as mapped by the New York Geological Survey (Van Tyne and Wickerham, 1980).



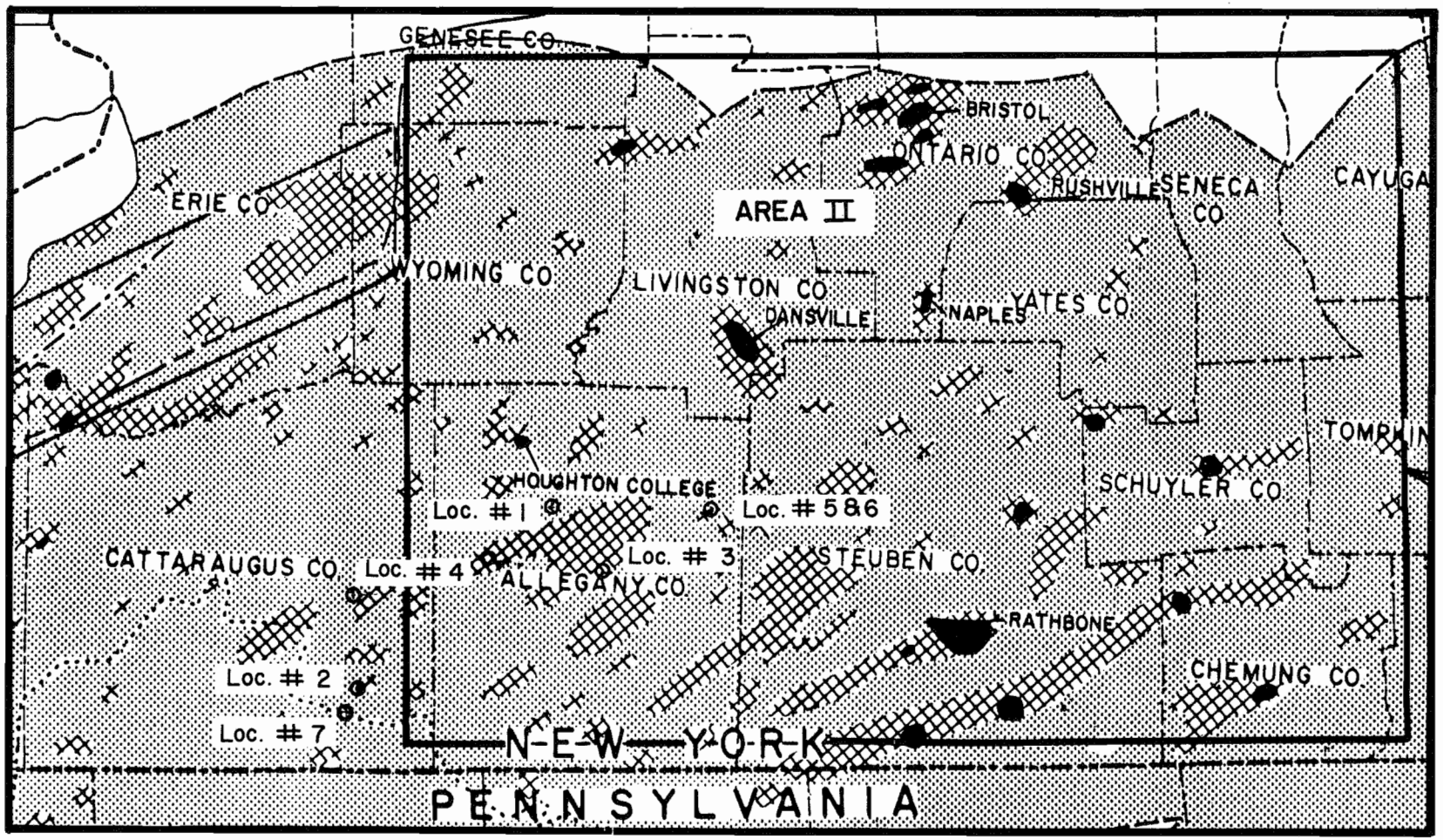
EXPLANATION

- Area of favorable shale gas potential
- RATHBONE — Area of reported gas production and field name from Devonian Shale
- Area of reported gas shows from Devonian Shale
- Devonian Shale outcrop area

SCALE

10 0 10 20 30 40 MILES

Figure 166 Map showing existing Devonian Shale gas fields, reported gas shows, and areas of potential Devonian Shale production in western and west-central New York.



EXPLANATION

— Area of favorable shale gas potential

RATHBONE — Area of reported gas production and field name from Devonian Shale

— Area of reported gas shows from Devonian Shale

o — Proposed well location

SCALE : 1:1,000,000

1 inch equals approximately 16 miles

10 0 10 20 miles

Figure 167. Map showing the proposed locations for the Devonian gas wells in western and west-central New York.

WELL PROGNOSES

Location No. 1

Well/Location: Houghton College — Allegany Co., New York; Canedea Twp.; Houghton 7½' Quadrangle W78°10'09" N42°25'39"

Elevation (ground) approx. 1370' (topo)

Target Formations: Marcellus Shale, Middle Devonian
Geneseo Shale, Upper Devonian
Rhinestreet, Upper Devonian

Key Beds:

Unit	Est. Top	Est. Base
Pipe Creek		910'
Rhinestreet	1080'	1540'
Geneseo	1920'	1940'
Tully	1940'	2070'
Marcellus	2380'	2425'
Onondaga	2425'	

Note: (1) The location is in the hills, just west of the Genesee River Valley; the site appears to be at least partially a glacial terrace. Estimate thickness could vary from 50' to over 100'.

Location No. 2

Well/Location: Portville Central School — Cattaraugus Co., New York; Portville Twp.; Portville 7½' Quadrangle W78°20'03" N42° 2'05"

Elevation 1430' (topo)

Target Formations: Middle Devonian, Marcellus Shale
Upper Devonian, Geneseo Shale
Upper Devonian, Rhinestreet Shale

Key Beds:

Unit	Est. Top	Est. Base
Perrysburg Formation (Dunkirk-Hume Shales)		2065'
Pipe Creek Shale	2185'	2215'
Rhinestreet Shale	2525'	3160'
Geneseo Shale	3460'	3510'
Tully Limestone	3510'	3525'
Marcellus Shale	3930'	3960'
Onondaga Limestone	3960'	

Note: (1) The location is adjacent to areas of fracturing (NE-SW) and normal faulting (up to NW).

(2) The location is within the Allegheny River Valley, near the glacial margin. Glacial drift could be up to a couple of hundred feet thick. Conductor casing should be set in bedrock.

(3) The well is located between the Portville (Upper Devonian Oil & Gas fields) and Cores Upper Devonian Gas field) producing from the Chipmunk and Richburg-Waugh-Porter sandstone intervals, respectively. (Lower Upper Canadaway through Upper Perrysburg). During drilling, these sandstones should be carefully evaluated for up-hole potential.

Location No. 3

Well/Location: Allegheny Co. BOCES — Allegany Co., New York; Amity Twp.; Belmont 7½' Quadrangle N78° W78° 2'24" N42°14'03"; Elevation 1370' (topo)

Target Formation: Middle Devonian, Marcellus Shale; Upper Devonian, Dunkirk-Hume Shales

Key Beds:

Unit	Est. Top	Est. Base
Perrysburg Formation (Dunkirk-Hume Shales)		870'
Pipe Creek Shale	1110'	1125'
Rhinestreet Shale	1560'	2410'
Geneseo Shale	3000'	3025'
Tully Limestone	3025'	3080'
Marcellus Shale	3575'	3610'
Onondaga Limestone	3610'	

Note: (1) The well location is within the Genesee River Valley, on the east side adjacent to the uplands. Estimate glacial thickness is approximately 100 feet.

(2) Nearest production is from the Corbin Hill field (oil) from the Scio sandstone (Upper Canadaway Group, undiff.)

(3) Approximately 50'-75' of Onondaga Limestone.

Location No. 4

Well/Location: Franklin Central School — Franklinville, Cattaraugus Co., NY; Franklinville Twp.; Franklinville 7½' Quadrangle W78°27'38" N42°20'32"; Elevation (ground) approx. 1590' (topo)

Target Formation: Upper Devonian, Rhinestreet
Upper Devonian, Dunkirk

Key Beds:	Unit	Est. Top	Est. Base
	Perrysburg (Dunkirk-Hume Sh)	1200'	1250'
	Pipe Creek Shale	1375'	1390'
	Rhinestreet Shale	2030'	2290'
	Geneseo Shale	2465'	2490'
	Tully Limestone	2490'	2500'
	Marcellus Shale	2880'	2900'

Note: (1) Location of well lies just outside of area of interest as projected by Tetra Tech. Lack well control to project key beds.

(2) The well location is in the Ischua Valley; glacial deposits might range up to a couple of hundred feet.

Location No. 5

Well/Location: Alfred University — Allegany Co., New York, Alfred Twp., Alfred 7½' Quadrangle W77°47'01" N42°15'23", Elevation 1950' (topo)

Target Formations: Middle Devonian, Marcellus Shale
Upper Devonian, Rhinestreet Shale
Upper Devonian, Dunkirk-Hume Shale

Key Beds:	Unit	Est. Top	Est. Base
	Perrysburg Formation (Dunkirk-Hume Shale)		1120'
	Pipe Creek Shale	1340'	1380'
	Rhinestreet Shale	1720'	2850'
	Geneseo Shale	2855'	3385'
	Tully Limestone	3385'	3440'
	Marcellus Shale	3935'	3970'
	Onondaga Limestone	3970'	

Note: (1) The location is on the bedrock hills behind Alfred University; it is anticipated that 0' to 50' of glacial drift will be penetrated.

(2) The Onondaga Limestone is less than 50' thick in this area.

(3) Nearest production is south of the proposed location from the Alfred field; production is from the shallow Upper Devonian Alfred gas sand.

Location No. 6

Well/Location: Alfred — Allegany Co., New York
Alfred Twp.
Alfred 7½' Quadrangle W77°78'10"
N42°15'23"
Elevation 1980' (topo)

Target Formation: Middle Devonian, Marcellus Shale
Upper Devonian, Rhinestreet Shale
Upper Devonian, Dunkirk-Hume Shale

Key Beds:

Unit	Est. Top	Est. Base
Perrysburg Formation (Dunkirk-Hume Shales)		1150'
Pipe Creek Shale	1370'	1410'
Rhinestreet Shale	1750'	2880'
Geneseo Shale	3385'	3415'
Tully Limestone	3415'	3470'
Marcellus Shale	3965'	4000'
Onondaga Limestone	4000'	

Note: (1) The location is located on the hills behind the College of Ceramics; it is anticipated that 0' and 50' of glacial drift will be penetrated.
(2) The Onondaga Limestone is less than 50' thick in this area.
(3) Nearest production is south, from the Alfred field; producing from the shallow Upper Devonian Alfred gas sand.

Location No. 7

Well/Location: St. Bonaventure University — Cattaraugas, New York
Allegany Twp.
Olean 7½' Quadrangle W78°29'17"
N42° 4'47"
Elevation 1420' (topo)

Target Formations: Middle Devonian, Marcellus Shale
Upper Devonian, Rhinestreet Shale
Upper Devonian, Dunkirk Shale

Key Beds:

Unit	Est. Top	Est. Base
Dunkirk Shale	1450'	1520'
Pipe Creek Shale	1950'	1975'
Rhinestreet Shale	2270'	2920'
Geneseo Shale	3150'	3170'
Tully Limestone	3170'	3180'
Marcellus Shale	3575'	3600'
Onondaga Limestone	3600'	

Note: (1) The Onondaga Limestone is approximately 75'-100' thick in this area.

(2) The location is near the glacial boundary; it is in the Allegany River Valley. It is anticipated that up to a couple of hundred feet of glacial outwash could be present; however, this could be quite variable.

(3) Nearest production is from the Bradford and Five Mile fields, producing from the Upper Devonian Canadaway Group (Bradford 2nd & 3rd and the Chipmunk Sandstones).

(4) The location is adjacent to a normal fault (NE-SW) on the down-thrown block, mapped by Van Tyne & Foster (1979).

COMPLETION SUMMARY

The following completion summary is capsulized in part from an unpublished report submitted to the U.S. Department of Energy, Morgantown Energy Technology Center by Gruy Federal, Inc. (Rdissi, 1981).

Five of the proposed seven locations were drilled, stimulated, tested and completed during calendar year 1981. All technical operations performed on the wells went smoothly according to design. None of the wells had a natural show, but after stimulation, the open-flow rates ranged from a low of 19 Mcf/day to a high of 73 Mcf/day. The stimulation and completion results are shown on Table 6. Open-flow rates were below expectations for wells drilled within areas identified to have high potentials for commercial production based upon exploration parameters indicated by Eastern Gas Shales Project research. However, the summary of results shows that the wells drilled within Area II had larger after stimulation open-flow rates than the wells outside the area.

The absence of natural shows strongly suggest natural fractures did not intersect the reservoir at the proposed locations. Site No. 7 (St. Bonaventure), located on structure but outside of Area II, had the poorest after frac, open-flow rate.

Much more drilling within areas defined on the basis of characterization and structural parameters needs to be done to evaluate the merit of these parameters as exploration tools for Devonian shale exploration in the eastern United States.

Well Name	County	Producing Formation	Perforated Interval Ft	Total Depth Ft	1981 Com-ple-tion Date	Type of Frac	Frac Grad-ient Psi/ Ft	Stress Ratio	O.F. Bef. Frac MSCF/D	O.F. After Frac MSCF/D	Rock Pres-sure Psi After Hrs.
Portville Central School #1	Cattaraugus	Marcellus	4142-4176	4190	7-29	Foam	1.11	0.97	0	22	1680/312
Saint Bonaventure Well #1	Cattaraugus	Marcellus	3568-3630	3655	7-31	Foam	1.29	1.12	0	19	1080/183
Alfred University Well #1	Allegany	Marcellus	3932-3970	3979	8-08	Foam	0.94	0.82	0	40	1560/189
Houghton College Well #2	Allegany	Marcellus	2382-2416	2452	8-10	Foam	1.18	1.03	0	23	1220/184
BOCES Belmont Well #1	Allegany	Marcellus	3242-3282	3284	8-18	Foam	1.12	0.97	0	73	1600/115

All wells with 4½" production casing.

New York Summary of Stimulation and Completion
(Rdissi, 1981)
Table 6

Exploration Parameters Establishing Site Specific Areas for Devonian Shale Targets in Pennsylvania

INTRODUCTION

In an effort to evaluate the gas potential of the Devonian Shale sequence, the U.S. Department of Energy (DOE) funded the Eastern Gas Shales Project (EGSP). The initial EGSP objective was to classify, correlate, and identify the shale resource; a parallel objective was to test new methods of stimulating production. This report, as a state of the art assessment, is designed to provide specific drilling locations to test the Devonian shale exploration rationale.

Six wells have been targeted by the DOE to test the Upper Devonian black shale facies in northwestern Pennsylvania; three locations are designed to test the radioactive Dunkirk interval and three locations the radioactive Rhinestreet interval. The specific sites were chosen based upon favorable geochemical indications, areas of suspected stress which would enhance the potential for natural fracturing, and trends of production and/or natural hydrocarbon shows from the Devonian shales. Several of the potential locations are projected as utilizing existing wells or re-enter holes that have been plugged and abandoned.

The Devonian shales of northwestern Pennsylvania have produced commercial quantities of gas since the mid-1800's. However, the low-volume, low-pressure reservoir caused the operators to concentrate their efforts on conventional clastic reservoirs. The inability of the various sandstone reservoirs to supply the quantities of gas necessary to meet consumer demand has led the DOE and private industry to re-evaluate the Devonian Shale potential. Recent reserve calculations of the organic-rich facies potential, calculated from borehole geophysical log data, estimated approximately 45 trillion cubic feet of recoverable gas (National Petroleum Council, 1980). The quantity of recoverable gas reserves available, using conventional technology, and the price incentives offered by the Natural Gas Policy Act (NGPA) of 1978 makes the shale an extremely attractive resource, either as a primary target or as a dual zone completion possibility.

GEOLOGY

The Devonian shale sequence extends from the top of the Onondaga Limestone (Middle Devonian) to the base of the Berea Sandstone (Mississippian). The principal black, organic-rich shale facies with sufficient thickness and lateral extent to be commercial producers of gas are the Middle Devonian Marcellus Shale, the Upper Devonian Rhinestreet, and the Dunkirk Shales. Other black shales present in the Devonian interval are more useful as stratigraphic marker horizons but have locally been productive. Figure 168 shows the Devonian stratigraphic correlations of western Pennsylvania.

The organic-rich sediments were deposited as a part of the Catskill delta complex. This clastic wedge prograded westward from the Acadian highland source areas, and reflects a time-stratigraphic correlation between sediments deposited in the distal basins and the prodelta front. The total Devonian interval thickens southeastward from 1500 feet along the southern Lake Erie shoreline to more than 8000 feet along the Allegheny

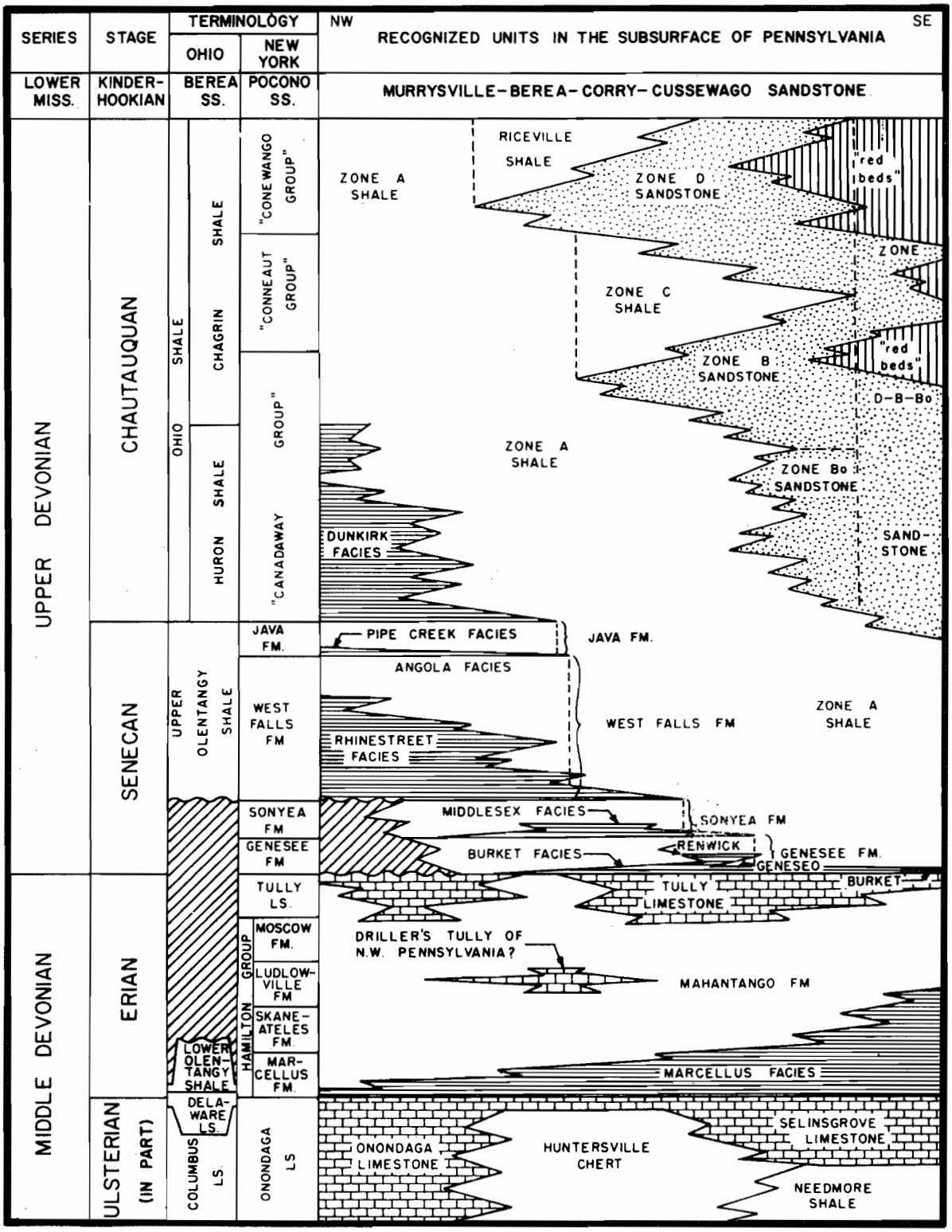


Figure 168. Schematic illustration of Upper and Middle Devonian stratigraphic units in the subsurface of western Pennsylvania and correlation with New York and Ohio stratigraphic sections. In part, after Oliver, et al. (1969) and Patchen (1977).

Front. In northwestern Pennsylvania the Rhinestreet and Dunkirk shales are the dominant organic-rich facies. The Rhinestreet attains a maximum radioactive shale thickness of greater than 200 feet in western Crawford County (fig. 169), whereas the Dunkirk radioactive shales exceed 100 feet in central Erie County (fig. 170). (Net radioactive shale thicknesses include all shales that exceed a 'clean' shale baseline by 20 API units or more.)

An evaluation of the Devonian black shales potential for hydrocarbon generation depends on three basic interrelated geochemical factors:

1) the organic carbon percentage (by weight) contained in the shale facies,
2) the type of organic matter, either of terrestrial or marine origin,
3) the degree of thermal maturity of the organic carbon.

For the black shales to serve as a source rock for hydrocarbon generation, a minimum average organic carbon content of 0.5 percent (by weight) must be present. This minimum level of organic carbon content is exceeded by all organic-rich facies in Pennsylvania, generally increasing to the northwest. The Rhinestreet exhibits a maximum organic carbon content of 3.17 percent (by weight) and the Dunkirk a maximum value of 2.31 percent, suggesting that sufficient organic matter is present for gas generation.

The type of organic matter contained in the shales governs the amount of gas (methane) generated. Studies indicate that terrestrial carbons yield greater quantities of methane than organic carbon derived from marine sources (Maynard, 1978). Preliminary data indicate the source of Devonian organic matter present in the black shale facies was the Acadian highlands to the east (Potter, et al., 1980).

The thermal maturity of the organic matter contained in the organic-rich facies is a function of post depositional heating which in turn is a function of the maximum depth of burial and basinal heat flow. One of the better methods of establishing the relative thermal maturity of the organic matter present in the black shales is to measure its vitrinite reflectance (Barrows, Cluff, and Harvey, 1979). The percentage of light reflected by vitrinite (an organic, coal-like mineral), is an indirect measurement of the degree of organic maturity. The various stages of hydrocarbon generation are shown in figure 171.

The presence of an extensive, interconnected natural fracture system is essential for any significant quantity of shale gas production. The fractures provide the secondary porosity and permeability necessary for the accumulation and migration of gas. Stress ratios, a ratio of minimum compressive stress to overburden stress, have traditionally been used to estimate the pressures needed to hydraulically fracture the formation; however, the stress ratios are also an indirect method of delineating areas which have a higher density of natural fractures. A stress-ratio map for the Appalachian basin is shown on figure 109, page 203. The preliminary values for northwestern Pennsylvania fall in the category of limited fracturing; but, areas which overlie deep-seated structures may have higher potential. An additional cause of fracturing is glacial on-loading and off-loading. Extension fractures develop perpendicular to the glaciated surface as the result of the release of compressive forces but are limited to shallow (less than 800 feet) formations.

In summary, a successful Devonian Shale exploration program should:

1) include a thick, laterally extensive source rock;
2) contain a high percentage of organic matter;
3) exhibit a sufficient thermal maturity for the generation of gas;
4) have an extensive system of natural fractures.

The specific locations recommended herein are grouped into a Rhinestreet interval and a Dunkirk interval and are attractive as either primary or dual completion targets.

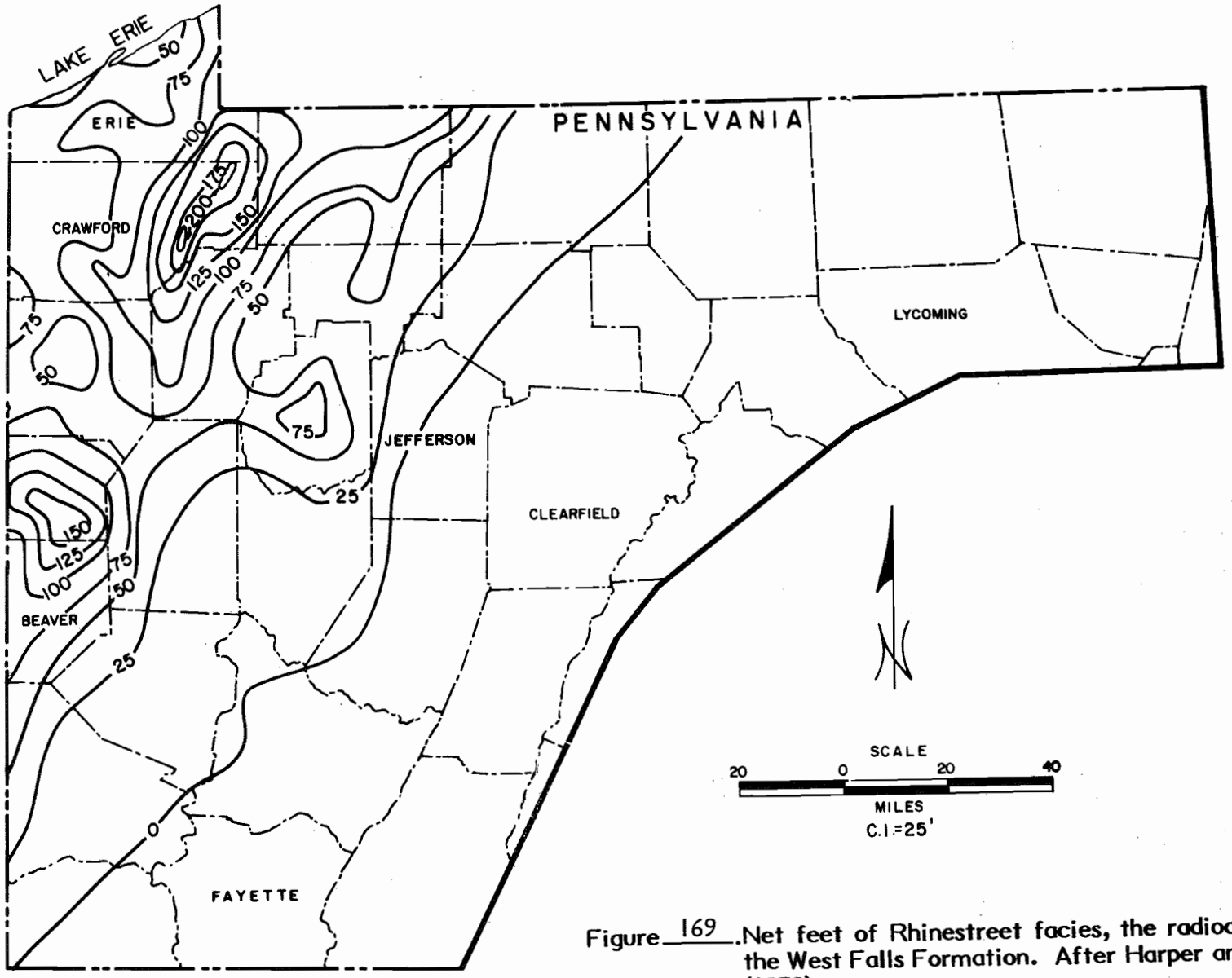


Figure 169. Net feet of Rhinestreet facies, the radioactive unit in the West Falls Formation. After Harper and Piotrowski (1979).

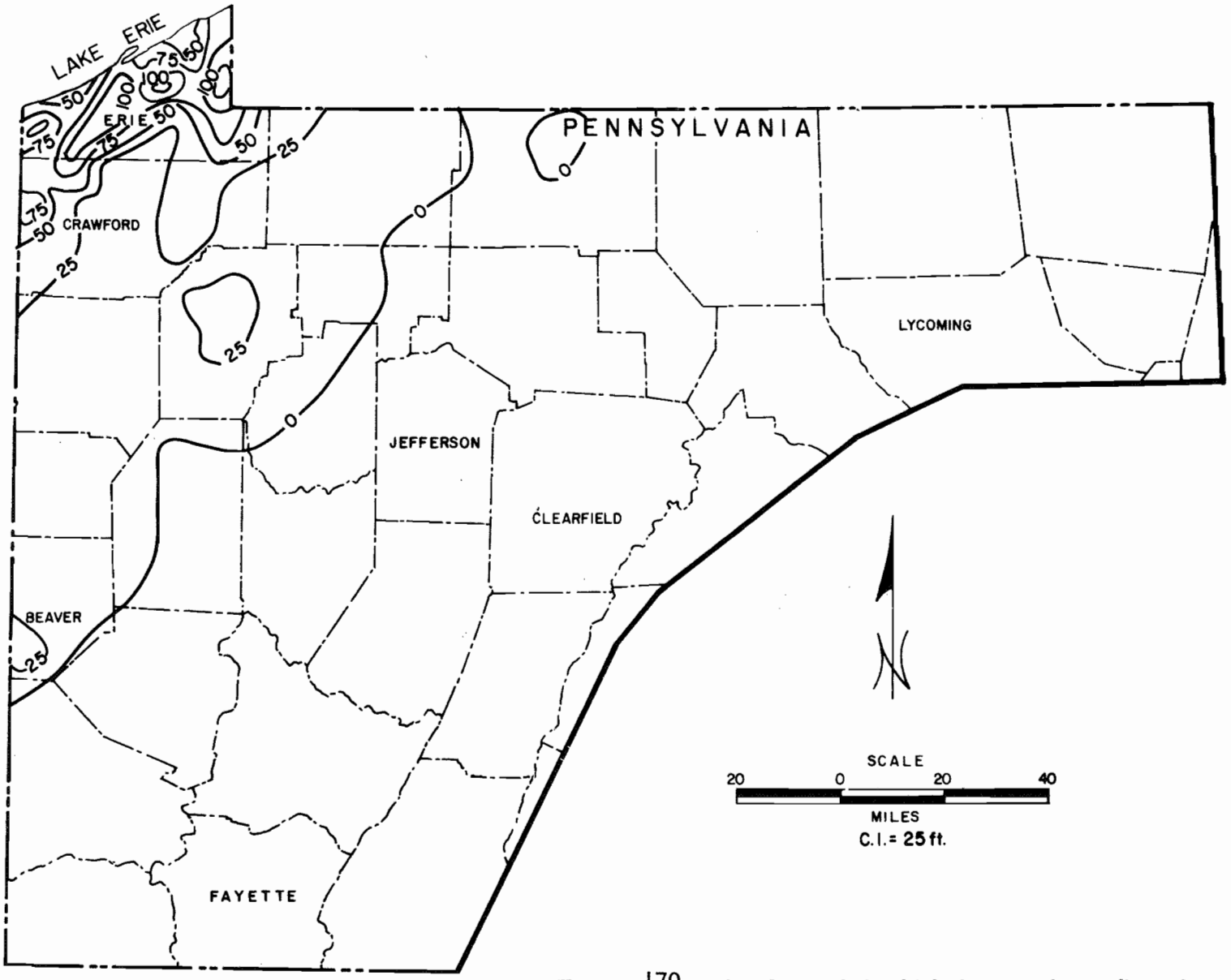


Figure 170. Net feet of Dunkirk facies, the radioactive unit in the Canadaway Group. After Piotrowski and Harper (1979).

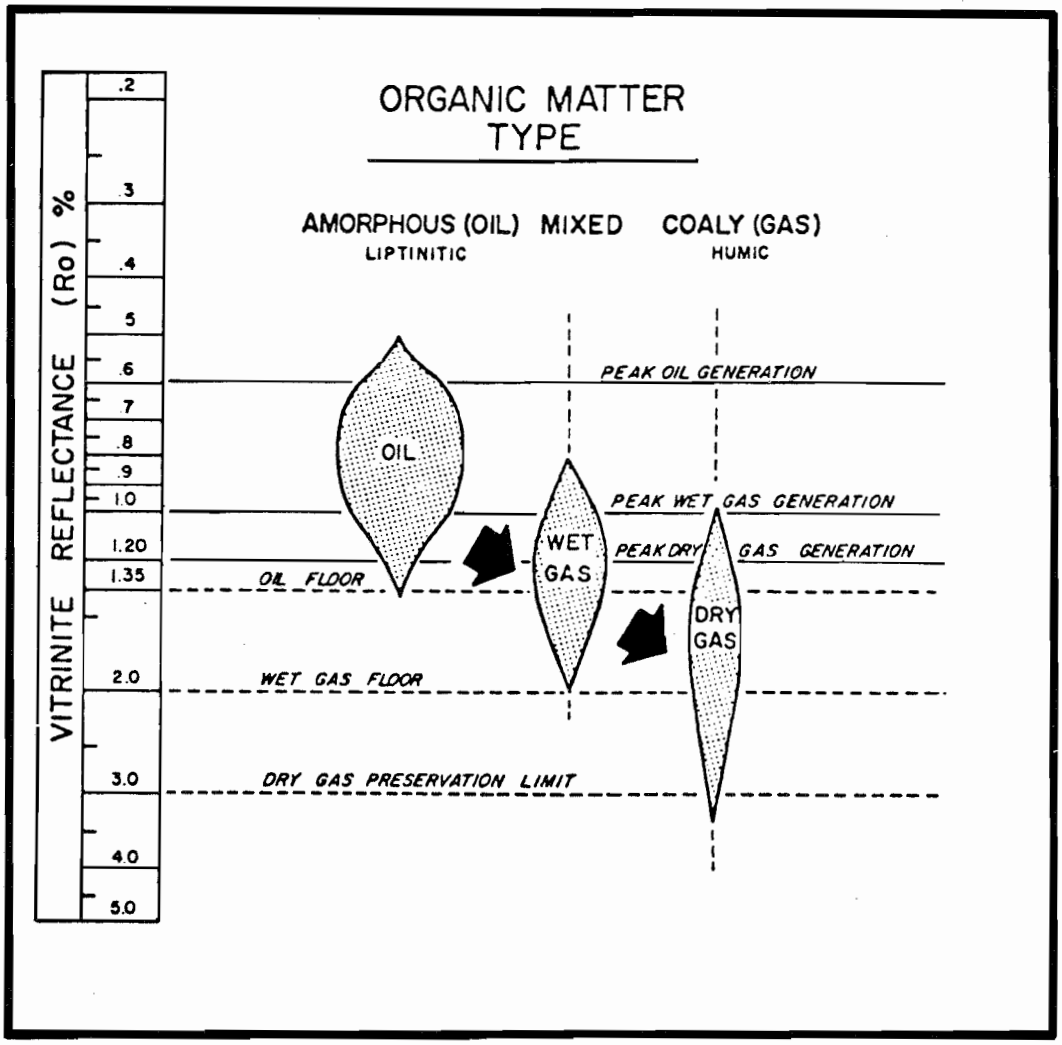


Figure 171 . Correlation of various maturation indices and zones of petroleum generation and destruction. After Dow (1977).

GEOLOGIC RATIONALE FOR DRILLING LOCATION SELECTION

Rhinestreet Shale

The first Rhinestreet well site proposes to reopen the Peoples Natural Gas #1 E.C. Rhodes, Lawrence County, Slippery Rock Township, Portersville 7½' quadrangle (fig. 172). This well, completed April 1965 in the Oriskany Sandstone, is positioned on the Homewood anticline. Aeromagnetic data show the location as lying on the west side of a possible basement fault, creating a potential natural fracture system. The organic carbon content is greater than 1.5 percent with a vitrinite reflectance of more than 2.50 percent (by weight); this level of thermal maturity is in the dry gas range. The proposed site is approximately 10 miles northwest of established Rhinestreet-Marcellus production (Peoples Natural Gas-Gruy Federal #1 Sokevitz, the EGSP Pennsylvania #5) with a reported initial production of 133 Mcf per day. The projected prognosis is stated at the end of the report.

The second Rhinestreet location proposed to reopen or offset the Peoples Natural Gas #1 G.H. Hohmann in Lawrence County, Plain Grove Township, Harlensburg 7½' quadrangle (fig. 172). This well, completed in July of 1966, is located along the northeast-southwest strike of the possible basement fault projected in the first location. The organic carbon content varies between 1.5 and 2.0 percent (by weight) with a vitrinite reflectance value of approximately 2.5 percent (dry gas range), indicating a favorable source. The total Rhinestreet interval is anticipated as being approximately 528 feet.

The third location is in Crawford County, Rome Township, Titusville North 7½' quadrangle (fig. 173), offsetting the Columbia Gas Transmission Corp. #1 H. Matteson. This well had a reported gas show in the brown shale (no depth given) and in the Marcellus at 3800 feet. The organic carbon content is between 1.5 and 2.0 percent with a vitrinite reflectance of approximately 1.0 percent (oil/wet gas range).

Dunkirk Shale

The first Dunkirk test location is in Erie County, along the Millcreek-Erie Township line, in both Swanville and Erie South 7½' quadrangles (fig. 174). It is recommended that the D. Fish #1 Karpinski Unit be offset (or reopened if plugged and abandoned). The well site is in the area of glacially induced fractures. The organic carbon content is approximately equal to 2.0 percent (by weight) with a vitrinite reflectance of 0.5 percent (early methane, early oil generation). The expected massive radioactive Dunkirk facies is between 80 and 100 feet; this interval has had frequent reports of gas shows.

The second location is in Erie County, Concord Township, Union City 7½' quadrangle, in the Alder Run Field (fig. 173, page 305). The area is outside of potential glacially induced fractures but is near an aeromagnetic anomaly that might provide local fracturing. The area exhibits marginal thermal maturity (0.5 percent vitrinite reflectance, early methane-early oil generation) with an organic carbon content of approximately 2.0 percent (by weight). The radioactive Dunkirk facies is approximately 70 feet, indicating a sufficient development of source beds.

The third Dunkirk test is along the southern Lake Erie shoreline in Erie County, Millcreek Township, Swanville 7½' quadrangle (fig. 174, page 306). Potential fracturing is of glacial origin. Additionally, a lineament, suggesting deeper structural movement, trends parallel to the shoreline. The source beds exhibit an average organic content of 2.0

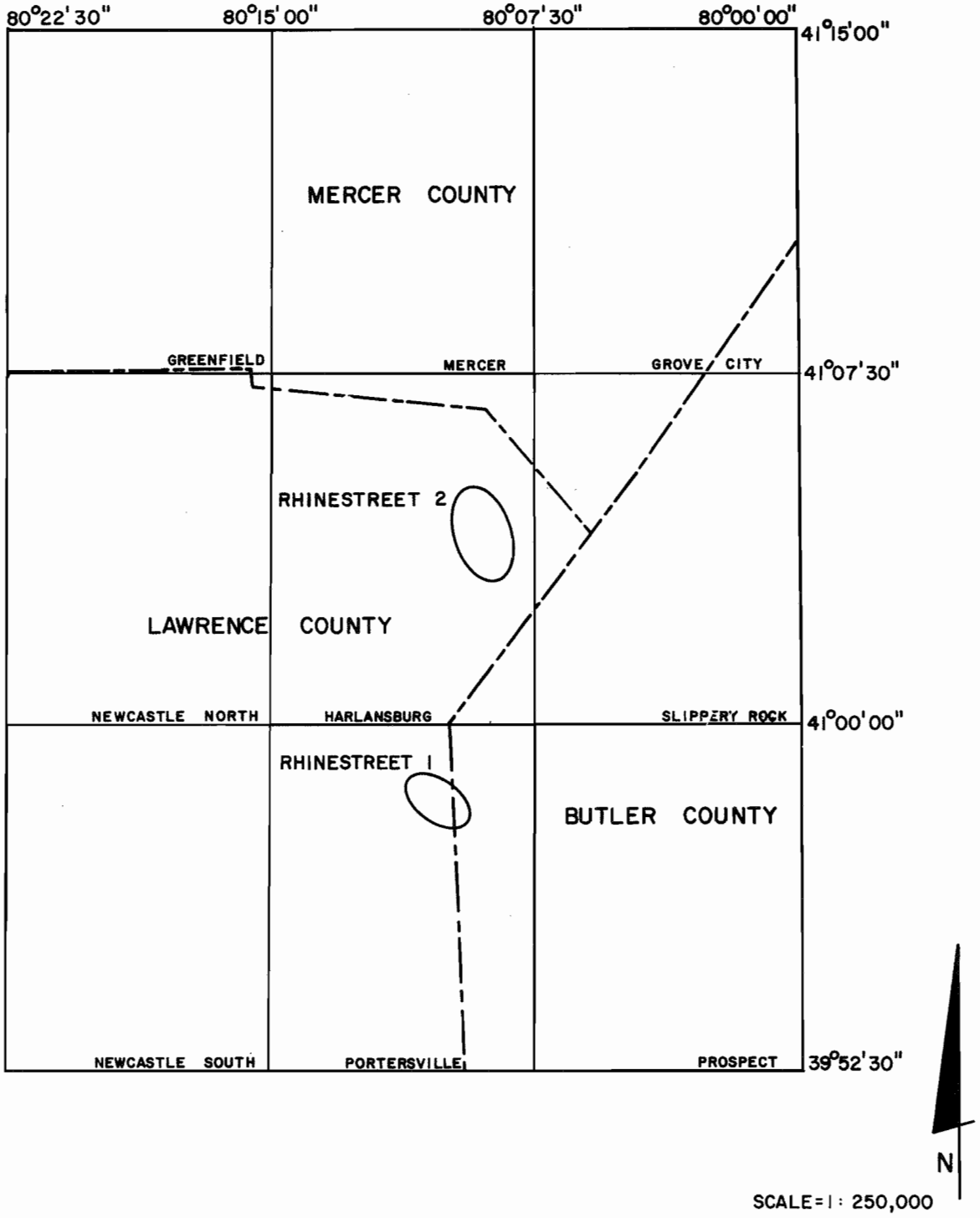


Figure 172 . Map showing prospective Devonian Shale (Rhinestreet) locations 1 and 2.

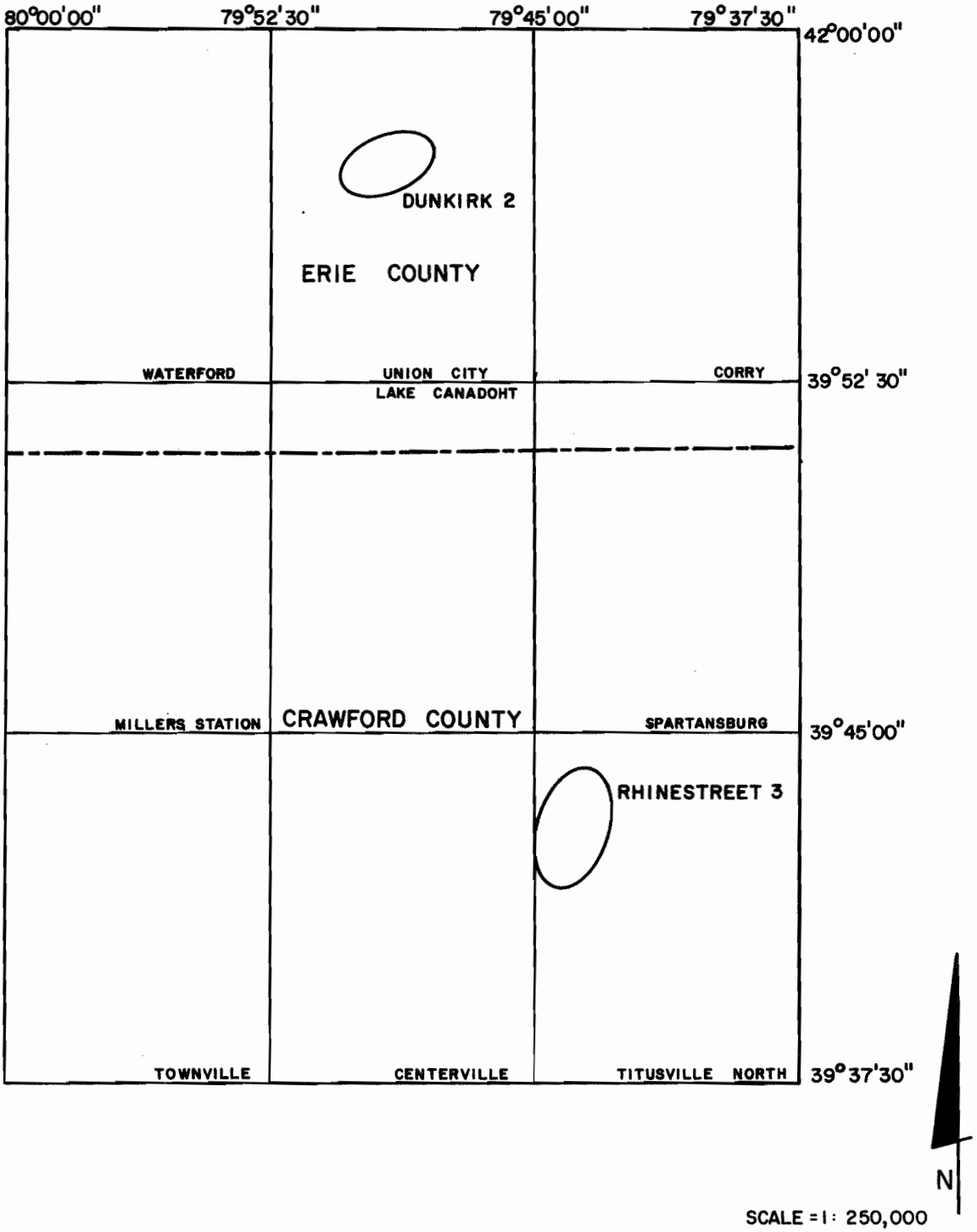


Figure 173 . Map showing prospective Devonian Shale (Rhinestreet and Dunkirk) locations 3 and 2, respectively.

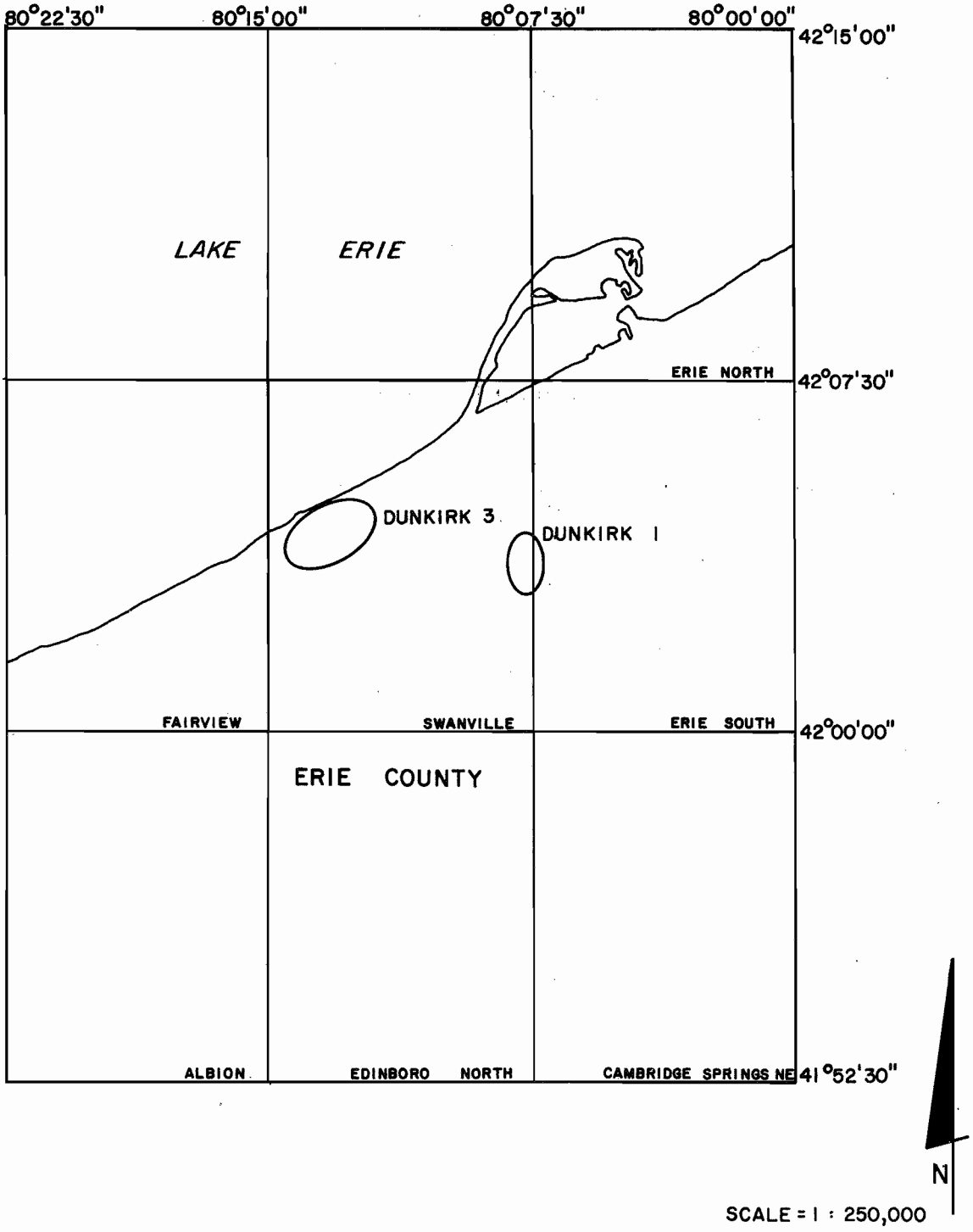


Figure 174 . Map showing prospective Devonian Shale (Dunkirk) locations 1 and 3.

percent by weight) with a vitrinite reflectance of 0.5 percent (early methane-early oil). The Dunkirk black shale in this area is more than 100 feet thick.

WELL PROGNOSES

Rhinestreet test #1

Location: Lawrence County, Pennsylvania
Slippery Rock Twp., Portersville 7½' Quad

Reopen the Peoples Natural Gas #1 E.C. Rhodes

Prognosis

Based on the E.C. Rhodes #1	Elevation 1153 K.B.	(subsea)
Radioactive black Rhinestreet	3958	-2805
Radioactive black Burket	4346	-3193
Tully Limestone	4359	-3206
Radioactive black Marcellus	4518	-3365
Onondaga	4533	-3380
Oriskany	4688	-3535

Rhinestreet test #2

Location: Lawrence County, Pennsylvania
Plain Grove Twp., Harlensburg 7½' Quad

Reopen or drill close to the Peoples Natural Gas #1 G.H. Hohmann

Prognosis

Based on G.H. Hohmann #1	Elevation 1288 D.F.	(subsea)
Berea	800	+ 488
Dunkirk	3340	-2052
(base)	3392	-2104
Rhinestreet	3812	-2524
(base)	4340	-3052
Tully	4440	-3152

Rhinestreet test #3

Location: Crawford County, Pennsylvania
Rome Twp., Titusville N. 7½' Quad

Prognosis

Based on Howard Matteson #1	Elevation 1650 Gr.	(subsea)

Dunkirk	2715	-1065
(base)	2731	-1081
Rhinestreet	2340	-1690
(base)	3511	-1861
Tully	3605	-1955

Dunkirk test #1

Location: Erie County, Pennsylvania
Millcreek-Erie Twp., Swanville 7½' Quad

If plugged reopen D. Fish #1 Karpinski Unit or drill close by.

Prognosis

Based on the D. Fish #1	Elevation 860 K.B.	(subsea)
Radioactive black Dunkirk	951	- 91
(base)	1031	-171

Dunkirk test #2

Location: Erie County, Pennsylvania
Concord Twp., Union City 7½' Quad

Prognosis

Based on Morvay #1	Elevation 1307 K.B.	(subsea)
Top of Dunkirk Shale Member	830	
Radioactive black Dunkirk	1660	-353
(base)	1730	-423

Dunkirk test #3

Location: Erie County, Pennsylvania
Millcreek Twp., Swanville 7½' Quad

Prognosis

Based on Warren Steel Products #1	Elevation 734 Gr.
Dunkirk	- 49
(base)	-164

Exploration Parameters Establishing Site Specific Areas for Devonian Shale Targets in Ohio

INTRODUCTION

The Eastern Gas Shales Project (EGSP), funded by the U.S. Department of Energy (DOE), has generated a large volume of technological information concerning the Devonian shales in the Appalachian Basin. An objective of the EGSP is to use this information, as reflected in advanced exploration and exploitation techniques, in several demonstration wells in Ohio.

GEOLOGY

The Devonian shale sequence in Ohio underlies approximately the eastern half of the state. The shales outcrop along a belt that extends from Adams County in southern Ohio to Erie County in northern Ohio, and then eastward along the southern shore of Lake Erie into western Pennsylvania and New York. The shale sequence dips to the southeast and thickens from about 400 feet in the central part of the state to more than 4000 feet in Belmont and Jefferson counties. The thickness and distribution of the Devonian shales in eastern Ohio is shown in figure 175.

A stratigraphic sequence of the Devonian shales in eastern Ohio includes, in ascending order, the Olentangy Shale; the Ohio Shale and its members--the Huron, Chagrin, and Cleveland Shales; and the Bedford Shale. Figure 176 is a schematic diagram showing the sequence and its relative configuration. The different stratigraphic units are identified and correlated in the subsurface by their distinctive signatures as recorded on gamma ray logs. A log showing typical gamma ray responses within the Devonian shales for a well drilled in central Ohio is presented in figure 177.

The shale sequence in Ohio represents the deep water westward facies of the Catskill delta, deposited during middle and late Devonian time. The delta deposited a clastic wedge that extends from eastern New York to east-central Ohio, and from central New York southward to northern Virginia.

Geochemical factors affecting the gas potential of the shales include the amount and type of organic matter and its thermal maturity. The organic carbon content within specific stratigraphic units increases westward and thermal maturation increases eastward. Marine type kerogen dominates in the western part of the basin; mixed and terrestrial type kerogen increase to the east (Zielinski, et al.)

Gas has been produced from the Devonian shales in Ohio for more than a hundred years. More than 1200 wells have produced or are producing hydrocarbons from the Devonian sequence. These wells typically produce about 50 Mcf per day, and are long-lived, with some wells producing for more than 50 years.

Two trends which exhibit excellent potential for gas production from the total Devonian interval are the east-central area (Cambridge Arch) and the Lake Erie shoreline area. In these areas (fig. 178), the shales are thought to have undergone extensive

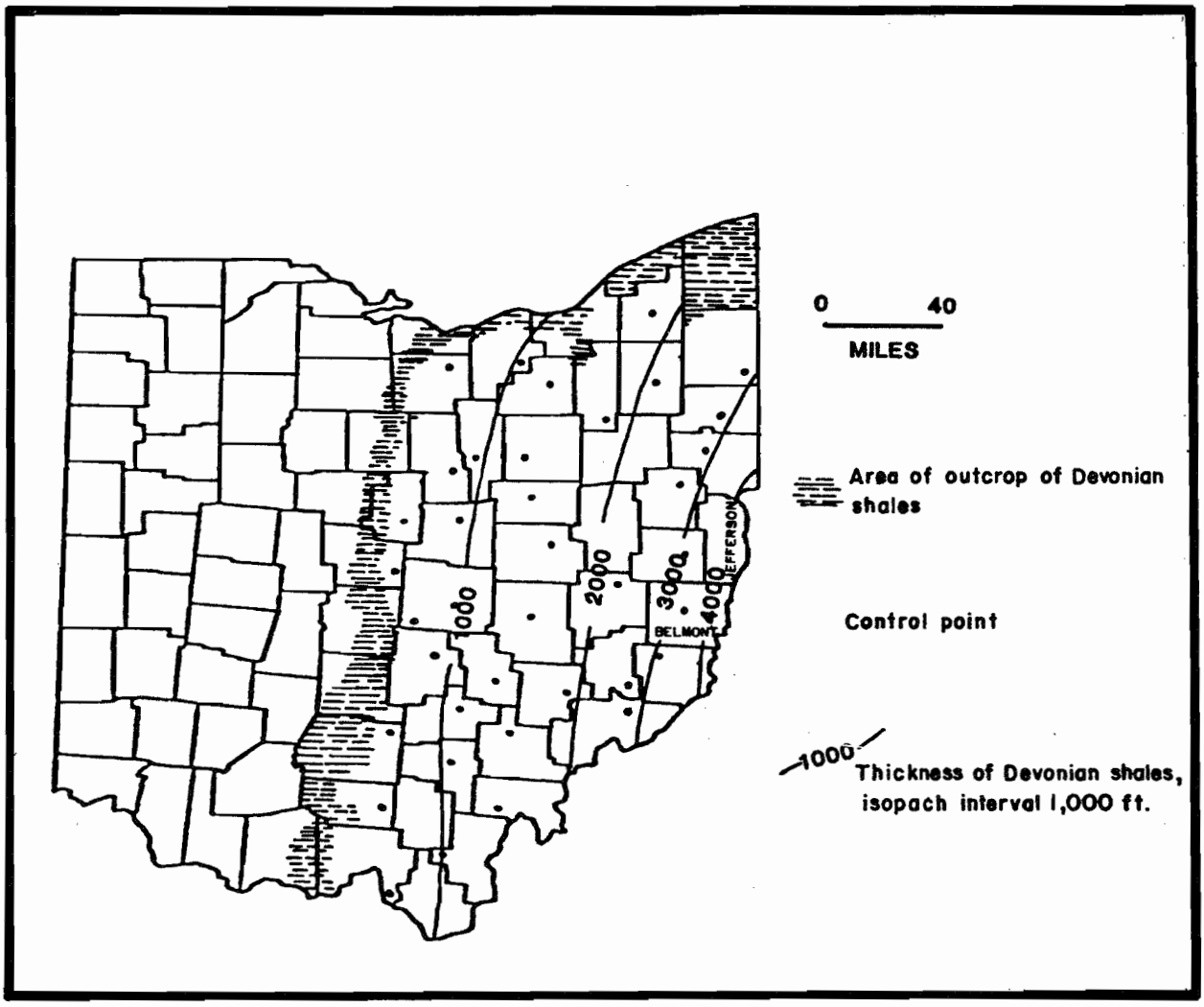


Figure 175 . Thickness of the Devonian shales in eastern Ohio. After Janssens and de Witt (1976).

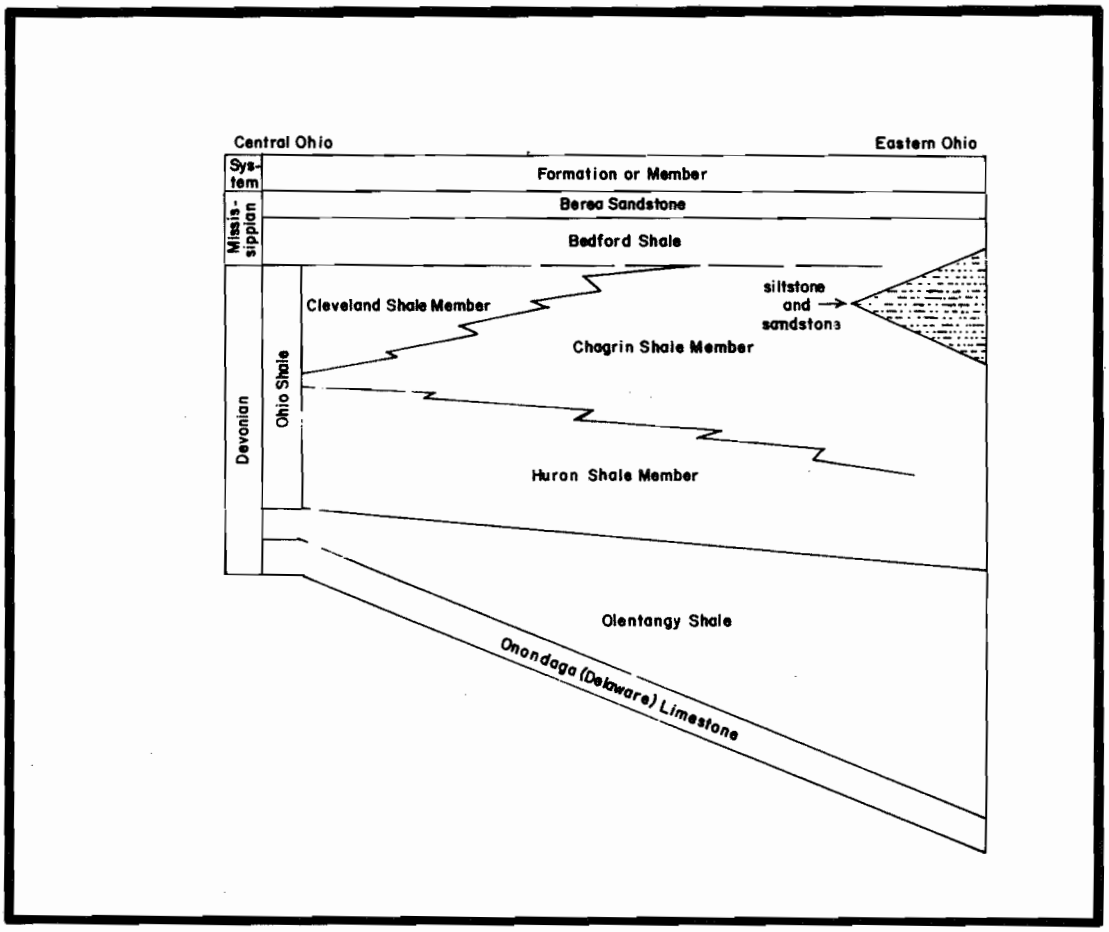


Figure 176 . Stratigraphic column and schematic of the relative thickness changes of the Devonian shales in eastern Ohio. After Janssens and de Witt (1976).

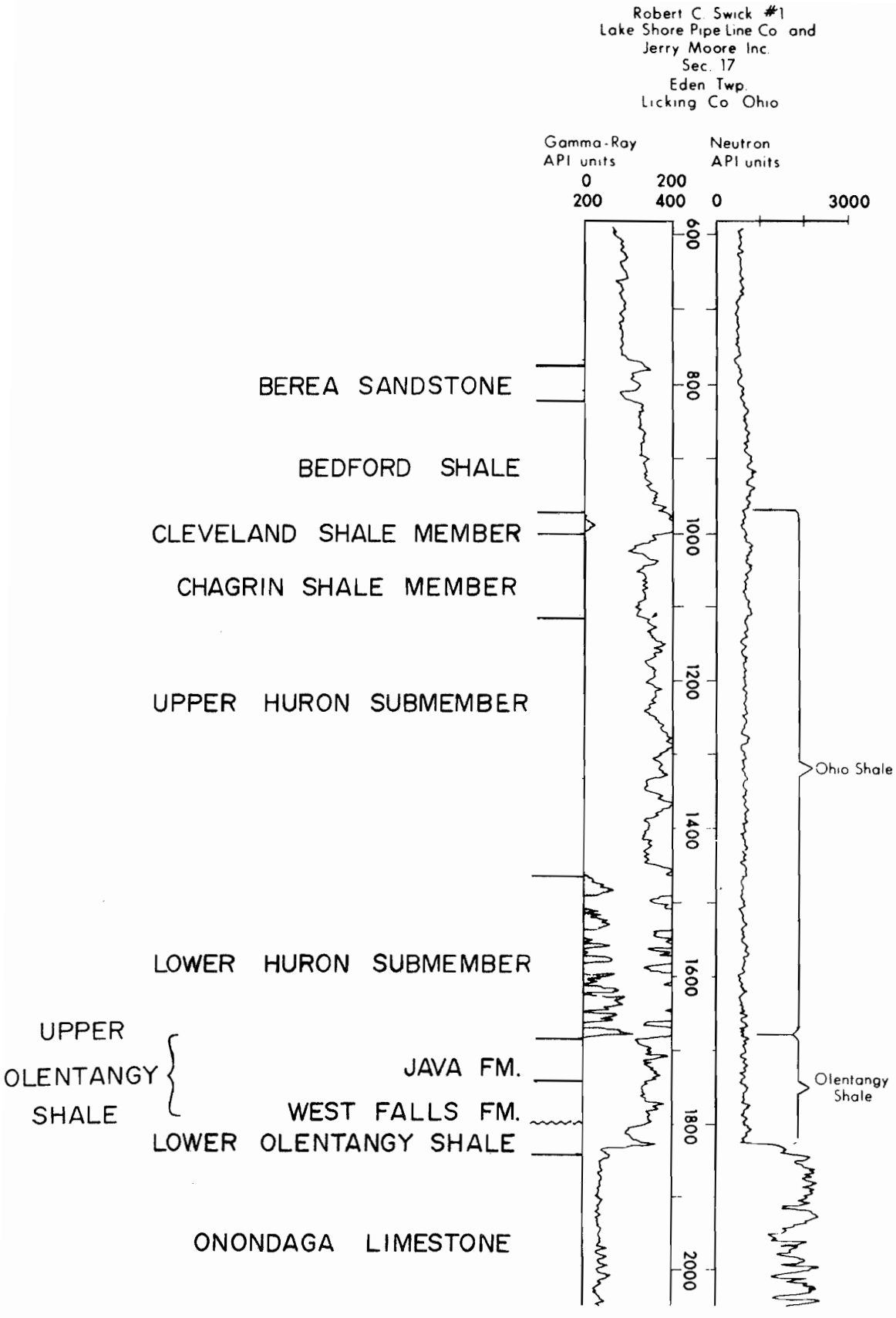


Figure 177. Typical gamma ray-neutron log response of a well drilled through the Devonian shales in central Ohio. Modified after Schwietering (1979).

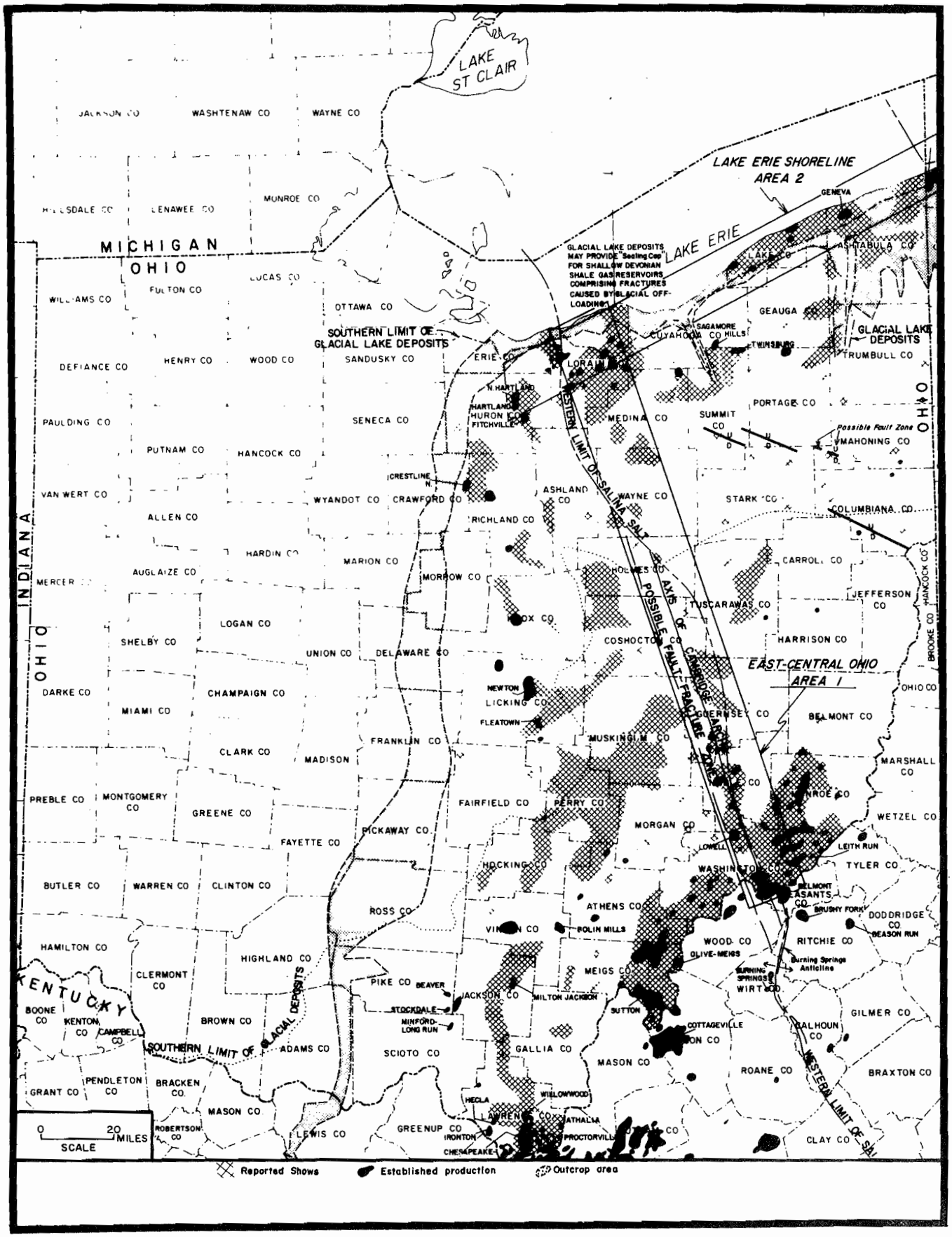


Figure 178 . Map showing favorable areas for Devonian Shale exploration.

fracturing by either glacial off-loading (Lake Erie) or by decollement-related events (Cambridge arch).

The Lake Erie shoreline trend extends from Lorain County to the Pennsylvania line and has produced shale gas from shallow Devonian wells since 1860.

Most past and present-day production is from silty shale and siltstone zones in the Chagrin Shale. These lithologies have numerous interbedded quartz laminae that appear to act as permeable reservoirs and conduits for gas even though some are cemented with carbonate (Potter, et al., 1980).

Organic-rich shales (as determined on the wireline log, shale having a gamma ray response 20 API units or greater to the right of the shale base line), approximately 150 to 200 feet thick, are the most likely hydrocarbon source rocks. These include the Cleveland and "Lower" Huron Members of the Ohio Shale. The mean organic carbon content for the shales in the Lake Erie trend is 2.23 wt.%. Atomic ratios (H/C and O/C) and carbon isotope studies indicate the kerogen is derived from intermediate (herbaceous) and/or marine (algal-amorphous) type organic debris. The thermal maturity, as measured by vitrinite reflectance, indicates that the organic material is immature (Zielinski, et al.)

Gas production is probably enhanced by the presence of natural fractures, formed as a result of Pleistocene glacial off-loading and on-loading. Extension fractures are believed to have developed due to tensile release following glacial retreat. Such fractures are thought to form perpendicular to the glaciated surface. The fractures are caused by the relaxation of compressional forces and are commonly referred to as "release fractures." The fractures occur at relatively shallow depths and are not expected to occur below 800 feet. Clays, within glacial lake deposits and tills, overlying the subcrop, provide an impermeable seal and hence a trapping mechanism for the fractured gas reservoirs (Tetra Tech, 1981).

The Lake Erie shoreline trend is undergoing considerable developmental drilling to the Silurian Clinton-Medina sandstones. As expected, many of these wells are encountering shows of gas in the Devonian shale, making dual zone completion a viable alternative. Dual objective proposals not only include the Clinton-Medina sandstones but also the Newburg, Knox, and sub-Knox horizons.

The east-central area is a long, narrow trend extending north-northwest from Washington County to Lorain County. The area is located along or near the western limit of the Upper Silurian Salina salt section. Reservoirs are possible throughout the upper Devonian shale sequence because of the probable decollement in the shale and associated fractures along the Cambridge arch. Thin-skinned thrusting is postulated in the Salina salt beds, causing a decollement surface near the base of the salt beds which ramped upward through the competent Onondaga Limestone into the Devonian sequence. Bedding plane thrusts produced folds with concomitant fractured reservoirs within the shale (Tetra Tech, 1981).

Many wells drilled to the Clinton-Medina encountered hydrocarbon shows in the Devonian shale along this trend. A number of those wells have been completed in the shale as commercial producers. Several hundred wells in Washington, Noble, and Monroe Counties have been completed in siltstone lenses in the Chagrin Member of the Ohio Shale. Significant quantities of gas are being produced from the intergranular porosity of the siltstone beds within the shale sequence (i.e.: Gordon, Fifth Sand, etc.) However,

production from these zones is believed to be enhanced by natural fractures in the siltstone and surrounding shale. The hydrocarbon source rocks are most likely the organic-rich zones within the Cleveland and Huron Members of the Ohio Shale and the Rhinestreet Shale (Upper Olentangy).

The average organic carbon content from a well in Noble County (Donahue, Anstey & Morrill-Shockling #1) was 0.79 wt.%, but in the same well the average for the Rhinestreet Shale was 2.35 wt.%. The organic carbon content tends to increase northward along the trend. Most of the kerogen appears to be derived from intermediate and/or marine sources, but terrestrial (woody-coaly) type kerogen predominates in the Chagrin Member. Thermal maturity, as measured by vitrinite reflectance, indicates that the carbon is moderately immature to moderately mature at the northern end of the trend, and mature at the southern end (Zielinski, et al.)

Drilling locations proposed within the Lake Erie shoreline trend (fig. 179) and the east-central (Cambridge arch) trend (fig. 180) have a sufficient thickness of organic-rich shale, favorable geochemistry, and a moderate to high fracture density.

GEOLOGIC RATIONALE FOR SELECTION OF PROPOSED LOCATIONS

Well Location #1--Cuyahoga County

Glacial drift is anticipated as being approximately 20 to 50 feet. There is approximately 200 to 225 feet of organic-rich shale. The area lies within a trend of reported gas shows, and is moderately well fractured (Struble and Hodges, unpublished).

Well Location #2--Lake County

Glacial drift varies from 60 to 100 feet. There is approximately 175 to 200 feet of organic-rich shale. The proposed location falls within an area of historic gas production and shows; the area is moderately fractured.

Well Location #3--Ashtabula County

Glacial drift varies from 20 to 50 feet. There is approximately 150 feet of organic-rich shale. The proposed location is adjacent to an area with gas shows from the Chagrin Shale, and is moderately fractured.

Well Location #4--Noble County, Jackson Township

The location is on the plunging nose of the Cambridge arch, lineaments trend northeast-southwest, and the fracture density is moderate to high. Commercial production has been reported from the Chagrin Shale in wells completed approximately two miles south of the location.

Well Location #5--Noble County, Noble Township

The location is near the intersection of two prominent geomorphic lineaments trending northeast and east-southeast, and locally, the fracture density is high.

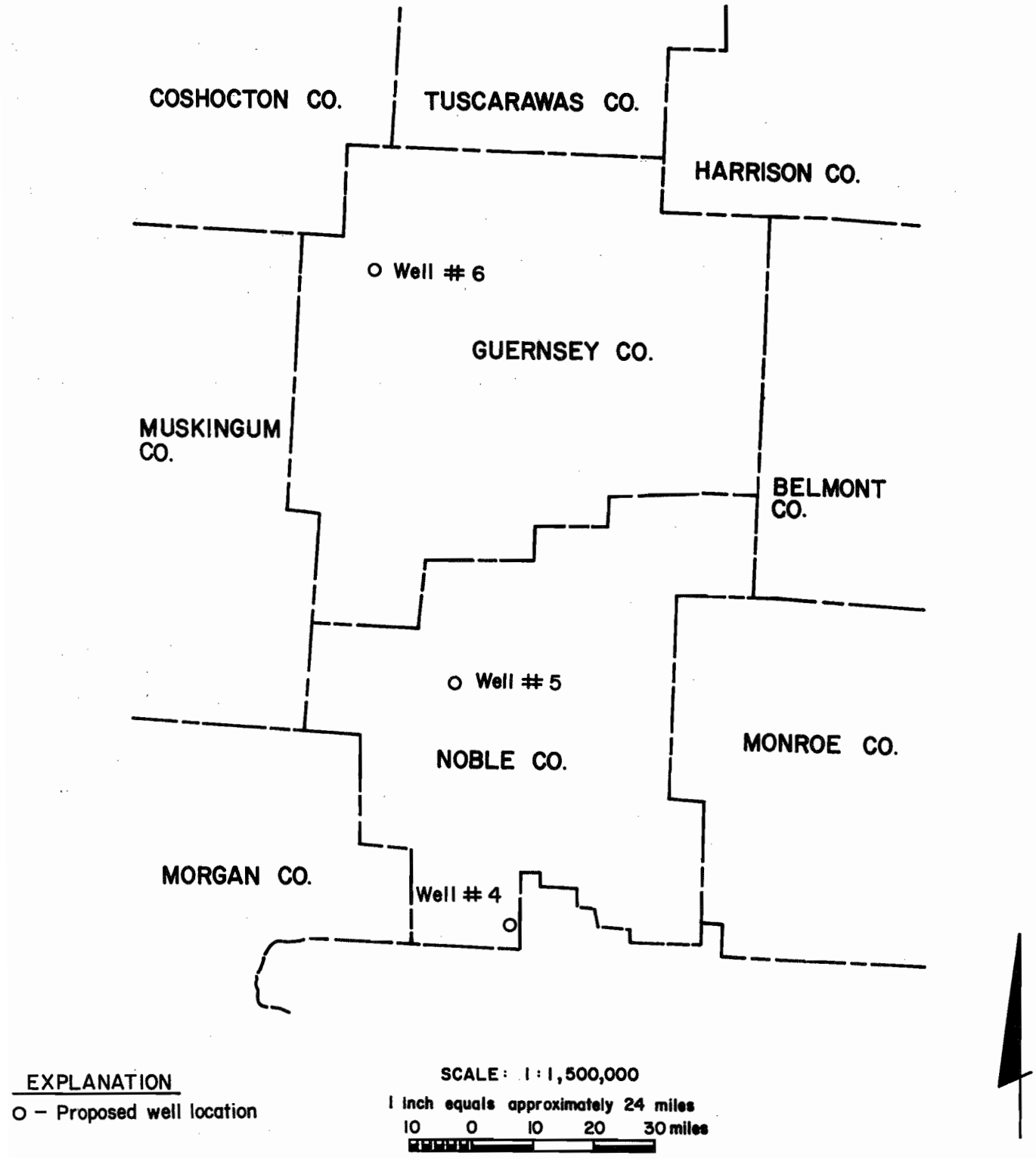


Figure 179. Proposed well locations for the East-Central (Cambridge Arch) Trend.

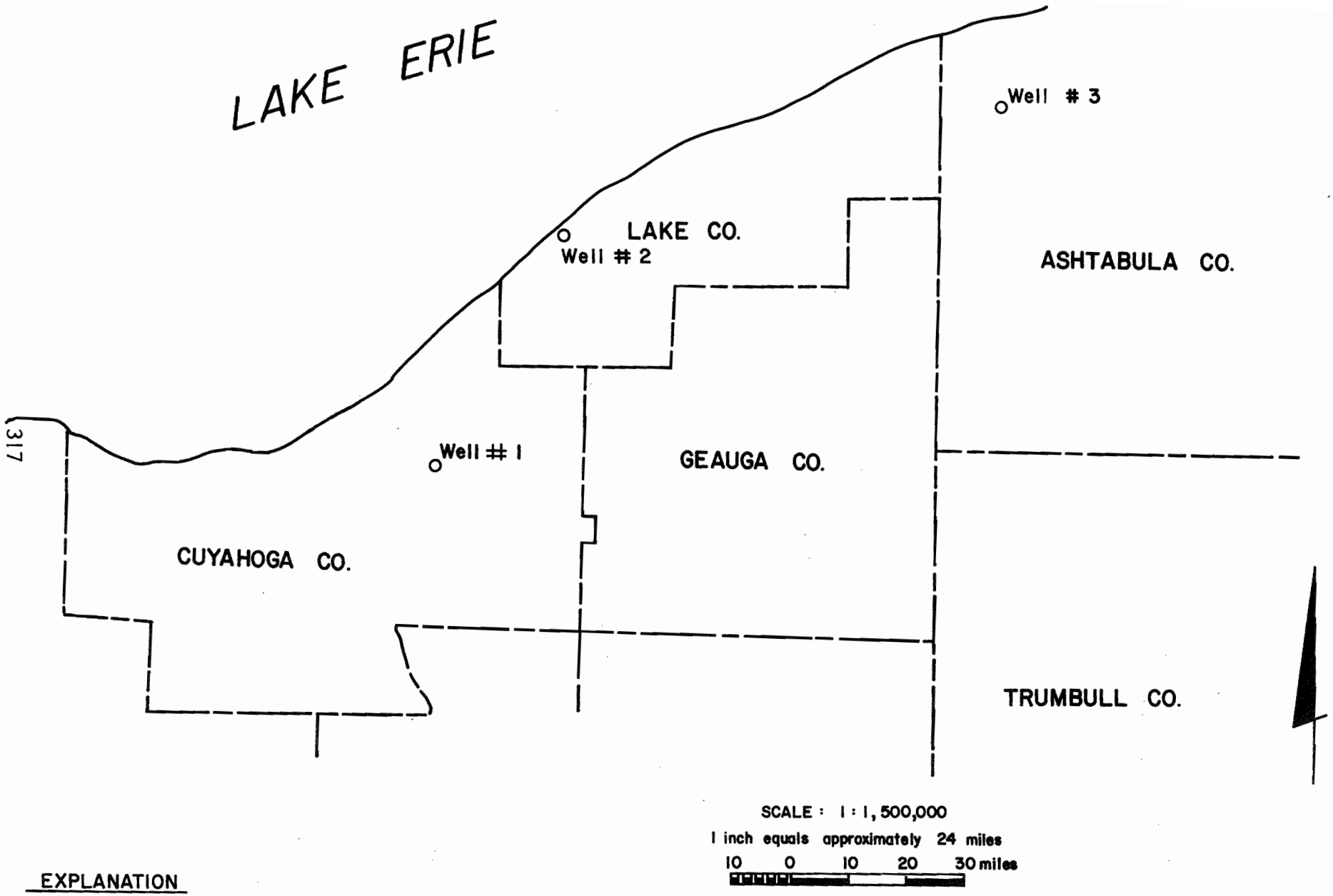


Figure 180. Proposed well locations for the Lake Erie Shoreline Trend.

Well Location #6--Guernsey County

The location is in an area of northeast and northward trending lineaments with a moderate fracture density. Commercial production has been reported from the Chagrin Shale in wells completed approximately two miles south of the location.

WELL PROGNOSES

Location No. 1

County:	CUYAHOGA	
Location:	Tract 4, L38, T8N, R11W, Brush High School	
Elevation:	970 Feet (Topo)	
Quadrangle:	East Cleveland, Ohio	
Total Depth:	1560 Feet (Onondaga)	
Formation Tops:	Cleveland	50
	Chagrin	75
	Huron	950
	Olentangy	1280
	Onondaga	1560

Location No. 2

County:	LAKE	
Location:	Card Tract L21, T10N, R10W, Jefferson School	
Elevation:	615 Feet (Topo)	
Quadrangle:	Eastlake, Ohio	
Total Depth:	1195 Feet (Onondaga)	
Formation Tops:	Chagrin	80
	Huron	590
	Olentangy	887
	Onondaga	1195

Location No. 3

County:	ASHTABULA	
Location:	Lot 16, T12N, R5W, Geneva High School	
Elevation:	700 Feet (Topo)	
Quadrangle:	Geneva, Ohio 7½ Quad	
Total Depth:	1480 Feet (Onondaga)	
Formation Tops:	Chagrin	50
	Huron	700
	Olentangy	1335
	Onondaga	1480

Location No. 4

County:	NOBLE	
Township:	Jackson	
Location:	Approx. 1250 feet from NL & 2400 feet from EL of Sec. 25	
Elevation:	900 Feet (Topo)	
Total Depth:	4330 Feet (Onondaga)	
Formation Tops:	Berea	1670
	Bedford/Chagrin	1680
	Huron	3000
	Olentangy	3550
	Onondaga	4330

Location No. 5

County:	NOBLE
Township:	Noble
Location:	Approx. 1000 feet from SL & 900 feet from WL of the SW¼ of Sec. 16
Elevation:	960 Feet (Topo)
Total Depth:	3920 Feet (Onondaga)

Formation Tops:	Berea	1460
	Bedford/Chagrin	1510
	Huron	2820
	Olentangy	3370
	Onondaga	3920

Location No. 6

County:	GUERNSEY
Township:	Knox
Location:	Approx. 300 feet from NL & 1520 feet from EL of Sec. 10
Elevation:	1065 Feet (Topo)
Total Depth:	3420 Feet (Onondaga)

Formation Tops:	Berea	1210
	Bedford/Chagrin	1280
	Huron	2530
	Olentangy	2980
	Onondaga	3420

Exploration Parameters Establishing Site Specific Areas for Devonian Shale Targets in Eastern Kentucky

INTRODUCTION

The dark, organic-rich shales which underlie the Appalachian, Michigan, and Illinois basins represent an important unconventional natural gas resource. Since the inception of shale gas production in 1821, near Fredonia, New York, approximately 2.5 Tcf of natural gas has been produced. Approximately 2.0 Tcf of this total has been produced from the Big Sandy Field of eastern Kentucky, located in Floyd, Knott, Perry, Pike and Martin Counties. It should be possible to extend or find new shale gas fields if the factors responsible for forming the Big Sandy Field can be delineated and applied to favorable geologic areas found elsewhere in eastern Kentucky.

Recent studies of the Big Sandy and other Devonian shale gas fields, under funding from the Department of Energy's (DOE) Eastern Gas Shales Project (EGSP), have characterized stratigraphic, geochemical, and structural parameters that influence potential gas occurrence in the Devonian shales. The following parameters are considered to be of paramount importance in the accumulation, generation, and production of shale gas.

PRODUCTION POTENTIAL INDICATORS

The deposition of thick sequences of black, organic-rich shales is generally considered as representing the source beds from which shale gas is generated. In eastern Kentucky, the Lower Huron Shale, unit 5 of Provo's classification (fig. 181), represents the thickest, most laterally continuous black shale facies.

The transformation of organic matter into petroleum and natural gas is a function of a variety of geochemical parameters. 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.

The presence of an extensive natural fracture system is required for significant shale gas production to occur. These natural fracture systems develop as the result of structurally induced forces and provide the porosity and permeability necessary for the accumulation and movement of natural gas in the reservoirs. Stress ratios, the calculated ratio of minimum of horizontal stress to overburden thickness, have been correlated to areas of structural activity; the lower the stress ratio value, the more structurally favorable the area. Figure 109, page 203 shows the stress ratio/fracture gradients prevalent throughout eastern Kentucky.

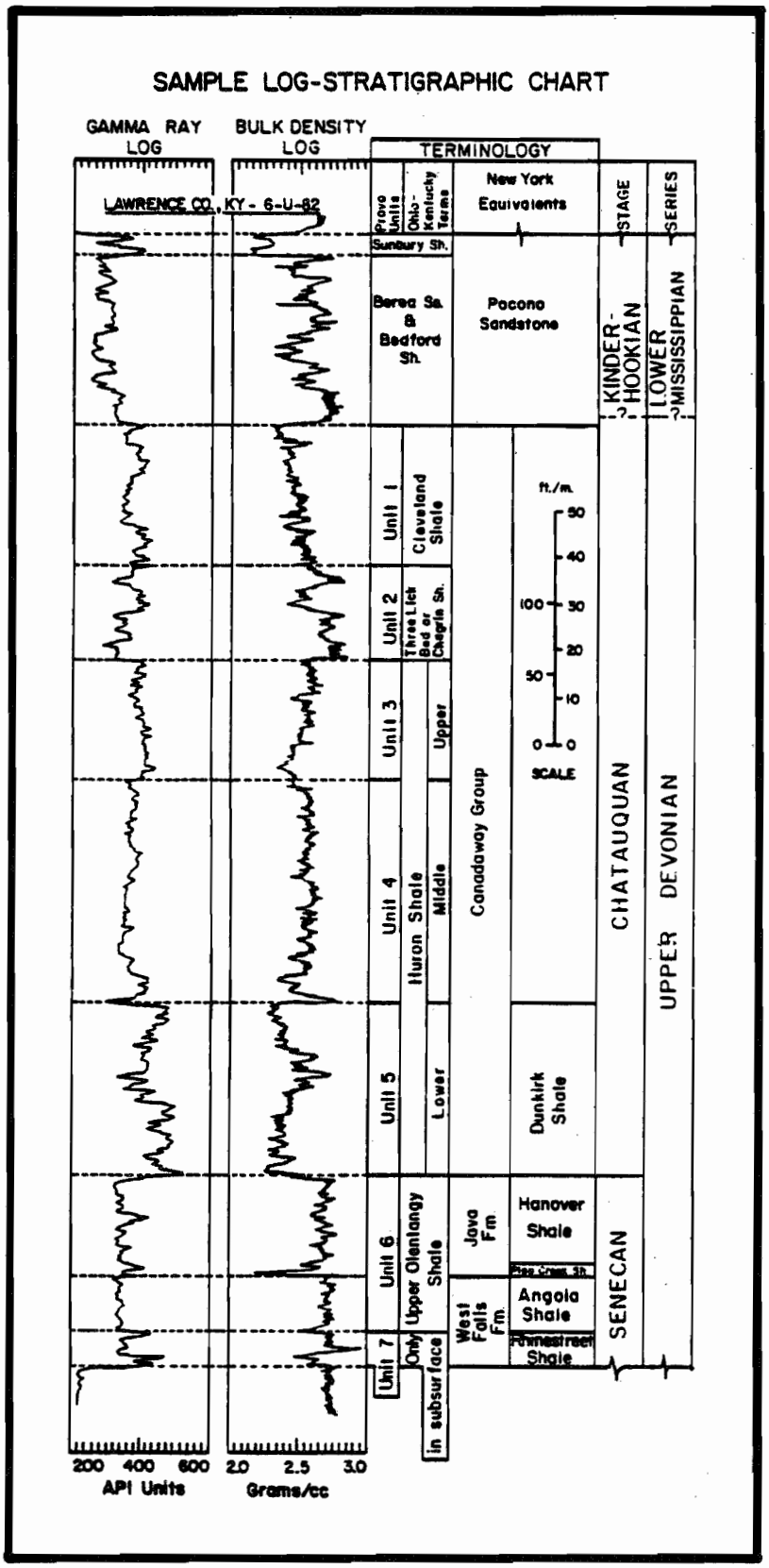


Figure 181 . Chattanooga (Ohio) Shale stratigraphic chart. After Provo, et al. (1977).

For these reasons, the "Lower" Huron Member of the Ohio Shale was chosen as the most representative target to test the Devonian Shale exploration rationale. The Lower Huron is a black shale that exhibits the most uniformly radioactive facies within the Ohio Shale sequence in eastern Kentucky. This high radioactivity, caused by the radioactive elements present in the organic material incorporated in the shale, indicates a correspondingly high organic content in this zone. The amount of organic carbon should be well above the .5% weight thought to be necessary for economical hydrocarbon generation. The "Lower" Huron Member of the Ohio Shale is easily picked from gamma ray logs (fig. 181, page 322).

The black Lower Huron is overlain by the greenish-gray Middle Huron throughout eastern Kentucky. If the Lower Huron is indeed a source rock, the silty facies within the Middle Huron could represent a potentially favorable reservoir. Organically lean facies will not be as susceptible to fracturing as the organic-rich Lower Huron, allowing gas to migrate from the black shale facies to the less fractured silty zones within the Middle Huron. Therefore, the operator should be aware of the shale gas potential in the silty and/or fractured Middle Huron.

The factors, then, that should be satisfied in choosing a specific shale well location include:

(1) An area with relatively thick potential source rock.
(2) An area that is thermally mature:
    a) A horizon with organic carbon greater than .5% by weight.
    b) An area suspected to have an intermediate (part humic and part sapropelic) type of kerogen present.
(3) An area with faults, fractures, and joints in the shale to encourage secondary porosity.

These points were those that were used in determining locations for shale wells to be drilled in eastern Kentucky. No shale area exhibited all of the above features, so a balance had to be reached between them.

GEOLOGIC RATIONALE FOR SELECTION OF DRILLING LOCATIONS

Well #1--Morgan-Magoffin Co. Line (fig. 182)

This is an area with a relatively thick (approximately 100') Lower Huron section. The Lower Huron is primarily a black, organic-rich shale. The organic carbon percentage contained within the black shale facies should be well above .5% by weight. The target is very attractive structurally, lying near the Irvine-Paint Creek fault system. The fault complex originated as a deep seated basement normal fault that has propagated upward, displacing the overlying sediments. Additionally, this movement should have caused some type of splay faulting in the shale adjacent to the fault trace. The drilling location is also just west of the Paint Creek uplift, which was not a positive feature in Devonian time. Its movement started in the late Devonian and increased during Mississippian, Pennsylvanian, post-Pennsylvanian, and Cretaceous time, and should have placed enough stress on the Devonian shales to have caused further fracturing. Although there has been limited work with stress ratio analyses in eastern Kentucky, it appears that this area is within the .43-.7 range required.

The biggest negative aspect to this location is one that is a uniform problem throughout eastern Kentucky: the kerogen appears to be thermally immature. The

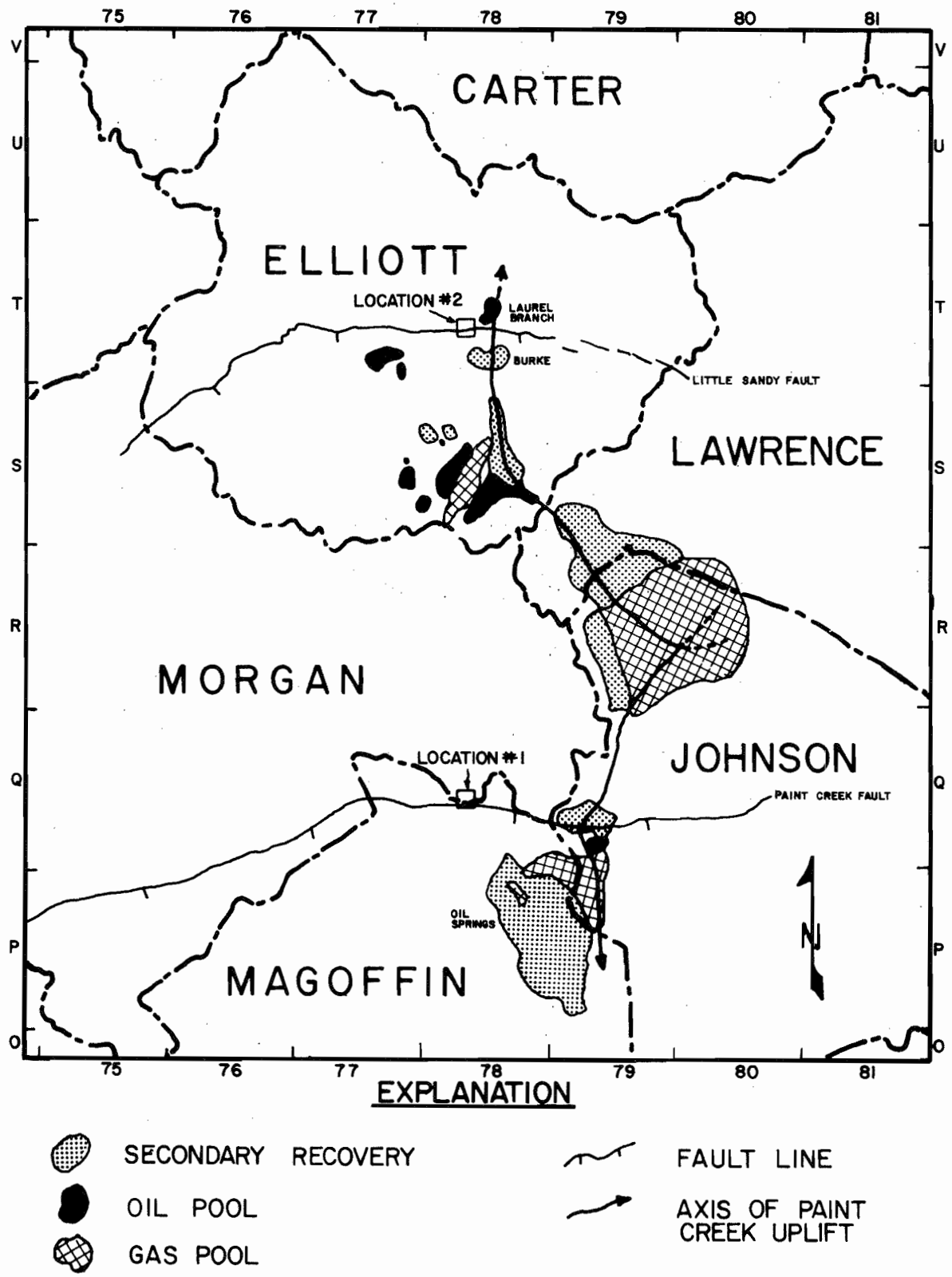


Figure 182 . Devonian Shale Targets in Magoffin/Morgan and Elliott Counties.

amount of gas produced per unit of shale is significantly less than that produced from shale in other areas with similar characteristics (Table 7). The thermal maturation indices bear this out (Table 8).

There has been shallower production in this area. It is northwest of the Big Sandy (Devonian) gas field and is just outside of the Oil Springs (Mississippian-Pennsylvanian) secondary recovery area. Texas International Petroleum's #1-Lowell Hopkins was completed recently (3-13-81) west of this location (Carter Coordinate 14-Q-77). It was reported as a commingled Corniferous-Devonian Shale well (P.I. Report 8-28-81).

Well #2--Elliott Co. (fig. 182, page 324)

This is an area with very similar geologic characteristics to the first location. Again, the Lower Huron is about 100 feet thick and is an organic-rich black shale. Its organic carbon percentage should be above the needed figure. The structure involved is very similar to the first location. It is situated along the Little Sandy fault trace and is in the area affected by the deep-seated fault that not only has propagated upward, affecting the overlying strata, but has led some investigators to conclude that it is a high angle normal fault that has reserved itself (Silberman, 1972). The location's regional stress ratio is marginally favorable (.7), but could be locally much more heavily fractured for the aforementioned reasons.

Two small Mississippian fields are near the Little Sandy fault zone, the Laurel Branch field and the Burke secondary recovery area.

Again, the kerogen in the shale is probably thermally immature.

Well #3--Clay County (fig. 183)

The reasons for choosing this area are different from those in either Well #1 or Well #2. The Lower Huron section in Clay County is about 30 feet thick, and the entire Ohio Shale sequence is only somewhat over 100 feet thick. However, the Lower Huron exhibits a more uniform radioactive facies than the Lower Huron of farther east. It thins and is draped over the Rockcastle River uplift of Laurel, Clay and Oswley Counties. This feature was positive during Devonian time, but the shale may have been subjected to stress and generated during rejuvenation in the Mississippian-Early Pennsylvanian time. The rationale for choosing this location was to find an area off of the structural crest where the angle of dip of the shale beds changes. Structure contour maps and isopach maps of the Lower Huron show such a local anomaly in the area of the pick. Tensile fractures should be present to stimulate secondary porosity gas flow.

Geochemically the area contains more organic carbon by percent than the other two, but again, the kerogens are probably thermally immature.

There has been historical shale gas production from the crest of the Rockcastle River uplift. The Little Goose Gas Field is about 3-4 miles northeast.

Table 7. **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	-

Table 8. **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

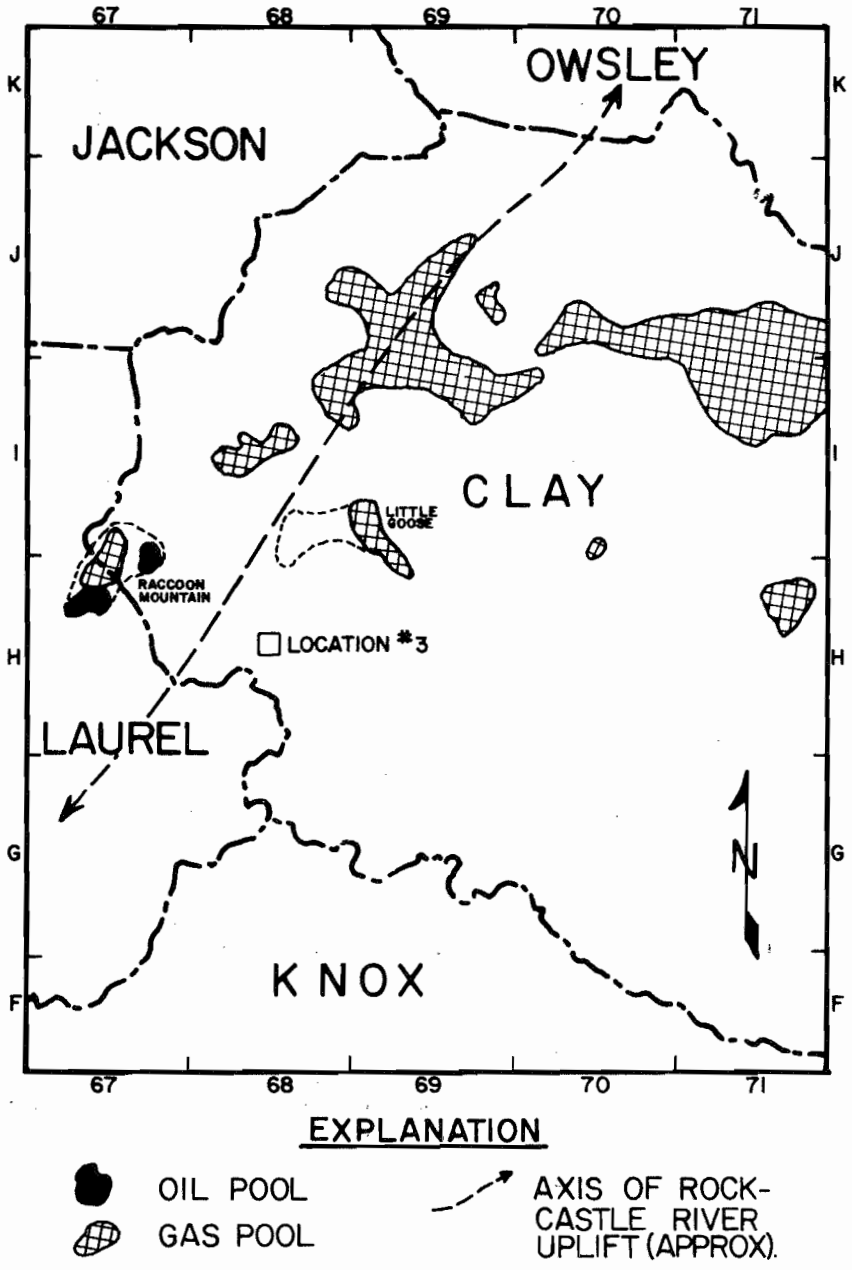


Figure 183 . Devonian Shale Target in Clay County.

WELL PROGNOSES

Well #1--Morgan-Magoffin County Line

Well Location/Description

1. Saylersville North Quadrangle
2. Carter coordinate system: 12-Q-78, 13-Q-78; or 18-Q-78
3. Well should be in vicinity of Paint Creek Fault; on east end of Lacey Creek Syncline; and west of the crest of the Paint Creek Uplift
4. This will be near the Morgan/Magoffin County Line

Target: Lower Huron Member of the Ohio Shale

Prognosis:

Average Elevation 1050 feet

Unit	Est. Top	Est. Base
Berea	1250	1300
Ohio Shale	1300	
Lower Huron	1580	1700
Corniferous	1800	

Well #2--Elliott County

Well Location/Description

1. Isonville Quadrangle
2. Carter coordinate system: 15-T-78 or 16-T-78
3. Well is in Elliott County
4. Well should be in the vicinity of Little Sandy Fault, and west of the crest of the Paint Creek Uplift

Target: Lower Huron Member of the Ohio Shale

Prognosis:

Average Elevation 850 feet

Unit	Est. Top	Est. Base
Weir 1	735	750
Weir 2	775	800
Sunbury Shale	840	860
Berea	860	925
Ohio Shale	990	
Lower Huron	1270	1370
Corniferous	1400	

Well #3--Clay County

Well Location/Description

1. Location at intersection of Hima, Blackwater, Portersburg and Manchester Quadrangles
2. Carter coordinate system: H-68-8, 9, 12, 13, and 14
3. Well is in Clay County
4. Well should be on the SE flank of the Rockcastle Uplift, in the Urban Fork-Little Goose Creek area

Target: Lower Huron Member of the Ohio Shale

Prognosis:

Average Elevation 1200 feet

Unit	Est. Top	Est. Base
Big Lime	960	1150
Ohio Shale	1500	
Lower Huron	1640	
Corniferous	1670	1670

Exploration Parameters Establishing Site Specific Areas for Devonian Shale Targets in the Michigan Basin

INTRODUCTION

Recent studies undertaken by Eastern Gas Shales Project investigators have shown that the Devonian shales occurring within the Michigan basin are excellent source-rocks for the generation of hydrocarbons, and have good potential as reservoirs for local accumulations of natural gas. Two factors responsible for increased interest in the Devonian shales of the Michigan basin as an exploration target for natural gas were (1) sharp increases in natural gas prices at the wellhead, and (2) knowledge that the shales had potential as natural gas reservoirs from previously demonstrated drilling and production history and reported shows of oil and gas. Natural gas from the Devonian shales was discovered in Ostego County, Michigan in 1940 and new discoveries have been reported intermittently through 1977. Another factor which stimulated early interest in detailed investigations of the Devonian-age shales in Michigan was the extremely thick Antrim/Ellsworth shale sequence in the basin. The thickness and distribution of the Antrim/Ellsworth sequence is shown on figure 69, page 134. The stratigraphic position of the Antrim/Ellsworth sequence in the Devonian System is shown on the generalized stratigraphic column (fig. 184).

The Michigan basin, oval in shape and centered in the middle of the Lower Peninsula, is bounded by the following structural elements: (1) the Findlay arch and the Algonquin axis to the southeast and east; (2) the Canadian shield to the north; (3) the Wisconsin highlands to the northwest and west; and (4) the Kankakee arch to the southwest. Devonian-age shales underlie approximately 120,000 square miles of area within the confines of the basin. The areal distribution of the basin and the bounding structural elements is shown on the generalized subcrop map of the Paleozoic rocks (fig. 185).

PRODUCTION POTENTIAL INDICATORS

Four factors were used to characterize the potential of the Devonian shales of the Michigan basin as a potential reservoir for natural gas. Two of the factors, shale thickness, and historical gas production and reported shows of oil and gas, were previously mentioned. Two other important factors are organic carbon content of the shales, and secondary porosity resulting from natural fractures.

Analysis of 280 Michigan basin Antrim shale samples demonstrated the atypical richness of organic carbon of the Antrim sequence when compared to other black shale sequences worldwide (Tetra Tech, Inc., DOE/METC, 123, 1981). On the average, the Antrim was found to be three or four times richer in organic carbon than the Dunkirk/"Lower" Huron and Rhinestreet black shale sequences, which are considered the hydrocarbon source rocks for the Appalachian basin. Because of this rich organic carbon content, the Antrim sequence is considered to have greater than usual potential as a source rock for generation of natural gas. Shale beds with high organic content can be correlated with high gamma ray responses on radioactive logs because of the association of radioactive elements with organic content. Therefore, analysis of gamma ray logs permits basin wide mapping of the thickness and distribution of the radioactive shales and development of lithofacies maps. Figure 149, page 259 shows the distribution and

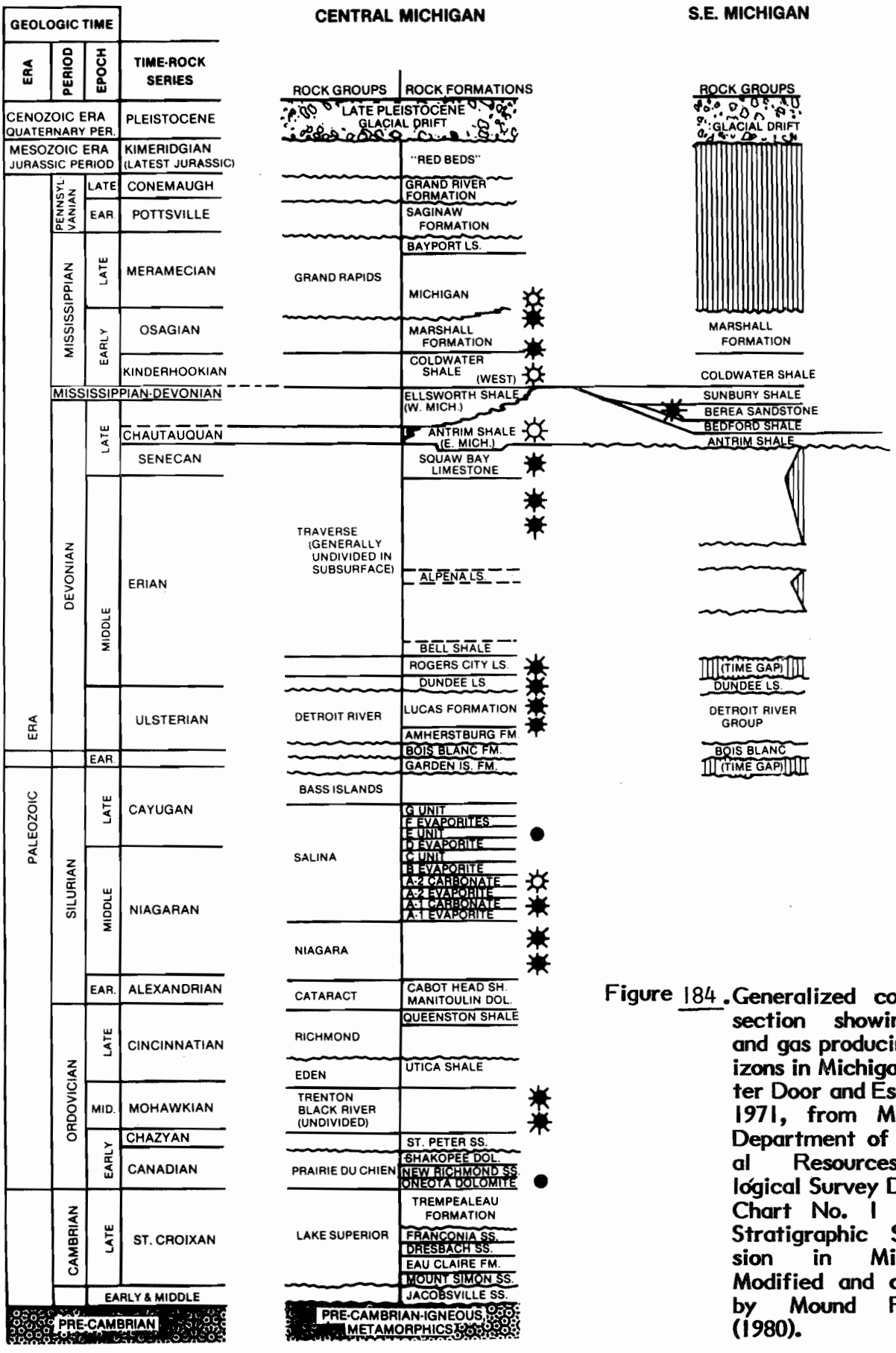


Figure 184. Generalized columnar section showing oil and gas producing horizons in Michigan. After Door and Eschman, 1971, from Michigan Department of Natural Resources--Geological Survey Division Chart No. 1 (1964), Stratigraphic Succession in Michigan. Modified and adapted by Mound Facility (1980).

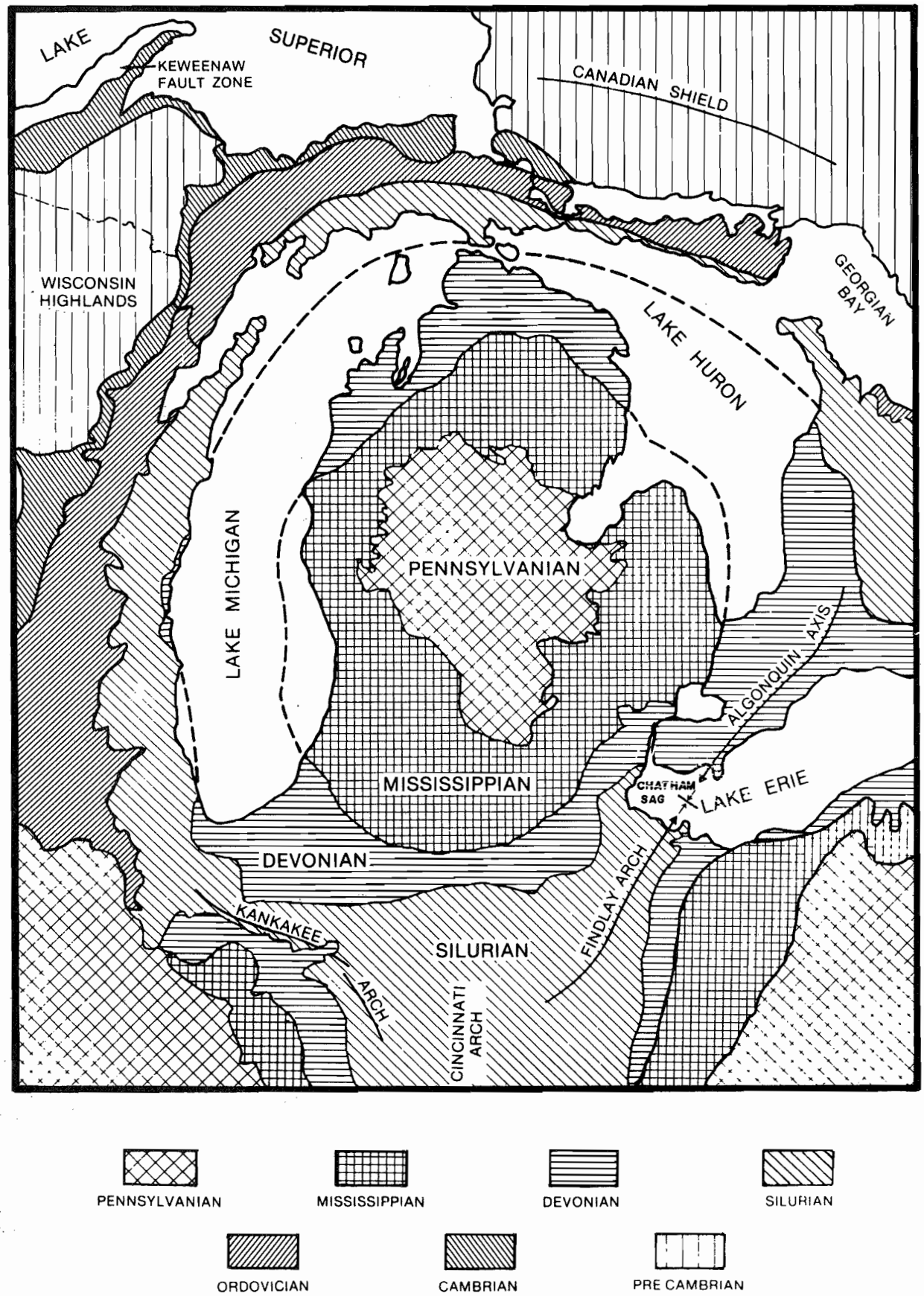


Figure 185 . Subcrop map of Paleozoic rocks beneath the glacial drift in the Michigan basin and surrounding area. Mound Facility (1980).

thickness of net radioactive shale in the Bedford/Antrim interval, and figure 186 shows the percent radioactive shale versus nonradioactive shale for the Bedford/Antrim interval.

Natural fractures within rocks of the Michigan basin have been recognized by geologists for many years (Tetra Tech, Inc., DOE/METC, 1981). An orthogonal systematic joint set distributed throughout the basin shows a relatively predictable spacing and preferred orientation. Another joint set is associated with local structural features within the confines of the basin. Production of oil and gas from Devonian carbonates below the Antrim is associated with closures along the axis of anticlinal structures with general northwest-southeast trend. These anticlinal trends have been projected nearly across the basin by geologists within the Michigan Geological Survey by connecting the producing field along the observed structural grain of the basin (Michigan Geological Survey, 1937). The age of the anticlinal structures is interpreted to be post-Devonian, so that fractures generated along and over these folds should intersect Antrim shales, hence within the Michigan basin maximum fracture development is anticipated along the axis of the anticlinal structural trends or at the intersection of anticlinal trends.

Based upon the data from the geochemical, stratigraphic, and structural investigations as well as Devonian shale production and hydrocarbon show data, the northeastern portion of the Lower Peninsula of Michigan appears to offer the greatest potential for the development of the natural gas resource within the Antrim shale sequence. The area with the greatest potential is indicated by the cross-hatched area of figure 151, page 261.

GEOLOGIC RATIONALE FOR SELECTION OF DRILLING LOCATIONS

The proposed drilling locations and alternates fall within the area of the Michigan basin identified as having the greatest potential for gas production from the Devonian Antrim Shales.

Proposed sites are located in the area exhibiting thick radioactive shale, high organic carbon content, geologic structure and associated fractures and production and shows of oil or gas from the Berea or Antrim shale.

The proposed locations and alternate prospect areas are located at the junctions of anticlinal trends which intersect at nearly right angles. Locations 1 and 2, and Alternate Site 1 mark the areas where the northeast-southwest projection of the Pinconning anticline intersects northwest trends of anticlinal structures through Bay, Midland, Iosco, and Ogemaw counties. The Pinconning projection also aligns with a lineament that generally defines the northwest shore of Saginaw Bay. Location 3 and Alternate Site 2 mark the intersection of northwest anticlinal trends by a northeast-southwest projection along the axis of the North Adams anticline. Alternate Sites 3, 4 and 5 are located where fracture of southwest projections of lineaments defining the southeast shore of Saginaw Bay intersect with the northwest anticlinal trends. The locations and structural features are shown on figure 187.

Fracture development resulting from the past shale anticlinal generation is anticipated to be enhanced at the point of intersection of the projected structural features.

In the vicinity of Location 1 (T14N-R3E), Location 2 (T19N-R6E) and Location 3 (T22N-R4E), near the interpreted intersection of the above cited structural trends, production of oil or gas from the Berea, or shows of gas from the Berea are reported. The production and shows are from within the Berea sandstone overlying the Antrim shale; hence, this juxtaposition strongly suggests the gas has migrated upward into the sandstone from the underlying Antrim.

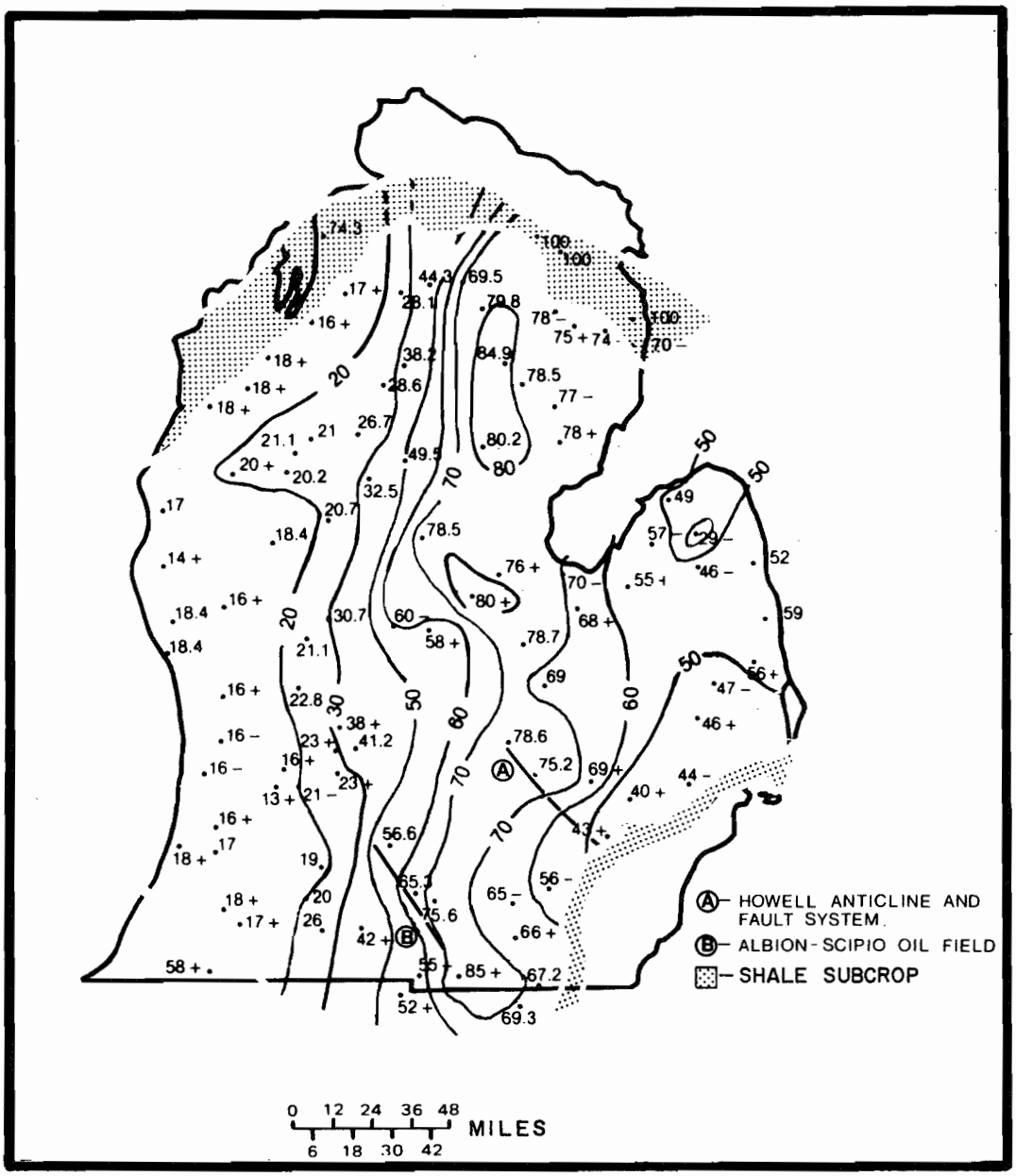


Figure 186 . Percent radioactive shale greater than 20 API units over Bedford or lower Ellsworth baseline in the Bedford/Antrim or Ellsworth/Antrim Shales. Mound Facility (1980).

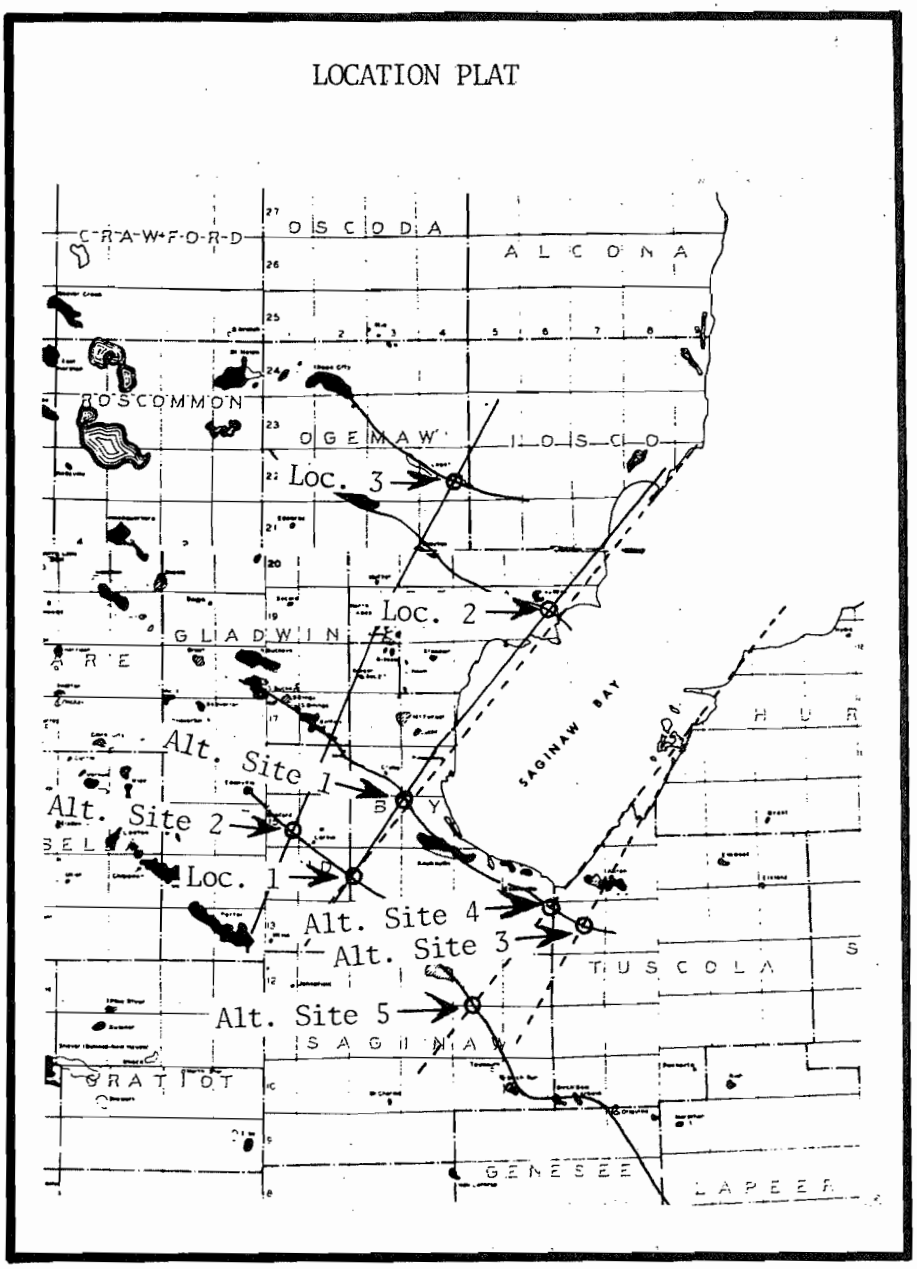


Figure 187 . Location Plat, Michigan basin drilling locations.

WELL PROGNOSES

Location No. 1

County:	BAY
Township:	Williams
Location:	CSW¼ Section 18 T14N-R3E (Alternate CSW¼ Section 7 T14N-R3E)
Elevation:	645 Feet (Topo)
Quadrangle:	Midland South (Alternate, Midland North)
Casing:	8-5/8 @ 650 feet 5-1/2 @ 2800 feet
Total Depth:	2800 feet (Traverse)

Formation Tops:

Berea	2289 (-1644)
Bedford	2335 (-1685)
Antrim	2440 (-1790)
Traverse	2784 (-2134)

Location No. 2

County:	ARENAC
Township:	Au Gres
Location:	CNW¼ Section 15, T19N-R6E (Alternate CNE¼ Section 16, T19N-R6E)
Elevation:	590 Feet (Topo)
Quadrangle:	Au Gres, Michigan
Casing:	8-5/8 @ 390 feet 5-1/2 @ 3000 feet
Total Depth:	2100 feet (Traverse)

Formation Tops:

Berea	1530 (-940)
Antrim	1700 (-1110)
Traverse	2071 (-1480)

Location No. 3

County:	OGEMAW	
Township:	Logan	
Location:	CNW¼ Section 26, T22N-R4E	
Elevation:	830 Feet (Topo)	
Quadrangle:	Sage Lake, Michigan	
Casing:	8-5/8 @ 600 feet 5-1/2 @ 2200 feet	
Total Depth:	2325 feet (Traverse)	
Formation Tops:	Berea	1780 (-950)
	Antrim	1940 (-1010)
	Traverse	2308 (-1470)

Alternate Prospect Site 1 (No Map)

Bay County

T15 and 16N-R3 and 4E

Section 6, T15N-R4E; Section 31 T16N-R4E

Section 1, T15N-R3E; Section 36 T16N-R3E

Alternate Prospect Site 2

Midland County, Lincoln Township

T15N-R1E

Sections 14, 15, 22 and 23

Averill, Michigan Quadrangle

Alternate Prospect Site 3

Bay County, Gillford Township

T13N-R7E

Section 15

Quanicassee, Michigan Quadrangle

Alternate Prospect Site 4 (No Map)

Bay County

T13N-R6E N-1/2 Section 1

T14N-R6E S-1/2 Section 36

Alternate Prospect Site 5 (No Map)

Saginaw County

T12N-R5E S-1/2 Section 33

T11N-R5E N-1/2 Section 3

Exploration Parameters Establishing Site Specific Areas for Devonian Shale Targets in the Illinois Basin

INTRODUCTION

A portion of the Department of Energy's (DOE) search for future energy reserves is the evaluation of unconventional gas sources not considered by the private energy companies. In the eastern United States, this assessment, the Eastern Gas Shale Project (EGSP), includes the Devonian black shales which underlie portions of the Appalachian, Illinois, and Michigan basins. The locations presented in this report were chosen as a current state-of-the-art assessment of the Devonian shale exploration rationale in the Illinois basin. The proposed locations fall within that portion of the basin considered to have the greatest shale gas potential (fig. 146, page 254).

The New Albany Shale has produced commercial quantities of gas in southern Indiana and western Kentucky and shows have been reported in southeastern Illinois. Recent reserve estimates have assigned 86 trillion cubic feet of natural gas to the black shales of the Illinois basin (National Petroleum Council, 1980). The quantity of potential gas reserves and the price incentives enacted by the Natural Gas Policy Act (1978) make this an extremely attractive resource.

The Devonian shale sequence of the Illinois basin is considered to represent not only a favorable source bed from which shale gas was generated, but also a potential reservoir, given the proper geologic conditions. The gas shows and production correlate with the area of the thickest black shale accumulation, which, in turn, is the area of the highest percentage of organic-rich black shale facies. This area also exhibits the highest thermal maturity of sedimentary organic matter in the Illinois basin. Extensive faulting and fracturing is present throughout the area, providing the porosity and permeability necessary for commercial shale production. These geologic parameters are considered to be of paramount importance for the accumulation, generation, and production of shale gas.

GEOLOGY

The New Albany Shale Group ranges in age from Middle Devonian through early Mississippian, with deposition centered in southeastern Illinois and western Kentucky (fig. 84, page 158). Paleogeographic reconstruction of the depositional environment indicates that the black, organic-rich facies was deposited in an anoxic, deep basin that accumulated a maximum shale thickness of 460 feet. These shales conformably overlie the Middle Devonian limestones (Hunton Megagroup) and, in turn, are conformably overlain by Mississippian age limestone (Chouteau). Black shale facies contained within the New Albany include the Blocher, middle Selmier, and Grassy Creek shales (fig. 188). The Grassy Creek is generally considered as having the thickest, most laterally continuous organic-rich facies. It has the highest organic carbon content and gas-release values from the Devonian shale section. For these reasons, the Grassy Creek Shale should be considered as having excellent potential.

Transformation of the organic matter, buried syndepositionally with the inorganic sediments of the New Albany Shale, into petroleum and natural gas is dependent upon a

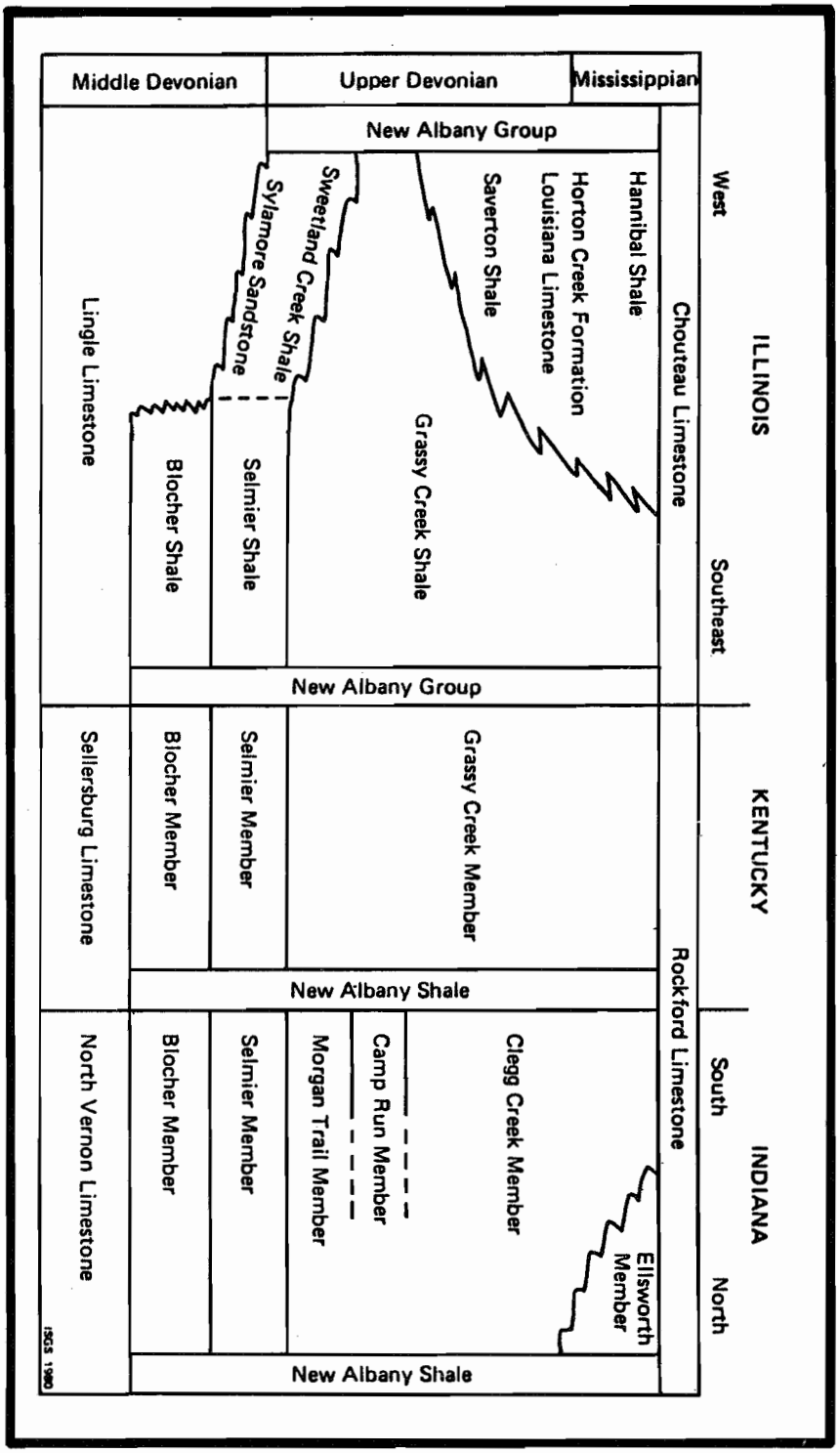


Figure 188. Stratigraphic nomenclature of the New Albany Shale Group in the Illinois basin. From Illinois State Geological Survey, Lineback (1980).

variety of geochemical processes. One of the best methods of establishing the relative thermal maturity of the organic material contained within the black shale facies is to measure its vitrinite reflectance (Barrow, Cluff, and Harvey, 1979; Potter et al., 1980). Hydrocarbon generation does not occur in sediments exhibiting a mean vitrinite reflectance value of less than 0.5. Figure 189 shows the isoreflectance of vitrinite for Illinois, from which areas of higher thermal maturity can be estimated. However, the geochemical processes responsible for the generation of methane are generally associated with areas of low permeability, restricting the flow.

Gas production from Devonian shales in western Kentucky and the Appalachian basin is derived primarily from extensive natural fracture systems that provide the secondary porosity and permeability necessary for the accumulation and migration of gas within the reservoir. Gas movement from non-fractured shale reservoirs is generally considered uneconomic because of the very low porosity and permeability of the shales. The New Albany Shale of southeastern Illinois and western Kentucky has been subject to extensive deformational forces, providing a locally extensive fracture system. Major structural axis include the 38th Parallel Fault System (represented by Rough Creek-Shawneetown-Cottage Grove complex), the Wabash Valley-Fluorspar Area System (both are northeast trending complexes but not connected), and the Hicks Dome. The influence of particular structures on the proposed drilling locations will be discussed with the exploration rationale of the site.

A successful exploration program for the prediction of commercial shale gas reserves should include, but not be limited to:

1) An area having a thick, laterally extensive source rock;
2) A source rock that contains a high percentage of organic carbon;
3) The area should be thermally mature, indicating that a sufficient time-temperature gradient has been established for the generation of methane;
4) The presence of extensive natural fractures to allow the storage and movement of gas.

These points were used in determining locations for shale wells in southeastern Illinois and western Kentucky. Few drill sites exhibit all of the aforementioned criteria, thus a balance was struck to achieve the optimum favorable location.

GEOLOGIC RATIONALE FOR DRILLING LOCATION SELECTION

Well No. 1--Saline County, Illinois--T9S, R5E

The gross shale thickness of the New Albany Group is in excess of 350 feet. Cumulative radioactive facies thickness varies between 150 and 175 feet (radioactive shale values were calculated from gamma ray curves that exceed a normal shale base line by a minimum of 60 API units). The Grassy Creek Shale is considered to represent the primary target, but the other organic-rich facies should also be considered as having potential. The organic carbon content of the Grassy Creek in Saline County range between 4.38 and 7.28 percent (Illinois State Geological Survey, 1980); vitrinite reflectance values vary from 0.9 to 1.0 indicating that a sufficient time-temperature gradient has existed to establish the source rock as thermally mature and that the generation of methane was initiated.

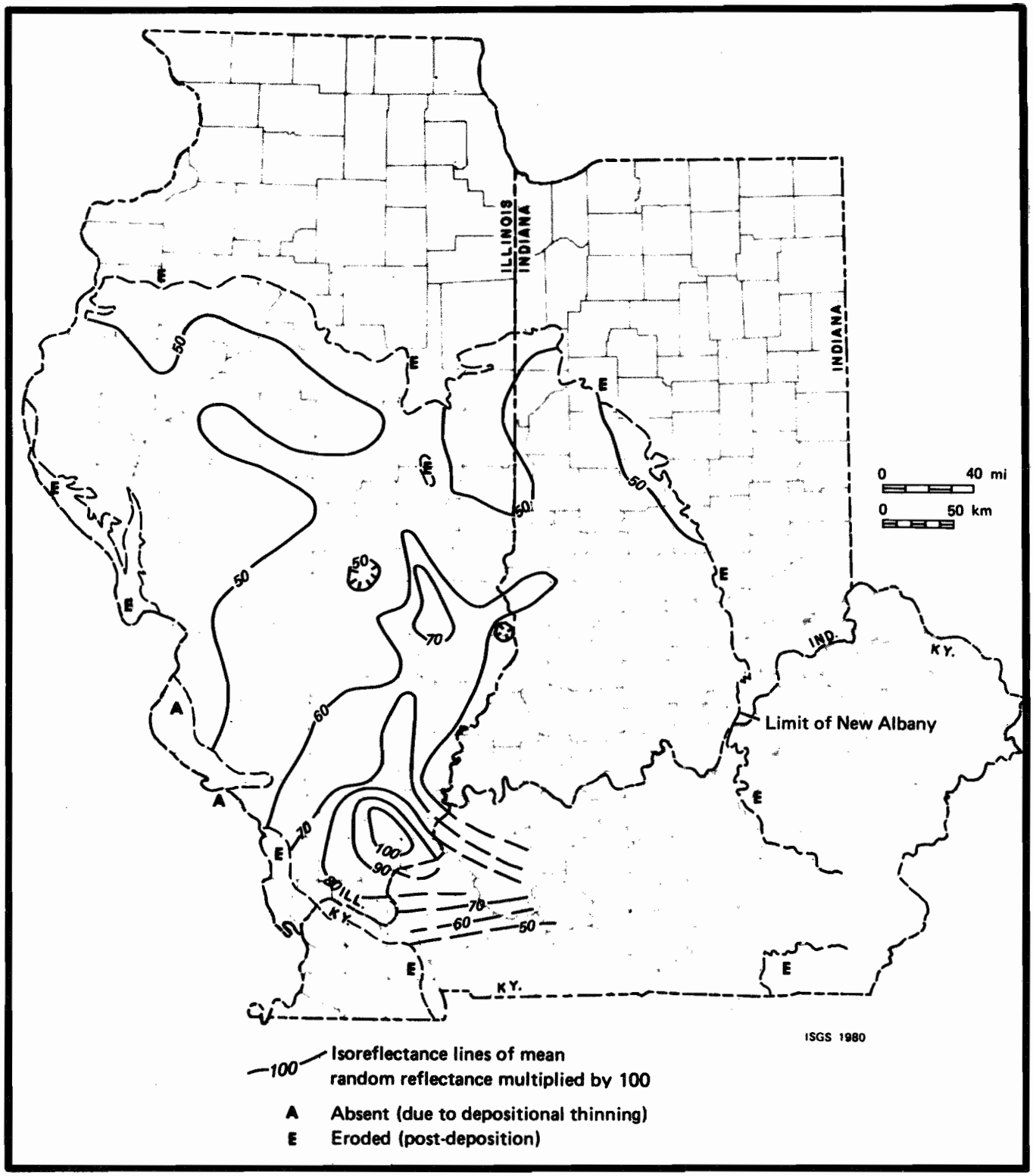


Figure 189. Mean random reflectance of vitrinite in the New Albany Shale Group (R_o percent x 100). Limited data from Indiana and Kentucky. From Illinois State Geological Survey, Lineback (1980), after Barrows, Cluff, and Harvey (1978).

The proposed location is within the Cottage Grove fault system (fig. 190). This system is interpreted as an east-west right-lateral wrench fault with a normal component, the downthrown block generally to the south. This fault complex was active from Devonian time throughout the rest of the Paleozoic (Krauss and Treworgy, 1979), suggesting that not only was sedimentation influenced, in part, by structural displacement, but also that after lithification the shales were subject to repeated episodes of deformation. The Cottage Grove complex is expected to provide an excellent fault-fracture system, allowing production of commercial quantities of shale gas.

The C.E. Brehm #1 Ozment (a dry hole drilled in 1965) is the only recorded well to penetrate the Devonian shale interval in T9S,R6E. The well had no reported gas shows from the New Albany section. However, the lack of natural shows from this well does not preclude the area's shale potential. Rather, low formation pressures and permeabilities, coupled with the use of high-density mud-based fluid systems, severely retard gas flow into the well bore.

The area has produced from several Mississippian age reservoirs, north of the proposed location, making dual completion a distinct possibility.

Well No. 2--Saline County, Illinois--T10S,R7E

Geologic conditions for this area are similar to the first area. The New Albany Shale is slightly thicker, approximately 350-400 feet, with a corresponding thicker cumulative radioactive shale interval (175 to 200 feet). The organic carbon content of the Grassy Creek is somewhat lower, approaching 4.38 percent (Illinois State Geological Survey, 1980); moreover, vitrinite reflectance values of 1.0 percent or greater are anticipated. The test location is within the east-west trending Shawneetown-Rough Creek Fault System, which is characterized by high angle normal and reserve faults, generally down-thrown to the south, and with a component of strike-slip displacement (fig. 191). Fault movement is thought to have been initiated during the Middle Cambrian and continued during the Devonian (Krauss and Treworgy, 1979). Large scale displacement, possibly occuring during early Permian time, reversed the previous normal fault movement. Additionally, the well location is immediately north of the Hicks Dome (thought to represent late Pennsylvanian-early Permian displacement). Tension associated with the uplift formed a series of radial faults in the New Albany, potentially enhancing the porosity and permeability developed by the Shawneetown Fault Complex.

Well No. 3--Crittenden County, Kentucky--K-17

The New Albany Shale depocenter is centered in western Kentucky with a maximum thickness of between 420 and 440 feet expected at the proposed location (fig. 192). Net radioactive shale thickness is in excess of 200 feet. Data concerning the percentage of organic carbon contained in the Grassy Creek Shale is unavailable, but assumed to correlate closely with those values observed in Illinois. The vitrinite reflectance values vary between 0.8 and 0.9 percent, indicating that the location has a minimal degree of thermal maturity. The proposed location is within the intensely faulted Moorman syncline, along the eastern margin of the Fluorspar Area fault complex. The faulting exhibits an en echelon normal pattern trending northeast-southwest with the downthrown block to the southeast. Structural relief varies from a few tens-of-feet to several hundred feet.

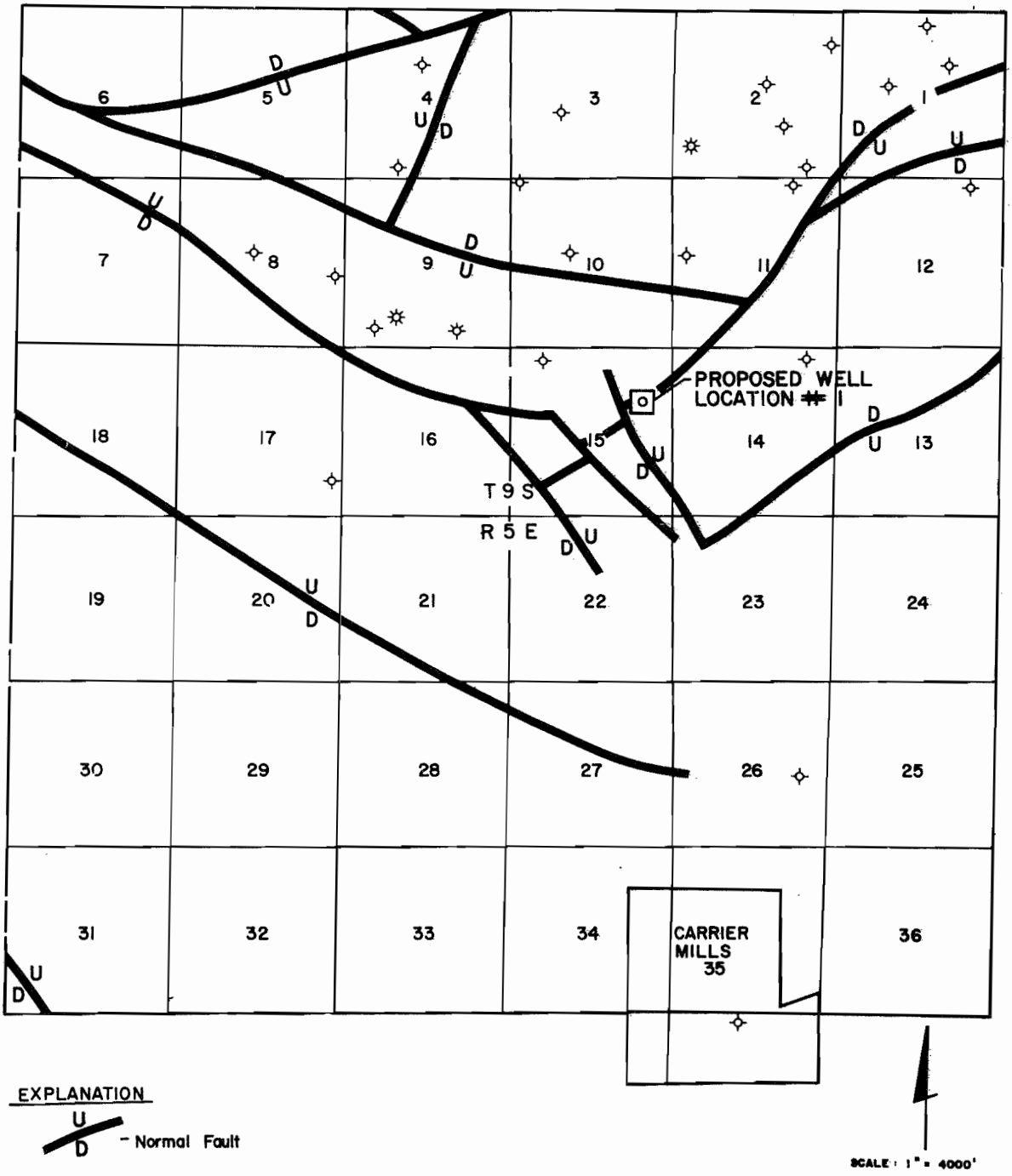


Figure 190 . Proposed New Albany location 1, Saline County, Illinois showing a portion of the Cottage Grove Fault System.

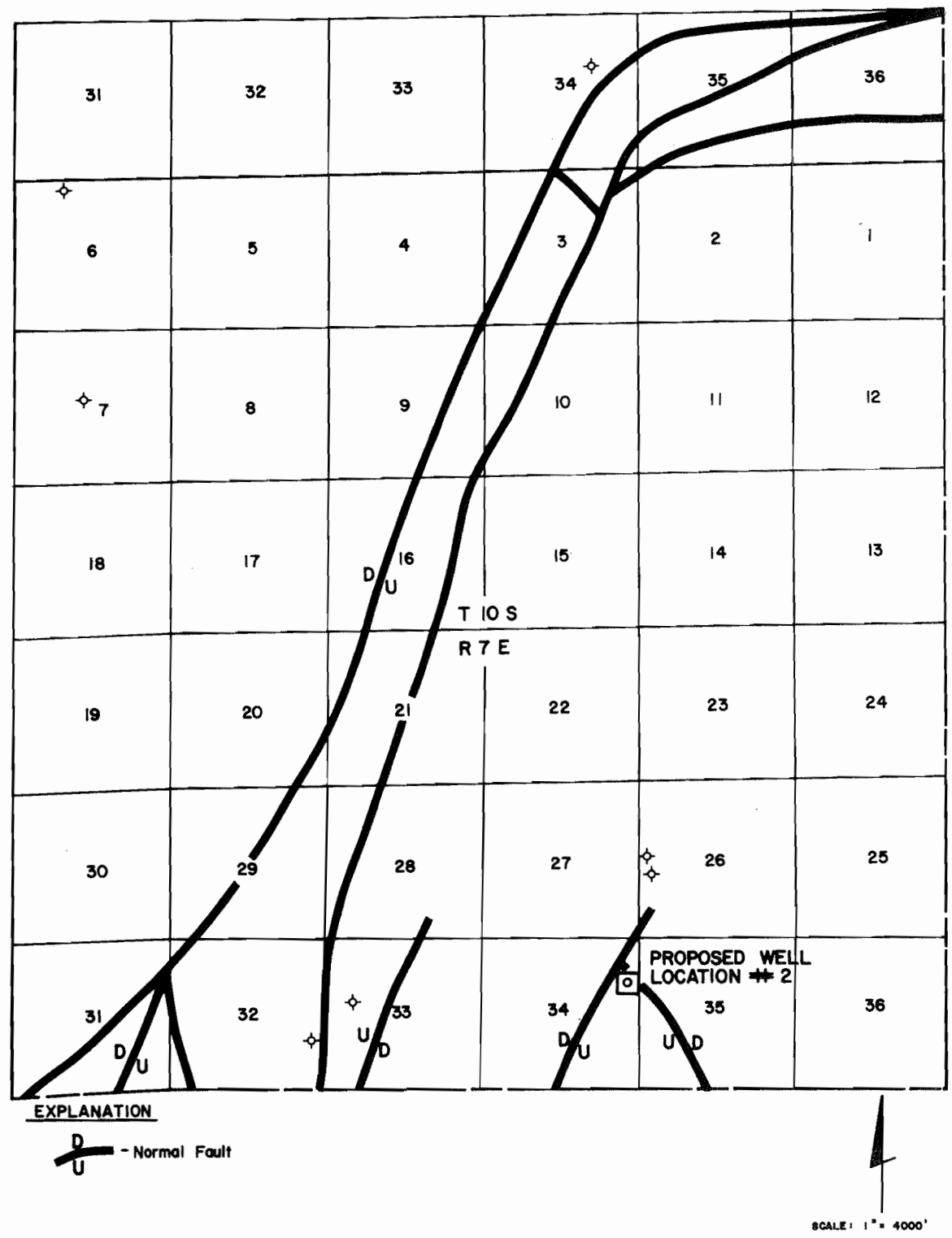


Figure 191. Proposed New Albany location 2, Saline County, Illinois showing a portion of the Shawneetown Fault System.

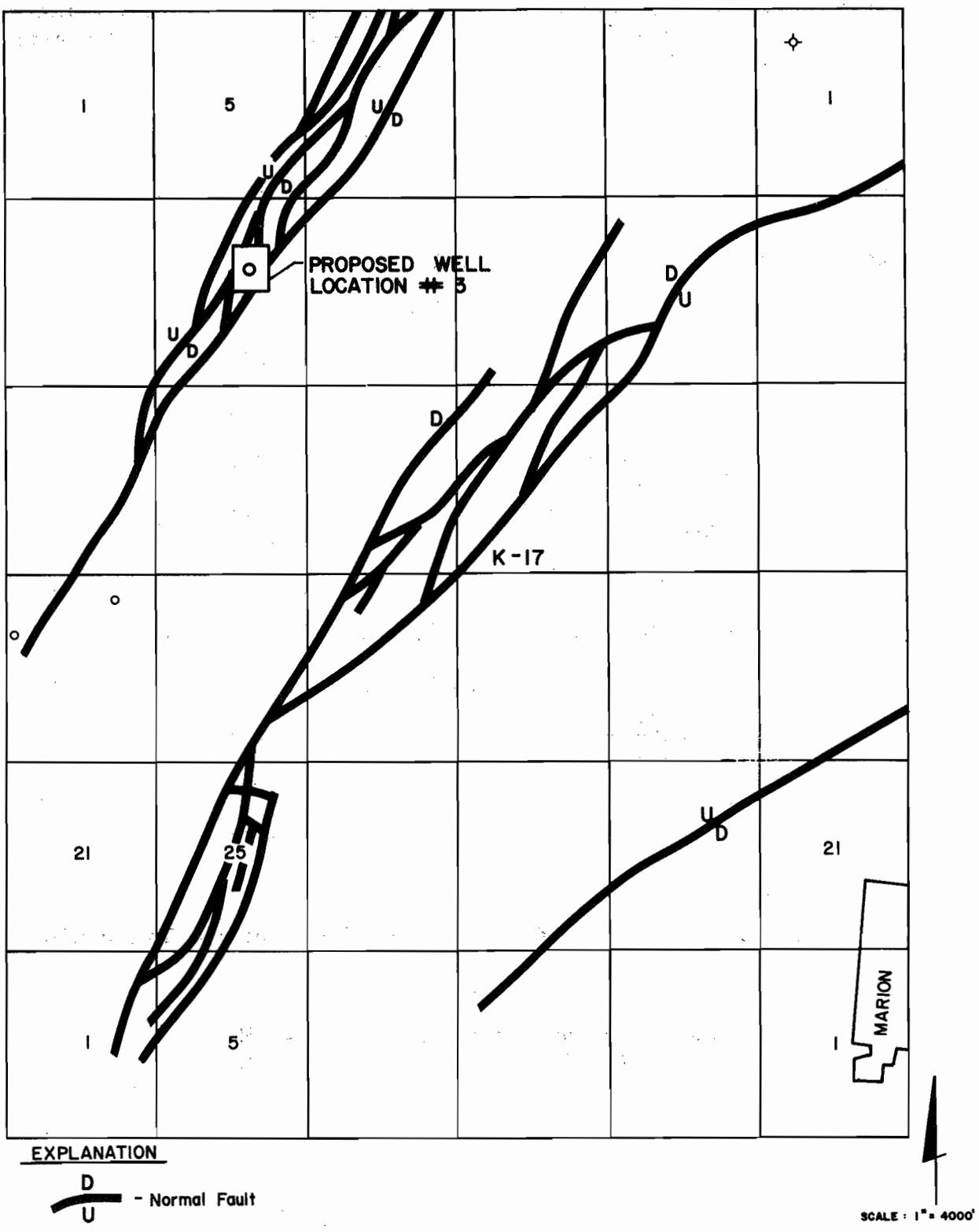


Figure 192 . Proposed New Albany location 3, Crittenden County, Kentucky showing a portion of the eastern edge of the Fluorspar Area Fault Complex.

No wells in this township and range have penetrated the Devonian interval but the next township and range immediately west has had several wells that penetrate the New Albany and provide regional control. Production in this area has historically been restricted to the shallower, post-Devonian sediments.

WELL PROGNOSES

Location #1--Illinois, Saline County--T9S,R5E, NW¼ of SE¼ of NE¼

	Top (Subsea)
Vienna Ls	-1471
Glen Dean Ls	-1610
Cypress Ss	-1914
Aux Vases Ss	-2151
Ste Genevieve Ls	-2254
Salem Ls	-2815
New Albany Shale	-3743
Lingle Ls (Devonian)	-4203

Location #2--Illinois, Saline County--T10S,R7E, Section 34, NE¼ of NE¼

	Top (Subsea)
Aux Vase	-100
Ste Genevieve Ls	-120
Ste Louis Ls	-330
Chautea Ls	-2000
New Albany	-2015
Lingle Ls (Devonian)	-2390

Location #3--Crittenden County, Kentucky--Twp K-R17, Section 6, SW¼ of NE¼

	Top (Subsea)
New Albany/Chattanooga Sh	-1150
Devonian (Lingle) Lm	-1575

EXPLORATION PARAMETERS ESTABLISHING SITE SPECIFIC AREAS FOR DEVONIAN SHALE TARGETS IN WEST VIRGINIA

INTRODUCTION

Recent studies have been conducted to determine regional stress-ratio relationships (or fracturing gradients) for the Appalachian basin. Correlation of historical production with the stress ratio (the ratio of minimum horizontal stress to overburden stress) indicates that a regional mapping of this factor could delineate prospective areas for commercial development of shale gas production. Maximum natural fracturing density should occur in the areas of minimum horizontal stress (compressive), indicated by a low stress ratio. Typical stress-ratio values range from slightly less than 0.43 to greater than 1.0. A stress-ratio map based on theoretical values determined for each county containing Devonian shales within the Appalachian basin is presented in figure 109. Portions of western, southwestern, and eastern West Virginia lie within the area where stress-ratio values range from 0.43 to 0.7. Theoretically, gas production from the Devonian shale sequence should be optimized within these areas.

The importance of fractures with respect to gas production was demonstrated by Bagnall and Ryan (1976)* for Devonian shale wells in three southwestern West Virginia counties. Wells that displayed the highest average initial production—greater than 300 thousand cubic feet (Mcf) per day—showed a steep production decline curve, but leveled off at approximately 45 Mcf and continued at that rate for years. Wells ranging from 200 to 300 Mcf per day leveled off more quickly but at lower production rates, as did wells averaging between 100 and 200 Mcf. Wells with average initial flows of less than 100 Mcf per day were nearly horizontal lines from the first year to year 25.

These findings substantiate the conclusion that gas production is controlled by the presence or absence of fractures within the Devonian shale reservoirs. The wells that produced better initially intersected more fractures, and produced free gas and adsorbed fracture gas at higher rates than wells that intersected fewer fractures. Once the "flush production" (i.e., production from free and adsorbed fracture gas) is over, the larger blocks of shale between fractures yield their adsorbed gas very slowly to the fractures and then to the wellbore. When this occurs, the production decline curves are nearly horizontal and remain so for many years as this type of gas continues to bleed off very slowly. Thus, wells intersecting more fractures level off at higher flow rates than wells intersecting fewer fractures.

GAS PRODUCTION POTENTIAL

Few wells have been drilled entirely through the Upper and Middle Devonian sequence in the north-central portion of the state where gas is produced from 17 named Upper Devonian Hampshire (Catskill) and Chemung Sandstones. In the southwestern counties, however, gas is produced from several Devonian shale zones. Between these two areas, underlying an area of Mississippian gas production, occurs the key facies change from productive sandstone to organic-rich black shales.

Gas has been produced from the Devonian shale sequence for over 50 years from wells in southwestern West Virginia. Approximately 3,000 wells have been drilled in this area, although many of these did not penetrate the entire shale section to the Onondaga. Gas production from this area has been primarily from the Huron Member of the Ohio Shale, with the lower portion of the unit constituting the primary source of the gas. Thin intervals of gray shale are intercalated with the black radioactive shale. Gas shows have often been observed immediately below these gray shales, suggesting that these shales may form a barrier to the vertical migration of gas within the interval.

*Bagnall, William D., and Ryan, W., "Geology, reserves and production characteristics of the Devonian shale in southwestern W.Va.," MERC/SP-76/2, pp. 41-53.

Most Devonian shale gas wells have been drilled just through the Huron Shale interval. In wells drilled through the entire Devonian shale sequence to test the Oriskany or Huntersville, a second gas-producing black shale section often is encountered. This interval consists of the Rhinestreet Shale Member of the West Falls Formation and older units. Gas shows have been recorded most often from two parts of this interval: the lower part, which corresponds to the older units (Sonyea Formation, Genesee Formation, and/or Marcellus Shale), and at the upper boundary, which is probably due to the interbedding of black Rhinestreet Shale and the overlying gray Angola Shale.

The third area of concentrated gas well drilling is the so-called "Benson trend" in north-central West Virginia. Although more than 4,000 wells have been drilled within this trend to produce from various Upper Devonian sands, 99 percent have penetrated only the upper 2,500 feet of Upper Devonian strata, down to the Benson sand. The lower 3,500 to 4,500 feet of Upper and Middle Devonian shales are relatively untested in this area.

The black radioactive Devonian shale is the main reservoir in 27 named gas fields in southwestern West Virginia, which extend over 500,000 acres (nearly 781 square miles). Reserve estimates calculated from the 3,000 plus wells producing in these fields approach 1 Tcf. However, in 21 of these fields, Devonian shale gas production is comingled with production from other shallow pays, especially Mississippian sandstones from the Maxton to the Berea or from the Greenbrier Limestone. Additionally, gas is produced from the deeper Onondaga Limestone and Oriskany Sandstone in three other fields. The net result is that accurate data for calculating Devonian shale gas production and reserves are not available.

The success ratio for Devonian shale gas wells in these southwestern West Virginia fields has been quite high, exceeding 90 percent. Furthermore, wells are reasonably shallow with an average depth of about 3,500 feet. Initial open flows are low, averaging only 350 Mcf per day. Per well reserves have been estimated at 350 million cubic feet by Brown (1976),* assuming a 150-acre well spacing.

The areas of favorable or potentially favorable trends, shown in Figure 193, include parts of or all of twenty-three counties in southwestern and west-central West Virginia. 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 in-place reserves (Table 9). Recoverable reserves will be the result of optimal geologic and geochemical conditions and technological advances.

*Brown, P.J., "Energy from shale—a little used natural resource," FE-2271-1, Natural Gas from Unconventional Geologic Sources, Nat Acad Sci, 1976.

Table 9. Devonian Shale resource assessment for West Virginia (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	128	22,984	49	640	22,984	246
Gray Shale	3,252	22,984	209	2,741	22,984	176
	Average Depth (Feet)	Total (TCF)	Average (BCF/Sq Mi)	Average Depth (Feet)	Total (TCF)	Average (BCF/Sq Mi)
Total Shale Resource	6,275	258	11	6,275	422	18

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

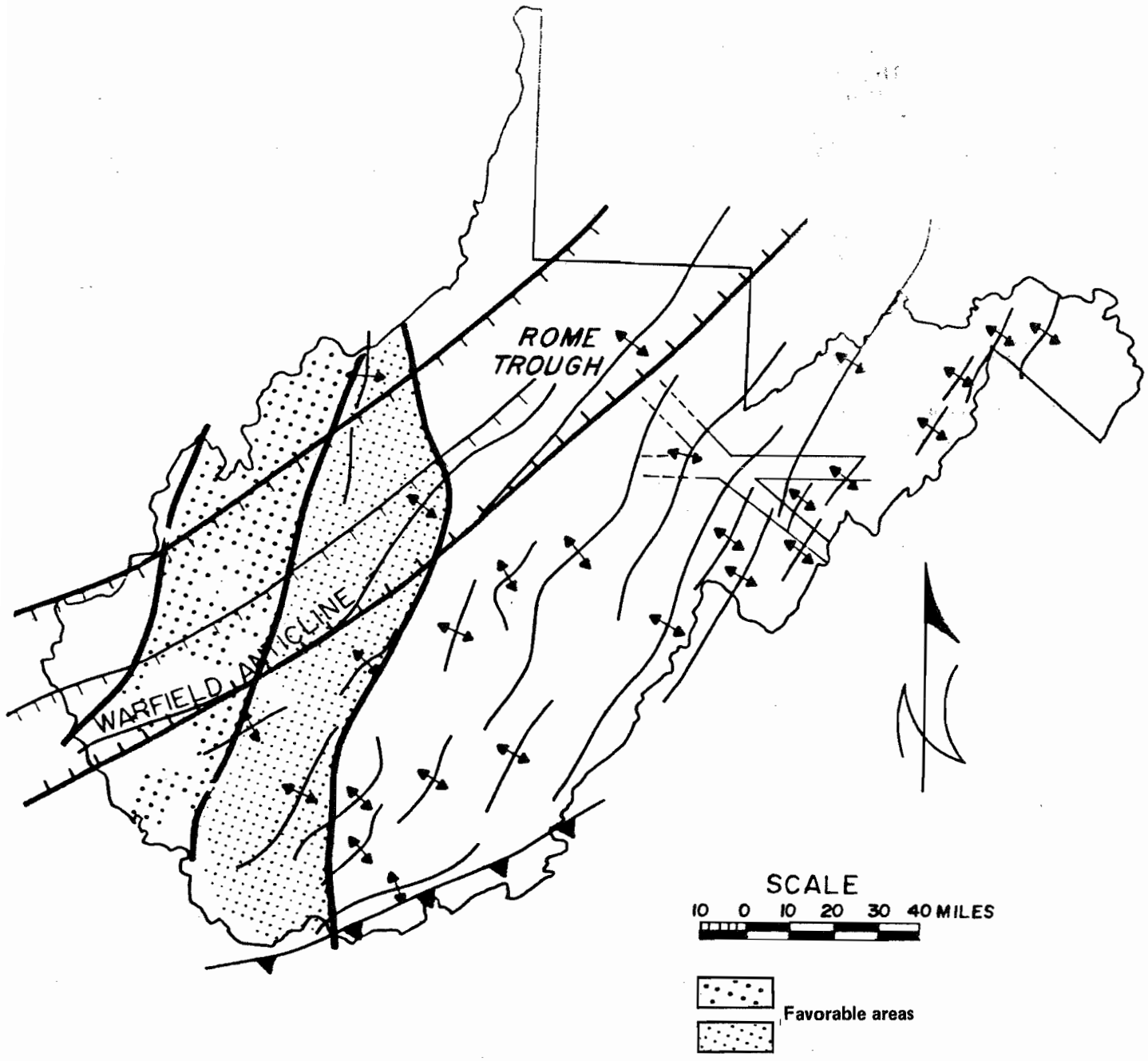


Figure 193. Areas of favorable gas potential.

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