Petroleum Geology of the Devonian and Mississippian Black Shale of Eastern North America

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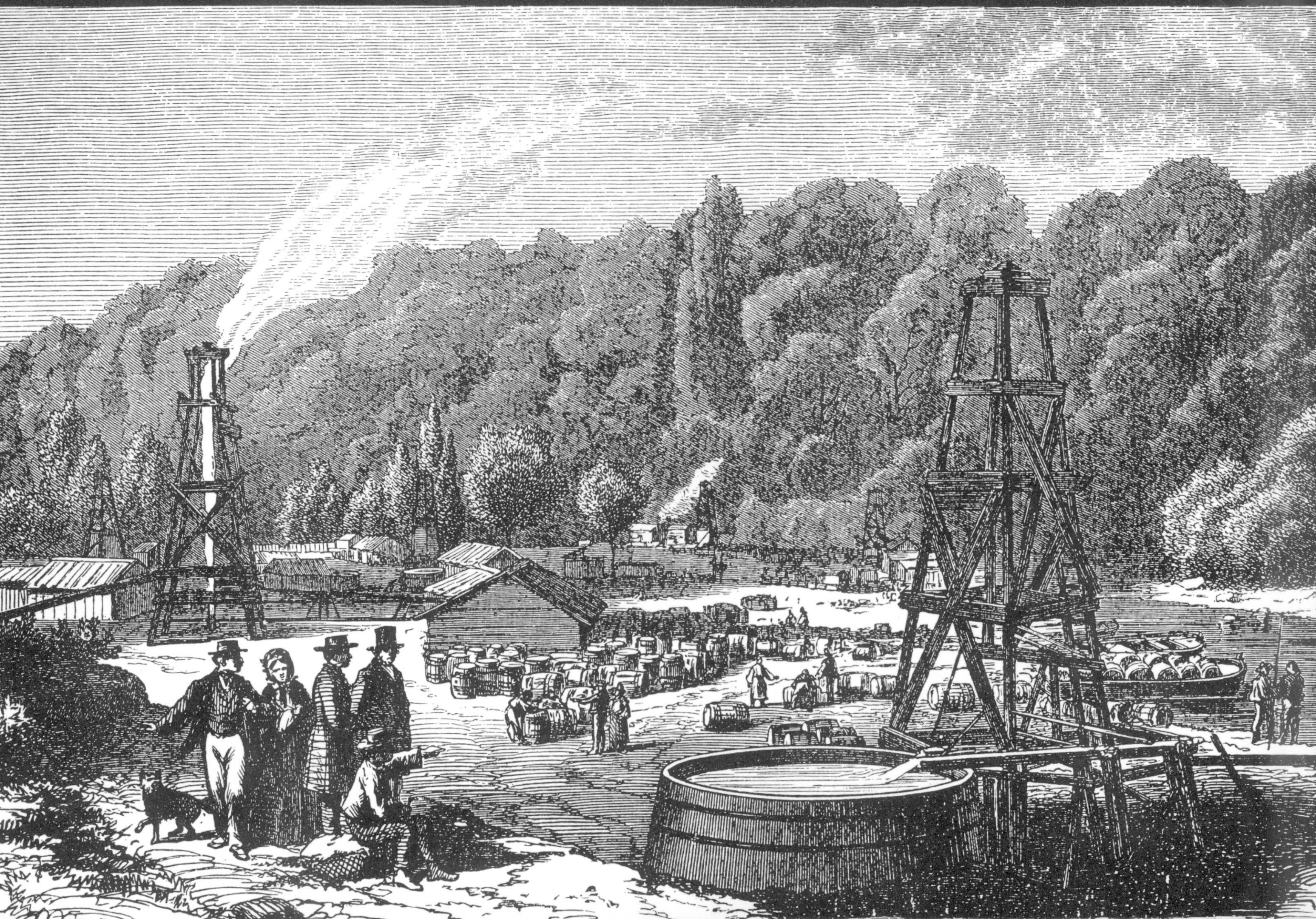

Petroleum Geology of the Devonian and Mississippian Black Shale of Eastern North America

Edited by JOHN B. ROEN and ROY C. KEPFERLE

Selected reports on the geological framework related to the assessment of the hydrocarbon potential of the Devonian and Mississippian black shale of the Appalachian, Illinois, and Michigan basins This bulletin is the result of studies undertaken for the Morgantown Technology Center of the U S Department of Energy

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Introductory Review—Devonian and Mississippian Black Shale, Eastern North America

By JOHN B. ROEN

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Introductory Review—Devonian and Mississippian Black Shale, Eastern North America

By John B. Roen

EARLY DEVELOPMENT HISTORY

The exploration and the development of resources to satisfy the requirements of society are, by and large, driven by economic considerations. Although geologic questions regarding those resources are answered by academic curiosity, economics provides the impetus to solve such questions, especially those directly related to profitable exploitation. Because of its dark color, significant organic-matter content, and exploitation possibilities, the black shale of Devonian and Mississippian age of eastern North America has attracted interest first as an economic prospect and subsequently as a geologic problem for well over a century. The study and the exploitation of the shale played an important role in the development of the Nation's gas industry, in the scientific establishment of the petroleum source-rock theory, and in the interpretation of the stratigraphy of the Devonian System of the Eastern United States.

Although the earliest references to the shale were indirect, they are worth noting from a historical viewpoint. They referred to occurrences of oil and gas whose source was later found to be the black shale. Between 1627 and 1669, French explorers and missionaries recorded the existence of oil and gas springs in the western part of what is now New York State (Wells, 1963). The Indians of that region, who used the petroleum from these springs, directed the explorers to the various locations of hydrocarbon-yielding springs. The knowledge of the oil and gas occurrence remained primarily with the Indians and the French explorers. The lack of economic incentives failed to attract any attention (Wells, 1963). Preoccupation with the problems of settlement of the eastern seaboard, of westward expansion, and of various conflicts, including the French and Indian and the Revolutionary Wars, precluded resource exploration and development. Consequently, the utilization and the study of the natural resources were delayed in many areas until after the Revolution.

The late 1700's and early 1800's marked the real beginning of the systematic studies of the rock formations in the United States. The studies were concentrated on the application of the Wernerian classification scheme, on paleontology, and on agricultural uses of limestone (Wells, 1963). It was not until the westward exploration and settlement during the 1820's that interest began to develop in the Devonian and Mississippian black shale and then only as the result of the newly emerging coal industry. As the coal industry grew, many entrepreneurs were looking for sources of marketable fuel, consequently, the black, coal-like appearance, organic-matter content, petroliferous odor, and slightly combustible nature of the black shale piqued their interest. In 1819, David Thomas' (Wells, 1963, p. 31–32, 39) report on the black shales (then called aluminous schists or clay slates) of western New York impressed DeWitt Clinton who hoped that shales would lead to the discovery of coal that would create a need for transportation and promote the Erie Canal. In New York and other regions of the Appalachian area, the bituminous nature of the black shales led to expectations of nearby coal. Lapham (1828, p. 69) described a black shale found in the excavation of the Louisville and Shippensport canal and along the banks of the Ohio River. He thought this black shale of Devonian age correlated with the roof rocks of the coal bed at Pittsburgh, Pa. No coal, however, was found to be associated with Lapham's black shale locality. In Tennessee, bituminous black shales of Devonian and Mississippian age were found throughout the central and the eastern parts of the State. Here it was mistaken for coal, and considerable exploration and development money was spent before the error was realized (Troost, 1835, p. 6–8).

Early attempts to utilize the black shale as a raw material for carbon in industrial pigment, as an iron and phosphate ore, and as a source of alum and green vitriol proved to be very profitable. However, the odor and color led to continued attempts to exploit the shale as a fuel source.

As the economic viability of the shale was investigated during the early 1800's, the geologic community began to study the shale itself. The shales were recognized as being unique stratigraphic reference units. Statewide to basinwide correlations were suggested by Eaton (1828,

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p 361) and Safford (1869, p 130, 336) Perhaps the most significant early observation was the recognition of facies changes in the Devonian rocks in New York by Eaton (1828, p 155, 361, 367), who included the Devonian black shales in his Third Graywacke, which he considered to be a marine facies of his Second Graywacke Eaton's conclusions regarding the facies changes within the Devonian rocks across New York were largely ignored except by such staunch advocates of the Wernerian principles as W D Coneybeare and J D Featherstonhough who were highly critical of Eaton's concept (Wells, 1963)

During the 1800's and early 1900's, geologic investigations continued—Amos Eaton, Lardner Vanuxem, James Hall, John M Clarke, Dana D Luther, and H S Williams worked primarily in New York, J S Newberry, Edward Orton, W W Mather, C S Prosser, C R Stauffer, E M Kindle, and W W Borden studied the outcrop belt along the flanks of the Cincinnati arch, and Gerard Troost, J M Safford, C W Hayes, E O Ulrich, R S Bassler, and J H Swartz concentrated on the southern part of the Appalachian basin Amadeus W Grabau contributed significantly to the knowledge of the stratigraphy and paleontology of the Middle and Upper Devonian black shale and related rocks in New York, Ohio, and other areas

Almost 100 years (yr) elapsed before geologists made significant contributions to the facies concept put forth by Eaton Building on the foundations laid by the aforementioned individuals and doubtlessly others not mentioned, Barrell (1912), Chadwick (1924, 1933), Cooper (1930, 1933), and Caster (1934) contributed significantly to Eaton's facies concept They presented data that allowed the construction of a model demonstrating the relation of the rocks of the Devonian Catskill delta of which the black shale represented the distal marine facies

Concurrent with the period of increased interest in the geology of the black shales, these strata were recognized as an economic source of fuel Gas seeps emanating from fractures in the shale sequence had long been known These seeps were capped, and the captured gas was used predominantly for illumination Shallow wells were driven or dug near the seeps to increase the supply During the late 1820's or early 1830's, the first commercial shale gas well was drilled by William A Hart (Orton, 1899, p 496–497, Ley, 1935, p 1087) near a seep in Canadaway Creek to supply gas for lighting in the town of Fredonia, N Y The sinking of this well and the first commercial use of gas initiated the natural gas industry in the United States The source of gas for this well at Fredonia was the black Dunkirk Shale (Torrey, 1935) As demand increased, shale gas development spread westward along the southern shore of Lake Erie from New York across northwestern Pennsylvania and reached northeastern Ohio in the 1870's (Stout and others, 1935, p 905) From the early 1860's to the close of the 19th century, development spread to central and southern Ohio, southern Indiana, and western Kentucky In the southeastern part of the Illinois basin in Meade County, western Kentucky, gas was discovered in the Devonian and Mississippian black shale penetrated during a drilling campaign from 1863 to 1865 (Orton, 1891, p 171) By the 1920's, drilling for shale gas had progressed to various regions of Indiana, Kentucky, and West Virginia Exploration spread to eastern Kentucky, and, in 1920, gas was recovered from a Boyd County black shale well (Hunter, 1935) By 1926, the Devonian shale gas production was an established industry in eastern Kentucky and contiguous West Virginia According to Ley (1935), the gas fields in these adjoining States constituted the world's largest known occurrence of natural gas

During the early development period from the early 1800's to the 1930's, no shale gas production was reported from the Antrim Shale of the Michigan basin (Newcombe, 1935) Although the Michigan basin was subjected to exploration and drilling campaigns beginning in the late 1800's, the black Antrim Shale lacked any promising shows of gas

Through the years since its initial utilization in the 1820's at Fredonia, N Y , it has become readily apparent that the only sustained economic use of the black shale has been as a source of gas Continued geologic research and exploitation of the shale led to the classification of the shale as an unconventional source because the source and the reservoir rocks are the same shale beds Reservoir characteristics of the shale are poor, porosity and permeability relative to conventional hydrocarbon reservoirs are negligible Until the 1930's, no structural control could be definitely established for the shale gas accumulations in eastern Kentucky A short time later, it was recognized that the production of gas was more dependent on the existence of naturally occurring fracture systems (Billingsley and Ziebold, 1935, Browning, 1935, Lafferty, 1935) than on accumulation, as expressed by the anticlinal theory in conjunction with normal reservoir porosity and permeability This realization led to the application of downhole explosive techniques to increase production by creating fracture porosity both through enhancing the existing fracture system and by inducing new fractures This explosive technique, or "shooting" as it was called, had been patented by Col E A L Roberts and successfully used in 1866 for increasing oil production in a well at Titusville, Pa (Vance, 1961, p 593) The technique was applied to open uncased holes and was not easily controlled in lateral directions The results, however, were relatively good, although extensive clean-out operations generally were required This technique continued to be used until the 1950's when it began to be replaced by the newly developed "hydrafrac" process This process entails pumping liquids and fracture supporting proppants under high pressure into selectively isolated stratigraphic zones for fracture enhancement The technique is very successful, and various modifications are still in use

Concurrent with the development of the gas potential of the Devonian and Mississippian black shale, crude oil was being produced from many different reservoir rocks in many areas of the Appalachian basin At first, the oil was considered to be a nuisance when it was produced from brine wells in Kentucky, Ohio, Pennsylvania, and West Virginia Later, however, oil production was developed as an industry in Pennsylvania at Drake's well in Titusville The source rock for this oil was the leading question, and Devonian and Mississippian black shale was the answer Petroleum distilled from the shales in Tennessee (Safford, 1869) and other areas (such as Buena Vista, Ohio) during the 1850's (Hoover, 1960) led J S Newberry in 1860 (Orton, 1891, Dott and Reynolds, 1969, Owens, 1975) to the conclusion that the organic-rich black shale was the source of the oil produced in Pennsylvania and Ohio When reporting on his studies of black shales in Ontario, Canada, in 1861 and 1865, Alexander Winchell concurred with the "Newberry doctrine," as did H D Rogers in 1865 (Dott and Reynolds, 1969, Owens, 1975) In 1869, E B Andrews, one of the first proponents of the anticlinal theory, called the "Ohio black shale" the source of the oil in the Appalachian area (Owens, 1975)

In the 1940's, the advent of atomic power suggested a potential use for the black shale At localities throughout the world, black shale was found to contain significant amounts of uranium The need for domestic supplies of uranium for atomic use prompted the evaluation of the black shales that are well exposed in Tennessee The results of the investigation indicated that the shales in Tennessee contained a tremendous quantity of uranium but that it was dispersed in concentrations too low to be exploited at that time (Conant and Swanson, 1961, p 76) In addition to the uranium, other utilizations of the shale were considered (Conant and Swanson, 1961, p 69–70), petroleum, phosphate, black pigment, acid, and light-weight aggregate were of potential value, but only as byproducts of other benefaction processes

The detailed stratigraphic studies of Conant and Swanson (1961) and the age and the correlation determinations based on the conodont studies of Hass (1956) were predicated on the foundations established by earlier geologists, including Campbell (1946), who published an extensive study of the shale stratigraphy of the eastern interior area The reports of Haas (1957) and Conant and Swanson (1961) for the Atomic Energy Commission, which were completed more than 25 yr ago, are still regarded as the most comprehensive studies of central Tennessee

The early exploitation of the Devonian and Mississippian black shale established it as a viable energy source Geologic studies of the shale, which were required for economic development, resolved various lithostratigraphic correlations, provided a basis for the origin of petroleum in establishing the source rock theory, and supplied the geologic data necessary for resource estimation Perhaps most important was the realization that the wide areal extent and substantial thickness of black shale contained a vast resource of natural gas The shale gas fields, the largest of which were in Kentucky and West Virginia, consistently produced considerable volumes of gas from shallow depths for a relatively long period of time By the 1960's the shale was an important resource providing energy to the eastern part of the United States

RECENT WORK—EASTERN GAS SHALES PROJECT

Natural gas reserves in the United States began to diminish in 1968 as demand exceeded the reserves added by exploration drilling (U S Energy Research and Development Administration, 1976) In response to this increasing demand and decreasing supply, the U S Energy Research and Development Administration (ERDA), which became the Department of Energy (DOE) in 1977, initiated a program to evaluate the Nation's gas resources The black shale of Devonian and Mississippian age of the Eastern United States was determined to contain a vast undeveloped resource of gas that needed advanced production methods for recovery As the energy shortage became more readily apparent in the early to mid-1970 s, the ERDA initiated the Eastern Gas Shales Project (EGSP) in 1976 to evaluate the gas potential and to enhance gas production from the Devonian and Mississippian black shale of the Eastern United States The project was formulated and managed for the ERDA by the staff of the Morgantown Energy Research Center (MERC), which became the Morgantown Energy Technology Center (METC) in 1978

The objectives of the EGSP were to provide the gas industry with accurate resource and production estimates based on current and future extraction technologies and to formulate, effect, and test advanced exploration and recovery techniques for the black gas shale The general goals were to increase the production rate of individual wells and the total recoverable gas reserves of the Appalachian basin through new and innovative exploration and extraction methods An important element in the strategy to achieve these goals was to establish and document a geologic framework that would provide a basis for resource analysis and shale characterization Under the auspices of the MERC, various State, Federal, and private industrial organizations were brought together under cooperative agreements with the EGSP to participate in the research of the petroleum geology and geochemistry of the black shale in the Appalachian, the Illinois, and the Michigan basins Because greater shale gas production occurs in areas that have a higher density of natural fractures, a larger part of the EGSP's effort was concentrated in the Appalachian basin In addition, the greater areal extent of the Appalachian basin required the cooperation of a larger number of geologic research groups than did either the Illinois or the Michigan basin

Once again, a requirement of society—to have adequate energy independence and security—engendered a renewed and high level of interest in research to increase the economic potential of the black shale This renewed interest followed the central Tennessee black shale uranium studies by approximately 30 yr Both studies had similar goals and were sponsored by Federal energy agencies The more recent EGSP was, by far, the larger and more inclusive because it involved shale studies in three major basins of the Eastern United States

REGIONAL GEOLOGIC FEATURES

The EGSP studies included all but one of the four Paleozoic structural basins in eastern North America that contain the Devonian and Mississippian black shale The Appalachian, the Michigan, and the Illinois basins are adjoined along common boundaries defined by low, broad structural arches The basin not included in the study was the Black Warrior, which blends without marked structural discontinuity with the southern extremity of the Appalachian basin

The Appalachian is a northeast-trending, elongate, asymmetrical basin that deepens with corresponding thickening of basin fill to the east It is a foreland basin that developed during the late Proterozoic and Paleozoic and contains about 50,000 feet (ft) of sedimentary rock ranging from late Proterozoic to Permian in age The basin is a little greater than 1,000 miles (mi) in length and extends from the Adirondack uplift in the north to the Black Warrior basin in the south Its width, which is variable, ranges from less than 100 mi in Tennessee to about 300 mi southeastward across Ohio to Virginia The eastern surface limit of the basin is defined by a belt of metamorphic and igneous rocks of the Blue Ridge province that have been thrust westward over folded and faulted Paleozoic beds of the Appalachian foreland basin The western margin of the basin is characterized by relatively flat-lying middle Paleozoic rocks that lap onto several broad, positive, structural elements Along the northwestern border and separating it from the Michigan basin are the Findlay arch, the intervening Chatham sag, and the Algonquin arch The western border of the southern part of the Appalachian basin is defined by the Nashville dome, the Cumberland saddle, the Jessamine dome, and the Cincinnati arch West of these structural features is the northwest-trending oval intracratonic Illinois basin, which deepens southeastward toward the Nashville dome Development of the Illinois basin began in Cambrian time with the basin fill that ranges from Cambrian to possibly Permian in age There are 14,000 ft of sedimentary rock in the deep Fairfield subbasin and a possible 20,000 ft of rock preserved in the Moorman syncline These deep structural features are part of the Illinois basin Post-Paleozoic rocks in the basin include an overlap of Mesozoic and Tertiary rocks of the Mississippi embayment in the south and a Pleistocene glacial cover in the northern part of the basin The western edge of the basin is defined by the Pasacola arch, the Ozark dome, and the Mississippi River arch The northeastern boundary is the Kankakee arch, which separates the Illinois basin from the Michigan basin to the north The Michigan basin, which is also intracratonic, is roughly circular in shape It contains about 17,000 ft or more of Precambrian through Mesozoic rocks that are covered by a widespread veneer of Pleistocene glacial deposits

Although the basins have different structural settings, bordering source areas, and sediment distribution systems, all three have common characteristics represented by their basin fill In a broad stratigraphic sense, the sedimentary rock sequence of the three basins is cyclic in nature and consists of carbonates overlain by organic-rich black shale that grades into coarser clastics Specifically, the Devonian and Mississippian black shale sequence in each basin is underlain by carbonates and overlain by clastics The general lithologic appearance and bedding characteristics of the black shale are similar in each basin This lithologic similarity may be attributed to the nearly identical depositional environment suggested for the black shale sequence in the three basins

However, some compositional differences may be related to variance in the source areas Petrographic examination indicates the silt-sized quartz in the Michigan basin is polycrystalline (Matthews, this volume) and may reflect a source in the igneous-metamorphic terrane of the Canadian shield source The monocrystalline quartz of the Appalachian black shale may indicate multicycle detritus from a predominantly sedimentary source terrane of the Appalachian Highlands to the east (Broadhead, this volume)

The total organic-carbon content of the black shale sequence is generally about the same for all three basins It ranges from less than 1 percent to more than 10 percent by weight The distribution of organic carbon is not known in the Michigan basin The Illinois basin, which has a sufficient areal distribution of data, has a random distribution that shows no obvious trends (Frost, 1980) In the Appalachian basin, however, the average organic-carbon content of the black shale sequence increases westward (Roen, 1984) Variations in the composition of the black shale kerogen are indicative of the marine basin depositional environment and the terrestrial source area contribution The Michigan (Matthews, this volume) and the Illinois (Cluff, this volume) basins contain predominantly Type II kerogen derived primarily from autochthonous marine planktonic organisms The Appalachian black shale, in addition to the Type II marine planktonic contribution, has an eastward-increasing amount of Type III kerogen derived from organic matter of terrestrial plants of the Appalachian source area to the east This regional variation among the three basins suggests that the Appalachian highlands were an area of prolific plant growth, that the Canadian shield source areas supplying the Michigan and the Illinois basins were relatively barren of terrestrial plants, and that the epeiric seas inundating eastern North America contained relatively more marine kerogen precursors in a westward direction, which was probably the result of the progressive reduction of the quantity of terrestrial material as the distance from the eastern source became greater. Perhaps the low, broad arches separating the Michigan and the Illinois basins from the Appalachian basin prevented the continued westward transport of the small amount of terrestrial plant detritus that reached the western part of the Appalachian basin.

Stratigraphic correlation studies of the black shale began in the mid-1800's with efforts concentrated on local areas rather than on regional intrabasin or interbasin studies. Regional data to substantiate long-range correlations within or between basins were not accumulated until approximately the 1920's. Beginning at about the same time, paleontologic data were being utilized to suggest local, as well as long-range, correlations. As the result of studying conodonts, Haas (1956) suggested regional correlations of black shale units not only within the Appalachian basin, but also between that basin and the Illinois and the Michigan basins. Stratigraphic studies and correlations of black shale units within and between the three eastern Paleozoic basins advanced significantly as a result of several factors. The downhole gamma-ray logging technique provided a geophysical basis for confirming suggested biostratigraphic correlations and a basis for establishing new correlations. In the mid-1950's, the gamma-ray log was beginning to have widespread use in the eastern basins, and, by the 1970's, it provided sufficient regional control for Schwietering (1970, 1979) to propose regional correlations through the subsurface of the Appalachian basin. The regional stratigraphic correlations presented in this volume are based, to a great extent, on the black shale's response recorded on the gamma-ray log. The recognition of widespread, vertically restricted key beds and marker zones within the black shale sequence has advanced the stratigraphic knowledge considerably. The marker units are represented by very thin ash beds that are distinguished by dark-brown to bronze biotite flakes and by the small (less than 5-millimeter) oval and bilobed carbonaceous remains of the plant fossil *Foerstia*.

Three, and perhaps four, ash beds have been recognized in the black shale sequence of the Eastern United States. These thin, hard-to-recognize, essentially time-stratigraphic markers are key stratigraphic beds and, when used in conjunction with other data, were extremely useful in long-distance subsurface correlations. Of these beds, only the Tioga Ash Bed, which is the oldest, is known to occur in all three basins. In the Appalachian basin, the Tioga occurs near the base of the black Marcellus Shale of Middle Devonian age. The Tioga and its correlatives in the Illinois and the Michigan basins (Dennison and Textoris, 1977) occur below the lowest black shale, which is Late Devonian in age and is, therefore, only of value as a marker unit in the black shale sequence of the Appalachian basin. The Belpre Ash Bed, which is found near the base of the Rhinestreet Shale Member of the West Falls Formation (and equivalent beds), and the Center Hill Ash Bed in the Dowelltown Member of the Chattanooga Shale (and equivalent beds) are widespread (Collins, 1979, Roen, 1980, Roen and Hosterman, 1982) and have proven to be useful in establishing long-range correlations in the Appalachian basin black shale sequence. These ash beds are Late Devonian in age. Strata of equivalent age occur in the Illinois and the Michigan basins, however, these particular ash beds have not been reported in either of these basins. The possibility of a fourth bed has been reported from the base of the Huron Member of the Ohio Shale in the Appalachian basin (Roen, 1980). As yet, this ash bed has not been reported from either the Illinois or the Michigan basins.

With regard to interbasin, regional correlation, the *Foerstia* zone is the most significant stratigraphic marker in the Devonian black shale and related rocks of eastern North America. The classification of *Foerstia* has been debated for several years. Schopf and Schwietering (1970) suggested that because of its occurrence only in marine strata and its fucoidal resemblance, *Foerstia* is of algal origin, however, Gray and Boucot (1979) suggested that, because of its thalloid appearance, *Foerstia* has a strong affinity for a terrestrial origin. Recently, Romankiw and others (1988) have presented results of solid-state carbon-13 nuclear magnetic resonance (NMR) spectroscopy that provide data on the chemical structure of the fossil. Their data indicate that the structure of *Foerstia* has a definite similarity to that of coalified wood, which indicates a land plant affinity for *Foerstia*.

Its terrestrial nature, restricted stratigraphic distribution (less than 1 to a few tens of feet), and widespread areal distribution suggest that *Foerstia* was extremely sensitive to habitat change and thrived only for a short period of time. To date, *Foerstia* has been found in black to greenish-gray silty shale, which indicates that its occurrence was not controlled by lithologic facies. Schopf and Schwietering (1970) suggested the habitat was the littoral zone, however, the NMR data suggest a terrestrial origin for *Foerstia*, and therefore, it may have flourished above the littoral zone. In any case, the limited stratigraphic interval indicates that the conditions for *Foerstia* growth were temporarily restrictive and that its growth was initiated and terminated by a relatively abrupt change in ecologic conditions.

The existence of *Foerstia* in the Devonian shales of the Eastern United States has been known since before the turn of the 19th century (Schopf and Schwietering, 1970). Specific localities and stratigraphic positions have been noted by several authors, including Hasenmueller and others (1983). As its value as a stratigraphic marker became readily apparent through an increasingly large geographic area, more concerted efforts were made to locate the zone. Matthews (1983) identified the *Foerstia* zone in core material from the Antrim Shale in the Michigan basin. Based on the stratigraphic position of the *Foerstia* zone, the summary by Hasenmueller and others (1983) indicated that the Huron Member of the Ohio Shale in the Appalachian basin correlates with the Clegg Creek Member (Lineback, 1970) of the New Albany Shale in the Illinois basin, the upper part of the Antrim Shale in the Michigan basin, and the upper part of the Gassaway Member of the Chattanooga Shale in the southern part of the Appalachian basin. In the Kettle Point Formation in Ontario, Canada, Russell (1985) found the *Foerstia* zone in the Chatham sag between the Michigan and the Appalachian basins. The existence of the *Foerstia* zone provides a stratigraphic datum common to the three basins that affords refinement of the regional stratigraphy and establishes a firm basis for paleogeographic interpretation for the Devonian and Mississippian black shale of eastern North America.

THIS BULLETIN

The reports that resulted from the EGSP and other independently sponsored studies were numerous and added a very significant amount of new information to the already overwhelming volume of literature on the black shale. Because most reports were interim or administrative, they are not found in formal publications or in readily accessible repositories. The main purpose of this bulletin is to combine, under one cover, the results of the selected geologic framework and petroleum geology studies of the Devonian and Mississippian black shale. In addition, the volume provides reference to much of the significant literature in regard to the black shale of eastern North America. The chapters in this bulletin deal with the stratigraphy of the black shale and related rocks, basin analyses, resource appraisal, and petrologic and geophysical characteristics of the black shale as it relates to petroleum, structural, and stratigraphic controls of gas production. For introductory summaries regarding the papers in this volume, the reader is referred to the table of contents and the authors' abstracts.

The publication of this volume has followed a long and tortuous route. The research for the papers presented here was carried out at various times from the late 1970's to the early 1980's. The call for papers occurred in late 1984, and the proposal for publication as a Memoir was accepted in 1985 by the American Association of Petroleum Geologists (AAPG). Unfortunately, the precipitous economic decline of the petroleum industry in 1985–86 was reflected by the AAPG. The necessary financial support was not available for AAPG publication of the Memoir, and, in 1986, the project was put in abeyance to examine available options. Efforts by AAPG personnel and the volume editors to find other finances and a publisher for a large volume containing many figures and oversize plates were unsuccessful. A proposal that the U.S. Geological Survey publish the volume was made and accepted, and preparation was resumed. After necessary style changes and revisions were made, the volume was submitted to the Survey in 1988 and approved by the Director in 1989 for publication as a bulletin.

Because many of the chapters in this bulletin were prepared by U.S. Geological Survey authors, the stratigraphic nomenclature conforms to the current Survey usage. Chapters authored by geologists not employed by the Geological Survey have not been reviewed by the Geologic Names Committee of the Survey. Therefore, the stratigraphic nomenclature and correlations in these chapters may not conform to the current usage followed by the Survey.

DEVONIAN-MISSISSIPPIAN BOUNDARY REVISION SUBSEQUENT TO THIS BULLETIN

Following the completion and submittal of the papers in this volume but before their publication as Bulletin 1909, Gutschick and Sandberg (1991) presented evidence suggesting that the Devonian-Mississippian boundary should be elevated within the stratigraphic sequence of the Michigan basin. According to their findings, the Bedford Shale and the overlying Berea Sandstone and the Ellsworth Shale of the Michigan basin are Late Devonian in age. They indicated that these Upper Devonian units are separated from the overlying Sunbury and Coldwater Shales, both of Early Mississippian age, by a hiatus (Gutschick and Sandberg, 1991, fig. 2). Accordingly, the Devonian-Mississippian systemic boundary in the Michigan basin may be at the top of the Berea Sandstone, the top of the Bedford Shale where the Berea is absent, and the top of the Ellsworth Shale. Because the same sequence of rocks or their correlatives are present in the Appalachian basin and because of Gutschick and Sandberg's discussion of fossil evidence pertaining to that sequence in the Appalachian basin, their revision for the Michigan basin may be applicable to the Appalachian basin. It is suggested that their revision be considered in regard to the appropriate stratigraphic sequences described in the chapters of this bulletin.

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I am greatly indebted to the authors who contributed to this volume. Much of the research involved in the results presented here was conducted under the auspices of the EGSP. I wish to acknowledge the EGSP managers at the DOE's METC for their assistance and encouragement throughout the project's duration. In addition, I would like to acknowledge several sponsoring agencies—the Ontario Geological Survey for Russell's contribution, the Gas Research Institute for the papers by Patchen and Hohn and Schumaker, and the New York Energy Research and Development Authority for Van Tyne's chapter Aside from the authors and the sponsoring agencies, many individuals supplied assistance and advice in the preparation of the bulletin I would like to thank my coeditor, Roy Kepferle, for his assistance and Laure G Wallace for her administrative and technical help In particular, I would like to express my gratitude to one special person, who, throughout our association, has unselfishly shared with me his vast knowledge of the Devonian and Mississippian black shales That person is Wallace de Witt, Jr

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Chapter B

Stratigraphy of Devonian Black Shales and Associated Rocks in the Appalachian Basin

By WALLACE de WITT, JR., JOHN B. ROEN, and LAURE G. WALLACE

Detailed documentation of the stratigraphic framework and extent of the Devonian black gas shales in the subsurface of the Appalachian basin

U.S. GEOLOGICAL SURVEY BULLETIN 1909
PETROLEUM GEOLOGY OF THE DEVONIAN AND MISSISSIPPIAN BLACK SHALE OF EASTERN NORTH AMERICA

CONTENTS

PLATES

[Plates are in pocket]

FIGURES

Stratigraphy of Devonian Black Shales and Associated Rocks in the Appalachian Basin

By Wallace de Witt, Jr., John B. Roen, *and* Laure G. Wallace

Abstract

Although gas has been produced from Devonian black shales rich in organic matter in the Appalachian basin since 1821, the subsurface stratigraphy and the correlation of the gas-productive rocks were not well known because criteria were not available to subdivide the fine-grained rocks of the Devonian shale sequence. However, as the use of gamma-ray wire-line geophysical logs became widespread in the 1960's, data became available for identifying and tracing individual beds of black shale.

Because organic matter in the black shales preferentially absorbed uranium during its transportation and deposition, the black shales are characterized by strong positive deflections on gamma-ray logs. By comparing gamma-ray logs from many closely spaced wells and correlating their conspicuous black shale log signatures with named stratigraphic units that crop out on the periphery of the basin in New York, Pennsylvania, Ohio, Kentucky, Virginia, West Virginia, and Tennessee, we established a stratigraphic framework for the Devonian shale sequence and resolved the relation of black shales in the New York Devonian section to the Chattanooga Shale of central Tennessee. Previously suggested correlations based upon conodont zonation were corroborated by the gamma-ray stratigraphy.

We found that the older black shales of the Devonian sequence—the Marcellus Shale, the Millboro Shale, the Geneseo and the Renwick Shale Members of the Genesee Formation, the Burket Shale Member of the Harrell Shale, and the Middlesex Shale Member of the Sonyea Formation—are found mainly in the eastern and the central parts of the Appalachian Plateaus. They are thickest in the east, thin westward, and do not crop out along the Cincinnati arch. The Rhinestreet Shale Member of the West Falls Formation and the Dunkirk Shale Member of the Perrysburg Formation crop out in western New York and merge westward into other named units in Ohio and Tennessee. Several of the black shales thin southward across Ohio and Kentucky to meld into the Chattanooga Shale in south-central Kentucky and contiguous Tennessee. The Rhinestreet is a bed in the lower part of the older Dowelltown Member of the Chattanooga Shale, whereas the Huron and the Cleveland Members of the Ohio Shale and the younger Sunbury Shale merge into the Gassaway Member of the Chattanooga Shale. In southwestern Virginia near Big Stone Gap, the Sunbury conodont fauna occurs in the upper part of the Big Stone Gap Member of the Chattanooga Shale. Data on the extent and the thickness of individual black shales presented here will aid in exploiting the gas and oil resources of the Devonian shale sequence in the Appalachian basin.

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INTRODUCTION

The purpose of this report is to illustrate and document the stratigraphy and the extent of the black gas shales of Middle and Late Devonian and Early Mississippian age in the Appalachian basin by means of a framework of stratigraphic sections and maps showing the extent of specific lithostratigraphic units.

The term "gas shales" used herein refers to a sequence of dark-gray, dark-brown, or black shales rich in organic detritus, which are source beds and reservoir strata for large amounts of natural gas in the western and the central parts of the Appalachian basin. They have been targets for gas well drillers for more than 160 years (yr). Despite this long period of exploitation, the stratigraphy of the gas shales has been delimited only recently in much of the Appalachian basin as the result of a regional analysis involving the studies of many geologists (Roen and de Witt, 1984, p. 1–2). The term "shale gas" refers to the gas extracted from the Devonian gas shale sequence.

Drilling for Shale Gas

The first well drilled for the purpose of recovering natural gas was located near a gas seep in the bed of Canadaway Creek in the village of Fredonia, Chautauqua County, N.Y., in 1821. The black Dunkirk Shale Member of the Perrysburg Formation (Pepper and de Witt, 1951) was the source bed for the gas, which was used in the village for heating, cooking, and illumination. Residents of western New York quickly appreciated the advantages of natural gas as a fuel superior to wood or coal, and drilling shallow wells to the Devonian gas shale sequence spread westward along the southern shore of Lake Erie The drillers used techniques perfected during, the preceding decades by the salt well drillers of the Appalachian area Drilling activity moved westward, reaching Erie, Pa , about 1840 and Cleveland, Ohio, by 1880 Throughout this shale gas area, the wells usually were shallow, less than 1,500 feet (ft) deep The settled production per well was comparatively low Wells yielding 50,000 cubic feet per day (ft^3/d) were considered to be good domestic wells Gas pressure was generally low, usually only a few ounces to several tens of pounds above atmospheric pressure Offsetting these factors was the long productive yield of the shallow shale gas wells when properly tubed and maintained Several of the original shale gas wells near Fredonia produced for more than 60 yr, and, although they were abandoned about 1885, they were still capable of yielding gas (Ley, 1935, p 950–951) Many of these shallow, low-pressure shale gas wells were abandoned early in the present century as the result of improper maintenance rather than of exhaustion of gas within the Devonian shale sequence itself

A more recent and commercially important phase of Devonian shale gas exploitation began in the 1920's in eastern Kentucky When several deep exploratory wells were drilled through the Devonian gas shale sequence to test the petroleum potential of the subjacent "Corniferous" limestone, they encountered flows of gas from the shales in excess of 1 million cubic feet per day at normal formation pressures A shale gas drilling quickly followed during which about 10,000 wells were drilled to the gas shale sequence in the Big Sandy area of Floyd, Knott, and Pike Counties, Ky , and adjacent Lincoln, Logan, and Mingo Counties, W Va The shale gas wells of the Big Sandy have several interesting peculiarities characteristic of the shale gas reservoirs Although a relatively small number of wells had large unstimulated initial yields, about 40 percent of the wells had no indication of gas in the shale sequence when drilled (Ray, 1976, p 103), and about 90 percent required stimulation of the 400- to 800-ft black shale section by using several tons of gelatinated nitroglycerine before yielding commercially exploitable volumes of gas (Hunter and Young, 1953) Commonly, large-volume wells were closely offset by nonproductive dry wells The distribution of producing wells is random Local structures apparently had little effect on the localization of gas or dry wells Like the low-pressure shallow wells along the southern shore of Lake Erie, the 2,000- to 4,000-ft-deep shale gas wells of the Big Sandy area yielded gas in volume for 40 to 60 yr before reaching the limit of economic profitability During their first few years of productivity, most shale gas wells in the Big Sandy area showed a sharp decrease in yield to about 40 percent of the well's initial flush production, at which time the decline curve stabilized and exhibited a very slow rate of decrease for the following 40 to 60 yr

These and related characteristics led exploration geologists to conclude, after years of lively debate, that the black shales were the source of gas in the shale sequence and that much of the gas produced during the initial flush-production phase was contained in an extensive network of natural fractures cutting the gas shale sequence Gas produced during the long period of slowly decreasing decline came from the shale matrix by slow desorbtion into the fracture system and was in a dynamic equilibrium with the well's ability to yield gas at the existing reservoir pressure They concluded that, to obtain a successful gas well, the well bore must penetrate the natural fracture system or be linked to the fracture system by permeable pathways established by the well-stimulation techniques In a newly drilled well that intersects the fracture system, gas escapes rapidly from the relatively permeable fractures

Eventually, the volume of gas desorbing from the organic matter in the matrix of the shale and moving slowly through the low permeable shale into the fracture system balances the volume of gas passing from the fractures into the well bore This event is indicated by a marked deflection and flattening of the decline curve After the flow of rock to the well reaches this steady state, the decline curve shows a very slow rate of decreasing volume of gas for several decades As a result of the complicated relations existing between source rocks and natural fracture systems in the gas shale sequence, successful exploration geologists require detailed knowledge of the stratigraphy and the geometry of the regionally extensive black gas shales and the tectonic history of the Appalachian basin to select the areas most favorable for the extraction of gas from the Devonian gas shale sequence

Literature

The volume of literature discussing the nomenclature and the stratigraphy of the Devonian black shales is large We do not propose to present even a brief synopsis of the data here because of space limitations For those interested in the early history of work on the black shales in the western part of the basin, Hass (1956, p 23) and Conant and Swanson (1961, p 16–19) discussed many of the important papers on the Chattanooga Shale and related strata Even the contributions of recent years are voluminous Roen and de Witt (1984, p 2–19) presented a selected annotated bibliography of the recent literature on the black gas shales, including many stratigraphic papers by geologists involved in the U S Department of Energy's Eastern Gas Shales Project (EGSP)

Methods of Study and Presentation of Data

The stratigraphic framework illustrating the relation of the Devonian gas shales and associated rocks consists of an interlocking net of stratigraphic sections across the western and the central parts of the Appalachian basin (pl 1) The cross sections presented here were based mainly upon the analysis and the detailed correlation of gamma-ray logs from many wells drilled for oil or gas and were augmented by data from outcrop sections, descriptions of drill cores, and hand-held scintillometer profiles of selected outcrops Analysis of conodont faunas corroborated litho-stratigraphic correlations, particularly in parts of New York, Ohio, Pennsylvania, and Tennessee

Of the several thousand gamma-ray logs analyzed in our study, we selected 136 of the best for the stratigraphic framework In addition to the subsurface gamma-ray logs, scintillometer traces were prepared for the outcrop sections (Ettensohn and others, 1979) The logs are identified in the locality register (see Appendix) and are keyed by number to the location of stratigraphic sections and wells (pl 1) To differentiate the Devonian black gas shales from other rocks of the sequence in a consistent manner, we drew a gray shale base line along intervals in the gamma-ray logs known to be predominantly light- to medium-gray shale (fig 1) Generally speaking, shales containing more than 1 5 weight percent of organic matter are black (N1), grayish black (N2), dark gray (N3), brownish black (5Y 2/1), or olive black (5YR2/1) (Color designations are from Goddard and others (1948))

We arbitrarily designated as "black gas shales" all shales whose gamma-ray log traces were greater than 20 American Petroleum Institute (API) units in positive value above the gray-shale base line on the gamma-ray log trace (fig 1) We concluded that the 20 API positive deflection of the gamma-ray curve to the right of the gray shale base line was a valid response to the amount of radioactive material in the rock The shale might be dark brown or dark gray, but if its gamma-ray signature was more than 20 API units to the right of the gray shale base line, then we classified it as a black gas shale for this study

Whenever possible, we projected named surface stratigraphic units into the subsurface in concurrence with other geologists working on the EGSP so that our strati-graphic framework for the Devonian gas shale sequence would be based upon existing surface stratigraphy Thus, geologists who study the gas shales have one or more well-exposed outcrop sections to examine for the various types of rock present and characteristics of a particular gas shale We also accepted other geologists' applications of surface nomenclature to subsurface units where our data corroborated their correlations Thus, we used the charac-teristic configuration on gamma-ray traces and other sub-surface data in combination with well-known and long-established surface stratigraphy to identify and project

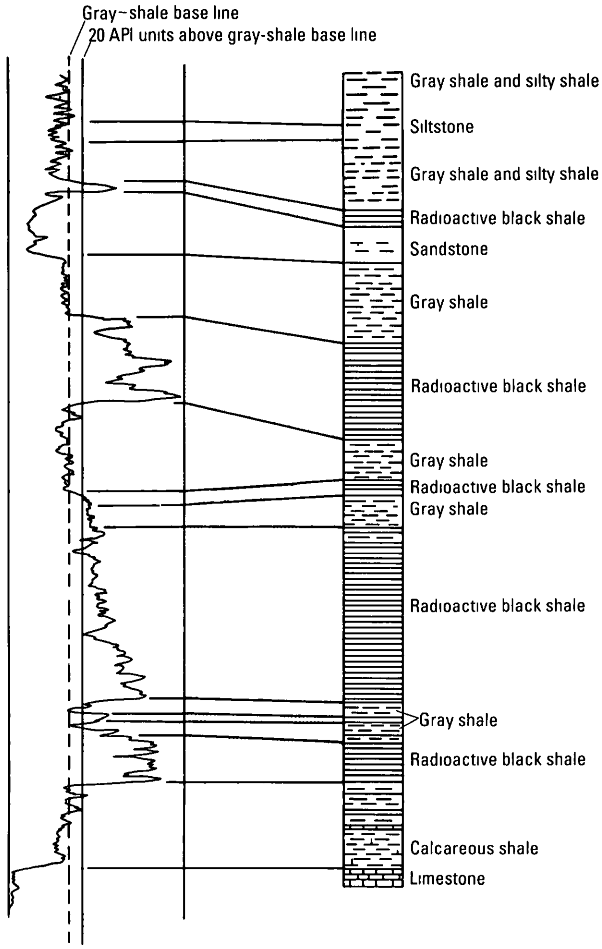

Figure 1 Comparison of a gamma-ray log and a litho-graphic log indicating the reactive response to rock types API, American Petroleum Institute

lithostratigraphic units throughout their subsurface extent in the Appalachian basin Where appropriate, we chose to use stratigraphic units from the New York standard section for the Devonian rocks in the United States rather than to introduce new names into the stratigraphic nomenclature By applying names from known surface exposures, we demonstrated the correlation of units from widely spaced outcrops in the States along the periphery of the Appala-chian basin from New York to Tennessee

Many of the names of the units shown in the accompanying lithostratigraphic cross sections have been used for many years by the U S Geological Survey However, their usage generally has been restricted in areal extent to the vicinity of outcropping strata because a lack of data precluded tracing these units into the subsurface In our basinwide study, we greatly extended the range of many units by using gamma-ray log correlations In addition to correlating and mapping the subsurface extent of these regionally extensive black gas shales, we identified and correlated a number of named stratigraphic units in the sequences of gray shale, mudrock, siltstone, sandstone, and limestone intercalated in the Devonian gas shale sequence. We show, by map and cross section, the subsurface extent of these lithostratigraphic units. Some of the units shown are of limited extent and may be of interest only to local stratigraphers, whereas other units have great lateral extent and are key units for regional correlation. We do not have sufficient data to show the eastern limit or boundary of some of the finer grained units in the gas shale sequence. These areas of sparse data are indicated on the maps by the phrase "Eastern limit not mapped."

On plate 1, we show by structure contours the elevation of the base of the Devonian gas shale sequence in the western part of the Applachian basin from New York to the Kentucky-Tennessee State line. Throughout this area, the sequence rests upon the Onondaga Limestone in New York and the near temporal equivalent Huntersville Chert or Wildcat Valley Sandstone to the southwest. We also show an approximate drilling depth to the base of the sequence. An approximate depth to the base of the sequence may be obtained from locations within the study area by subtracting the drilling depth for a specific site from its surface elevation. Because the isopach lines showing the interval from the surface to the base of the sequence were developed from mathematically smoothed elevation data for topographic quadrangle maps throughout the Appalachian basin (Dimont and Urban, 1981), the drilling depths are only approximate.

The isopach maps accompanying our report show the net thickness, in feet, of radioactive black shale within the total Middle and Upper Devonian sequence (fig. 2) and, in specific, named formations and members in the sequence. The isopachs were compiled partly from our subsurface work and partly from statewide isopachs produced by State agencies working on the EGSP. Because the tops of individual black shale units are generally gradational into the overlying lighter gray shale, the top of a black shale cannot be delineated with any uniformity by geologists working in different parts of the basin. In contrast, the basal contact of the major black shale units is sharp and well defined. Consequently, from the base of one black shale to the base of a stratigraphically younger black shale provides a convenient sequence for study, and the interval often corresponds to a defined formation. For consistency, we measured the net thickness of radioactive black shale at 20 or more API units above the gray shale base line for each of the defined formations in the gas shale sequence. Inasmuch as thickness measurements obtained from different sources of subsurface data, such as wire-line geophysical logs, drill cuttings, sample studies, core drill records, or driller's logs, may vary considerably for each well studied, we restricted our isopach data base almost entirely to gamma-ray logs.

Throughout much of the western and the central parts of the Appalachian basin, the 20 API criteria are applicable, however, it cannot be applied with assurance in the eastern part of the basin. In the eastern part of the study area, the dark Upper Devonian shales lose the characteristic positive gamma-ray deflection in relation to contiguous lighter gray shales, which effectively precludes delineation and measurement of the thickness of the Upper Devonian gas shales there. The lack of a significant response on the gamma-ray log is probably caused by an eastward-increasing dilution of the shale by nonorganic detritus. The Middle Devonian Marcellus Shale, however, shows a strong positive deflection much farther to the east than the Upper Devonian black shales. This suggests that the variables affecting the log response of the younger black gas shales were largely inoperative within the presently preserved part of the Marcellus depositional basin.

Although the isopachs of the black gas shales are based upon the gamma-ray log response, which is dependent upon several variable factors, we believe the gamma-ray curve gives a reasonable approximation of the thickness and is more conservative than a determination of the black shale thickness by visual inspection (Wallace and de Witt, 1975) and considerably less conservative than isopachs based upon a 2-percent minimum of organic matter by volume (Schmoker, 1980, p. 2157). Several factors support this conclusion. The eye tends to see shales darker than their contained organic carbon and does not appear to be able to differentiate readily the color values of shales that contain more than about 2 weight percent of organic carbon (Hosterman and Whitlow, 1983, p. 6–7). Consequently, a black shale of 15-weight-percent organic carbon that is from the western part of the basin and that has a strong positive deflection on the gamma-ray log looks much like a black shale of a scant 2-weight-percent organic carbon that is found in the east-central part of the basin and that lacks the positive gamma-ray response. The 15-weight-percent organic-carbon black shale is a good gas shale, whereas the 2-weight-percent organic-carbon black shale may not produce sufficient gas to be classed as a gas shale.

Middle and Upper Devonian and Lower Mississippian gas shales were deposited as prodelta basinal black muds in an anoxic environment on the bottom of an epicontinental sea peripheral to the Catskill delta complex. The Catskill delta, which is a massive regressive deposit composed of mud, silt, sand, and pebbles from eastern source areas, filled much of the Appalachian foreland trough and spread westward on to the contiguous cratonic platform. Although regressive clastic strata dominated much of the central Appalachians during the Middle and the Late Devonian, seven extensive transgressive sheets of black mud spread eastward and interfingered with the lighter sediments of the Catskill deltaic sequence. In contrast, in the sediment-deprived western and southwestern parts of the basin, a thin sheet of black mud and some subordinate beds of gray or greenish-gray mud accumulated in a quiet anoxic marine environment. The black muds

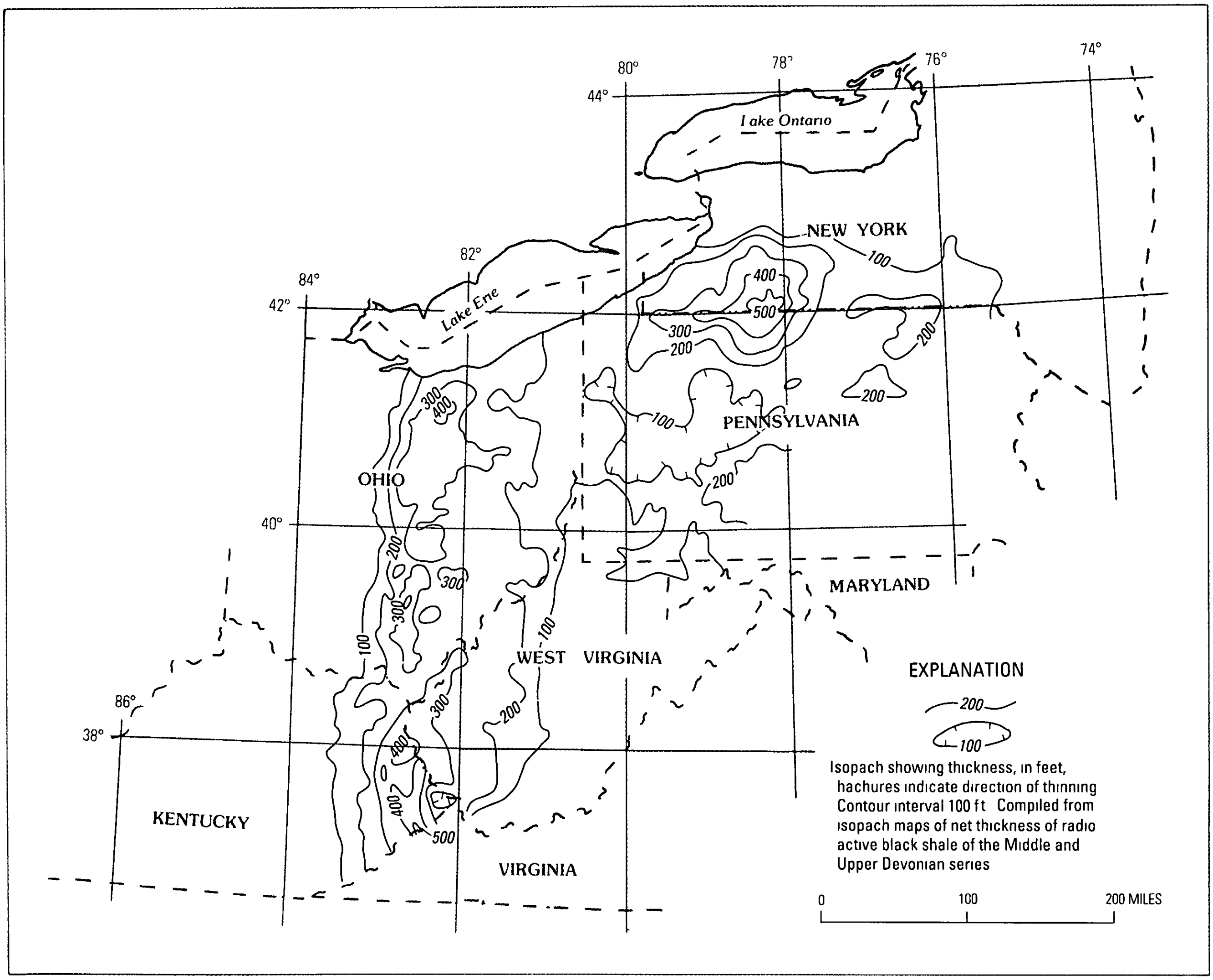

Figure 2. Total net thickness of radioactive black shale in rocks of Middle and Late Devonian age

upon lithification and diagenesis became the Devonian black gas shales

The gas shales crop out at many places (fig 3) along the periphery of the Appalachian basin Because the basin is asymmetric and has a steeply dipping faulted and locally overturned eastern flank, the gas shales dip gently into the basin from the north, the west, and the southwest under the Appalachian Plateaus In contrast, the shales are steeply dipping—vertical to slightly overturned in outcrops along the Allegheny front on the eastern side of the Plateaus The Marcellus Shale, which is the basal black shale of the gas shale seqence, dips from outcrops of more than 1,000 ft above sea level in east-central New York to more than 7,000 ft below sea level at several places adjacent to the Allegheny front in Pennsylvania The structural relief of the Marcellus is more than 8,000 ft In contrast, the structural relief on the Cleveland Member of the Ohio Shale, which is an upper member in the gas shale sequence, is about 3,500 ft

Acknowledgments

Much of the support for our study of the Devonian black gas shales was provided under interagency agreement DE-A121-79-MC 10866 between the U S Geological Survey and the Morgantown Energy Technology Center of the U S Department of Energy During the study, we monitored the work of and cooperated with personnel from several State surveys, universities, and national laboratories We have acknowledged the expert assistance and help of these individuals and institutions in Roen and de Witt (1984)

STRATIGRAPHY

As stated in the section "Methods of Study and Presentation of Data," we have based our subsurface stratigraphic nomenclature on the standard reference section

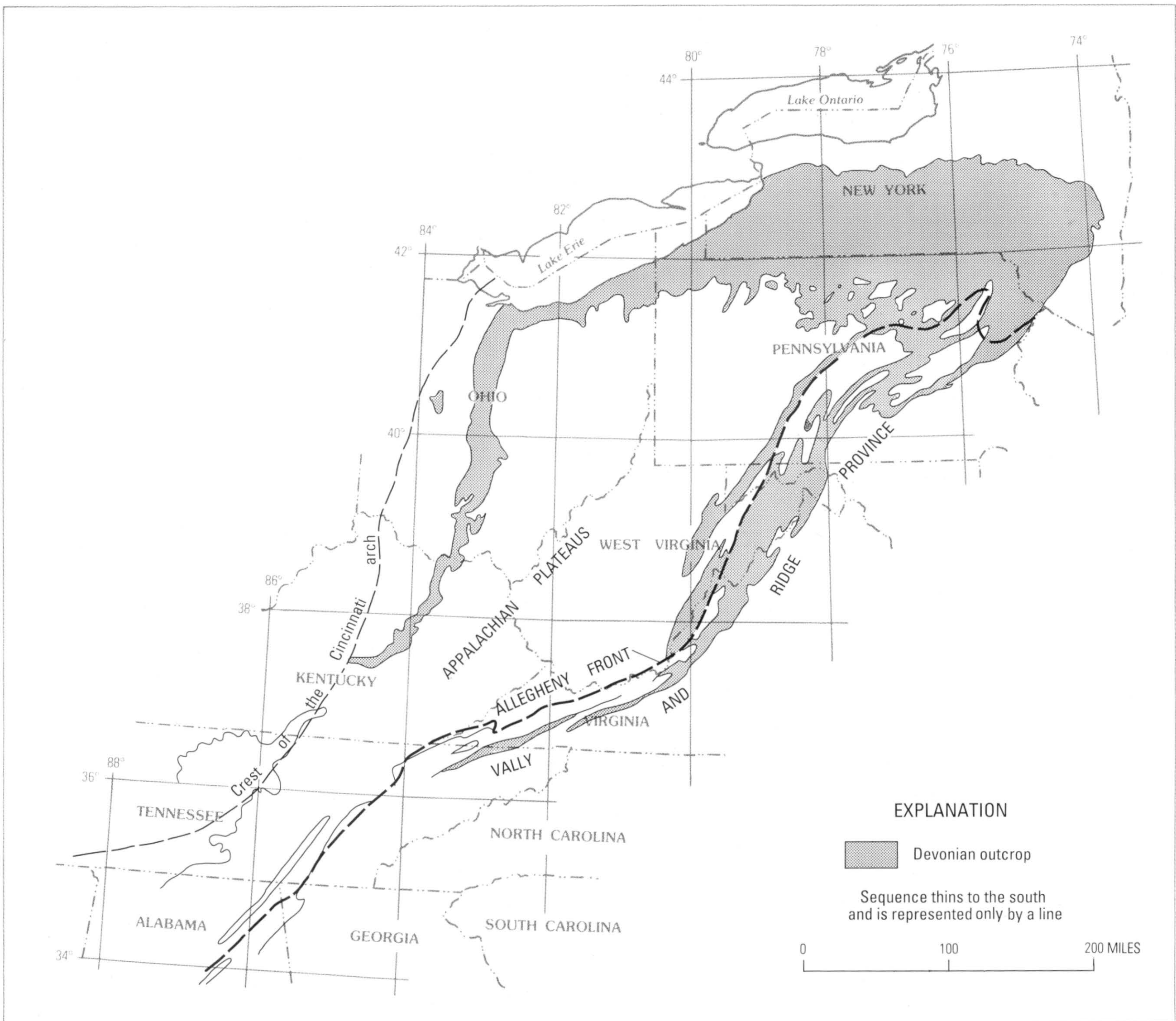

Figure 3. Outcrops of Devonian rocks in the Appalachian basin in relation to the Appalachian Plateaus and the Valley and Ridge province segments of the basin. (From de Witt and Roen, 1985.)

for the Devonian System in New York. We have done this for the following reasons: the surface stratigraphy is well defined, the outcrops show a cross section of the Catskill delta sequence from basinal shales in the west to correlative terrestrial sandstones and conglomerates in the east, and the transgressive or regressive nature of individual stratigraphic units is well documented.

When we complete our description of the youngest regionally extensive Devonian black shale in the New York reference section, we shift from New York to outcrops of Devonian and Mississippian rocks in Ohio along the eastern flank of the Cincinnati arch where younger rocks are exposed (fig. 3). We discuss the correlation of units there and to the south along the arch to south-central Tennessee. Although they are not strictly within the area of our study, we also discuss the correlation of black shale units in parts of the Valley and Ridge province from central Pennsylvania to southwestern Virginia and contiguous Tennessee.

Our paramount intent is to discuss and document the stratigraphy of the black shales; however, we deem it necessary to refer briefly to the lighter colored rocks that are interleaved with the black shales and that make up a considerable part of the total Devonian shale sequence in the east. We show, by map and cross section, the subsurface extent of many of these lighter units and briefly describe their relation to the black gas shales to enhance our delineation and documentation of the regional stratigraphic framework of the Devonian gas shale sequence.

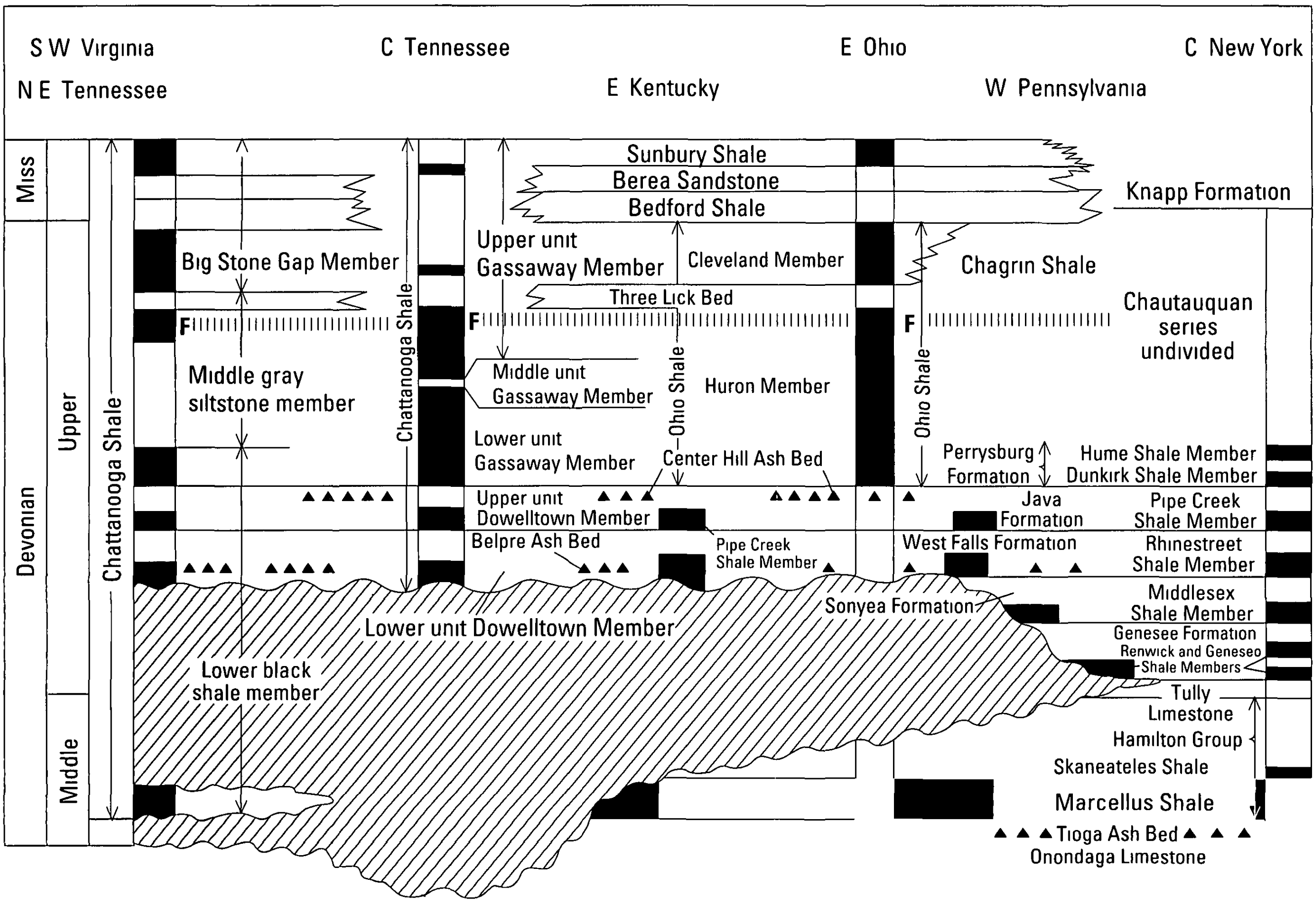

Figure 4. Correlation of Devonian and Mississippian black gas shales and some related rocks in the Appalachian basin IIIII *F* IIIII, *Foerstia* zone, ▲, ash bed

HAMILTON GROUP

Rocks of the Middle Devonian Hamilton Group (Vanuxem, 1840), which are typically exposed in central New York, are the oldest strata of the Devonian gas shale sequence They consist of black and dark-gray shale in the lower part and lighter gray shale and mudrock in the upper part The group overlies the Onondaga Limestone The Hamilton Group (pls 2–8) is subdivided in ascending stratigraphic order into the Marcellus, the Skaneateles, the Ludlowville, and the Moscow Shales The group is subdivided by several thin, but extensive, fossiliferous limestones that crop out at many localities across New York Each formation can be subdivided further into several members by using lithologic and paleontologic criteria

Marcellus Shale

The black Marcellus Shale (Hall, 1839, p 289), which is the oldest of the regionally extensive black gas shales (fig 4), is typically exposed in New York, where it has been subdivided into several members (Oliver and others, 1969) It crops out in the Valley and Ridge from southeastern New York to northern West Virginia The Marcellus or its partial equivalent, the Millboro Shale, is present in the subsurface (fig 5) in New York, Pennsylvania, Ohio, western Maryland, Virginia, West Virginia, and northeastern Tennessee (pls 2–8) Throughout most of its extent, the Marcellus consists of "sooty" black shale and a few beds of medium-gray shale and limestone nodules or beds of dark gray to black limestone The Marcellus, which is about 1,000 ft thick in central Pennsylvania, thins to the north, the west, and the south and feathers out of the sequence in the subsurface of eastern Ohio, western West Virginia, and southwestern Virginia Rickard (1984, p 828) suggested that the Marcellus Shale may be separated from the older Seneca Member of the Onondaga Limestone and the equivalent Delaware Limestone by a disconformity in western Pennsylvania and Ohio Throughout its extent in the basin, the Marcellus makes a strong positive deflection on gamma-ray log curves, which facilitates its identification and correlation in the central and the eastern parts of the area The deflection is most conspicuous where the Marcellus lies directly upon carbonate rocks

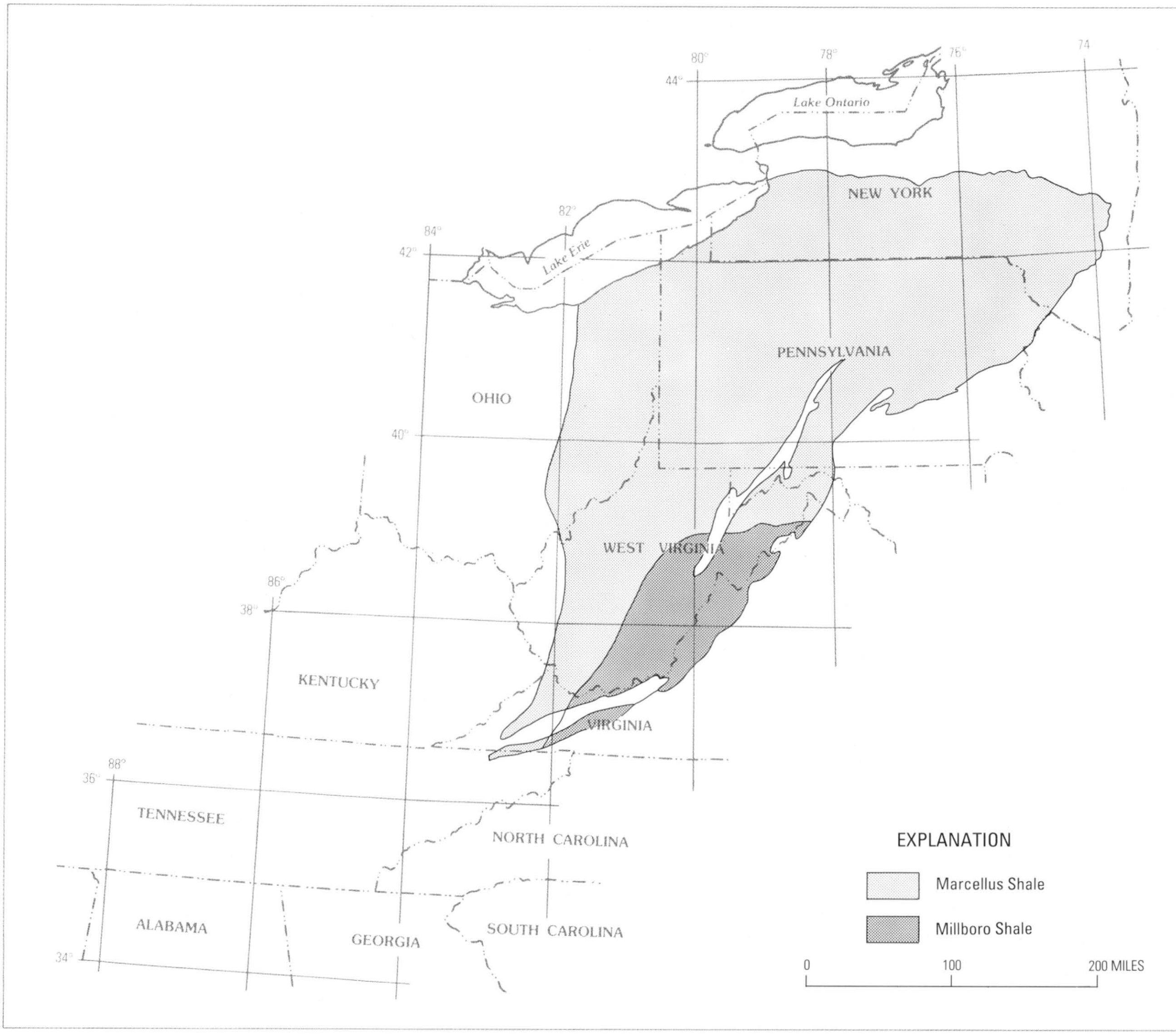

Figure 5. Areal extent of the Marcellus and Millboro Shales in the Appalachian basin. (Modified from de Witt and Roen, 1985.)

The net thickness of radioactive black shale in the Hamilton Group (fig. 6), which is dominantly the Marcellus Shale but locally includes some black Skaneateles Shale, exceeds 250 ft in eastern Bradford County, Pa., and contiguous northeastern Tioga County, N.Y. Small areas that are more than 100 ft thick are present in Somerset County, Pa., and Garrett County, Md. A similar local area that has more than 100 ft of radioactive Marcellus Shale lies in northeastern Monroe County, Ohio. The radioactive black shales thin to a featheredge to the south and the west. Locally in eastern New York and east-central Pennsylvania, some beds of sandstone are intercalated in the Marcellus, presumably closer to the source of coarser grained clastic detritus.

Cherry Valley Limestone Member

A laterally persistent bed of limestone within the Marcellus Shale, the Cherry Valley Limestone Member (Clarke, 1903, p. 26), was named for exposures near Cherry Valley, Otsego County, N.Y. It is an extensive unit in the subsurface of New York, Pennsylvania, and West Virginia (fig. 7; pl. 4, Nos. 64–78).

Purcell Limestone Member

The Marcellus Shale in central Pennsylvania contains the Purcell Limestone Member (Cate, 1963, p. 232), which is composed of a gray silty shale and mudrock, as well as some beds of siltstone, an abundance of limestone nodules,

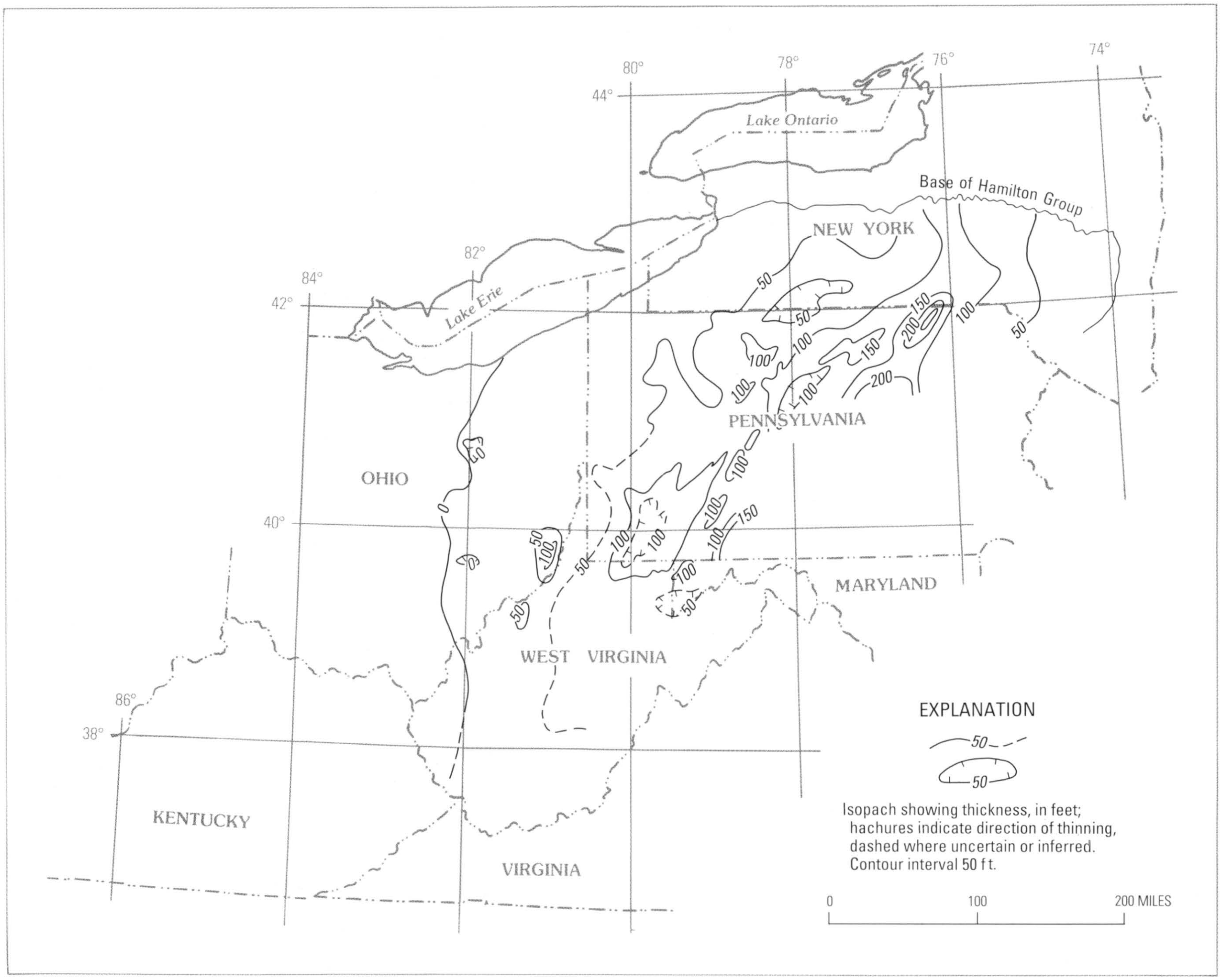

Figure 6. Net thickness of radioactive black shales in the Hamilton Group.

and a scattering of barite nodules about 1 to 2 inches (in.) in diameter (pl. 4). The Purcell extends into the subsurface of Pennsylvania, Maryland, and West Virginia (fig. 8; pl. 4, Nos. 64–75).

Tioga Ash Bed

The Tioga Ash Bed (Ebright and others, 1949, p. 10) is present at the base of the Marcellus Shale in many outcrops in the Valley and Ridge province and in the subsurface in much of the northern part of the Appalachian basin. Originally, geologists believed that the Tioga was a single ash fall or possibly several closely spaced beds in a section only 1 or 2 ft thick. Rickard (1984, p. 822), however, showed that the name "Tioga" had been applied to at least three discrete ash falls that locally coalesce. Elsewhere, they occur in the upper part and at the top of the Onondaga Limestone. The uppermost unit of the Tioga occupies the stratigraphic postion originally assigned to the Tioga by C.R. Fettke (Ebright and others, 1949). Used with care, the Tioga beds are excellent units for regional correlation.

Skaneateles Shale

The Skaneateles Shale (Vanuxem, 1840), which overlies the Marcellus Shale, consists mostly of dark- to medium-gray fossiliferous shale and mudrock. The Skaneateles Shale extends into the subsurface of eastern Ohio and north-central West Virginia (fig. 9; pl. 2, Nos. 14–15; pl. 3, Nos. 42–55, 27) before its identity is lost in a thick sequence of dark-gray rocks of the Hamilton Group. In part of its western extent, mainly in the subsurface of southwestern New York, northwestern Pennsylvania, and northeastern Ohio, the Skaneateles Shale contains a black shale

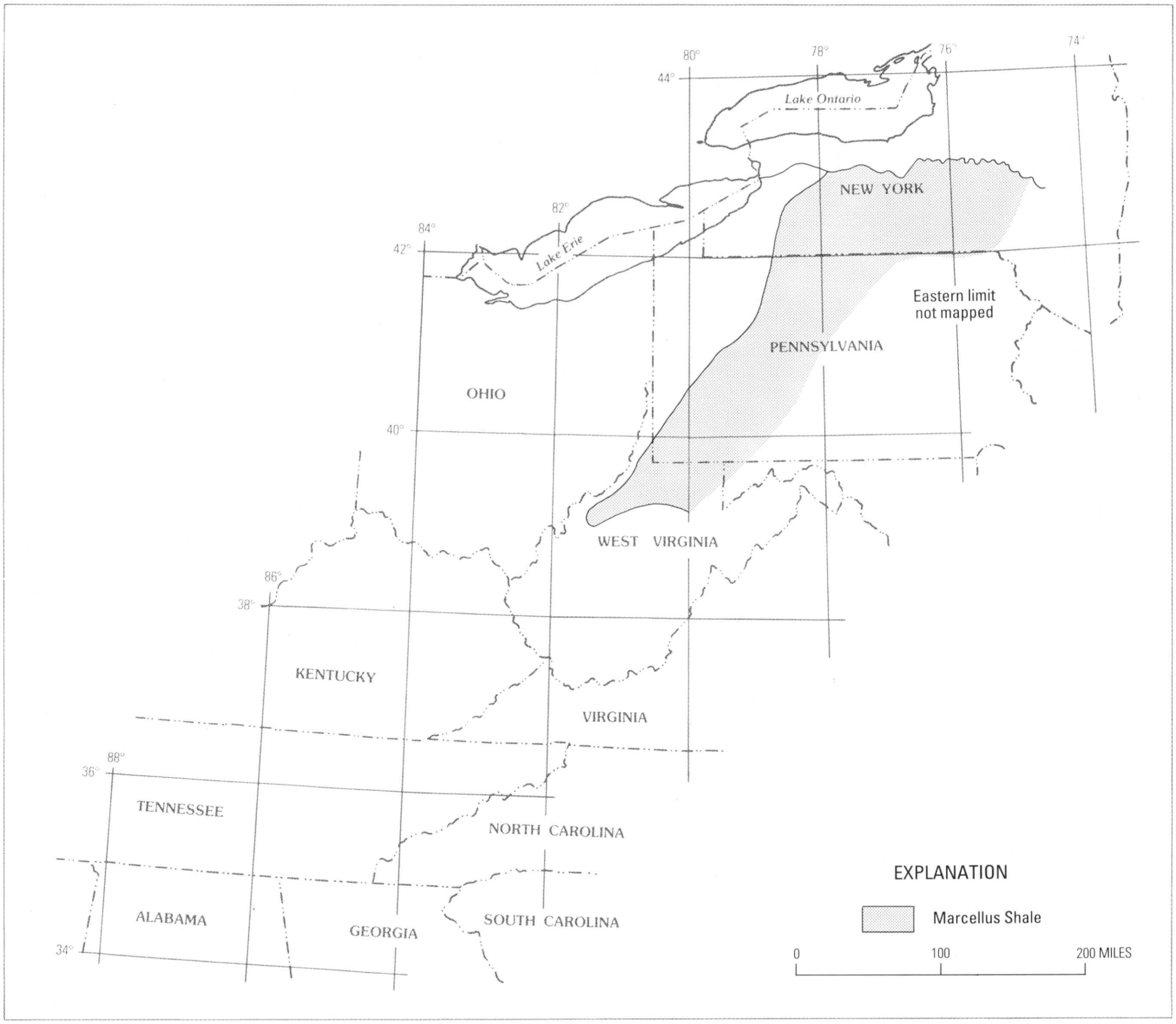

Figure 7. Areal extent of the Cherry Valley Limestone Member of the Marcellus Shale.

facies that resembles the Marcellus Shale, for which it can be easily mistaken. The net thickness of radioactive black shale in the Hamilton Group includes the beds of black shale in the Skaneateles. In northern Ohio, along Lake Erie, the Plum Brook Shale (Cooper, 1941, p. 181) is a western correlative of the Skaneateles Shale. Both units include abundantly fossiliferous gray shales. To the south in central Ohio, the lower gray shale part of the Olentangy Shale (Winchell, 1874, p. 287; Tillman, 1970, p. 206) also forms a part of the sheet of Skaneateles Shale. In the subsurface of Ohio, the Skaneateles grades westward into either the Plum Brook Shale or the lower part of the Olentangy Shale. The stratigraphic relation of the Olentangy Shale to contiguous units is complicated by the presence of the Middle Devonian unconformity within the shale. The stratigraphy of the Olentangy is discussed in the section on the Hanover Shale Member of the Java Formation.

Stafford Limestone Member

Marking the base of the Skaneateles Shale is the relatively thin, but extensive, Stafford Limestone Member (Clarke, 1894). The unit may be identified in the subsurface as far southwest as north-central West Virginia and southeastern Ohio (fig. 10; pl. 5). Throughout its extent, the Stafford Limestone Member serves to separate the Marcellus Shale from the overlying Skaneateles. The presence of the Stafford as a marker unit is particularly important in the western part of the basin where the Skaneateles becomes a dark-grayish-black facies that is very similar to the Marcellus.

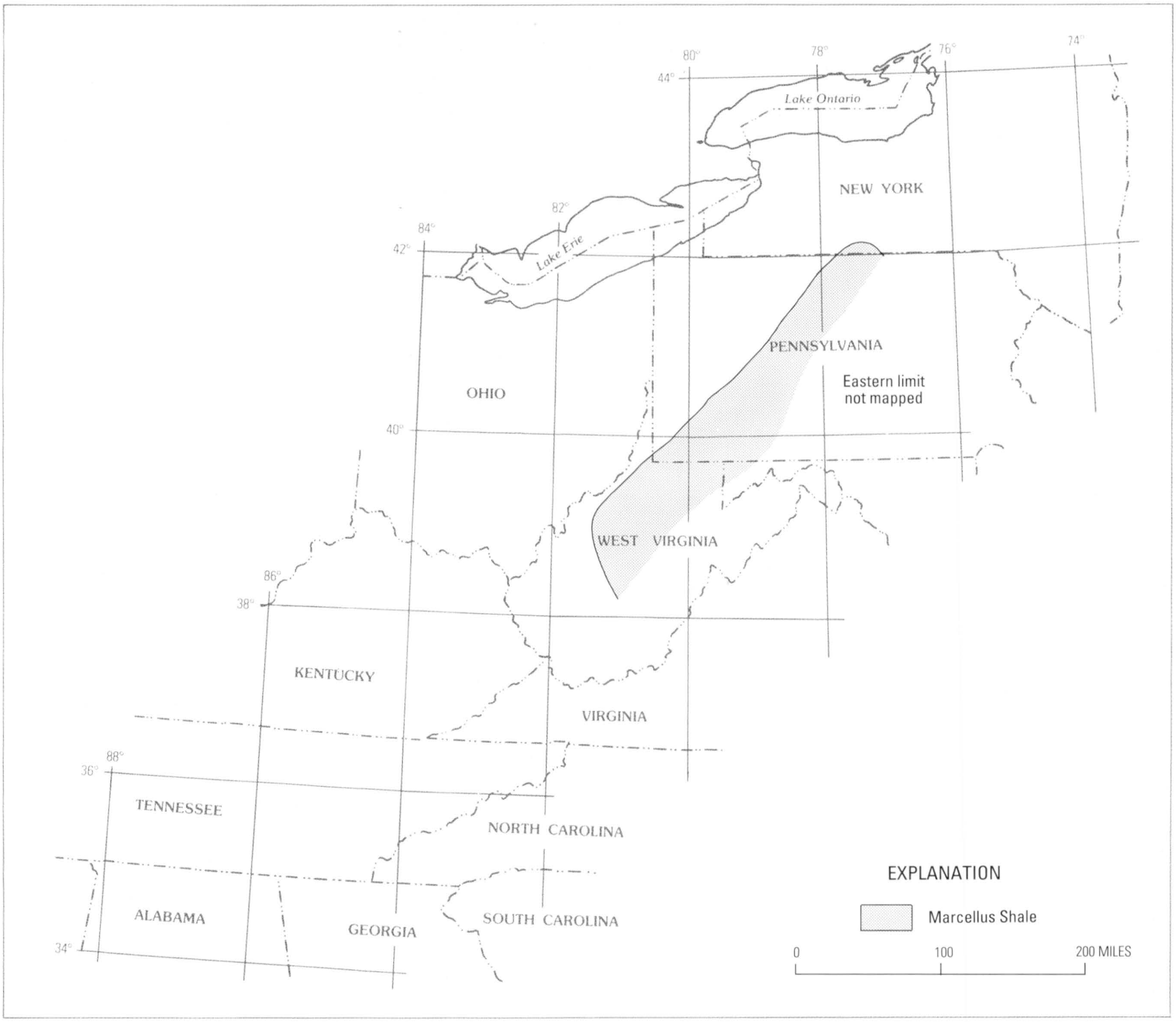

Figure 8. Areal extent of the Purcell Limestone Member (Cate, 1963) of the Marcellus Shale.

Ludlowville Shale

The Ludlowville Shale (Hall, 1839), which crops out in western and central New York, consists of dark shale in the lower part and lighter gray shale and mudrock in the upper part. In the subsurface, the Ludlowville is a recognizable unit westward from New York into northeastern Ohio (pl. 2, Nos. 16–30) and southward into extreme western Maryland and adjacent West Virginia (fig. 11; pl. 3, Nos. 37–55, 27). Locally in northwestern Pennsylvania, the Ludlowville is a dark-gray limestone as much as 80 ft thick including its basal member, the Centerfield Limestone Member. In the central part of the basin, particularly near the eroded upper edge of the Hamilton Group, several of the thin limestone key beds feather out, and, in their absence, the Ludlowville cannot be separated from other formations in the group. The massive gray shale is treated as the undivided composite of several shales; for example, the Moscow and the Ludlowville undivided (pl. 3, Nos. 42–46).

Centerfield Limestone Member

The Centerfield Limestone Member (Clarke, 1903) is the extensive basal member of the Ludlowville Shale. The fossiliferous limestone is rarely more than 20 ft thick in the subsurface of western Maryland, western New York, western Pennsylvania, eastern Ohio, and northeastern West Virginia (fig. 12; pl. 2, Nos. 22–30; pl. 4, Nos. 64–78).

In north-central Ohio, a Centerfield correlative, the Prout Limestone (Stauffer, 1907, p. 592), overlies the Plum Brook Shale and underlies Upper Devonian black shale. A

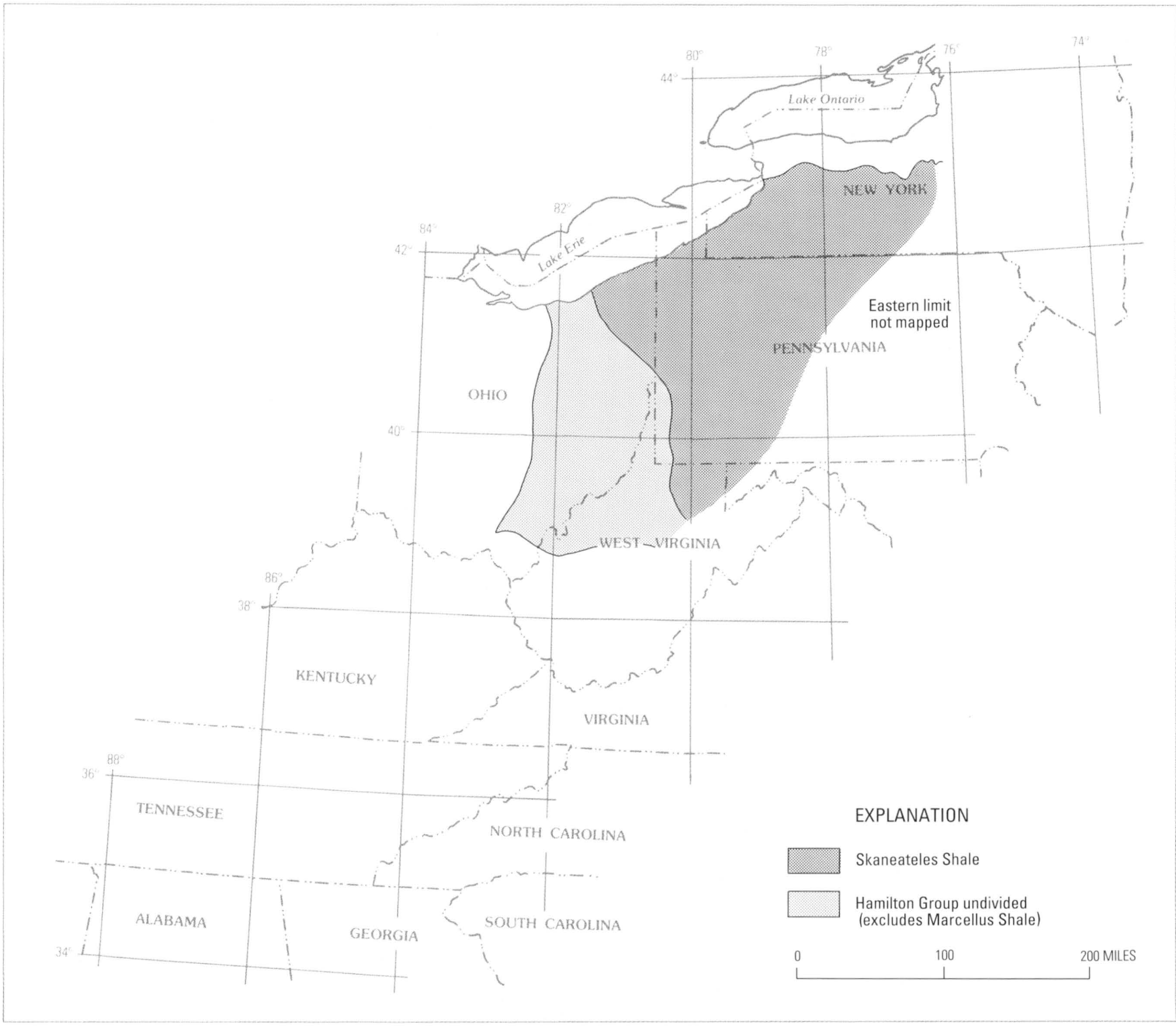

Figure 9. Areal extent of the discrete Skaneateles Shale and the undivided Hamilton Group, excluding the Marcellus Shale.

considerable hiatus separates the Prout from the overlying black shale.

Moscow Shale

The Moscow Shale (Hall, 1839), which is the youngest unit of the Hamilton Group, is composed largely of medium-gray calcareous mudrock and shale in western New York. It is a recognizable subsurface unit westward into western Pennsylvania and southward into western Maryland and contiguous West Virginia (fig. 13; pl. 7, Nos. 92–93, 43, 94, 67, 95). In southwestern Pennsylvania and adjacent West Virginia, the limestone at the base of the Moscow is absent, and the Moscow and the Ludlowville cannot be recognized as discrete units. They are combined as the Moscow and Ludlowville undivided (pl. 7, Nos. 43, 93). The Moscow contains several extensive beds of fossiliferous limestone in the lower part.

Tichenor Limestone Member, Menteth Limestone Member, and Portland Point Limestone Member

The Tichenor Limestone Member (Clarke and Luther, 1904, p. 32; Cooper, 1930; Baird, 1979) is the basal member of the Moscow Shale in the subsurface of western Pennsylvania and western New York (fig. 14; pl. 4, Nos. 66–78; pl. 5, Nos. 83, 77). Baird (1979) showed that the Tichenor grades laterally into the lower tongue of the Portland Point Limestone Member of the Moscow Shale (Cooper, 1930, p. 218; pl. 4, Nos. 75–76) north of Ithaca,

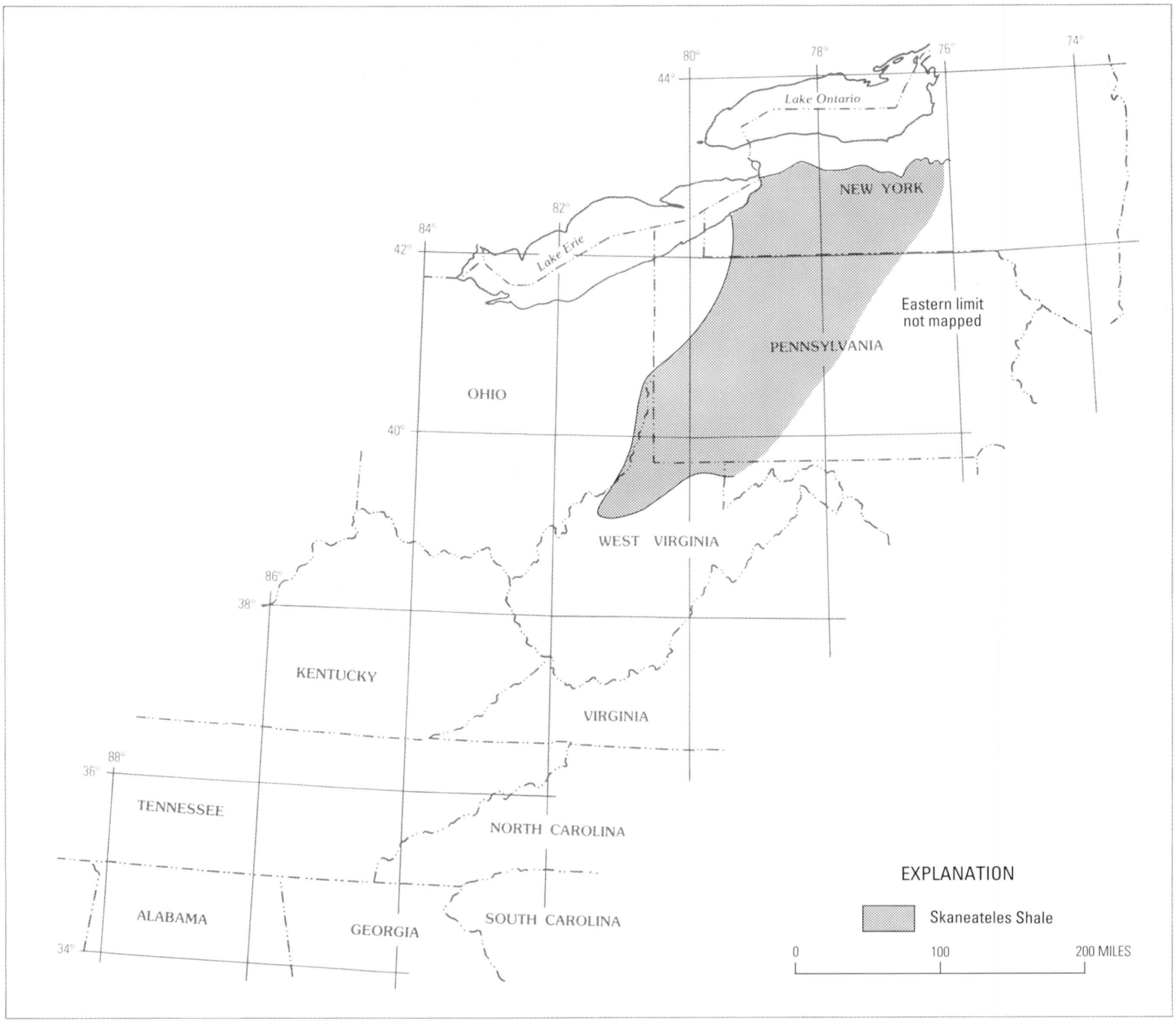

Figure 10. Areal extent of the Stafford Limestone Member of the Skaneateles Shale.

Tompkins County, N.Y. Thus, the Portland Point becomes the basal member of the Moscow Shale at and east of the member's type exposure north of Ithaca on the eastern side of Cayuga Lake. In northwestern Pennsylvania, the Tichenor grades into the top of a massive unit of limestone about 80 ft thick, which well drillers consistently identify as Tully Limestone. We believe that the drillers' "Tully" represents the Centerfield-through-Tichenor interval and not the younger Tully Limestone. Our assumption agrees well with the findings of Wright (1973), who assigned this thick limestone to the Tichenor and older beds. Samples from the upper part of the drillers' "Tully" in the core from Monsanto Research Corp. No. 3 EGSP well at Presque Isle State Park, Erie County, Pa., yielded conodonts, predominantly elements of *Polygnathus linguiformis linguiformis*, a smaller number of *P. varcus*, and *Tortodus intermedius*; Anita Harris (U.S. Geological Survey, written commun., 1980) stated, "In terms of the central New York section, these conodonts represent a stratigraphic interval below the Tully Limestone and above the Cherry Valley Limestone Member of the Marcellus Formation." These paleontologic data support assignment of Tichenor age and older for rocks previously thought to be of Tully age in northwestern Pennsylvania.

Baird (1979) showed that the Menteth Limestone Member of the Moscow Shale is separated from the older Tichenor locally by as much as 60 ft of the dark Deep Run Shale Member of the Moscow Shale (Cooper, 1930, p. 219) in outcrop in west-central New York (pl. 5, Nos. 82–83). The shale thins to the east where the Menteth grades into the upper tongue of the Portland Point Limestone Member of the Moscow Shale. The Deep Run Shale Member also thins

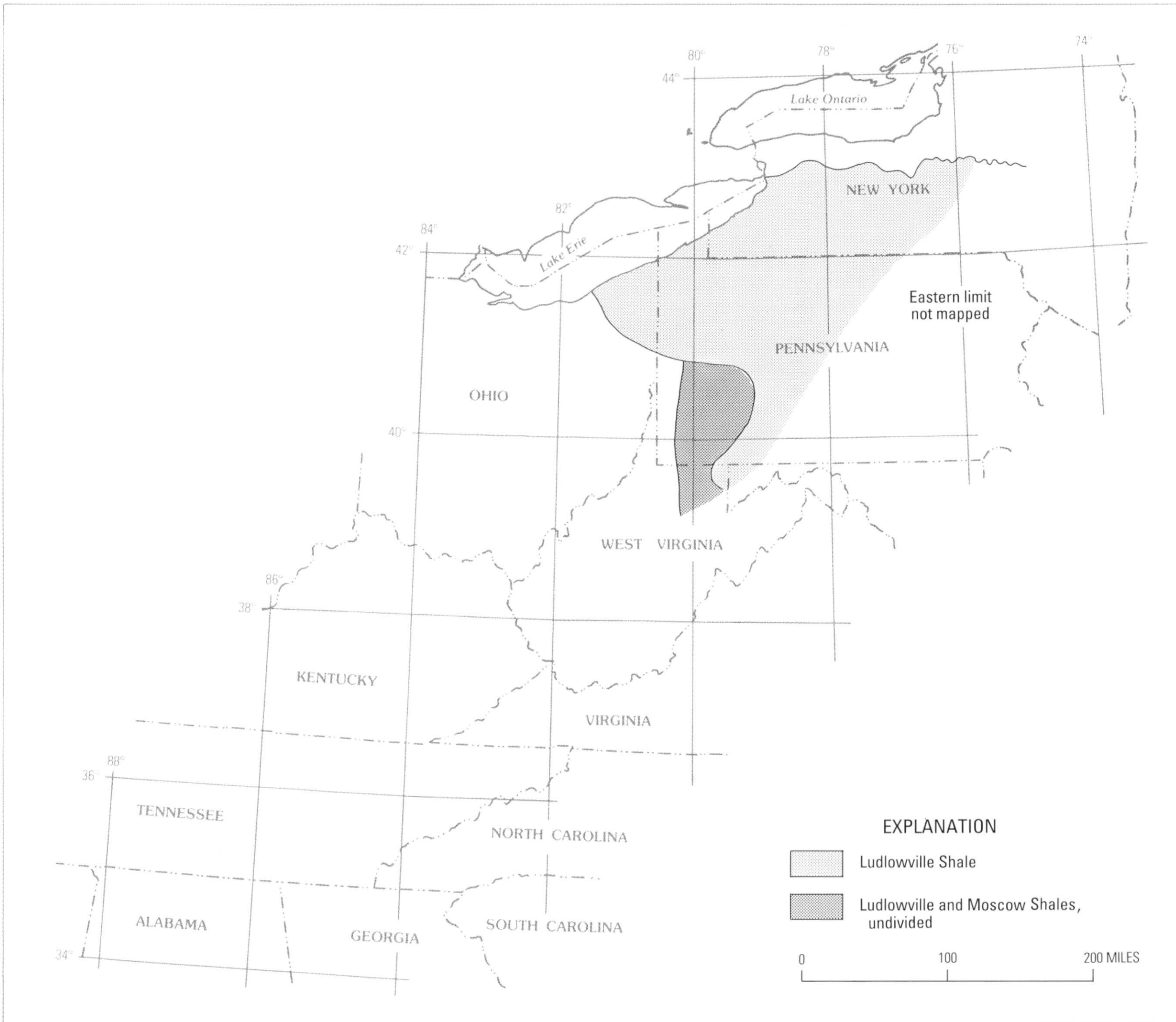

Figure 11. Areal extent of the discrete Ludlowville Shale and the undivided Ludlowville and Moscow Shales.

to the west, and the Menteth lies on and merges with the top of the Tichenor Limestone Member of the Moscow Shale. The Menteth can be recognized in the subsurface across western Pennsylvania into extreme western Maryland (fig. 15). It is not as extensive as the older Tichenor.

Correlations of Units in the Hamilton Group

The Skaneateles, the Ludlowville, and the Moscow Shales grade southward into the Mahantango Formation (Willard, 1935, p. 205) in central and eastern Pennsylvania. The formation is composed of fossiliferous gray shale, siltstone, and sandstone. The Mahantango, which is more than 2,000 ft thick in eastern Pennsylvania, thins westward to less than 100 ft in northeastern Ohio and changes facies to a dark-gray shaley mudrock.

In surface sections in central Virginia and adjacent West Virginia, the Marcellus Shale and the overlying Mahantango Formation merge into about 1,000 ft of black shale, which Butts (1940, p. 308–317) named the Millboro Shale for exposures near Millboro Springs, Bath County, Va. (fig. 5). Although it is not within our study area, we believe that data on the Millboro Shale are important in any discussion of the Devonian shale sequence. Apparently, the Millboro represents a coalescence of the Marcellus, a black shale and mudrock facies of the Mahantango of Pennsylvania, and the overlying black Burket Shale Member of the Harrell Shale (fig. 16; see section "Relation of the Genesee Formation to the Burket Shale Member of the Harrell Shale"; Butts, 1918, p. 523). The constituent units in the Millboro cannot be identified visually, although paleontologic data show a Marcellus fauna in the lower part of the

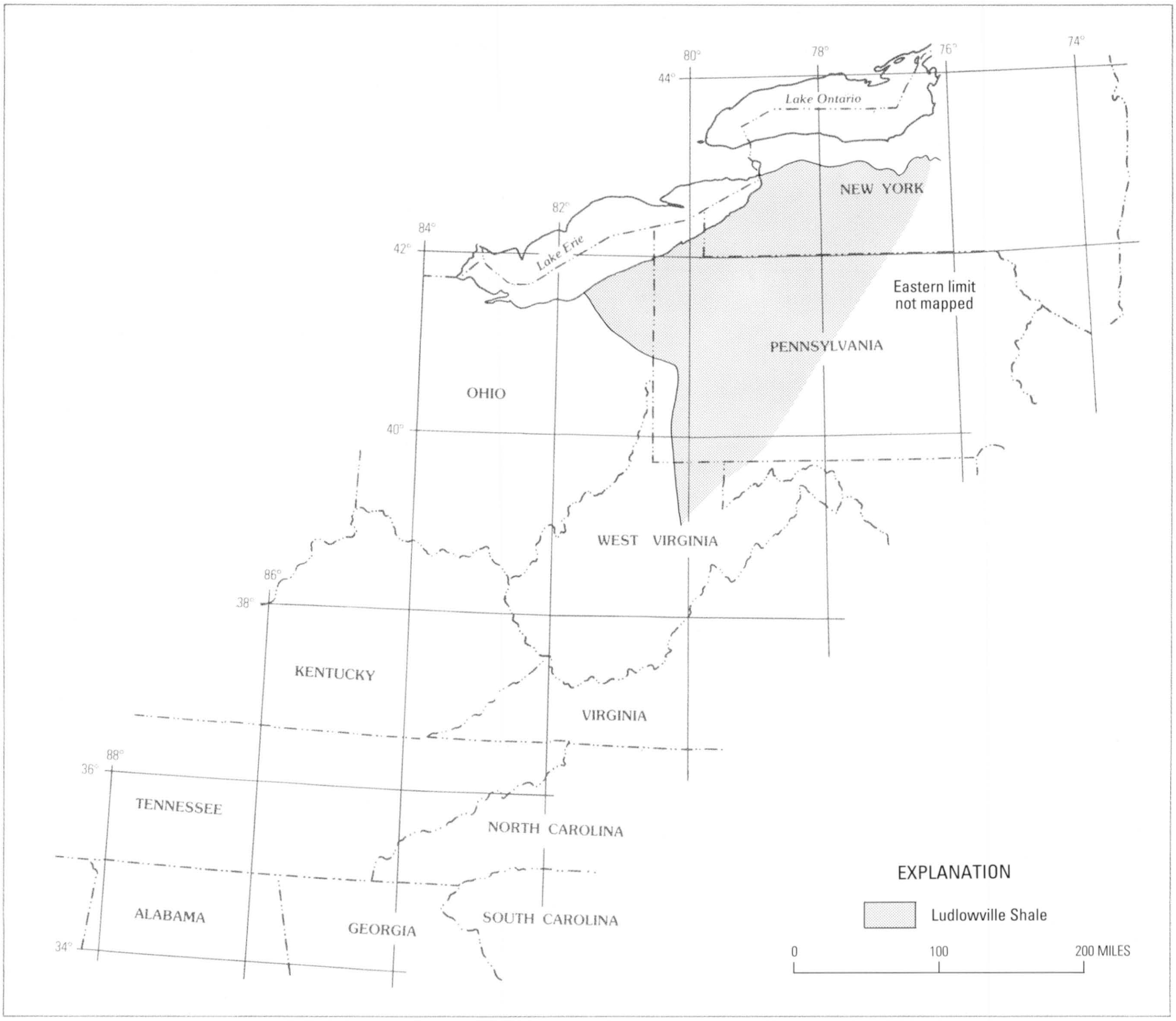

Figure 12. Areal extent of the Centerfield Limestone Member of the Ludlowville Shale.

Millboro and a Burket fauna in the upper part; for example, to the northwest in Monongalia County, W. Va., the Marcellus and the Burket cannot be visually distinguished in the 385-ft black shale and mudrock section in DOE's MERC No. 1 test well. However, 123 ft of the Marcellus at the base of the sequence and 45 ft of the Burket at the top are clearly shown by their gamma-ray signatures (Schwietering and others, 1978, fig. 1).

TULLY LIMESTONE

The Tully Limestone (Vanuxem, 1839) is a dark-gray to black, cobbly weathering, fossiliferous limestone that overlies the Hamilton Group in central New York, where it is typically exposed. The Tully is present in outcrops in Pennsylvania and West Virginia (pl. 4, Nos. 63–78). It has long been a key unit for well drillers. In the subsurface, the Tully extends southwest from the New York outcrops to southeastern Ohio and north-central West Virginia (fig. 17). It attains a maximum thickness of more than 200 ft in Lycoming County in north-central Pennsylvania (Heckel, 1973, fig. 14) and thins to a featheredge that has a fringe of limestone nodules on the periphery of the formation.

Middle Devonian Unconformity

A late Middle Devonian unconformity (fig. 4) in the central and the western parts of the Appalachian basin had considerable effect on the position and the extent of several of the black gas shales. East of Canandaigua Lake in eastern

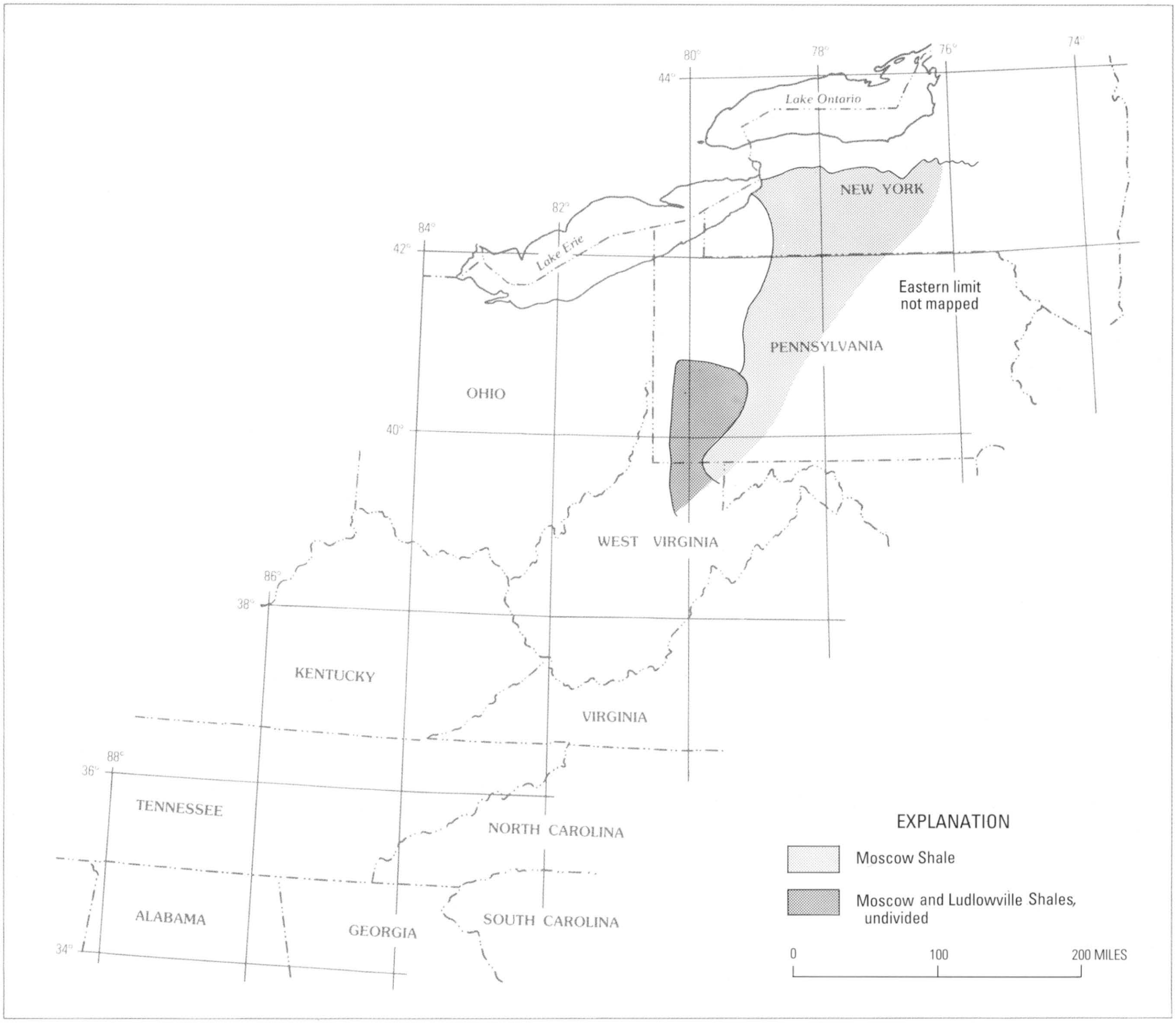

Figure 13. Areal extent of the Moscow Shale and the undivided Moscow and Ludlowville Shales.

Ontario County, N.Y., a small hiatus is present between the Tully Limestone and the basal Genesee Formation. West and southwest of the lake, the hiatus increases in scope as older rocks underlie the unconformity and as progressively younger Upper Devonian rocks overstep westward above the unconformity. Thus, in north-central Ohio, middle Upper Devonian shale rests upon lower Middle Devonian shale. Southward, the hiatus is greater; Upper Devonian black shale rests upon Middle Silurian rocks in central Kentucky, whereas Upper Devonian black shale rests upon Upper Ordovician shale and limestone in central Tennessee. The presence of the unconformity explains the restriction of the lower Upper Devonian gas shales to the eastern part of the study area. In contrast, the regressive silts and sands filled the eastern part of the basin during the latter one-half of the Late Devonian and confined the black gas shales largely to its western and southern parts.

GENESEE FORMATION

From western New York to central West Virginia (pl. 3, Nos. 27–39; pl. 4, Nos. 62–78; pl. 5), the Genesee Formation (Vanuxem, 1842; de Witt and Colton, 1959, p. 2815), which overlies the Tully Limestone, consists largely of black and dark-gray shales and mudrock and some beds of medium-gray shale, many calcareous nodules, several beds of limestone, and a scattering of beds of siltstone. In ascending stratigraphic order, the formation is subdivided into the following members—the Geneseo Shale, the Lodi

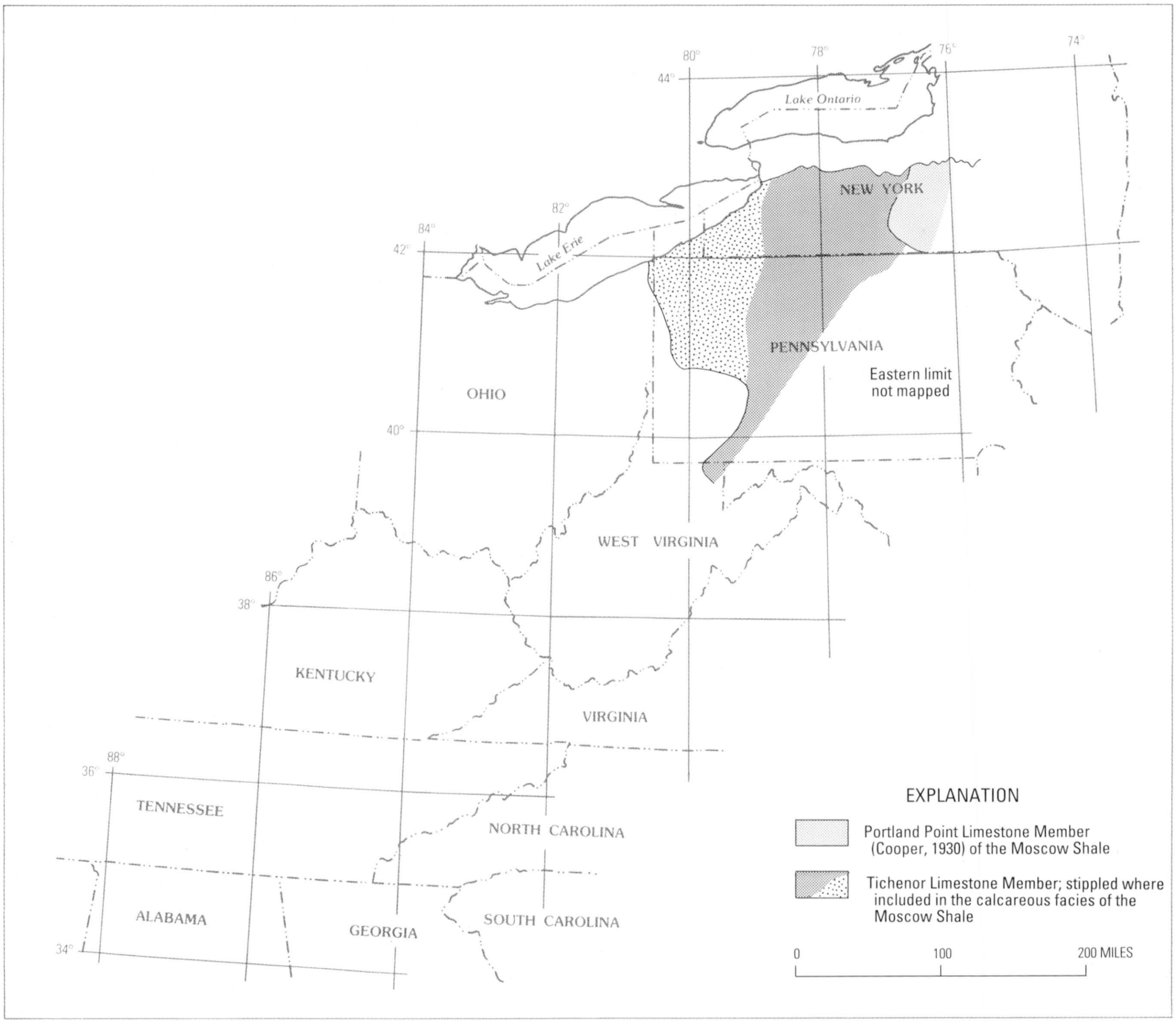

Figure 14. Areal extent of the Tichenor Limestone Member, which grades into the lower tongue of the Portland Point Limestone Member of the Moscow Shale.

Limestone, the Penn Yan Shale, the Renwick Shale, the Genundewa Limestone, and the West River Shale. To the east, near Seneca Lake, several of the shaly members grade into eastward-thickening units of thick-bedded siltstone and sandstone—the Sherburne Flagstone Member (de Witt and Colton, 1959), the Ithaca Member (de Witt and Colton, 1959), and the Crosby Sandstone of Torrey and others (1932). The stratigraphy of these coarser grained units is not included in our discussion of the gas shale sequence.

Geneseo Shale Member

The Geneseo Shale Member of the Genesee Formation (Chadwick, 1920, p. 118; de Witt and Colton, 1959, p. 2815), which crops out in central and western New York, is the next younger black gas shale above the Marcellus Shale. The member is composed largely of grayish-black, brownish-black, and black shales and some layers of dark-gray siltstone, a few beds of nodular brownish-black limestone, and some limestone septarian nodules as much as 4 ft in diameter. The Geneseo Shale Member is a recognizable member of the Genesee Formation from south-central New York to southwestern Pennsylvania (fig. 18). In outcrop, the Geneseo is 130 ft thick near the southern end of Cayuga Lake (de Witt and Colton, 1978). It thins to the east and grades laterally into an eastward-thickening sequence of gray shale, siltstone, and sandstone in eastern New York. The Geneseo thins westward to 44 ft in the reference section at Menteth Gully on the western side of Canandaigua Lake and to a featheredge in Erie County in

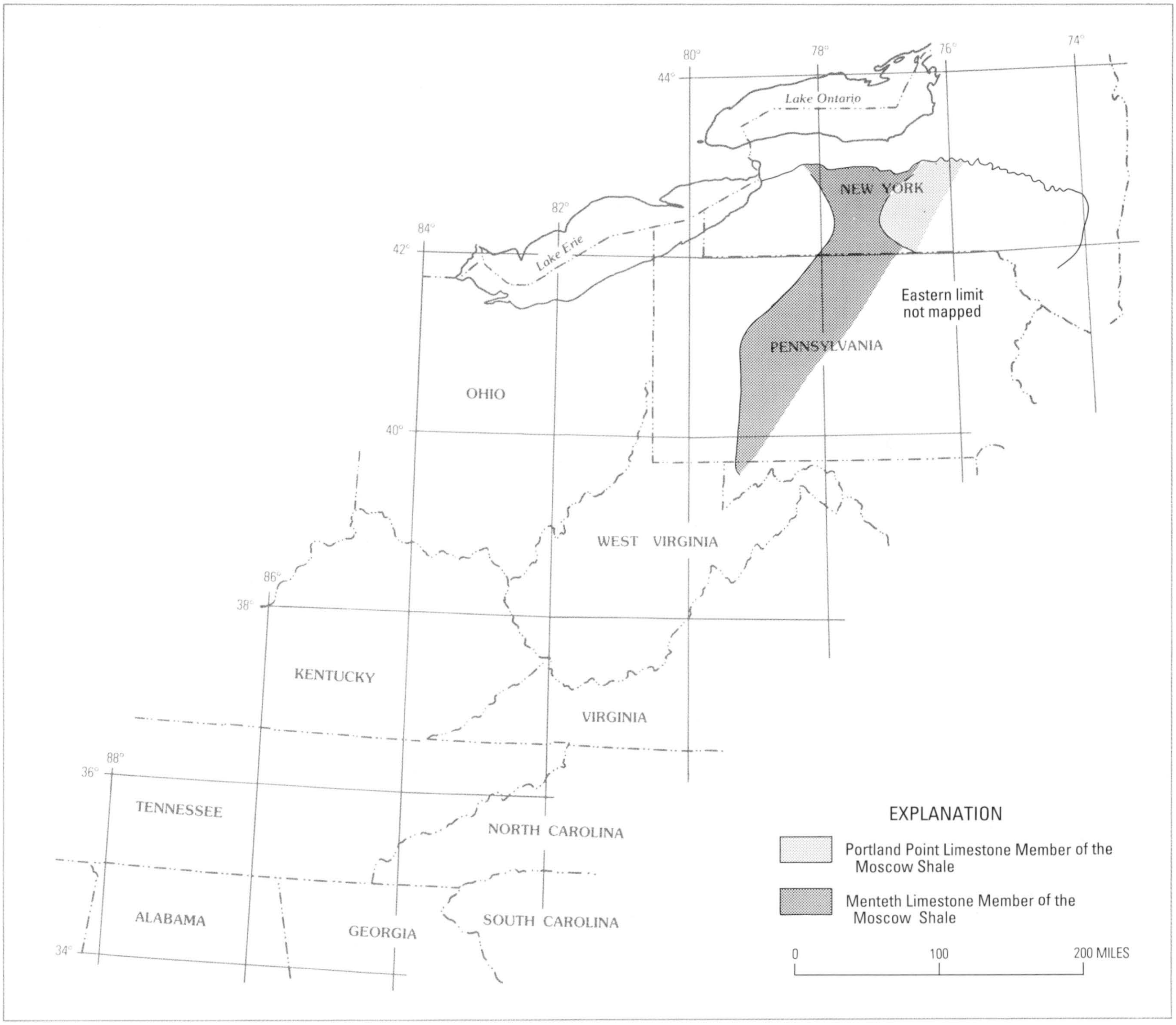

Figure 15. Areal extent of the Menteth Limestone Member, which grades into the upper tongue of the Portland Point Limestone Member of the Moscow Shale.

western New York (pl. 5, Nos. 79–80). The Geneseo thins to the southwest across Pennsylvania. The gray shale above the Penn Yan Shale Member also thins, which permits the younger black Renwick Shale Member to coalesce with the Geneseo. Because data are not present to separate the two black shales, the unit in southwestern Pennsylvania and contiguous parts of Maryland, Ohio, and West Virginia is shown (fig. 18) as the undivided Geneseo and Renwick Shale Members of the Genesee Formation.

In Cayuga County east of Cayuga Lake, the Geneseo interfingers with the subjacent Tully Limestone in a lenticular zone, which is as much as 15 ft thick and is composed of brownish-black shale intercalated with lenticular nodular beds of argillaceous brownish-black limestone. To the west, the Geneseo lies unconformably upon the Tully Limestone. West of Canandaigua Lake, the Tully feathers out of the section, and the Geneseo lies on gray Moscow Shale. Recently, Kirchgasser and others (1985, p. 242–254) placed the Geneseo Shale Member in the Middle Devonian on the basis of its fauna. The Middle-Upper Devonian boundary lies in the basal part of the overlying Penn Yan Shale Member. The Penn Yan and younger members of the Genesee Formation are of Late Devonian age.

The net thickness of radioactive black shale in the Genesee Formation exceeds 125 ft in southern Steuben County adjacent to the New York State line. Presumably, most of this black shale is the Geneseo Shale Member. The radioactive black shale thins to the south and the southwest where data are sparse and the Geneseo Shale Member thins to a featheredge (fig. 19).

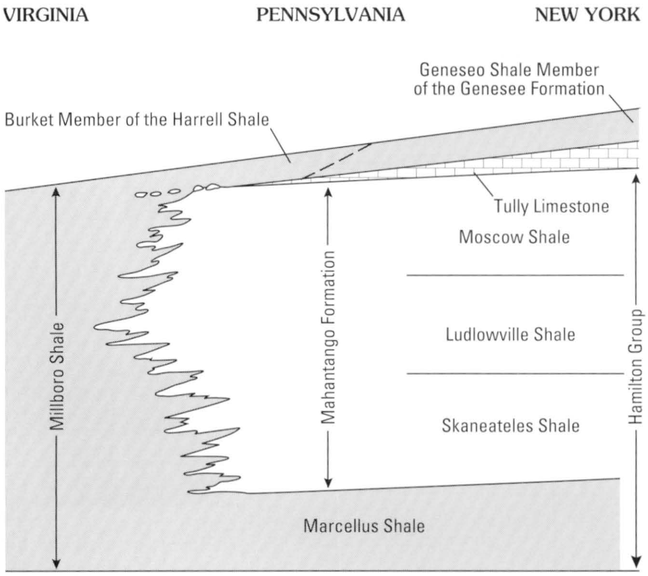

Figure 16. Relation of the Marcellus Shale and the Geneseo Shale Member of the Genesee Formation in New York to the Millboro Shale of western Virginia. No horizontal or vertical scale.

Lodi Limestone Member

In outcrop along Seneca Lake in the vicinity of Lodi, Seneca County, N.Y., the Lodi Limestone Member (Clarke, 1895, p. 101) consists of a closely spaced set of large discoidal limestone nodules intercalated in a bed of dark-gray fossiliferous calcareous siltstone overlying the Geneseo Shale Member. Locally, the nodules coalesce to form a lumpy-surfaced bed of black argillaceous limestone about 6 in. thick. The fauna of the Lodi Limestone is distinctive and has been identified in outcrop as far west as eastern Erie County, N.Y. (Kirchgasser, 1985, p. 229), although the Lodi is represented there by a single layer of sparse nodules. The Lodi appears to increase in thickness to the southwest of Seneca Lake, N.Y., and is a good unit for local correlation at the top of the Geneseo Shale Member in Allegany and Steuben Counties (fig. 20; pl. 5, Nos. 79–83).

Penn Yan Shale Member, Genundewa Limestone Member, and West River Shale Member

In ascending stratigraphic order, the gray shale sequence above the Geneseo Shale Member of the Genesee Formation west of Canandaigua Lake in western New York is the Penn Yan Shale Member, the Genundewa Limestone Member, and the West River Shale Member (de Witt and Colton, 1959, p. 2815). There, the boundary between the Middle and the Upper Devonian lies within the lower part of the Penn Yan Shale Member of the Genesee Formation. The Penn Yan and the West River Shale Members consist mainly of dark- to medium-gray shale or mudrock and some beds of black shale, a profusion of limestone nodules, and a few thin beds of dark-gray siltstone. The Genundewa Limestone Member (Clarke and Luther, 1904; de Witt and Colton, 1959, p. 2818) is an irregular- to flaggy-bedded limestone composed largely of the shells of the minute pteropod *Styliolina fissurella*. The Genundewa is a local unit (fig. 21; pl. 2, Nos. 27–30; pl. 3, Nos. 27, 55; pl. 5).

The Penn Yan (fig. 22; Grossman, 1944, p. 6465; de Witt and Colton, 1959, p. 2818) and the West River (fig. 23; Clarke and Luther, 1904; de Witt and Colton, 1959, p. 2819) Members are recognizable units in the subsurface (pl. 4, Nos. 70–78; pl. 5). The West River Member (fig. 23) oversteps the Penn Yan Member (fig. 22; pl. 4, Nos. 69–70) to the southwest along the Middle Devonian unconformity and is present in southwestern Pennsylvania and central West Virginia (pl. 6, Nos. 61–69). East of Canandaigua Lake, the Penn Yan and the West River grade laterally into coarser grained units, the Sherburne Flagstone Member and the Ithaca Member of the Genesee Formation (de Witt and Colton, 1959). These units are shown in the stratigraphic sections but are not discussed in detail.

Renwick Shale Member

The Renwick Shale Member of the Genesee Formation (de Witt and Colton, 1959, p. 2821) is a thin and somewhat less extensive black shale than the Geneseo Shale Member and occurs about 280 to 310 ft above the top of the Geneseo near Ithaca, Tompkins County, N.Y. The Renwick Shale Member consists of grayish-black shale that grades vertically into very dark olive gray shale. It commonly contains an abundance of scour channels a few inches to several feet thick filled by medium-gray siltstone. The Renwick is 36 ft thick at the type section on Renwick Brook north of Ithaca and grades laterally into a sequence of fossiliferous medium- to dark-gray shale and siltstone in eastern Cayuga County, N.Y., south of Skaneateles Lake. The Renwick thins west of Ithaca, where it intertongues with the Penn Yan Shale Member. It has been identified by Kirchgasser (1985, p. 229) in sections at Canandaigua Lake and north of Honeoye Lake in southern Ontario County, N.Y. By using gamma-ray logs, L.V. Rickard (*in* Kirchgasser, 1985, p. 230) traced the Renwick into the Genesee Valley near the type Geneseo in western Livingstone County. The Renwick is a recognizable unit in the subsurface in southern New York and western Pennsylvania (fig. 18; pl. 4, Nos. 70–78; pl. 5, Nos. 77–82). To the south, the black Renwick shale merges into the black shale that lies on the Tully Limestone in southwestern Pennsylvania and contiguous West Virginia and Ohio. This black shale may contain equivalents of the Geneseo Shale Member and the Renwick Shale Member of the Genesee Formation and possibly the Burket Shale Member of the Harrell Shale. In the absence of paleontological data, the component mem-

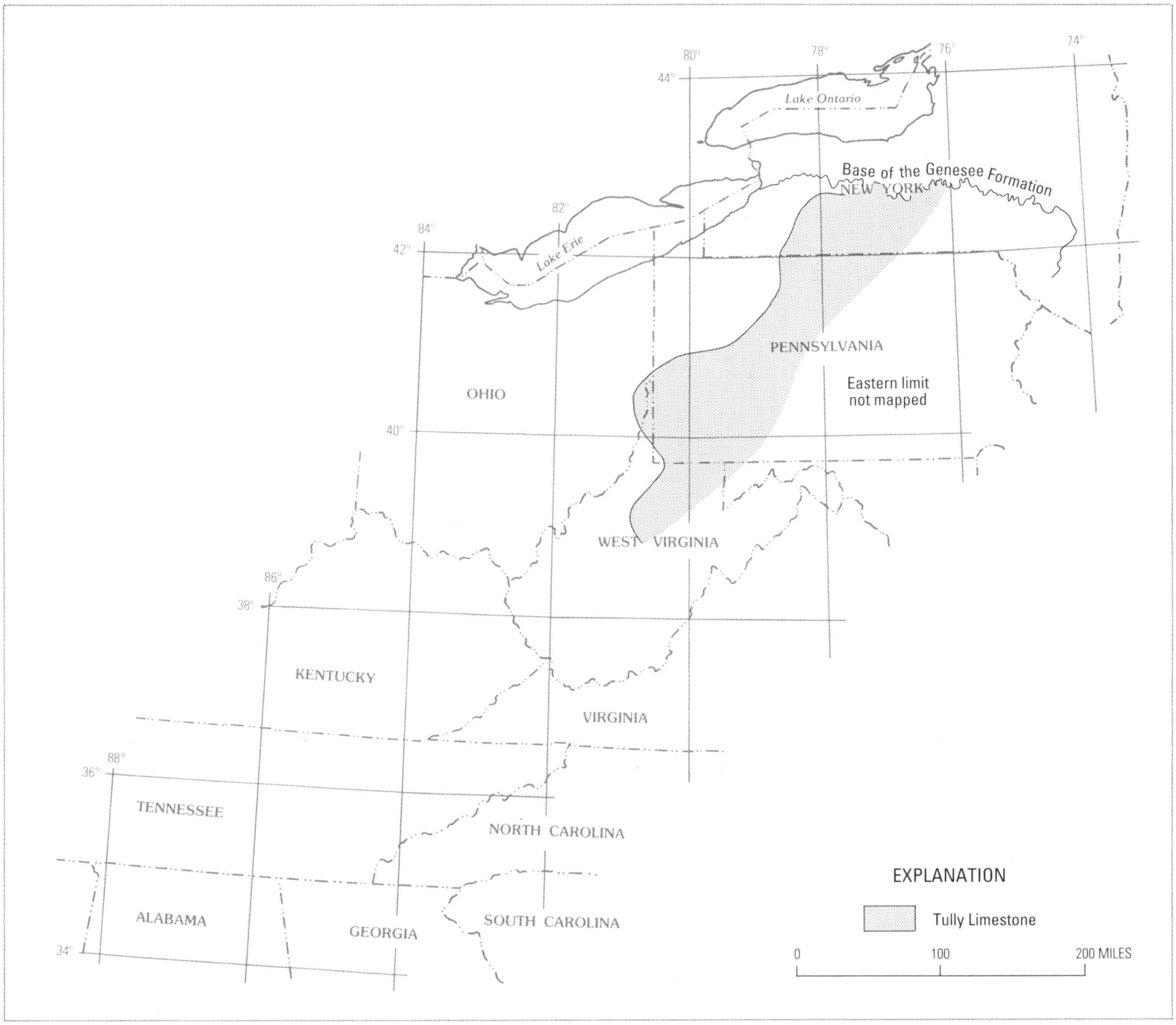

Figure 17. Areal extent of the Tully Limestone.

bers of the black shale unit cannot be identified positively. The Renwick is too thin to be a productive gas shale; however, it is a good key bed for local subsurface correlation.

Relation of the Genesee Formation to the Burket Shale Member of the Harrell Shale

Because the black Burket Shale Member of the Harrell Shale (Butts, 1918) is a correlative of the basal part of the Genesee Formation, we feel that it is an important adjunct to this discussion of Devonian gas shales, although it is not within the geographic boundaries of our paper and is not shown in our cross sections. In outcrops in the Valley and Ridge province of central Pennsylvania between Williamsport, Lycoming County, and Altoona, Blair County, the black Burket Shale Member lies conformably upon the Tully Limestone. The Burket is a black shale that has a few discoidal limestone nodules as much as 2 ft in diameter intercalated in the shale. The maximum thickness of the Burket in outcrop is about 120 ft. The member thins to the south, as do the underlying Tully Limestone and Mahantango Formation. As mentioned in the discussion of the Marcellus Shale, the Burket grades into the upper part of the Millboro Shale (fig. 16) in northern West Virginia, and its southeastern limit has not been established. Lithologically, the Burket Shale Member of the Harrell Shale and the Geneseo Shale Member of the Genesee Formation are very similar, and they occupy the same stratigraphic position above the Tully Limestone. Presumably, they are parts of the same black shale. However, a scattering of conodonts,

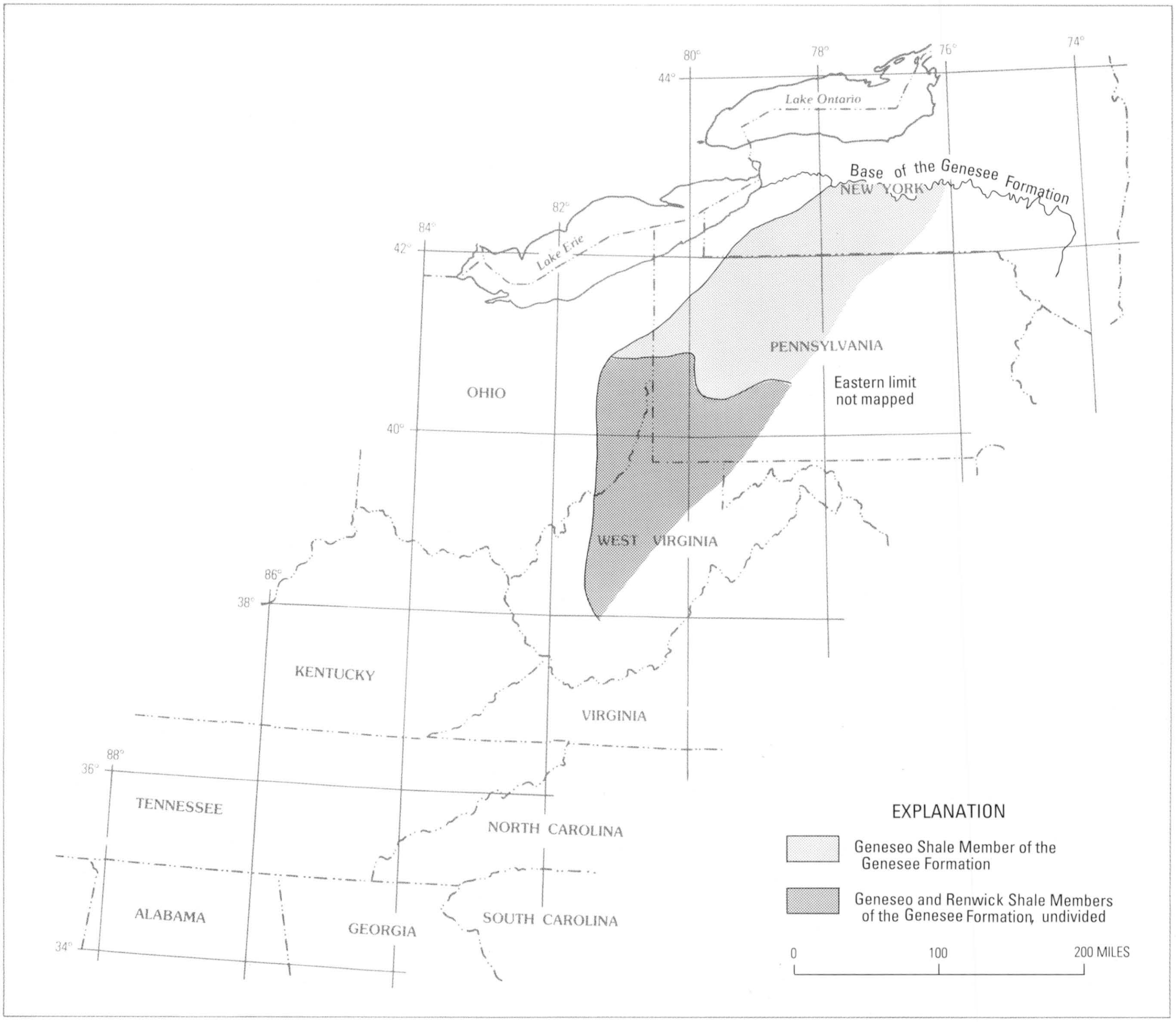

Figure 18. Areal extent of the Geneseo Shale Member and the undivided Geneseo and Renwick Shale Members of the Genesee Formation.

including *Ancyrodella* cf. *A. rotundiloba* Bryant from the basal Burket near Cumberland, Md. (Hass *in* de Witt and Colton, 1964, p. 50), suggests that the Burket may be equivalent to the Genundewa Limestone Member or the West River Shale Member of the Genesee Formation, which are of Late Devonian age, rather than to the Geneseo Shale Member, which is of Middle Devonian age. The relation of the Burket to the Geneseo is a problem waiting to be solved; however, we believe that they are parts of a single black shale facies and that a hiatus of brief extent is present at the base of the Burket in western Maryland. The black shale above the Tully Limestone in the MERC No. 1 well was identified as the Burket (Schwietering and others, 1978, p. 244). Gas production indicated that the black shale is a gas shale regardless of its designation as either Burket or Geneseo.

SONYEA FORMATION

In outcrop in western New York, the Sonyea Formation (Chadwick, 1933, p. 95; Colton and de Witt, 1958, p. 2815) consists of a basal black shale, the Middlesex Shale Member, and an upper gray shale that has limestone nodules, the Cashaqua Shale Member (pl. 2, Nos. 21–30; pl. 4, Nos. 60–78; pl. 7, Nos. 90–95). The members grade eastward into an eastward-thickening sequence of siltstone and silty shale, which is a part of the general turbidite facies of the Catskill delta.

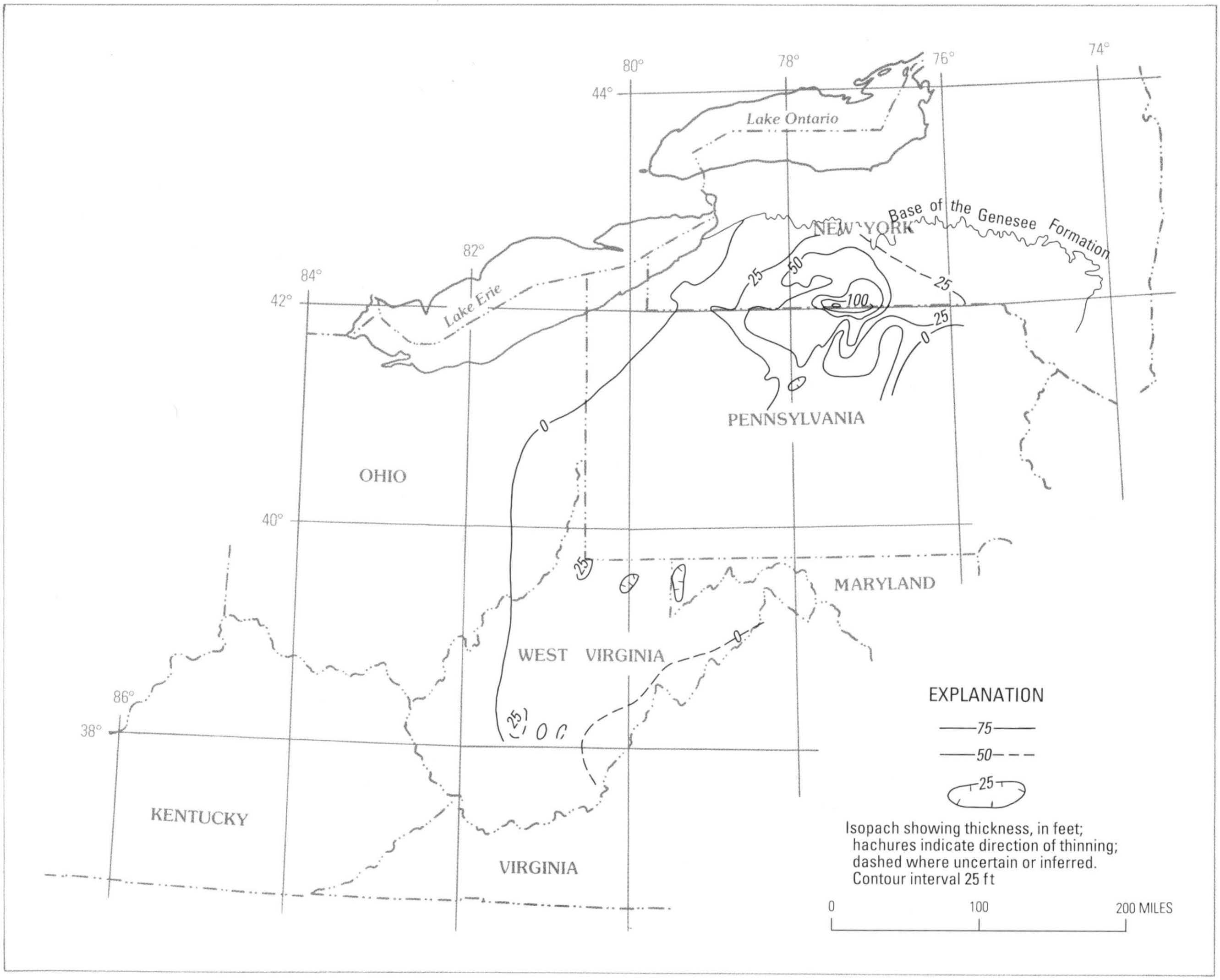

Figure 19. Net thickness of radioactive black shale in the Genesee Formation.

Middlesex Shale Member

The next younger black shale in the gas shale sequence is the Middlesex Shale Member, which is the basal unit of the Sonyea Formation (Colton and de Witt, 1958). It is of Late Devonian age and is well exposed in western and west-central New York. The member includes mostly brownish-black shale; some dark-gray shale is intercalated in the upper part. The Middlesex is about 65 ft thick in the reference section 0.8 mi south of the village of Middlesex, Yates County, N.Y. It thickens eastward to about 75 ft at Chidsey Point Gully on the western side of Keuka Lake, Steuben County, then thins to the east and tongues out in a sequence of medium-gray shale and light-gray siltstone in western Broome County near Binghamton (de Witt and Colton, 1978, p. A21). In eastern outcrops, the Middlesex contains a considerable quantity of fossilized plant fragments, which clearly indicates that these localities were close to the source of terrigenous organic detritus. The Middlesex thins westward from the reference section and is 6 ft thick at the mouth of Pike Creek in western Erie County, N.Y., where the member dips below the surface of Lake Erie. Unlike the older black gas shales, the Middlesex does not crop out in the Valley and Ridge province. The Middlesex is a well-defined black shale from its outcrop in New York westward in the subsurface into southwestern Pennsylvania and contiguous parts of Ohio, West Virginia, and Maryland (fig. 24; pl. 4, Nos. 60–78; pl. 5; pl. 6, Nos. 86, 48, 87, 72; pl. 7, Nos. 92–93, 43, 94, 67, 95). The member has been identified in southwestern West Virginia but apparently is not present in Virginia. In the subsurface, the net thickness of radioactive black shale in the Sonyea Formation, which is almost exclusively the Middlesex Shale Member, is more than 75 ft in southwestern New York and adjacent Pennsylvania (fig. 25). A second area of thick black shale underlies eastern Wood

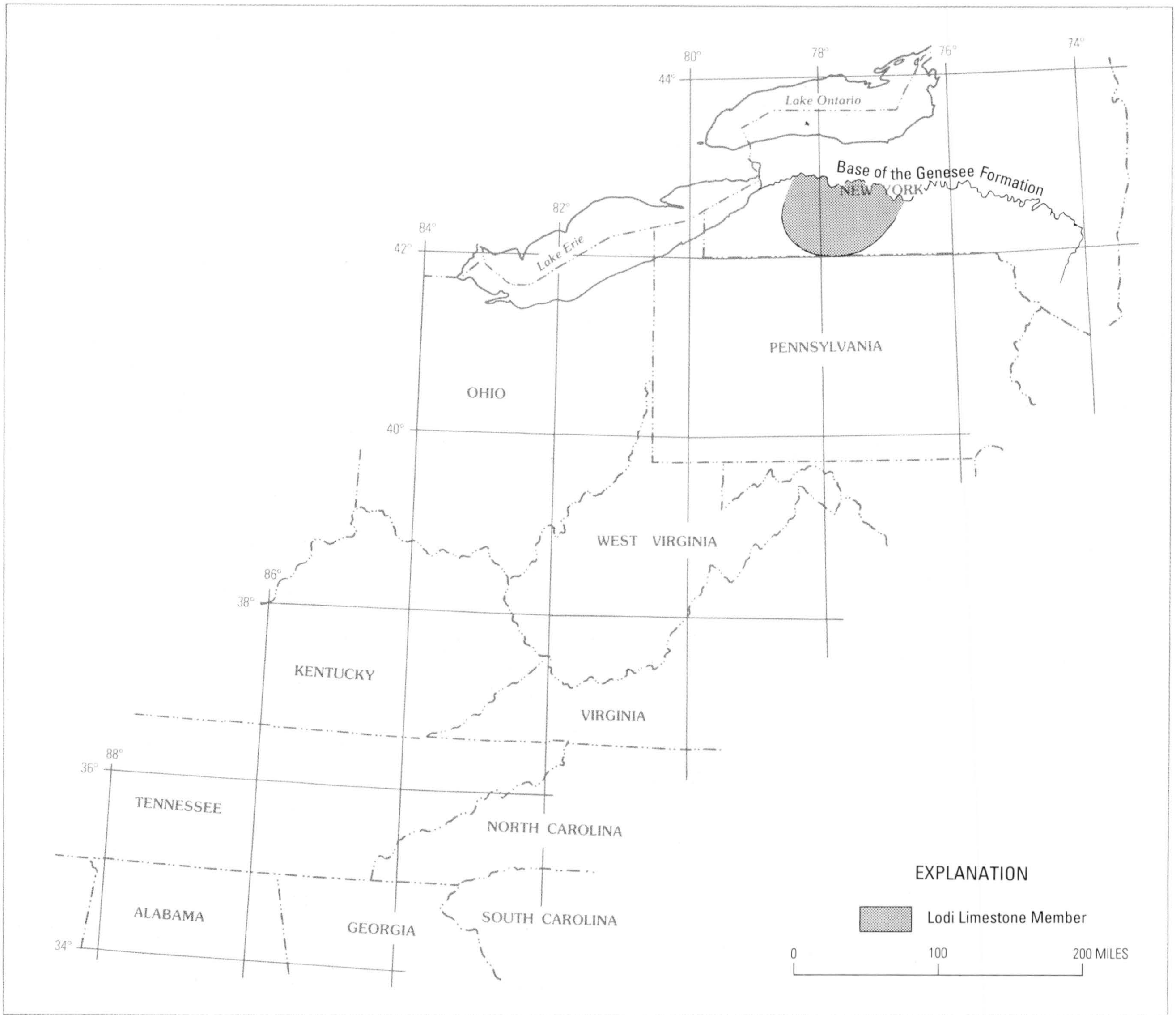

Figure 20. Areal extent of the Lodi Limestone Member of the Genesee Formation.

County, W. Va., along the trend of the Burning Springs anticline. The black shale thins to the east and the west in the subsurface and does not extend eastward to outcrops in the Valley and Ridge or westward to outcrops along the eastern flank of the Cincinnati arch.

Cashaqua Shale Member

A medium-gray shale that has an abundance of flat ellipsoidal limestone nodules and a few thin beds of black shale, the Cashaqua Shale Member of the Sonyea Formation (Hall, 1840; Colton and de Witt, 1958), overlies the Middlesex Shale Member of the Sonyea Formation in outcrops in western New York. The Cashaqua grades eastward into an eastward-thickening sequence of light-gray turbiditic siltstone and silty gray shale. In the subsurface, the gray Cashaqua is a recognizable unit from western New York to southwestern West Virginia (fig. 26; pl. 3, Nos. 39–43, 47–55, 27). It can be identified in southeastern Ohio, where the gray Cashaqua Shale Member oversteps the black Middlesex along the Middle Devonian unconformity (pl. 2, Nos. 26–30; pl. 8, Nos. 100, 101, 40, 63). The Cashaqua feathers out westward along the unconformity.

WEST FALLS FORMATION

In outcrop in western New York (pl. 2, Nos. 14–30; pl. 3; pl. 5, Nos. 29, 79–82), the West Falls Formation (Pepper and others, 1956) consists of a lower black shale,

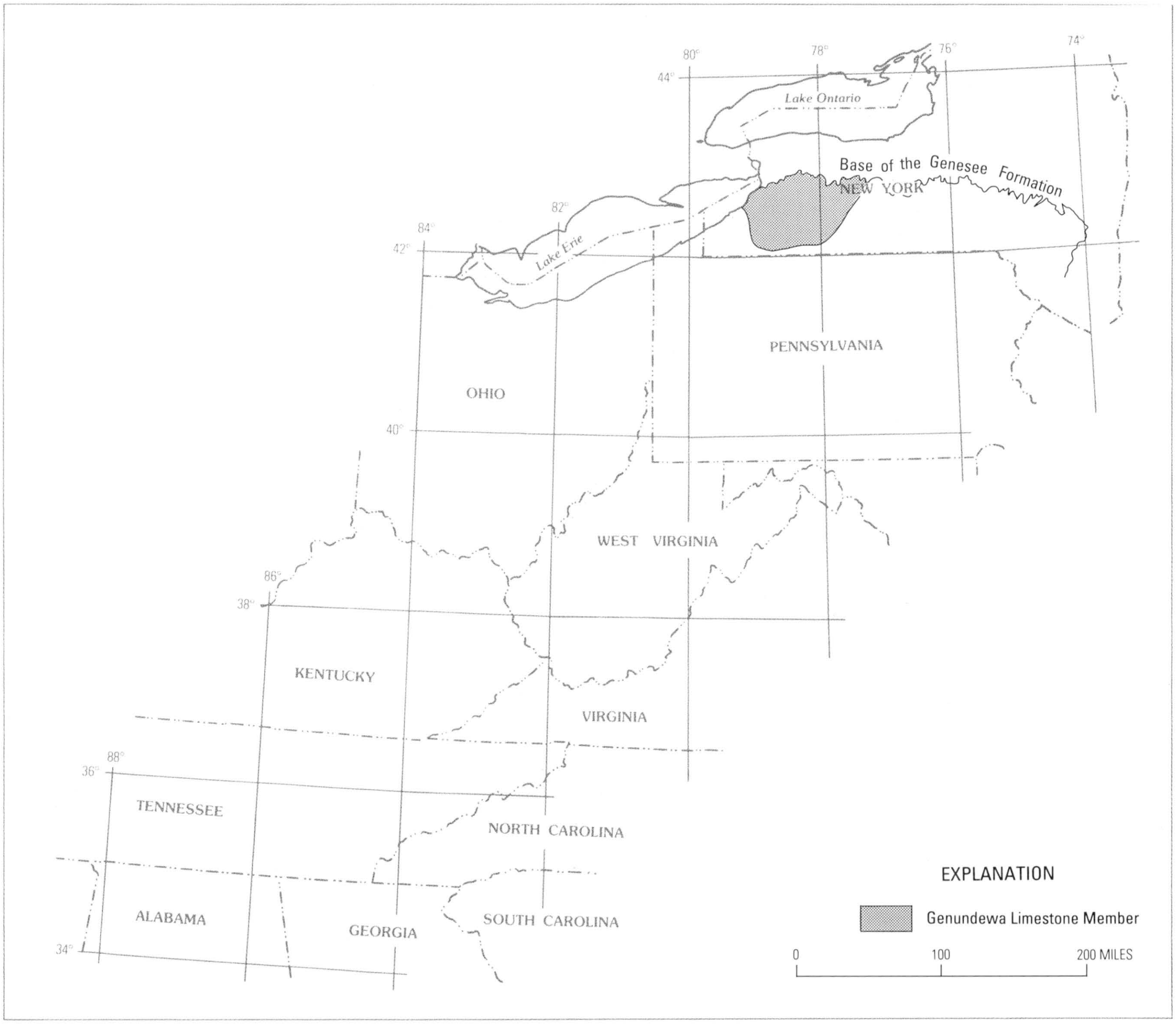

Figure 21. Areal extent of the Genundewa Limestone Member of the Genesee Formation.

the Rhinestreet Shale Member, and an upper gray shale and mudrock that has abundant limestone nodules, the Angola Shale Member. Both members interfinger to the east into an eastward-thickening sequence of siltier and sandier rocks. The Angola is not recognized east of the Genesee River, although the Rhinestreet is present further to the east near Elmira in central Chemung County, N.Y.

Rhinestreet Shale Member

The Rhinestreet Shale Member of the West Falls Formation (Clarke and Luther, 1904; Pepper and others, 1956) is one of the thickest and most extensive of the black gas shales. It is about 180 ft thick in outcrops along the canyon of Eighteenmile Creek, Erie County, N.Y. The member includes mainly brownish-black to black shale that has some interbedded medium-gray shale, a scattering of light-gray siltstone, and a profusion of discoidal to spheroidal limestone nodules and septaria as much as 4 ft in diameter. In outcrop, the Rhinestreet thins to the east and feathers out at the section near Elmira, Chemung County, N.Y.

The Rhinestreet is recognized as a discrete unit in the subsurface from western New York to eastern Tennessee (fig. 27; pl. 2, Nos. 15–29; pl. 3, Nos. 27, 46–55, 41–32; pl. 10). In outcrop in central Tennessee, the Rhinestreet is a bed about 6 ft thick in the lower part of the Dowelltown

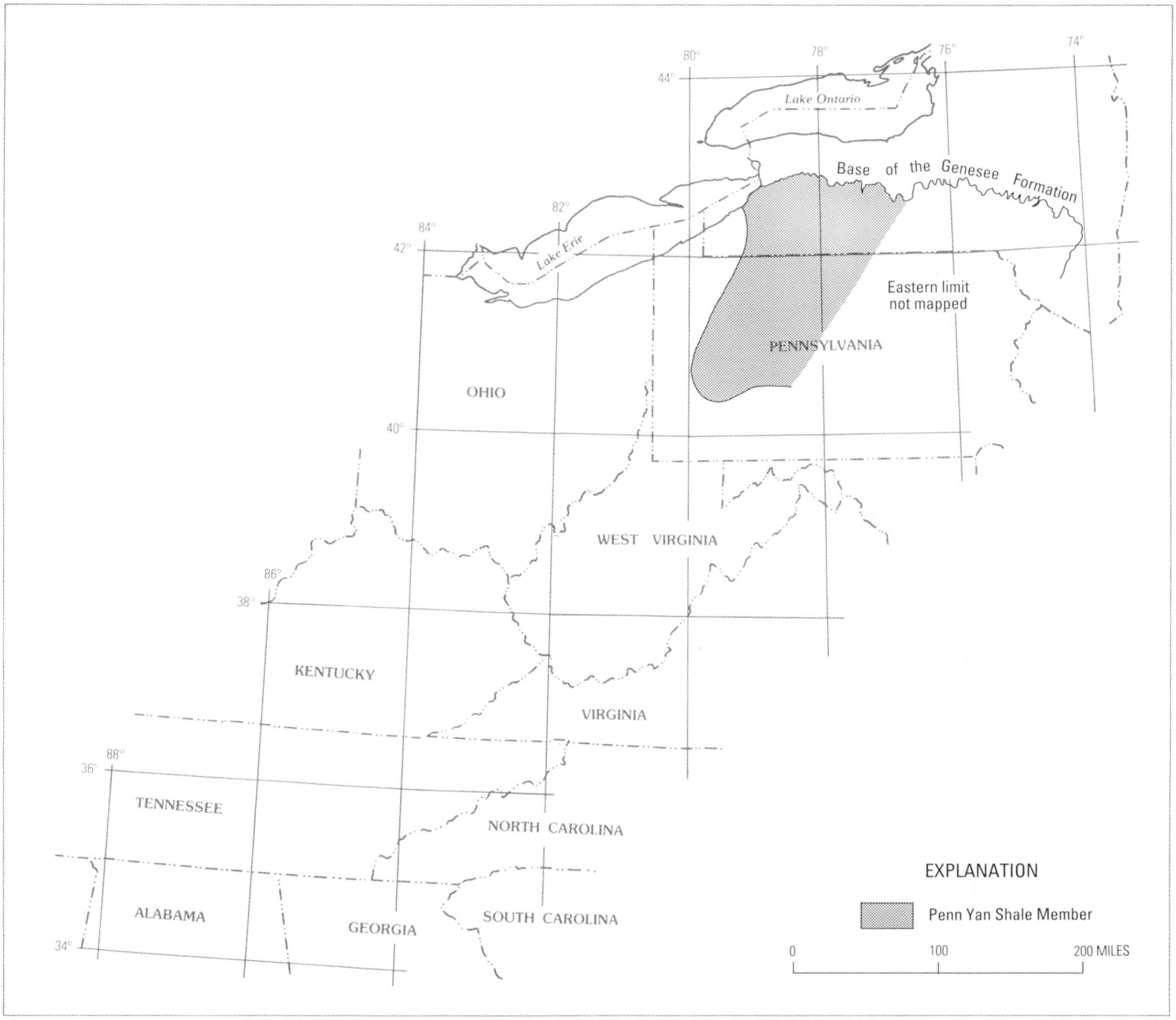

Figure 22. Areal extent of the Penn Yan Shale Member of the Genesee Formation.

Member of the Chattanooga Shale (Hayes, 1891, p. 143; Conant and Swanson, 1961, p. 16–19; de Witt and Roen, 1984, p. A48). The Rhinestreet conodont fauna is present near the base of about 1,000 ft of dominantly black shale in outcrops in the Valley and Ridge province of eastern Tennessee. In the subsurface, the radioactive black shale in the Rhinestreet Shale Member, which includes most of the black shale in the West Falls Formation, is more than 300 ft thick in southwestern New York and adjacent Pennsylvania (fig. 28). Locally, it is more than 150 ft thick in northern West Virginia. The member thins to the east by grading laterally into a sequence of lighter gray shale and light-gray turbiditic siltstone. The Rhinestreet thins to the west along the Middle Devonian unconformity, where it is overstepped by the younger Angola Shale Member of the West Falls Formation.

Belpre Ash Bed

A 1- to 2-in.-thick but relatively extensive ash-fall bed, which is known as the Belpre Ash Bed (Roen and Hosterman, 1982), is present in the lower part of the Rhinestreet Shale Member in the western part of the Appalachian basin (pl. 10, Nos. 113–111). Although the Belpre bed is too thin to produce a discrete gamma-ray signature, the presence of abundant bronzy mica in drill cuttings identifies the ash fall. The Belpre has been found in an exposure of the Rhinestreet in a cliff section along the southern shore of Lake Erie to the west of Pike Creek in Evans Township, Erie County, N.Y. (G.C. Baird, State University of New York College at Fredonia, Fredonia, N.Y., written commun., 1987). It is exposed in the basal part of the Rhinestreet Shale Member at Little War Gap,

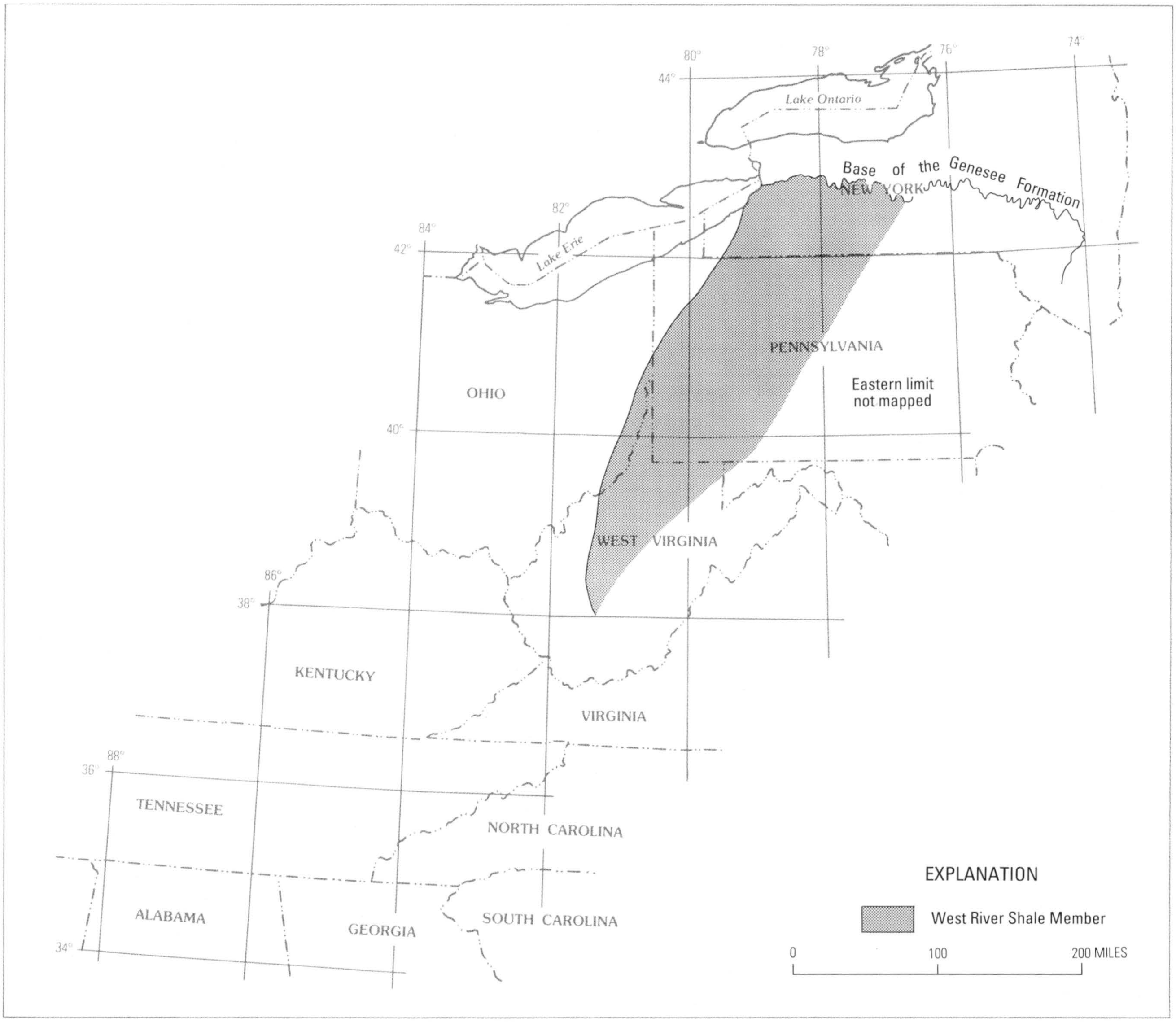

Figure 23. Areal extent of the West River Shale Member of the Genesee Formation.

Hawkins County, Tenn., where Rhinestreet conodonts were collected from black shale intercalated with the Belpre (Kepferle and Roen, 1981, p. 307); however, there the section is not sufficiently exposed to permit delineation of other gas shales in the sequence. The presence of the Millboro Shale to the northeast in southwestern Virginia suggests that the lower part, the Marcellus Shale segment, might extend into northeastern Tennessee in the vicinity of Little War Gap. If the Marcellus is present, then it must be in the 18 ft of intercalated greenish-gray and black shale beneath the ash beds and the black shales that contain the Late Devonian Rhinestreet conodonts. If the Marcellus is present, then the Middle Devonian unconformity would have Upper Devonian black shale lying on Middle Devonian black shale, a situation that would make the unconformity difficult to detect without paleontologic criteria.

Angola Shale Member

In outcrop in western New York, the Angola Shale Member of the West Falls Formation (Clarke, 1903, p. 24; Pepper and others, 1956) is composed of medium-gray mudrock and shale. It has an abundance of discoidal to spheroidal limestone nodules and septaria and a scattering of thin beds of siltstone or black shale. The Angola Shale Member overlies the Rhinestreet Shale Member of the West Falls Formation. In the subsurface, the Angola is recognizable from western New York south to eastern Tennessee and westward into Ohio and eastern Kentucky (fig. 29; pl. 10, Nos. 111–118, J–J′, No. 126). The Angola Shale Member can be recognized west of the pinchout of the Rhinestreet Shale Member on the surface of older rocks

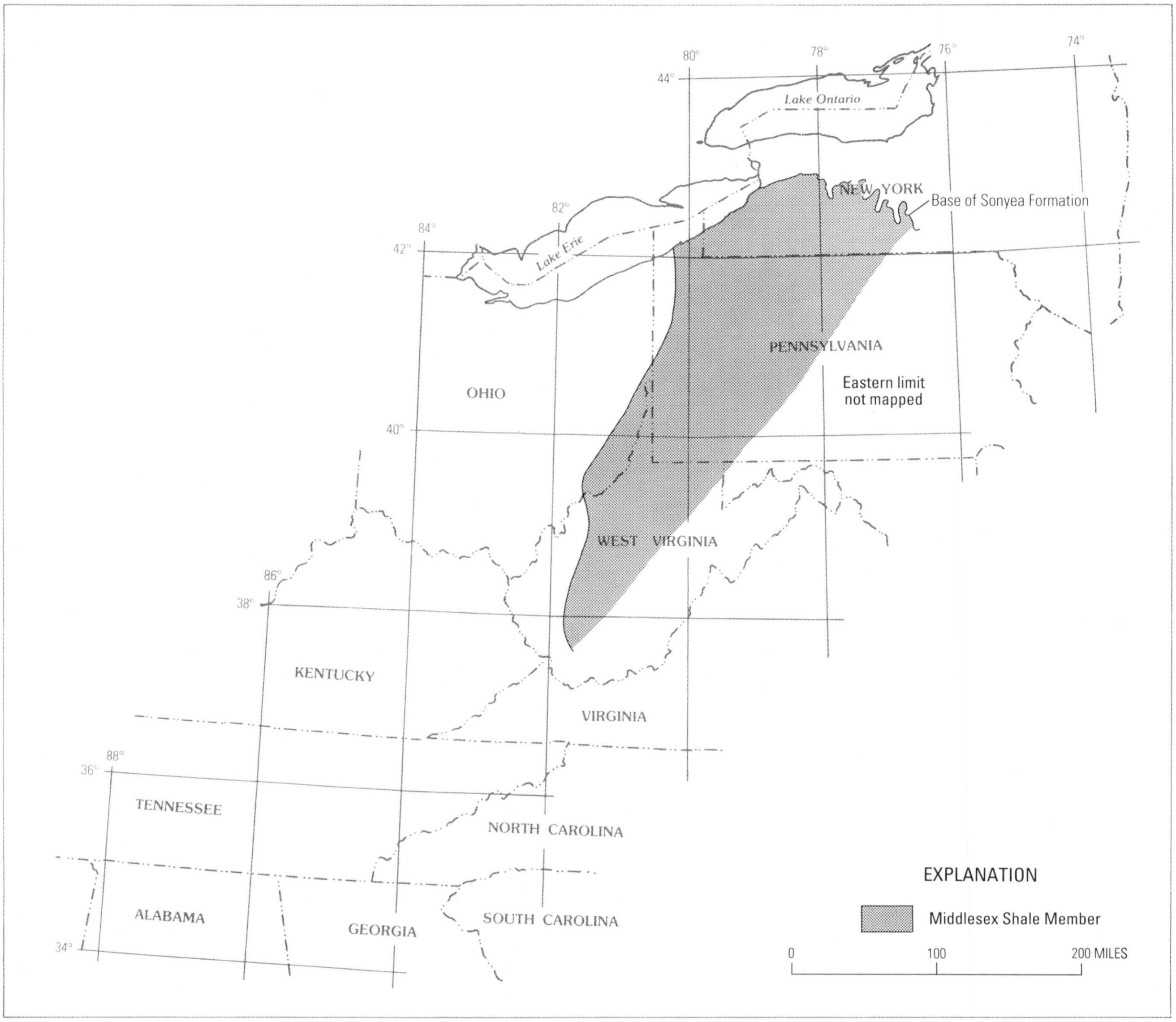

Figure 24. Areal extent of the Middlesex Shale Member of the Sonyea Formation.

below the Middle Devonian unconformity so long as the overlying black Pipe Creek Shale Member of the Java Formation is present. West of the pinchout of the Pipe Creek, the Angola merges with the younger Upper Devonian gray shales and cannot be identified positively.

JAVA FORMATION

In outcrop in western New York, the Java Formation (de Witt, 1960, p. 1933) consists of a basal black shale, the Pipe Creek Shale Member, and overlying gray shale and mudrock that have scattered beds of black shale and siltstone and a profusion of limestone nodules, the Hanover Shale Member. The Pipe Creek thins to the east and feathers out of the sequence in northern Steuben County (pl. 5, Nos. 81–82), whereas the Hanover thickens to the east and grades laterally into an eastward-thickening sequence of silty shale, siltstone, and greenish-gray sandstone, the Wiscoy Sandstone Member of the Java Formation.

Pipe Creek Shale Member

The Pipe Creek Shale Member of the Java Formation (pl. 2, Nos. 14–29; pl. 9, Nos. 104–108, 34, 109, 57, 110–111; Chadwick, 1923; Pepper and de Witt, 1950; de Witt, 1960, p. 1933) is the next youngest of the regionally extensive black gas shales. In contrast to the Rhinestreet, the Pipe Creek rarely exceeds 25 ft in thickness (fig. 30),

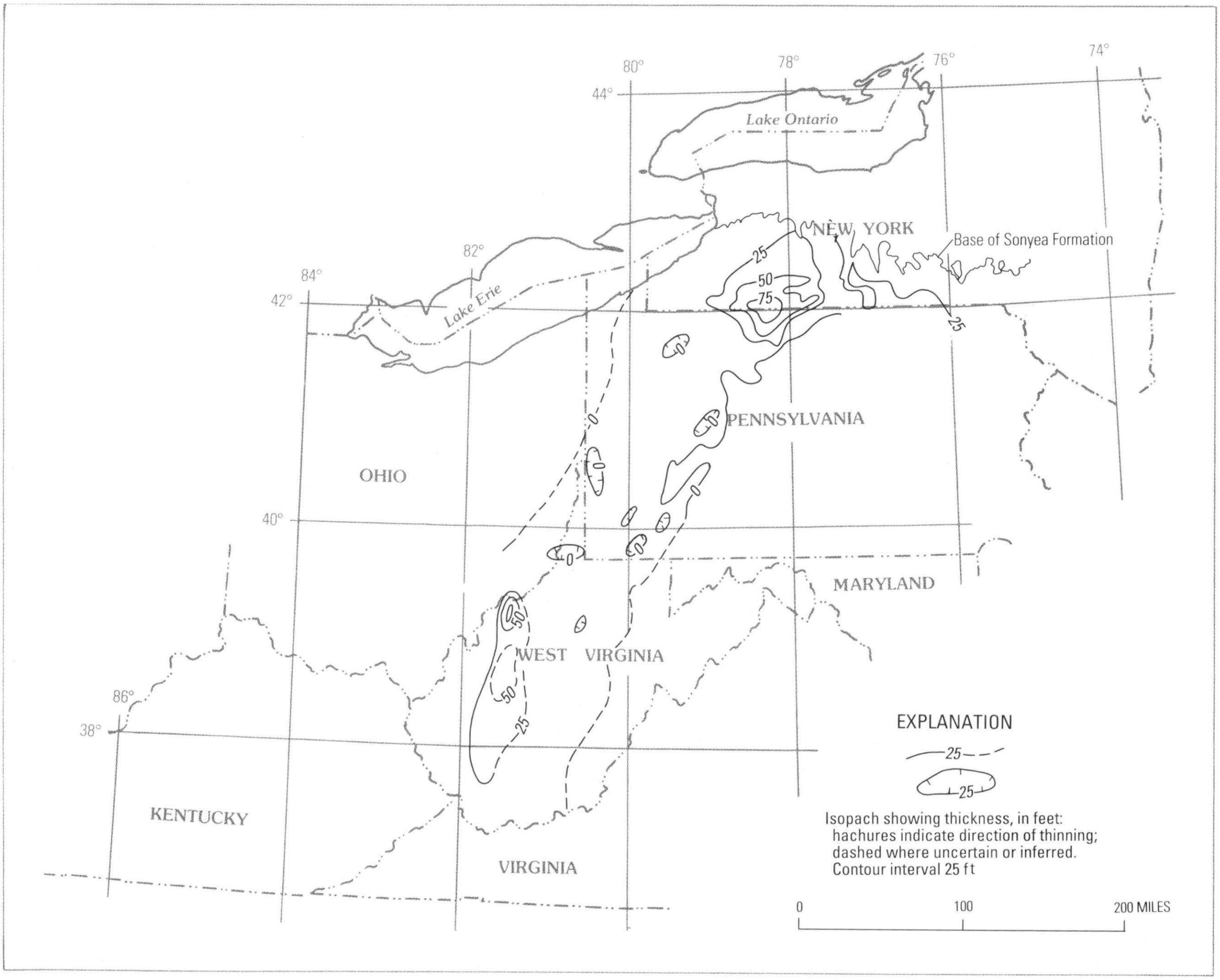

Figure 25. Net thickness of radioactive black shale in the Sonyea Formation.

although it makes up much of the radioactive black shale in the Java. The Pipe Creek Shale Member is 23 ft thick in the type section of the Java Formation at Java Village, Wyoming County, N.Y., where it is composed of fissile-weathering, brittle, brownish-black to black shale. The member thins to the east and feathers out of the sequence in southern Steuben County, N.Y. The Pipe Creek also thins west of Java Village and is about 6 in. thick where the member dips below the water of Lake Erie about 5 mi east of Dunkirk, Chautauqua County, N.Y.

In the subsurface, the Pipe Creek Shale Member (fig. 31) extends south from outcrops in western New York about 450 mi to the E.D. Smith well in the Early Grove gas field (No. 111 in Appendix) in the Greendale syncline, Scott County, Va., in the Valley and Ridge structural province (pl. 2, Nos. 14–29; pl. 6, Nos. 17, 84–6; pl. 7, Nos. 88–93; pl. 8, Nos. 100–101, 40; pl. 9, Nos. 103–111; pl. 10, I–I′, Nos. 111–118). The member thins to a featheredge to the east in New York and Pennsylvania and to the west in Ohio, eastern Kentucky, and northeastern Tennessee.

The Pipe Creek has a very strong positive deflection on the gamma-ray log and an equally strong negative deflection on the compensated density log. The two sharply marked peaks on log curves serve to identify the relatively thin Pipe Creek. Although the Pipe Creek Shale Member is too thin to be an important source bed for gas, it is a most important key unit for surface and subsurface correlation.

The characteristic geophysical log signatures that facilitate identification of the Pipe Creek suggest that the member may be a close correlative of the Center Hill Ash Bed in the upper part of the Dowelltown Member of the Chattanooga Shale of central Tennessee. Although we have not found evidence of ash-fall mica in the Pipe Creek in outcrop, mica is abundant in several sets of well cuttings from the southern one-half of the member's extent in the basin.

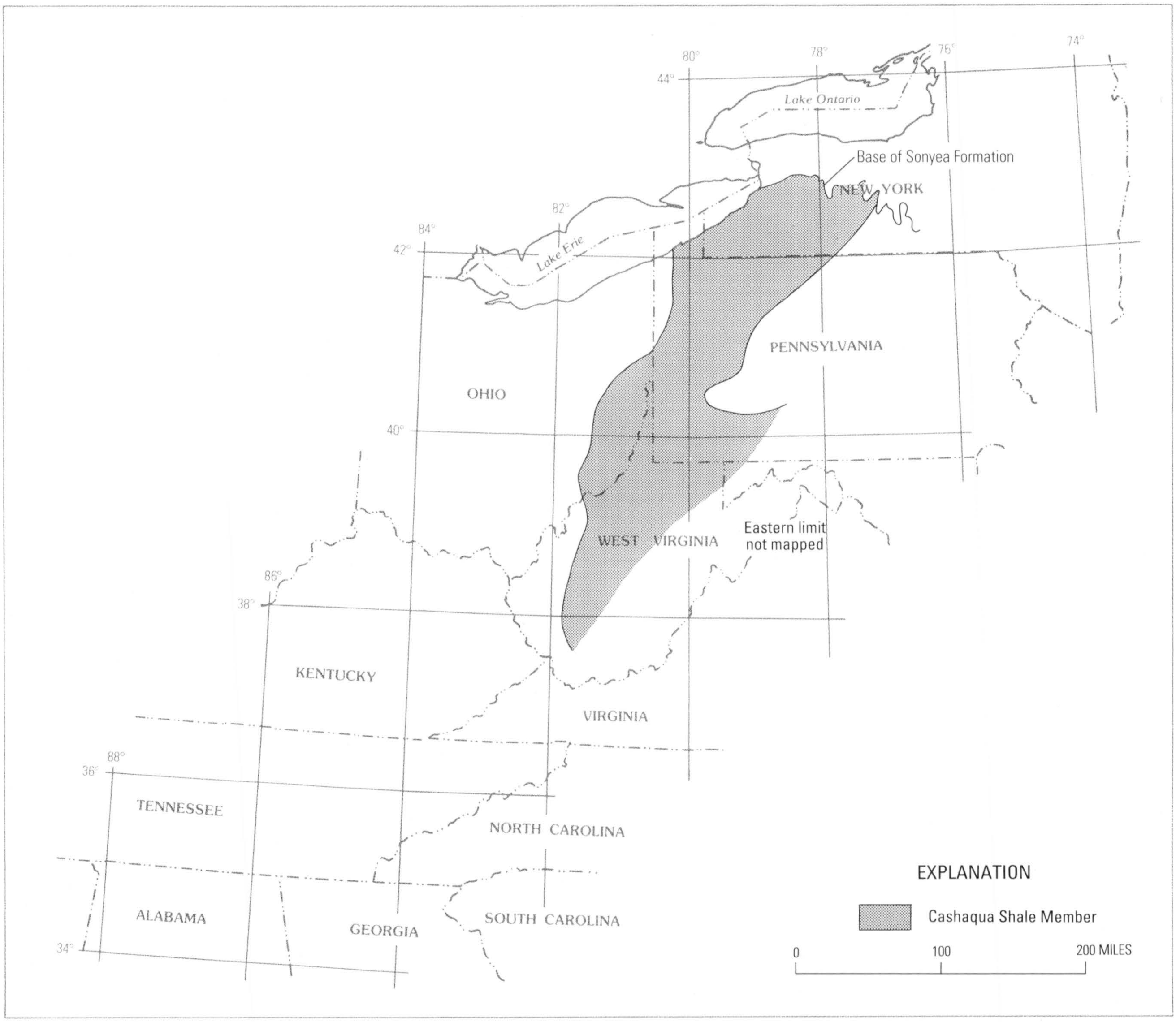

Figure 26. Areal extent of the Cashaqua Shale Member of the Sonyea Formation.

Hanover Shale Member

In exposures in western New York, medium- to greenish-gray mudrock and shale of the Hanover Shale Member of the Java Formation (Chadwick, 1933; Pepper and de Witt, 1950; de Witt, 1960, p. 1933) overlie the Pipe Creek Shale Member. The Hanover contains many spheroidal to discoidal limestone nodules and scattered beds of black shale, nodular lumpy limestone, and argillaceous siltstone. The Hanover Shale Member is a recognizable subsurface unit southward from western New York to eastern Kentucky and adjacent southwestern Virginia and northeastern Tennessee (fig. 32; pl. 2, Nos. 14–29; pl. 6, Nos. 17, 84–86; pl. 9, Nos. 103–111; pl. 10, I–I′, Nos. 111–118). To the west of the pinchout of the Pipe Creek Shale Member, the Hanover and the underlying Angola Shale Member of the West Falls Formation cannot be separated. The combined greenish-gray shales of the Hanover and the Angola grade westward into the upper part of Tillman's (1970, p. 24) Olentangy Shale in central Ohio. In central Tennessee, the combined Hanover and the Angola appear to be equivalent to the upper unit of the Dowelltown Member of the Chattanooga Shale. Because the Center Hill Ash Bed is probably a Pipe Creek equivalent, its presence 1 ft below the top of the 9.2 ft of interbedded gray and black shale in the upper unit of the Dowelltown Member at the reference section at Sligo Bridge (Conant and Swanson, 1961, p. 24) suggests that most of the interbedded unit is the Angola equivalent.

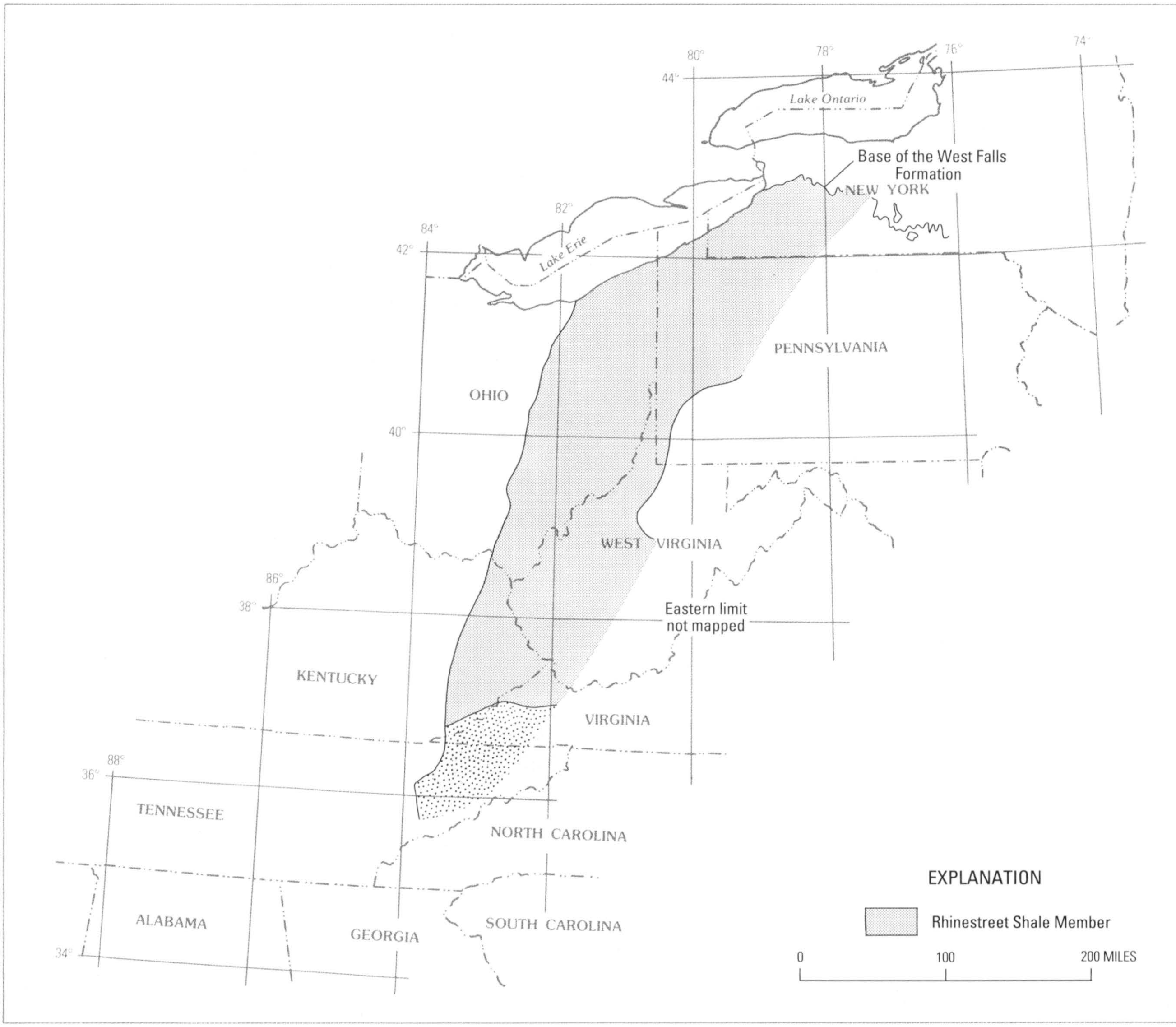

Figure 27. The areal extent of the Rhinestreet Shale Member of the West Falls Formation. In the south, the Rhinestreet cannot be positively identified in outcrop; however, it can be identified in the subsurface by its radioactive signature. Stippling indicates the area where the name "Rhinestreet" is applicable only in the subsurface.

Olentangy Shale

In central Ohio and adjacent northern Kentucky (pl. 2, Nos. 3–13; pl. 7, No. 11), the Olentangy Shale (Winchell, 1874, p. 284; Tillman, 1970) consists of a lower gray shale, which has calcareous nodules, and an upper greenish-gray shale, which has calcareous nodules and a scattering of thin beds of black shale. It overlies Middle Devonian limestones and underlies the black Huron Member of the Ohio Shale. Although the Olentangy is generally less than 50 ft thick, it has been recognized in outcrop to the south into central Kentucky and in the subsurface to the east of its outcrop in Ohio and Kentucky.

We can identify the Olentangy with certainty in the subsurface only a few miles east of its outcrop (fig. 33), and, at the western edge of the black Pipe Creek Shale Member of the Java Formation, we definitely drop the usage of the Olentangy.

Sparling (1988, p. 13–16), from his studies and review of the previous work, suggested that the lower gray shale of the Olentangy is Middle Devonian in age and is correlative with the Tully Limestone of New York and the Prout Limestone of north-central Ohio. The Prout in northern Ohio overlies the Plum Brook Shale, which is equivalent to the Skaneateles Shale. The Prout is absent in central

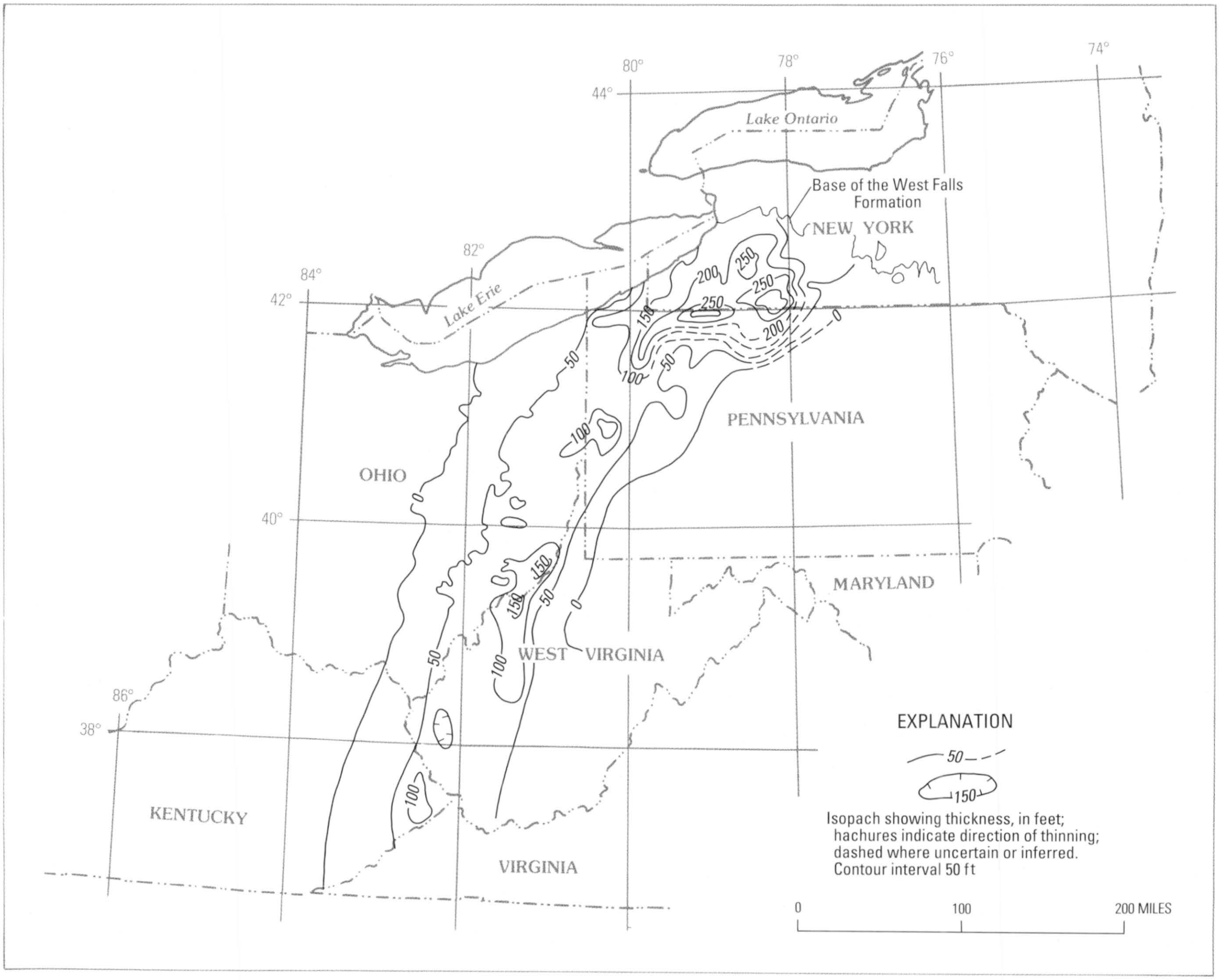

Figure 28. Net thickness of radioactive black shale in the West Falls Formation.

Ohio. Apparently it was not deposited there, or it was deposited and later removed by erosion along the Middle Devonian unconformity.

The upper greenish-gray shale of the Olentangy, which is lithologically and faunally different from the lower gray shale (Tillman, 1970, p. 211), is of Late Devonian age and appears to be the combined Angola Shale Member of the West Falls Formation and the Hanover Shale Member of the Java Formation. Both members include abundant calcareous nodules and scattered thin beds of black shale. We were unable to trace any of the beds of black shale in the upper part of the Olentangy into the black shale of the Pipe Creek Shale Member of the Java Formation. Consequently, we were unable to determine the amount of the upper part of the Olentangy that correlates with either the Angola or the Hanover.

PERRYSBURG FORMATION

In the type exposure at Big Indian Creek near Perrysburg, Cattaraugus County, in southwestern New York, the Perrysburg Formation (Pepper and de Witt, 1951) is a tripartite formation that consists of a basal black shale that has calcareous nodules, the Dunkirk Shale Member; a medial gray shale and siltstone sequence, the South Wales Member; and an upper gray shale and mudrock sequence that has calcareous nodules and scattered beds of siltstone and black shale, the Gowanda Shale Member. Most of these rocks are fine to very fine grained. To the south and the east, they grade into and interfinger with coarser grained quartzose rocks, including the extensive oil-producing Bradford sandstones (Fettke, 1938) of north-central Pennsylvania and adjacent New York. For the purpose of this report, our discussion of the New York stratigraphic

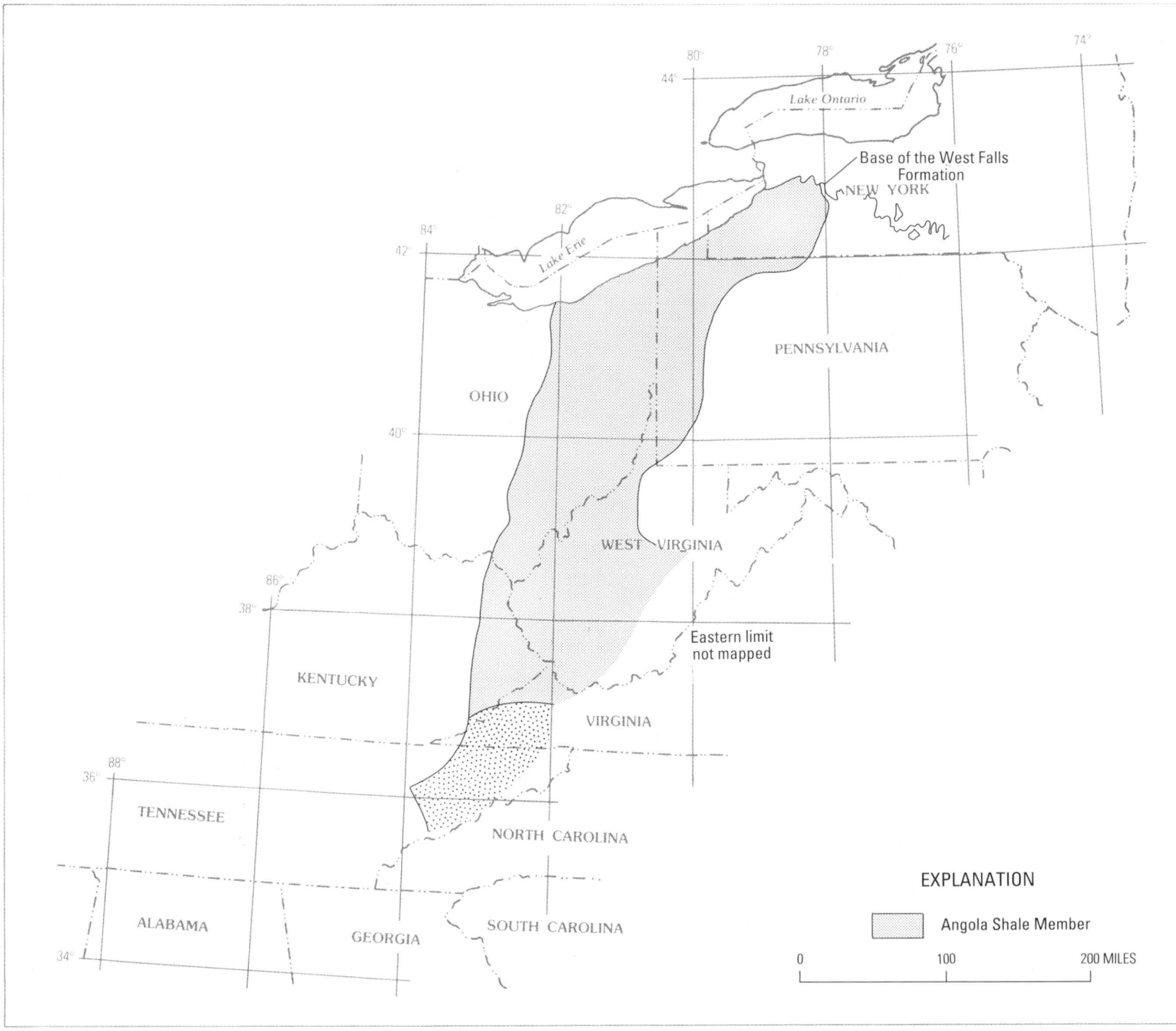

Figure 29. The areal extent of the Angola Shale Member of the West Falls Formation. In the south, the Angola cannot be positively identified in outcrop; however, it can be identified in the subsurface by its position and its radioactive signature. Stippling indicates the area where the name "Angola" is applicable only in the subsurface.

sequence terminates with the Dunkirk Shale Member, which is the youngest extensive black shale in the New York section.

Dunkirk Shale Member

The Dunkirk Shale Member of the Perrysburg Formation (pl. 2, Nos. 18–29; Clarke, 1903; Pepper and de Witt, 1951) and its lithologic equivalent, the Huron Member of the Ohio Shale (pl. 2, Nos. 3–17; Newberry, 1870; Pepper and others, 1954; Schwietering, 1979, p. 33) are parts of the most extensive Devonian black gas shale. The Dunkirk Shale Member is exposed in western New York from the vicinity of Dunkirk, Chautauqua County, east to the hills in southern Steuben County (pl. 5, Nos. 29, 79–81). The member is composed largely of grayish-black to black shale, locally containing crushed plant fossils, scattered beds of dark- to medium-gray shale in the upper part, a few beds or laminae of light-gray siltstone, and a large number of discoidal, ramous, ellipsoidal, and irregularly shaped limestone nodules. Some of the nodules are septaria as much as 6 ft in diameter and 4 ft thick. In outcrop, the Dunkirk is about 110 ft thick in central Erie County; it thins westward to about 50 ft near Dunkirk. The member thins eastward by grading laterally into an eastward-thickening sequence of medium-gray shale, siltstone, and some fine-grained, light-gray sandstone. In its

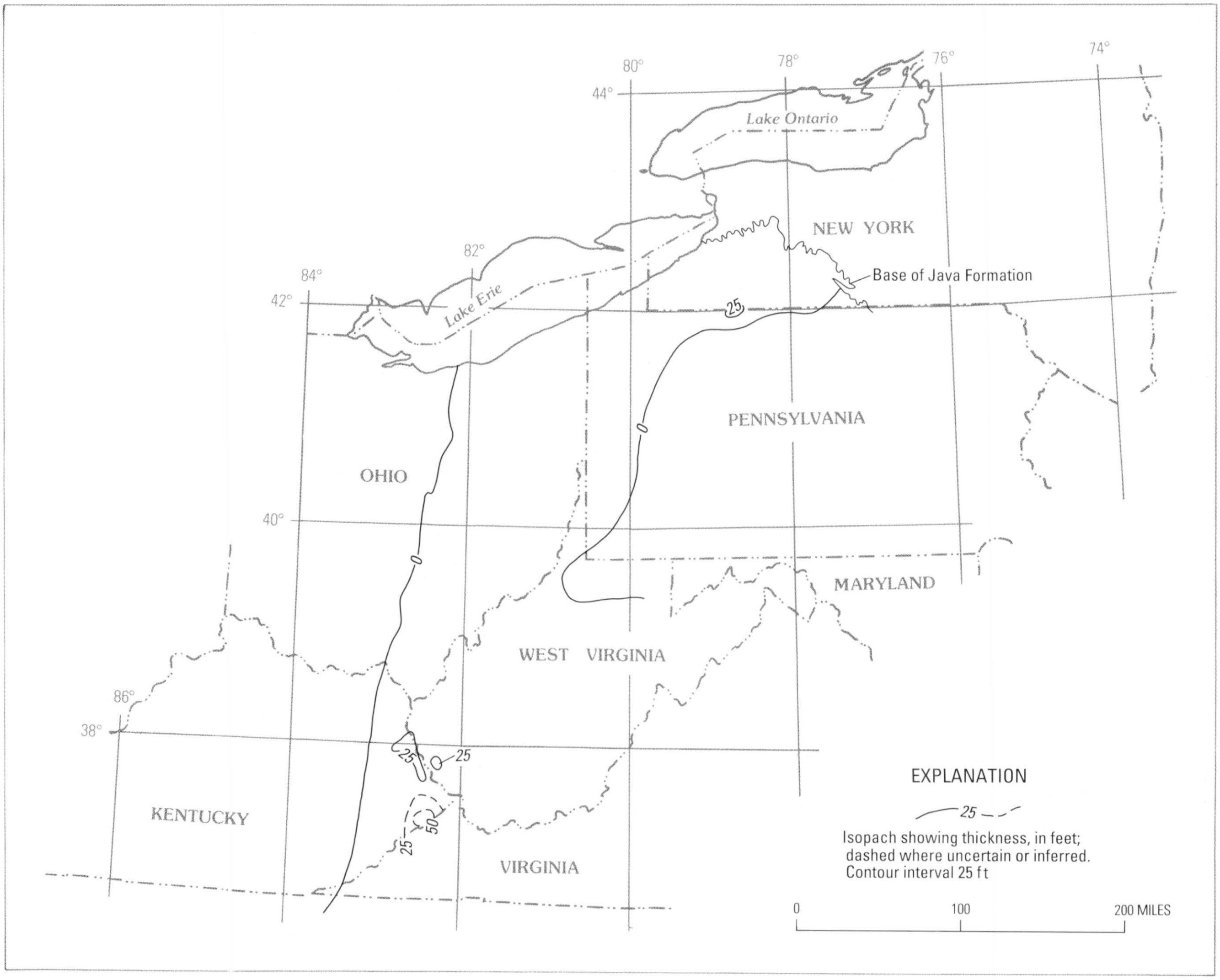

Figure 30. Net thickness of radioactive black shale (essentially, the Pipe Creek Shale Member) in the Java Formation.

easternmost exposures in Steuben County, the Dunkirk is about 1 ft thick.

In the subsurface, the Dunkirk Shale Member is a discrete unit south from the outcrop in western New York to north-central West Virginia (fig. 34; pl. 3, Nos. 27–49; pl. 7, Nos. 91–93). The net thickness of radioactive black shale in the Dunkirk Shale Member exceeds 100 ft in northwestern Pennsylvania and thins to a featheredge to the east and south (fig. 35). In the vicinity of the Pennsylvania-Ohio State line, the Dunkirk Shale Member grades westward into the lower part of the Huron Member of the Ohio Shale (pl. 2, Nos. 17–18; pl. 7, Nos. 90–91). Because the Dunkirk-Huron black shale facies is the stratigraphic bridge between the New York outcrops on the northern side of the basin and the Ohio, the Kentucky, and the central Tennessee outcrops on the western side of the basin, we wish to retain the appropriate name for the black shale within the stratigraphic sequence for each of the specific areas of outcrop. Consequently, the vertical boundary between the Dunkirk Shale Member of the Perrysburg Formation and the Huron Member of the Ohio Shale is an arbitrary subsurface boundary established as a matter of convenience and is not a lithologic subdivision of the black shale unit.

OHIO SHALE

In northern Ohio, the Ohio Shale (Andrews, 1871, p. 62–65; Pepper and others, 1954, p. 14) includes two sequences of dominantly black shale, the Huron Member below and the Cleveland Member above (pl. 2, Nos. 11–17). A westward-thinning tongue of gray, silty Chagrin Shale (Prosser, 1903, p. 521) separates the Huron and the

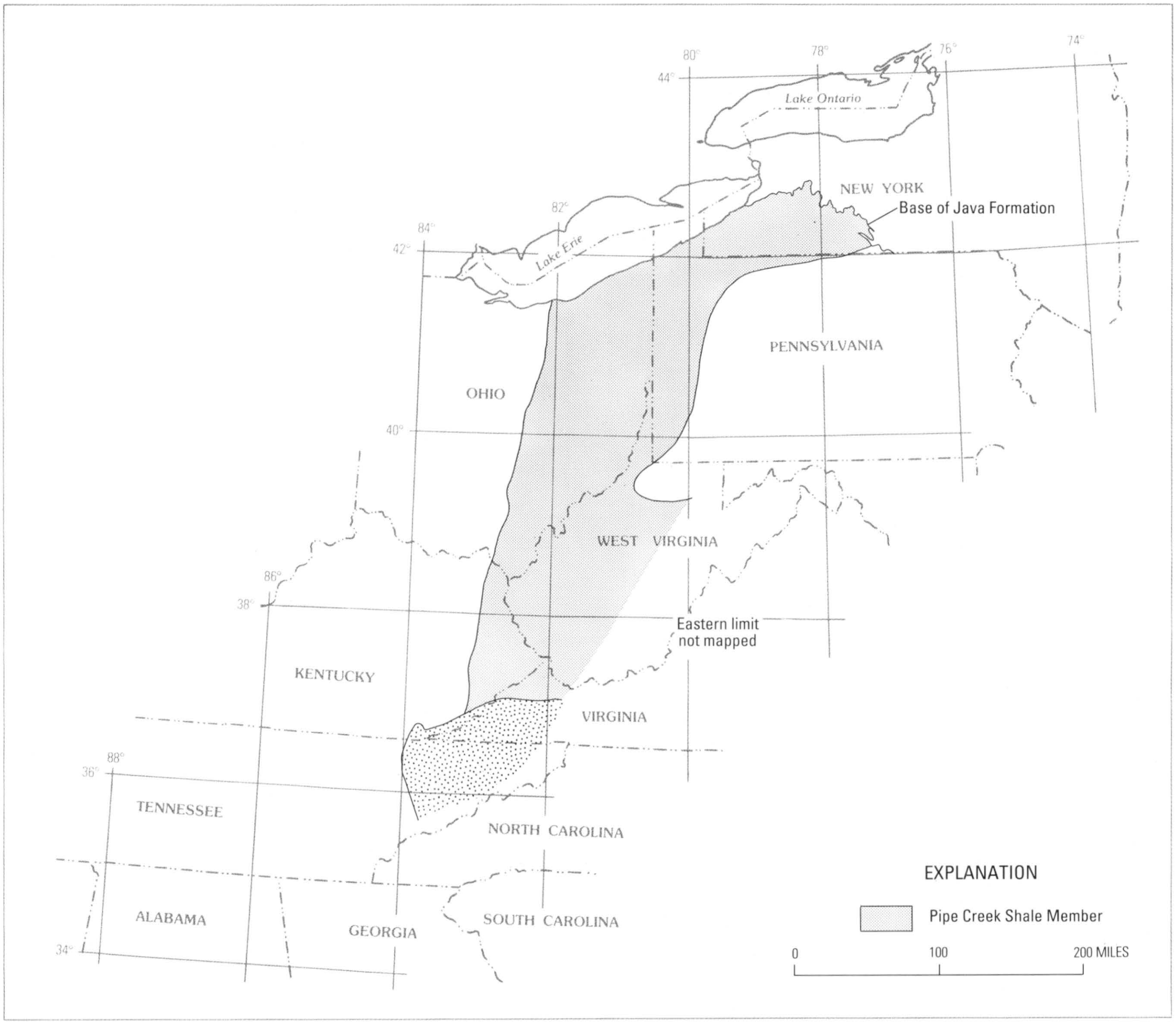

Figure 31. Areal extent of the Pipe Creek Shale Member of the Java Formation. In the south, the Pipe Creek cannot be positively identified in outcrop; however, it can be identified in the adjacent subsurface by its geophysical log signatures. Stippling indicates the area where the name "Pipe Creek" is applicable only in the subsurface.

Cleveland Members in much of northern and eastern Ohio. In outcrops in central and southern Ohio and much of northeastern and central Kentucky, the Three Lick Bed of the Ohio Shale, which is a featheredge of the Chagrin Shale (Provo and others, 1978, p. 1705), separates the Huron and the Cleveland Members. In southern Kentucky and central Tennessee, the Huron and the Cleveland Members of the Ohio Shale are present as beds in the Gassaway Member of the Chattanooga Shale (pl. 11, Nos. 127–135; de Witt and Roen, 1984, p. A50). The Huron is thicker and more extensive than the Cleveland. The lower northeastern part of the Huron Member lithofacies in northwestern Pennsylvania and adjacent western New York is the Dunkirk Shale Member of the Perrysburg Formation.

Huron Member

The Huron Member of the Ohio Shale is about 400 ft thick in its type exposure along the Huron River in Erie County, Ohio, adjacent to Lake Erie in northern Ohio. The member is mainly grayish-black, brownish-black, and black shale. Some beds of medium-gray shale are intercalated, particularly in the upper part of the member. Characteristically, the Huron contains zones of spheroidal to ellipsoidal dolomitic limestone nodules and septaria as much as 8 ft in diameter and 6 ft thick. A few beds of limestone from 1 to 4 in. thick are present in the member. In drill cuttings or cores, the thicker septaria may be misidentified as bedded limestone rather than nodules.

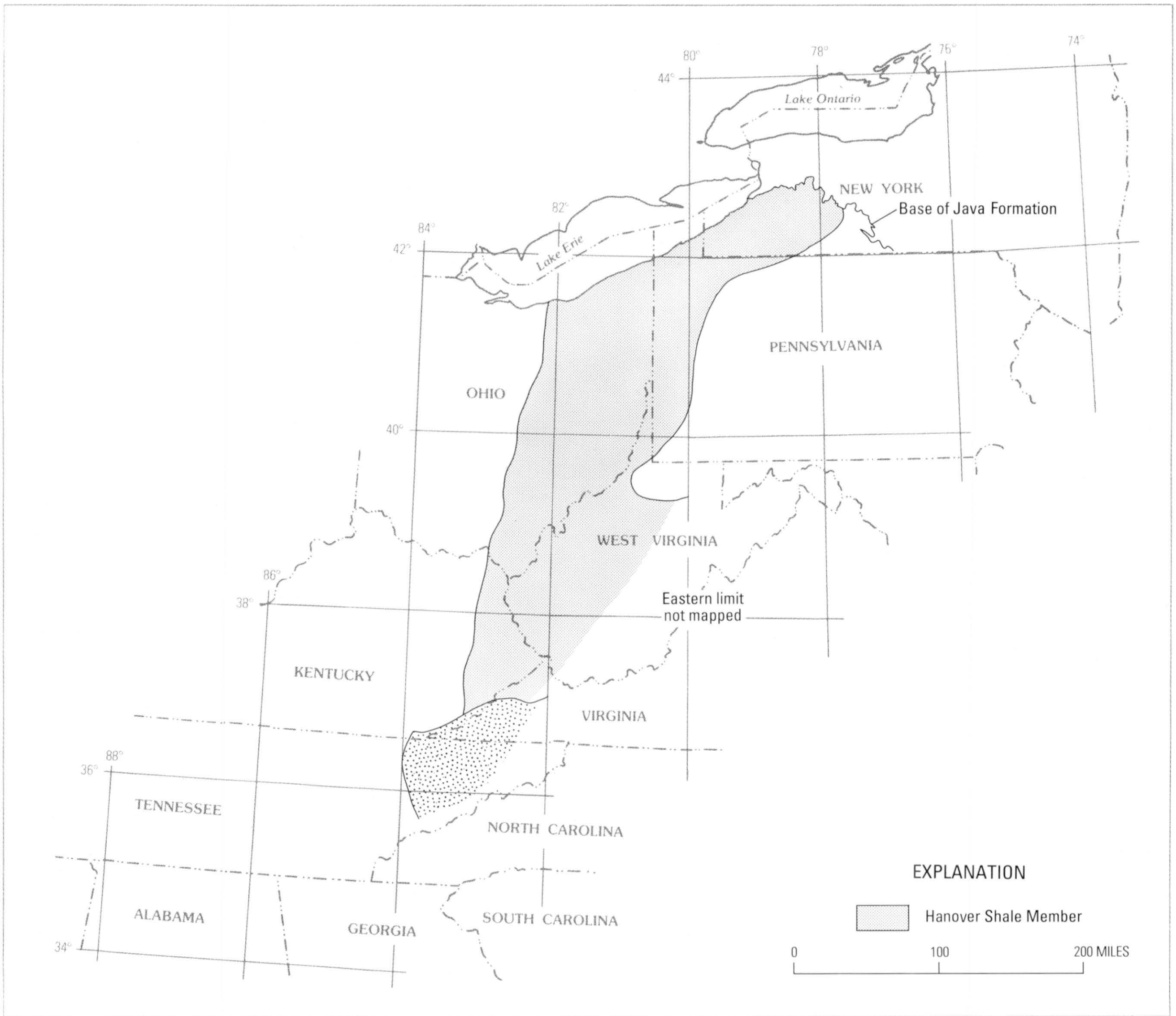

Figure 32. Areal extent of the Hanover Shale Member of the Java Formation. In the south, the Hanover cannot be positively identified in outcrop; however, it can be identified in the adjacent subsurface by its gamma-ray signature above the strong positive signature of the Pipe Creek Shale Member. Stippling indicates the area where the name "Hanover" is applicable only in the subsurface.

In outcrop, the member thins to the south across central Ohio and into northeastern Kentucky. In Powell and adjacent counties in east-central Kentucky, the Huron Member consists of about 100 ft of black shale that has a 10-ft zone containing the fossil alga *Foerstia* about 35 ft above the base. Southward and westward, the Huron grades laterally into the lower and the middle units of the Gassaway Member of the Chattanooga Shale (pl. 11; Kepferle and Roen, 1981; Roen and de Witt, 1984). The Gassaway Member (Conant and Swanson, 1961) thins to the south across Kentucky into central Tennessee where it is 16.7 ft thick in the reference section at Sligo Bridge in DeKalb County.

In the subsurface, the Huron Member thickens eastward across northern Ohio to about 650 ft near Painesville, Lake County, Ohio, and has an 87-ft-thick zone of *Foerstia* in the topmost beds. In eastern Ohio and southward into western West Virginia and adjacent Kentucky and Virginia, the Huron Member splits into an upper and a lower black shale sequence separated by an eastward-thickening wedge of gray shale and siltstone of the Chagrin Shale (pl. 2, Nos. 12–17; pl. 3, Nos. 31–34; pl. 7, Nos. 11–88; pl. 8, Nos. 9, 97; pl. 9, Nos. 34–110).

In northeastern Ohio, the upper part of the Huron Member interfingers with gray beds of the Chagrin Shale and can no longer be recognized. The lower part of the

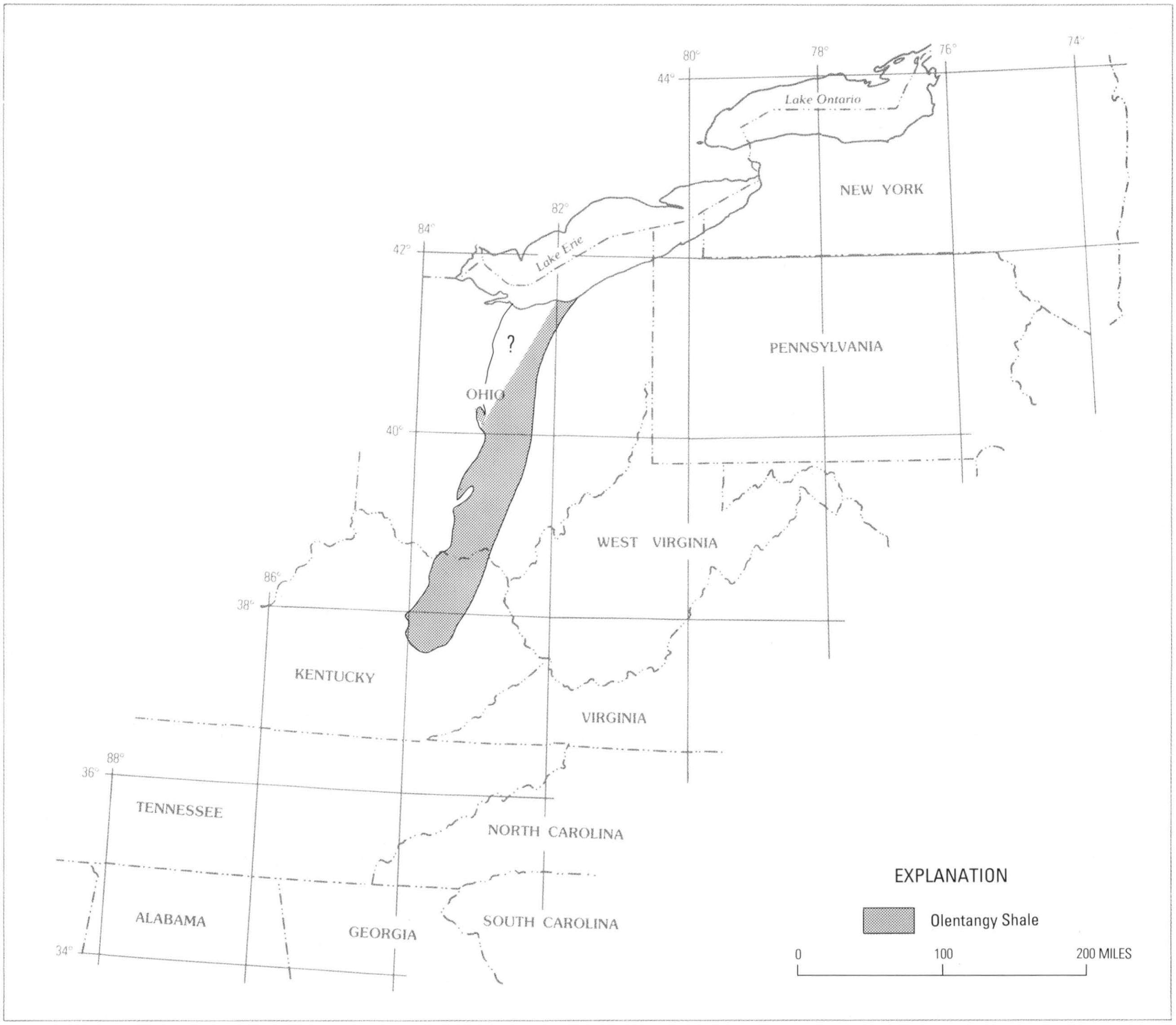

Figure 33. Areal extent of the Olentangy Shale (queried where it grades laterally into the Plum Brook Shale in northern Ohio).

member crosses an arbitrary vertical boundary and becomes the Dunkirk Shale Member of the Perrysburg Formation. The sheet of black Dunkirk-Huron-Gassaway shale is the most extensive of the Devonian black gas shales (fig. 34) and underlies the Appalachian basin from central New York southwest to southern Tennessee and northern Alabama (de Witt and Roen, 1984, p. A54).

In exposures in Erie County near Sandusky, Ohio, the Huron Member of the Ohio Shale lies with apparent conformity upon the Prout Limestone. Conodonts from the base of the Huron at Slate Cut, Huron Township, Erie County, are younger than conodonts from the Dunkirk Shale Member of the Perrysburg Formation in western New York (Hass, 1958, p. 766); this suggests correlation with the younger South Wales and Gowanda Members of the Perrysburg Formation. However, in north-central Ohio, the Huron Member of the Ohio Shale onlaps westward across the Middle Devonian unconformity at the top of the Prout Limestone. Consequently, in Ohio, the basal beds of the Huron are younger in Erie County than to the east in Cuyahoga and Lake Counties. In the shaft of the Morton Salt Company's mine near Painesville, Lake County, the basal 15 ft of the Huron Member contains a *Palmatolepis subrecta* conodont fauna (W.H. Hass, U.S. Geological Survey, written commun., field collection No. 9, 1957), which also occurs in the Dunkirk Shale Member of the Perrysburg Formation in southwestern New York (Hass, 1958). These data confirm the lithostratigraphic and the electric log correlation of the Dunkirk and the Huron.

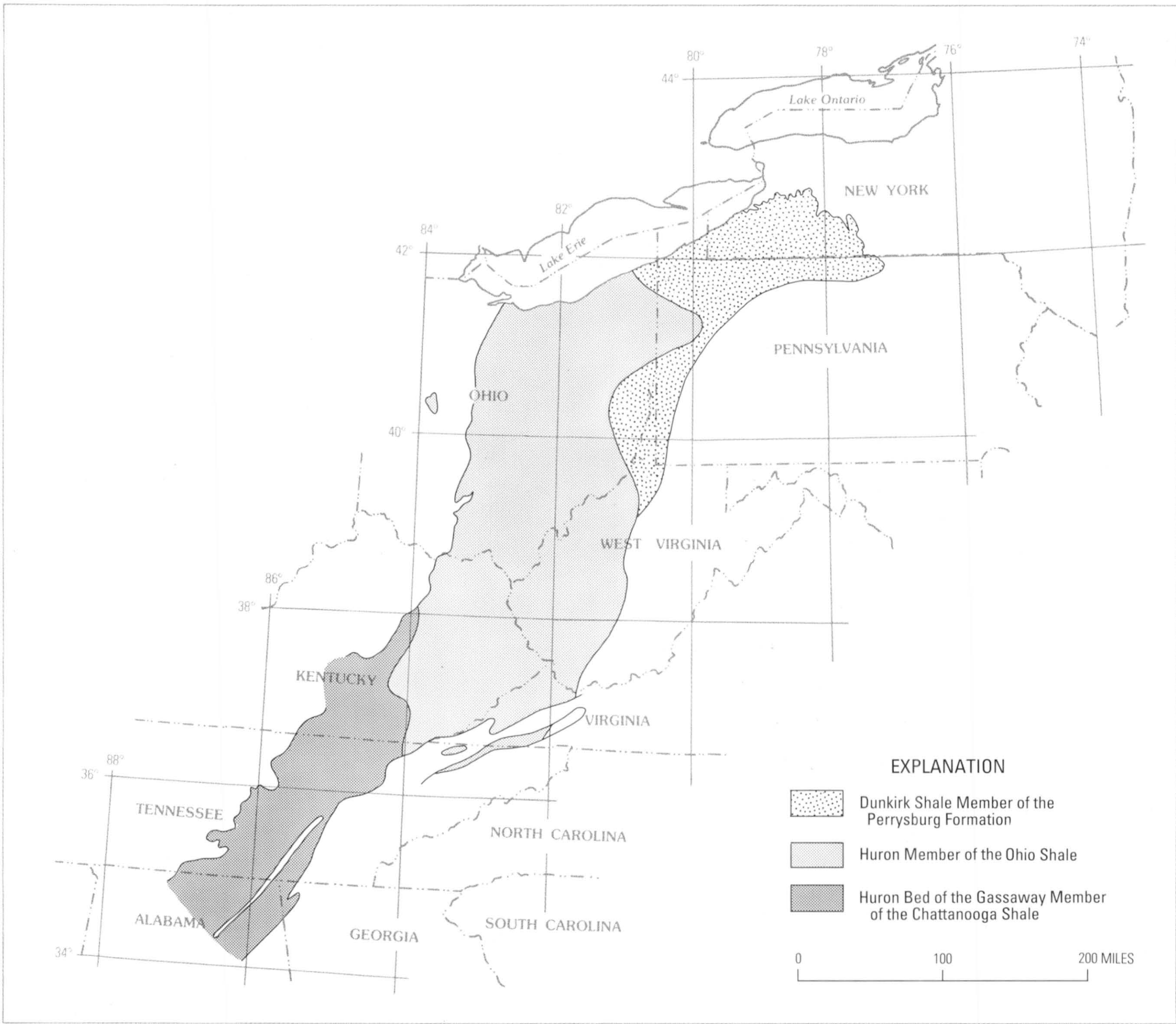

Figure 34. Areal extent of the Dunkirk Shale Member of the Perrysburg Formation, the Huron Member of the Ohio Shale, and the Huron Bed of the Gassaway Member of the Chattanooga Shale in the Appalachian basin (from de Witt and Roen, 1985).

Chagrin Shale and Three Lick Bed of the Ohio Shale

The Chagrin Shale (Prosser, 1903) and its featheredge, the Three Lick Bed (fig. 36), are the distal parts of a great eastward-thickening wedge of gray marine shale and turbiditic siltstone that lies between the basinal black shales of the gas shale sequence and the near-shore, coarser grained, neritic sandstones of the Late Devonian Catskill delta complex. This great wedge of gray clastic rock, of which the Chagrin and the Three Lick are a small part, extends from central New York southwestward into the Valley and Ridge province of northeastern Tennessee. The Chagrin is typically exposed in northeastern Ohio, where it is more than 1,400 ft thick in Ashtabula County (pl. 2, Nos. 14–17). In much of the outcrop area, it is overlain by the Cleveland Member of the Ohio Shale and is underlain by the Huron Member of the Ohio Shale. The gray shale, the mudrock, and the siltstone of the Chagrin grade westward and intertongue with the black shale of the Huron and the Cleveland Members. The Chagrin (pl. 2, Nos. 11–17; pl. 8, Nos. 96–97) thins to the southwest. In central and southern Ohio and eastern Kentucky, the Three Lick Bed separates the Cleveland Member of the Ohio Shale from the older Huron Member of the Ohio Shale throughout much of Kentucky east of the Cincinnati arch. Originally, the Three Lick Bed (pl. 10) was correlated with the middle unit of the Gassaway Member of the Chattanooga Shale in the vicinity

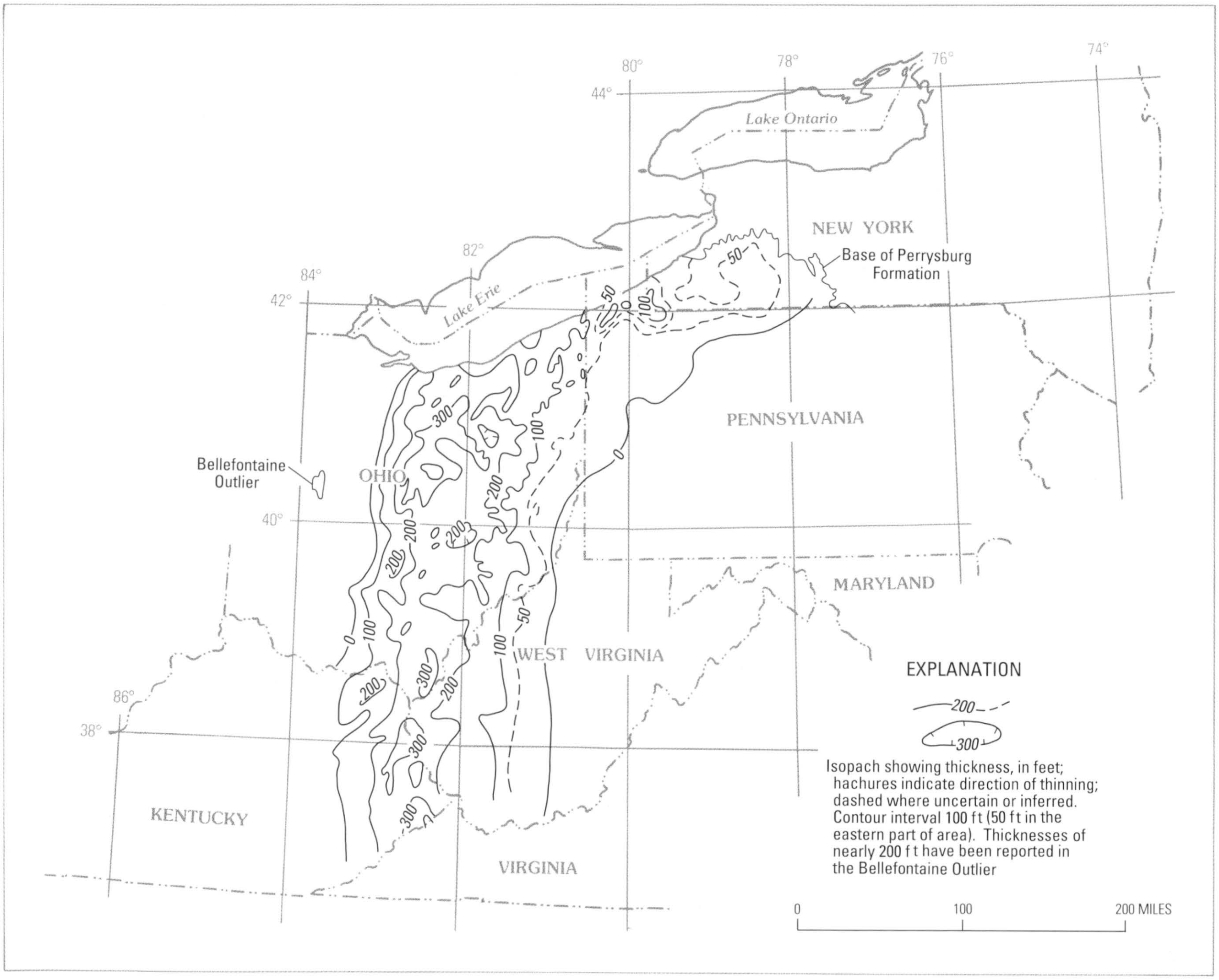

Figure 35. Net thickness of radioactive black shale in the Perrysburg Formation and the equivalent Huron Member of the Ohio Shale.

of the reference section at Sligo Bridge, DeKalb County, Tenn. (Provo and others, 1978). However, in the type exposure of the Three Lick Bed near Morehead, Rowan County, Ky., the zone of *Foerstia* occurs in the lower part of the Huron Member of the Ohio Shale about 75 ft below the base of the Three Lick Bed (Provo and others, 1978, p. 1705). Recently, Kepferle found *Foerstia* near the top of the upper part of the Gassaway Member of the Chattanooga at Hurricane Bridge, DeKalb County, Tenn. (pl. 11, No. 128; Kepferle and Roen, 1981), about 6 mi from the Chattanooga reference section at Sligo Bridge (pl. 11, No. 127). Because *Foerstia* occurs in a thin stratigraphic interval, the Three Lick Bed cannot be above the *Foerstia* zone in Kentucky and below it in Tennessee. These data invalidate the correlation of the Three Lick Bed of Kentucky with the middle unit of the Gassaway Member in central Tennessee. Apparently, the Three Lick Bed has pinched out of the sequence in the vicinity of the Kentucky-Tennessee State line (pl. 11, No. 129).

Cleveland Member

The Cleveland Member of the Ohio Shale (Newberry, 1870; Pepper and others, 1954, p. 16) is the youngest Upper Devonian black shale in the gas shale sequence in the western part of the Appalachian basin. As much as 70 ft of fissile black Cleveland is exposed near Cleveland, Cuyahoga County, Ohio. In its type area (pl. 2, Nos. 13–15), the Cleveland Member overlies the Chagrin Shale. Throughout its extent in central Ohio and northeastern Kentucky (fig. 37), the Cleveland contains a sparse conodont fauna, which indicates the very late Late Devonian age of the member (Oliver and others, 1969).

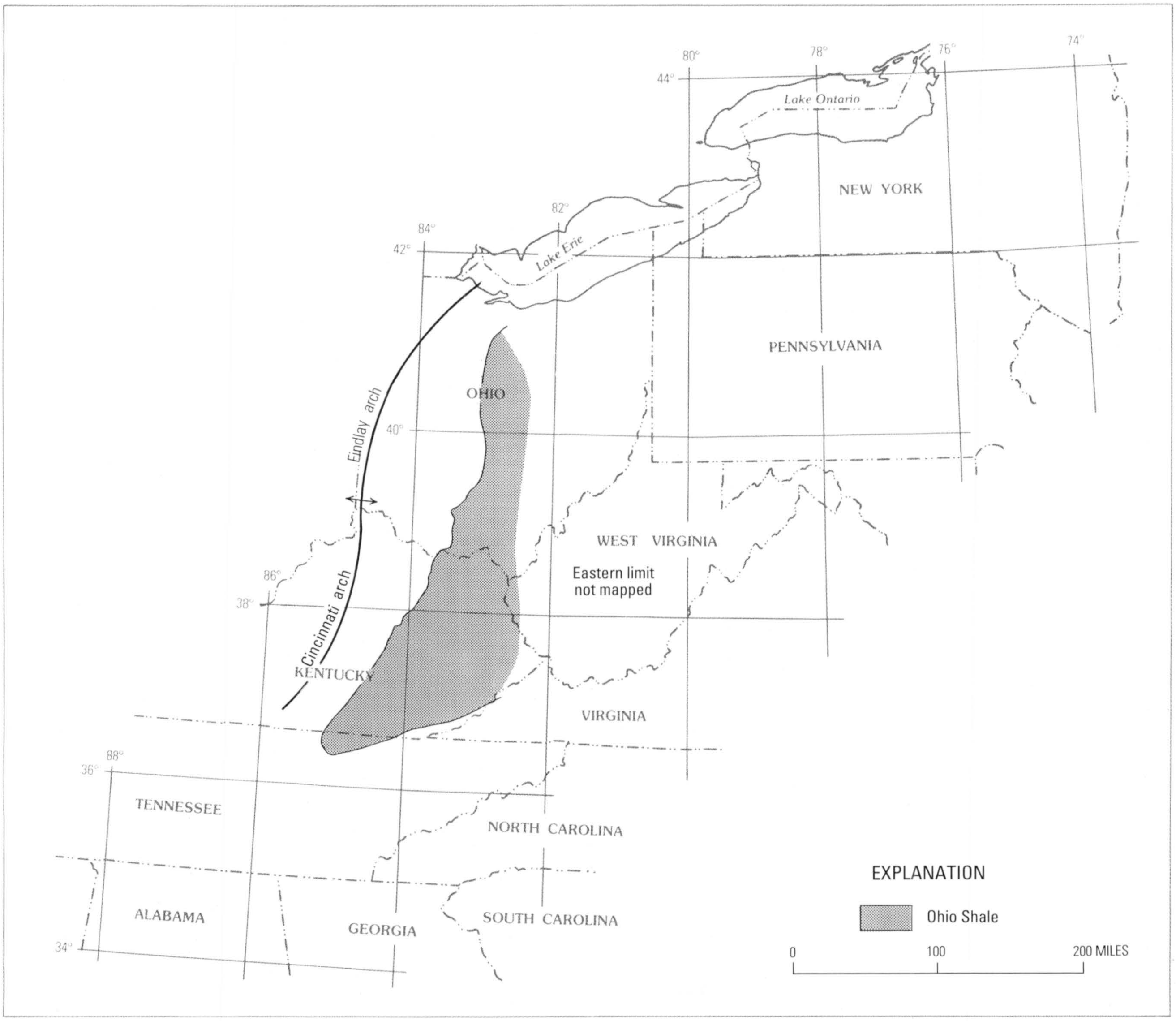

Figure 36. Distribution of the Three Lick Bed of the Ohio Shale. Beds thought to be the equivalent of the Three Lick Bed have been found between Raywick and Howardstown, Ky., on State Route 84 (Kepferle and Roen, 1981, p. 316, stop 28).

The radioactive black shale in the Cleveland Member is more than 125 ft thick in Ashland and Lorain Counties in northern Ohio (fig. 38). To the east and southeast, it thins to a featheredge in eastern Ohio and western West Virginia. The Cleveland Member thins gradually southward across Ohio and is about 45 ft thick in central Kentucky (pl. 11, Nos. 134–135). Southward in south-central Kentucky, thinning black shale of the Cleveland Member grades into the upper part of the Gassaway Member of the Chattanooga Shale. In southern Kentucky, the Cleveland is a bed in the Gassaway Member. Outcrops near Celina, Tenn., contain 5.4 ft of the Cleveland (Kepferle and Roen, 1981, p. 275), and the underlying Three Lick Bed can be identified with certainty. To the south in the vicinity of the reference section for the Chattanooga at Sligo Bridge, the Cleveland and the Three Lick are absent. There, the uppermost beds of the Gassaway Member are equivalent to the upper part of the Huron Bed of south-central Kentucky and part of the Huron Member of the Ohio Shale of Ohio. Hass (1956) noted many places in eastern and central Tennessee where conodonts in the uppermost part of the Gassaway Member indicate correlation with the Cleveland Member of the Ohio Shale.

CHATTANOOGA SHALE

The Chattanooga Shale (Hayes, 1891, p. 143) of Tennessee and northern Alabama is the distal fringe of the black gas shales in the southwestern part of the Appalachian

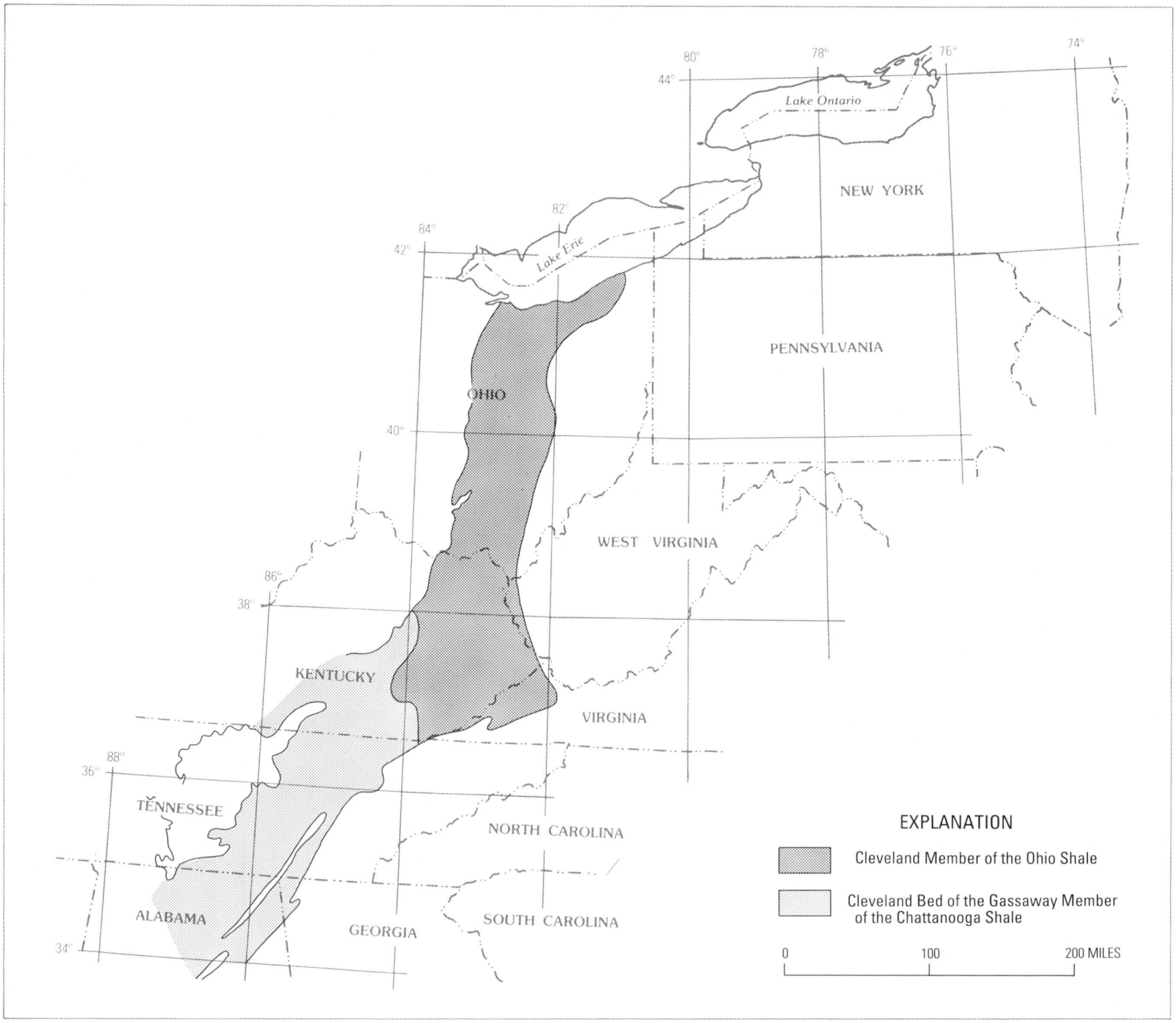

Figure 37. Geographic extent of the Cleveland Member of the Ohio Shale and the Cleveland Bed of the Gassaway Member of the Chattanooga Shale in the Appalachian basin. (From de Witt and Roen, 1985.)

basin that accumulated in anerobic waters of a sediment-deprived basin. It had been subdivided into two members (pl. 11, Nos. 127–128)—the Dowelltown below and the Gassaway above (Hass, 1956, p. 13)—in central Tennessee where the Chattanooga ranges in thickness from a featheredge to more than 35 ft.

Dowelltown Member

The Dowelltown Member consists of a lower black shale about 6 ft thick and an upper unit of interbedded medium- and dark-gray shale about 9 ft thick in the standard reference section at Sligo Bridge, DeKalb County, Tenn. (Conant and Swanson, 1961, p. 24). The lower black shale is the Rhinestreet Shale Bed, and the upper gray shale unit is the undivided Angola and Hanover Shales (pl. 11, No. 127; Roen and de Witt, 1984). The Center Hill Ash Bed (Roen and Hosterman, 1982), which was formerly called the Center Hill bentonite bed of Conant and Swanson (1961, p. 30), is generally about 1 in. thick and occurs in the upper part of the gray shale unit of the Dowelltown Member (pl. 11, Nos. 127–129).

Gassaway Member

The Gassaway Member consists of a basal black shale about 7.5 ft thick, a middle unit of intercalated black and medium-gray shale about 2 ft thick, and an upper black

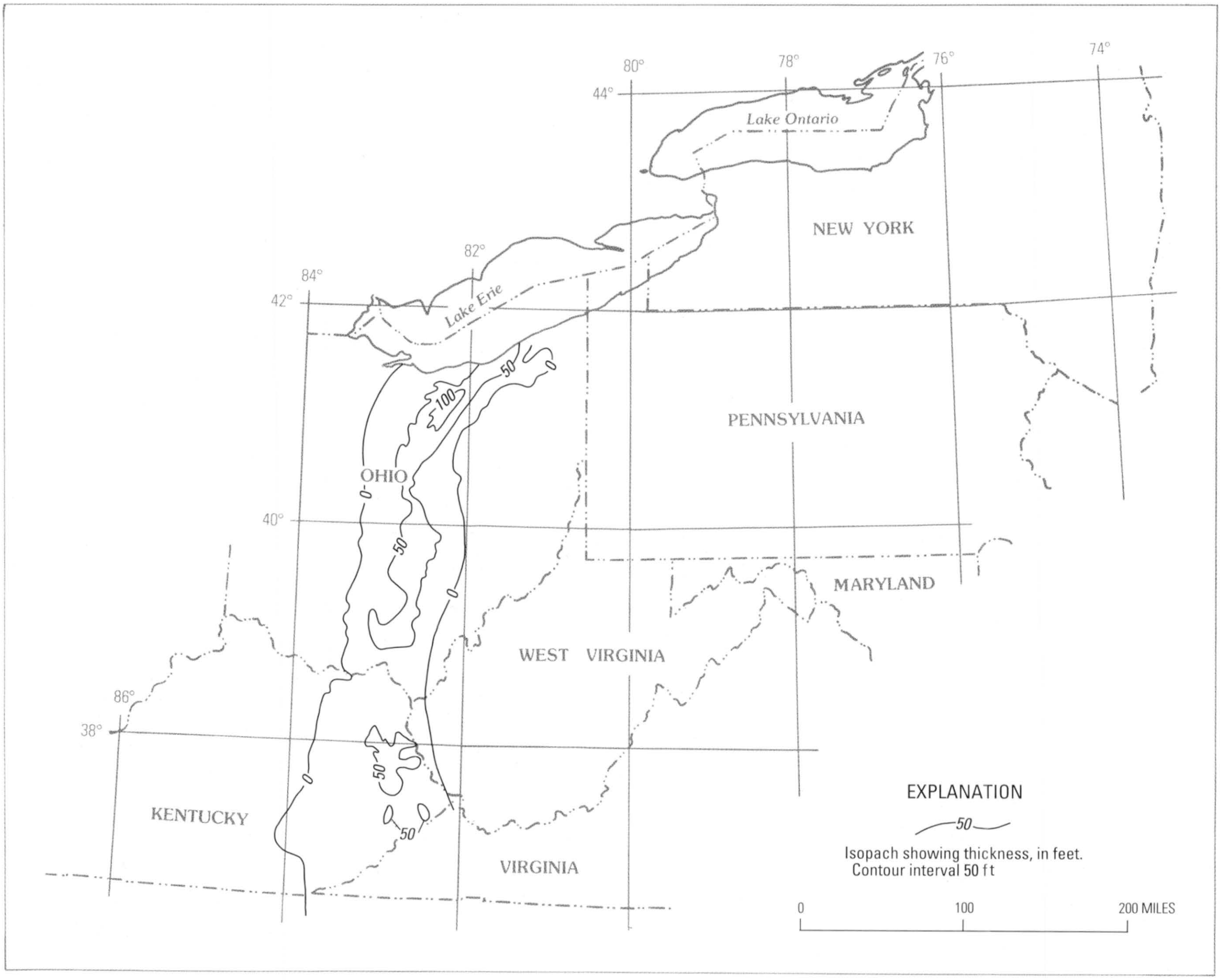

Figure 38. Net thickness of radioactive black shale in the Cleveland Member of the Ohio Shale.

shale about 7 ft thick at the standard section in central Tennessee (pl. 11, No. 127). There the Gassaway Member includes only the Huron Bed. Locally in north-central Tennessee, conodonts of the Cleveland fauna in the top beds of the Gassaway demonstrate the presence of the Cleveland Bed (Hass, 1956, p. 22, fig. 1). At other places in eastern Tennessee, a biostratigraphic zone several inches thick in the top of the Gassaway contains the conodont fauna of the Sunbury Shale.

In central Tennessee, the Chattanooga Shale is overlain by the Lower Mississippian Maury Formation (Conant and Swanson, 1961). The Maury Formation is not present to the southeast, and the Chattanooga is overlain by the Fort Payne Chert. In Kentucky, the Fort Payne grades laterally into the lower part of the Borden Formation. To the north in the vicinity of the Kentucky-Ohio State line, the name "Borden" is replaced by the Cuyahoga Formation for the same suite of gray silty and shaley rocks.

In south-central Kentucky, the Dowelltown Member is absent, and the Gassaway Member is again tripartite—the lower black shale, which is the Huron Bed; the middle gray shale, which is the Three Lick Bed; and the upper black shale, which is the Cleveland Bed and a thin layer of Sunbury Shale at the top in some places (pl. 11, Nos. 129–135; de Witt and Roen, 1984, p. A51). In east-central Kentucky, the Chattanooga Shale grades northward into the Ohio Shale, the Bedford Shale, the Berea Sandstone, and the Sunbury Shale (de Witt, 1981).

In the Valley and Ridge province, the Chattanooga thickens northeastward and is more than 1,000 ft thick in northeast Tennessee and adjacent southwest Virginia. There, the Gassaway and the Dowelltown are not recognized as separate lithostratigraphic units.

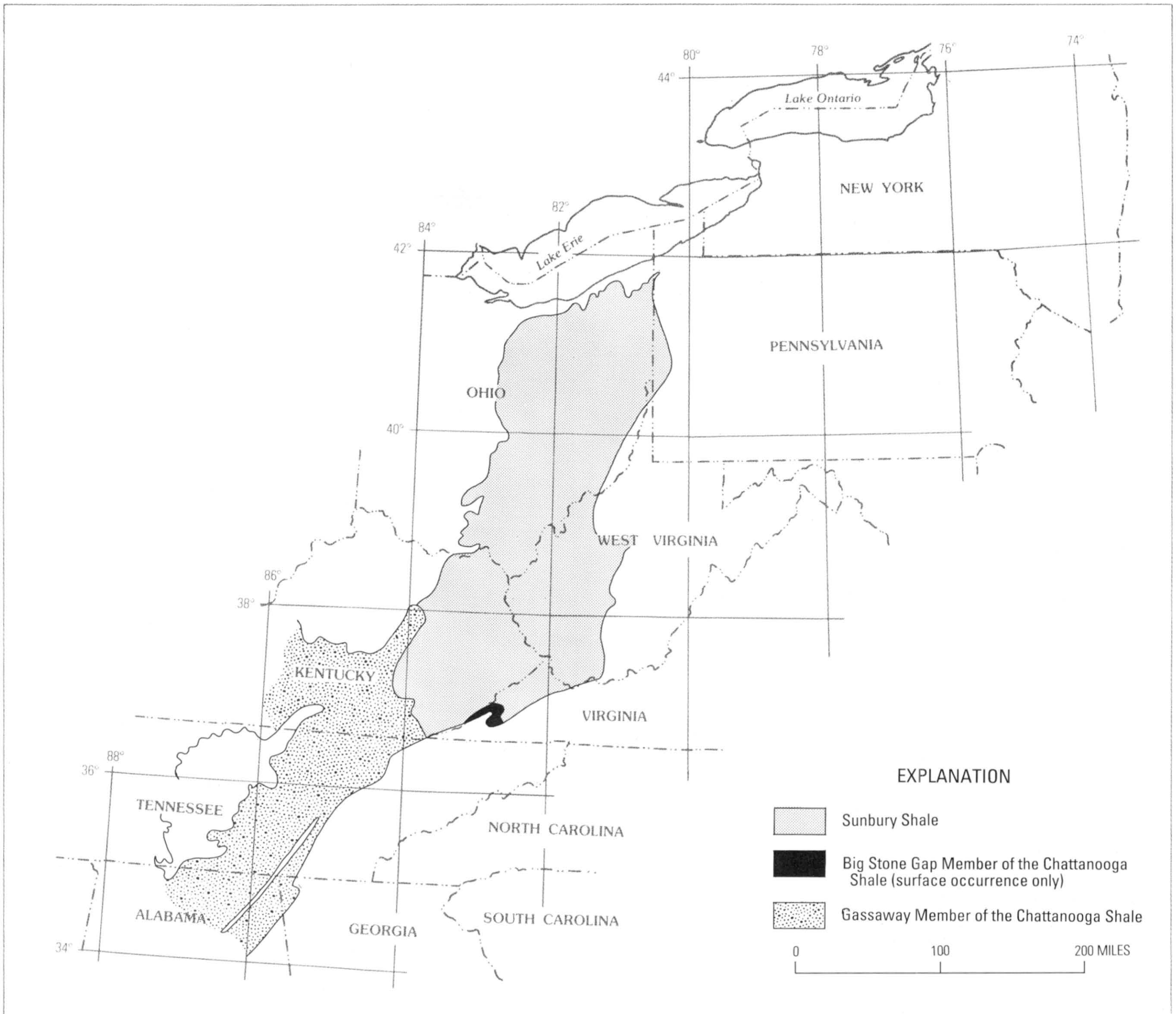

Figure 39. Geographic extent of the Sunbury Shale, the Big Stone Gap Member of the Chattanooga Shale, and the Gassaway Member of the Chattanooga Shale. (From de Witt and Roen, 1985.)

Big Stone Gap Member of the Chattanooga Shale

In the vicinity of Big Stone Gap, Wise County, Va., the Chattanooga Shale consists of three members—a lower black shale, a medial gray siltstone and interbedded black shale, and the dominantly black upper Big Stone Gap Member (fig. 39; Roen and others, 1964). The upper 60 percent of the 243-ft Big Stone Gap Member contains much brownish-black and black shale. The Sunbury Shale *Siphonodella* conodont fauna occurs in a 40-ft-thick zone of black shale about 110 ft below the top of the member, whereas the Bedford Shale conodont *Spathognathodus antiposicornis* occurs in the lower part of the member. These data demonstrate that the euxinic Sunbury black mass extended southward into the edge of the Valley and Ridge of southwestern Virginia (de Witt and Roen, 1985). The presence of *Foerstia* in the medial member and of many of the conodonts in the lower black shale member of the Big Stone Gap indicates that these beds are part of the Gassaway Member of central Tennessee (Roen and others, 1964, p. B47). Conodonts in the basal part of the lower black shale member suggest correlation with parts of the Millboro Shale of west-central Virginia.

BEDFORD SHALE AND BEREA SANDSTONE

Throughout much of its extent in the Appalachian basin, the Cleveland Shale is overlain by the lighter colored

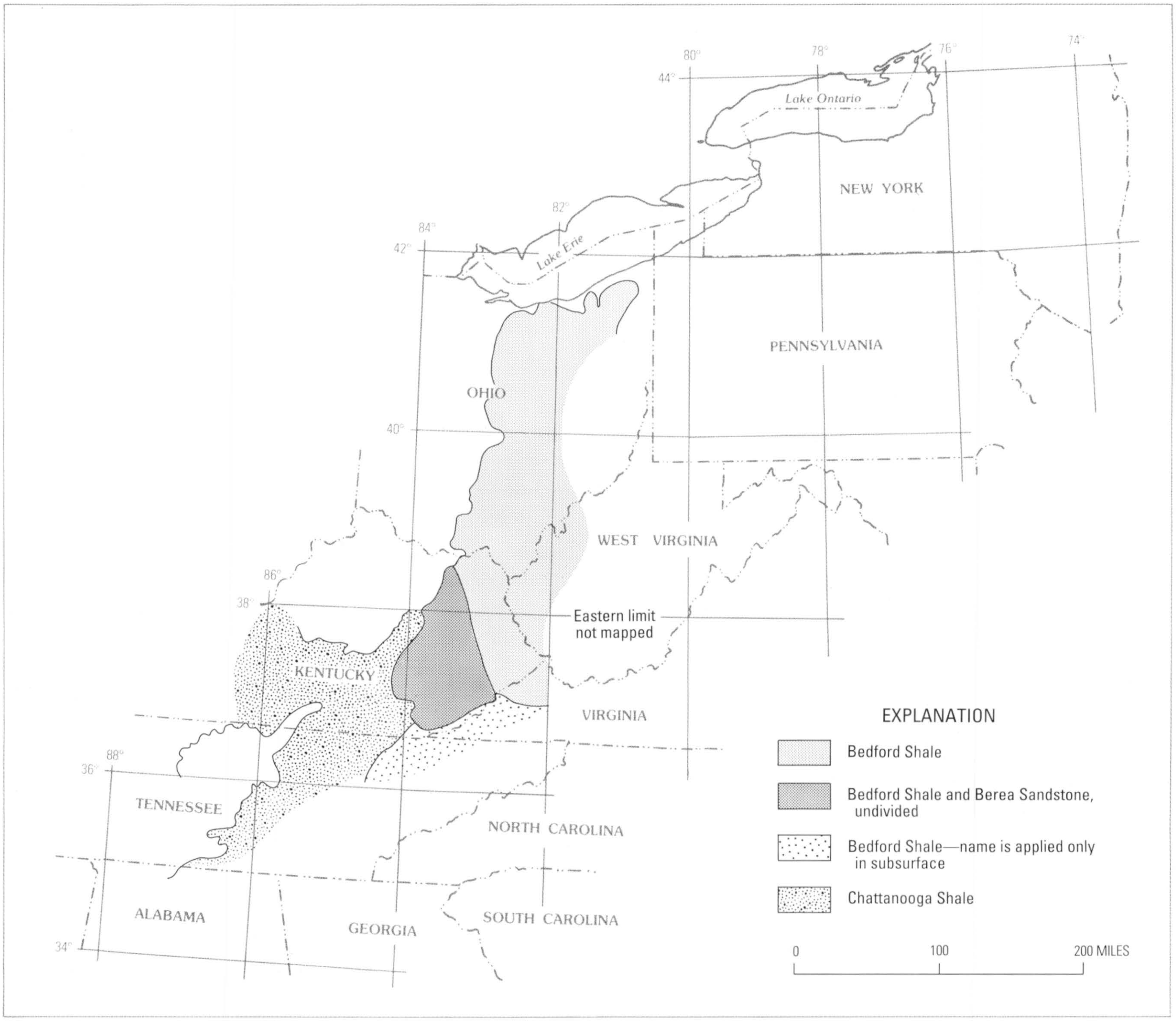

Figure 40. Areal extent of the Bedford Shale, the undivided Bedford Shale and Berea Sandstone, and the Chattanooga Shale.

clastic strata of the Bedford Shale and the coarser grained Berea Sandstone (pl. 2, Nos. 3–17; pl. 11, Nos. 102, 6, 136; Newberry, 1870; Pepper and others, 1954). The two units show a pattern of vertically increasing grain size. Locally in northern Ohio, the Berea fills channels cut in the subjacent Bedford Shale, whereas, elsewhere, a gradational boundary indicates the continuity of deposition. The total Bedford and Berea sequence thins from more than 300 ft in northern Ohio to a featheredge in central Kentucky (fig. 40; de Witt, 1981). In places in eastern Ohio and central West Virginia, the Bedford Shale overlaps the Cleveland Member of the Ohio Shale, bringing gray Bedford Shale upon gray Chagrin Shale.

SUNBURY SHALE

The Sunbury Shale (Hicks, 1878, p. 216, 221) was named for exposures of black shale on Rattlesnake Creek near Sunbury, Delaware County, Ohio. It is of Early Mississippian age and is the youngest of the regionally extensive black gas shales in the gas shale sequence. The Sunbury is a typical fissile black shale that weathers into small discoidal sharp-edged chips, which are commonly iron stained. Pyrite is a common accessory, particularly in the basal part of the formation, where a zone of pyrite about 1 in. thick separates a zone of small inarticulate brachiopods and the *Siphonodella* conodont fauna from the underlying

Berea Sandstone Although the Sunbury is sparsely fossiliferous, except for the zone at the base, a few plant fossils have been found in it in northern Ohio

The Sunbury Shale (fig 40, pl 2, Nos 2–16, pl 7, Nos 11, 88–90, pl 9, pl 10, pl 11, Nos 3, 136, 6, 102) is present only in the western part of the basin, it crops out at many places along the eastern flank of the Cincinnati arch in Ohio and northeastern Kentucky, where it ranges in thickness from 10 to 40 ft It thins to a featheredge in siltier rocks to the east

Throughout much of its extent in eastern Ohio, West Virginia, and northern Kentucky, the Sunbury Shale overlies the Berea Sandstone and the subjacent Bedford Shale These two formations thin to a featheredge in or near Powell County, Ky , which permits the southward-thinning black Sunbury Shale to rest upon the top of the black Cleveland Member of the Ohio Shale (pl 11, Nos 3, 135) Although the two shales are lithologically indistinguishable, they may be separated by their conodont faunas and by their gamma-ray signatures

In south-central Kentucky, the thinning Sunbury grades laterally into the upper unit of the Gassaway Member of the Chattanooga Shale (de Witt and Roen, 1984, p A51) and is present as a biostratigraphic zone in the top of the Gassaway in many places in north-central Tennessee The presence of the Sunbury component in the Gassaway can be demonstrated only by the occurrence of a *Siphonodella* conodont fauna in the black shale Consequently, delineation of the southern featheredge of the Sunbury Shale depends, to a great extent, on a large amount of surface and subsurface sample data

DEVONIAN BLACK SHALE ECONOMICS

The black Marcellus Shale is one of the most productive of the gas shales It has yielded gas in New York, Pennsylvania, West Virginia, and Virginia Many wells drilled to the older Oriskany Sandstone encountered moderate to large amounts of gas in the Marcellus, particularly in structures where natural fracturing shattered the Marcellus and developed zones of fracture porosity Not uncommonly, gas flowed vigorously from the Marcellus for a few hours or a few days before it was exhausted Apparently, the fractured zones were of small lateral and vertical extent In contrast, some of the Marcellus fractured reservoir rocks in the low-pressure area of western New York produced gas for many years with little diminution of daily flow A recent study of the porosity and the permeability of the Devonian gas shales indicated that the Marcellus Shale is a superior source bed for gas at depths of greater than 7,000 ft (Soeder and others, 1986)

Although little exploited because of its considerable depth in western Pennsylvania and adjacent West Virginia, the Geneseo-Burket facies is a viable target in this area This black shale produced gas for a time at the METC No 1 well from a depth of about 7,100 ft

The Rhinestreet Shale Member of the West Falls Formation is also one of the most productive of the gas shales It has produced gas in the belt of shallow low-pressure wells along the southern shore of Lake Erie as well as deeper in the Appalachian basin in Ohio, West Virginia, and eastern Kentucky Some of the shallow wells in the Dunkirk Shale Member of the Perrysburg Formation of Chautauqua County, N Y , were drilled deeper into the Rhinestreet Shale Member of the West Falls Formation, which considerably increased the volume of gas in each well

The Dunkirk Shale Member has produced gas in western New York and contiguous northwestern Pennsylvania The member produced gas in the first gas well at Fredonia, Chautauqua County, and was the source of gas and oil in Erie County, Pa

Along the southern shore of Lake Erie, the gray shales and the siltstones of the Chagrin and its equivalents have produced gas and small amounts of oil The source of these hydrocarbons is the contiguous black shales The reservoirs are mainly zones of fractures and joints, although some siltstones are sufficiently porous to be low-volume reservoir rocks Some wells had initial yields of as much as 4 million ft^3/d, but the supply of gas was quickly exhausted, and the wells were soon abandoned

The Huron Member of the Ohio Shale is another economically important gas shale It produced gas in shallow, low-pressure shale gas fields along the southern shore of Lake Erie and in several small fields to the south in central and southern Ohio, and it is the main source of gas in the Big Sandy field in eastern Kentucky and adjacent West Virginia The Huron is also the source of gas and high-gravity oil in southeastern Ohio and contiguous West Virginia

The Cleveland Member of the Ohio Shale has produced some gas in Ohio and Kentucky It is not as good a source bed as the Huron Member, although, locally, it yields sufficient gas for domestic wells

Although the Sunbury Shale is relatively thin in comparison to the Huron, the Rhinestreet, and the Marcellus, it has produced gas locally in southern Ohio It should be included in zones of shale being stimulated for gas if the Sunbury is in close vertical proximity to other black shales in the gas shale sequence

SUMMARY

The Devonian black shales, which are rich in organic matter, have produced gas in the Appalachian basin since 1821 and have been recognized as source beds for oil and gas since the drilling of the Drake oil well in 1859 However, the subsurface stratigraphy and geometry of these gas-producing shales were not well known until the use of gamma-ray logs became widespread in the 1960's The older gas shales—the Marcellus Shale, the Geneseo Shale Member of the Genesee Formation, the Burket Shale Member of the Harrell Shale, and the Middlesex Shale Member of the Sonyea Formation—were deposited mainly in the eastern and the northeastern parts of the basin from New York to southwestern Virginia They do not extend west to outcrops along the eastern flank of the Cincinnati arch on the western periphery of the Appalachian basin In contrast, the younger gas shales—the Rhinestreet Shale Member of the West Falls Formation, the Dunkirk Shale Member of the Perrysburg Formation, the Huron and the Cleveland Members of the Ohio Shale, and the Sunbury Shale—were deposited mainly in the western part of the basin These black shales thin to the south and merge into members of the black Chattanooga Shale of central Tennessee The Rhinestreet is designated a bed in the Dowelltown Member of the Chattanooga The Huron and the Cleveland Members of the Ohio Shale are designated beds in the Gassaway Member, which is the upper member of the Chattanooga Shale of central Tennessee and adjacent southern Kentucky Locally, the Sunbury conodont fauna occurs in the upper parts of the Gassaway Member of the Chattanooga in southern Kentucky and contiguous Tennessee and of the Big Stone Gap Member of the Chattanooga Shale in southwestern Virginia

The subsurface stratigraphic framework delineated in this report will enable explorationists to identify specific black gas shales in much of the Appalachian basin Coupled with detailed sample logs and suites of wire-line electric logs, our data will aid in defining and delimiting areas of greater potential gas productivity within any of the gas shales

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LOCALITY REGISTER

LOCALITY REGISTER

Wells and outcrops used in stratigraphic cross sections (pls 2–11) Numbers are keyed to index map (pl 1) and the cross sections

	EXPLANATION	SAMPLE
Number	County, State	7 Pike County, Ohio
	Quadrangle, township, town, district, section	Seal Township, Section 13
	Company	Continental Oil Co
	Well number and lease owner	No 1 Clarence Anderson
	Total depth, elevation	TD 1,441, Elev 696 kb
	State drilling permit number	Permit No 24
	API identification number	API No 34–13–06001
	(Reference)	

Depth and elevation in feet TD, total depth in feet Elevation (Elev) of well site above sea level in feet measured at the kelley bushing (kb), derrick floor (df), or ground level (gl), datum of reference not available for some wells (dna) Location, in feet, measured from latitude and longitude or from section or lot line Feet from the south line (FSL), the north line (FNL), the west line (FWL), and the east line (FEL) 8–A–62 is a location in section 8 of 5-minute rectangle A north and 62 east of the Carter Coordinate location system used in Kentucky and Tennessee API number is the American Petroleum Institute's unique well identification number Geo-Log is a sample study produced by the Geological Sample Log Company

1 Scott County, Tenn
8–A–62
Howard Atha
No 1 Ketchen Coal Co
TD 7,533, Elev 1,779 kb

2 Owsley County, Ky
22–L–69
Bowman
No 1 Hale
TD 1,442, TD 980 kb

3 Rowan County, Ky
Interstate I–64, outcrop section
(Provo and others, 1977)

4 Rowan County, Ky
4–T–75
Pennzoil
No 1 Jones
TD 4,491, Elev 1,199 kb

5 Carter County, Ky
3–V–77
United Fuel Gas Co
No 1 Stamper
TD 5,080, Elev 857 kb

6 Adams County, Ohio
Tener Mountain, outcrop section
(Provo and others, 1977)

7 Pike County, Ohio
Seal Township, Section 13
Continental Oil Co
No 1 Clarence Anderson
TD 1,441, Elev 696 kb
Permit No 24
API No 34–131–06001

8 Ross County, Ohio
Section 9
Hall and Coffman
No 1 Coffman
TD 3,809, Elev 735 gl
(Geo-Log)

9 Licking County, Ohio
Union Township
Burrell Petroleum Co
No 1 Garland Adams
TD 4,214, Elev 1,076 df, 1,074 gl

10 Licking County, Ohio
Hartford Township
W H Patten Drilling Co
No 1 F W Canaday
Elev 1,165 dna
(Geo-Log)

11 Richland County, Ohio
Troy Township, Section 34
Hadson Ohio Oil Co
No 1 Tony D, Augustine
TD 4,400, Elev 1,300 gl, 1,209 kb
Permit No 323

12 Richland County, Ohio
Butler Township, Section 30
Ashland Oil and Refining Co
No 1 Mast-Johnson Unit
TD 4,525, Elev 1,142 kb
Permit No 389
API No 34–139-00094

13 Ashland County, Ohio
Ruggles Township
Ohio Oil Co
No 1 S V Krause
TD 5,252, Elev 1,114 gl
(Fettke, 1961)

14 Lorain County, Ohio
Grafton Township
Central Oil Field Supply
No 1 R E Toole
TD 2,653, Elev 866 kb
Permit No 910
API No 34–093–00021

15 Medina County, Ohio
Brunswick Township
Natol Corp

No 2 Gilbert E Fuller
TD 3,335
Permit No 1,312

16 Geauga County, Ohio
Auburn Township, Section 3
East Ohio Gas Co -Quaker State Oil and Refining Corp
No 1 R and E Timmons
TD 4,110, Elev 1,216 gl
Permit No 26
API No 34-055-04004

17 Ashtabula County, Ohio
Windsor Township
Northern Natural Gas Producing Co
No 1 Clayton Clark "D"
TD 3,970, Elev 1,064 kb
Permit No 103

18 Ashtabula County, Ohio
New Lyme Township
Texaco, Inc (Russell McConnell, Inc)
No 1 Raymond and Vera L Kaderly
TD 6,367, Elev 1,053 6 kb
Permit No 214

19 Crawford County, Pa
Conneaut Township
Lake Shore Pipe Line Co
No 1 Hart
TD 3,772, Elev 1,117 gl
API No 37-039-00250

20 Crawford County, Pa
Girard Quadrangle I 376
James Drilling Co
C Z Clements
TD 4,093, Elev 1,258 gl
API No 37-039-00060

21 Erie County, Pa
Cambridge Springs Quadrangle, Washington Township
Redfern and Herd, Inc
J Vanco
TD 4,103, Elev 1,463 gl
API No 37-049-00543

22 Erie County, Pa
Northeast Quadrangle, Venango Township
Consolidated Gas Supply Corp
No N-988 B Dennee
TD 7,465, Elev 1,463 gl
API No 37-049-00569

23 Chautauqua County, N Y
Mina Township
Apache Corp -Hica Corp
No 1 H Carnahan
Elev 1,489 df
API No 31-013-19100

24 Chautauqua County, N Y
Pomfret Township
Flint Oil and Gas Co
No 1 Lyle H Bennett
Elev 755 gl
API No 31-013-04128

25 Chautauqua County, N Y
Sheridan Township
Rich and Blodgett
No 1 Howard Yonkers
TD 1,447, Elev 875 gl
API No 31-013-19101
(Tesmer, 1957, p 5-7)

26 Chautauqua County, N Y
Arkwright Township
Meridian Exploration Corp
No 4 Houck
Elev 1,240 gl
API No 31-013-04030

27 Cattaraugus County, N Y
Perrysburg Township
Iroquois Gas Corp
Thomasett
API No 31-009-04033

28 Erie County, N Y
Concord Township
Iroquois Gas Corp
No 796
TD 2,908, Elev 1,560 gl
API No 31-029-00506
(Fettke, 1961)

29 Erie County, N Y
Concord Township
Consolidated Gas Supply Corp
No 1 Edwin P Heary
Elev 1,647 kb
API No 31-029-11439

30 Wyoming County, N Y
Middlebury Township
Transamerican Petroleum Corp
No 1 Wellman
Elev 1,605 gl
API No 31-121-00003

31 Knox County, Ky
Petroleum Exploration Co
No 2 A Carnes
TD 5,335, Elev 1,050 gl
API No 16-121-04001

32 Perry County, Ky
Kentucky-West Virginia Gas Co
No 7239 Nicholas Combs
TD 2,734, Elev 1,090 kb
API No 16-193-28982

33 Floyd County, Ky
Signal Oil and Gas Co

No 1 Hall Heirs
TD 13,000
API No 16–017–04042

34 Martin County, Ky
Columbia Gas Transmission Corp
No 20336
TD 3,457, Elev 944 kb
API No 16–159–31020

35 Lincoln County, Ky
Laurel Hill District
Columbia Gas Transmission Corp
No 20403
TD 4,080, Elev 1,202 kb
Permit Lincoln No 1637
API No 47–043–06008

36 Mason County, W Va
Hannan District
United Fuel Gas Co
No 8995–T W F Johnson
TD 4,370, Elev 874 df
Permit Mason No 71
API No 47–053–00038

37 Jackson County, W Va
Union District
Commonwealth Gas Corp
No 1–822 Eastern Star
TD 5,200, Elev 789 kb
Permit Jackson No 1275
API No 47–035–04082

38 Wood County, W Va
Harris District
United Fuel Gas Co
No 9559–T Alton Phillips
TD 6,115, Elev 793 kb
Permit Wood No 594
API No 47–107–04004

39 Wood County, W Va
Walker District
Phillips Petroleum Co
No A–1–P 5175 Hope
TD 6,499, Elev 970 kb, 950 gl
Permit Wood No 518

40 Ritchie County, W Va
Grant District
Adena Petroleum, Inc
No 1 Lester Metz
TD 5,400, Elev 832 kb
Permit No Ritchie No 3242
API No 47–085–00001

41 Wetzel County, W Va
Church District
Smith Oil and Gas Co
No 1 Charles Stoneking
Elev 1,056 gl
Permit Wetzel No 410
API No 47–103–06001

42 Greene County, Pa
Waynesburg Quadrangle, E2, Franklin Township
J A Fox and others
No 1 Gordon
TD 8,659, Elev 1,395 gl, 1,405 kb
Permit Greene No 38
API No 37–059–00004

43 Washington County, Pa
Brownsville Quadrangle, D2, West Pike Run Township
Snee and Eberly, Peoples Natural Gas Co
No 1 Duane Duvall
TD 8,500, Elev 1,270 gl, 1,285 kb
Permit Washington No 173
API No 37–125–20173

44 Westmoreland County, Pa
Greensburg Quadrangle, A3, Franklin Township
Fox-Coen and Sloan
No 1 F H Sloan
TD 7,418
API No 37–129–00078

45 Westmoreland County, Pa
Freeport Quadrangle, H1, Washington Township
Peoples Natural Gas Co
No 1 Sloan
TD 7,108, Elev 1,222 kb
Permit Washington No 422
API No 37–129–00079

46 Armstrong County, Pa
Elders Ridge Quadrangle, D47
Peoples Natural Gas Co
No 43 Heasley
TD 7,450, Elev 1,969 df
Permit Armstrong No 1594
API No 37–005–04104

47 Armstrong County, Pa
Rural Valley Quadrangle, E4
Peoples Natural Gas Co
No 1 Martin
TD 15,574, Elev 1,480 kb
Permit Armstrong No 1201
API No 37–005–04017

48 Clarion County, Pa
Clarion Quadrangle, D6
Fairman Drilling Co
No 1 H Ausler
TD 5,825, Elev 1,270 gl
Permit Clarion No 247
API No 37–031–00006

49 Clarion County, Pa
Oil City Quadrangle
Linn and Patrick (Amoco)

No 1 Dunn-UNG
Elev 1,624 gl
API No 37–031–04024

50 Forest County, Pa
Sheffield Quadrangle, G5, Kingsley Township
E Linn and Patrick Petroleum Co
No 1 Collins and Clinger
Elev 1,609 gl
Permit Forest No 898
API No 37–053–04112

51 Warren County, Pa
Tidioute Quadrangle, A5
P H Benedum
No 1 Dusenbury
Elev 1,714 gl
Permit Warren No 257
API No 37–123–20257

52 Warren County, Pa
Warren Quadrangle, F9
Thornton Co
No 1 Lindbloom
Elev 2,019 gl
API No 37–123–00044

53 Warren County, Pa
Kinzua Quadrangle, A15
Felmont Oil Co
No F–180, No 1 Collins
Elev 1,689 gl
Permit Warren No 982
API No 37–123–00003

54 McKean County, Pa
Kinzua Quadrangle, A16
Pennzoil United Inc
No 1 W C Kenwanee
Elev 1,474 gl
Permit Warren No 7520
API No 37–083–27520

55 Cattaraugus County, N Y
New Albion Township
Humble Oil and Refining
No 1 D Heron
Elev 1,832 df
Permit Cattaraugus No 4153
API No 31–009–00093

56 Wise County, Va
Columbia Gas Transmission Corp
No 20118–T Pennsylvania-Virginia Corp
Elev 3,464 dna
API No 45–195–20178

57 Buchanan County, Va
Columbia Gas Transmission Corp
No 9781–T Pittston Coal Co
Elev 1,580 dna
API No 45–027–04041

58 McDowell County, W Va
Consolidated Gas Supply Corp
No P–618 Rose L Dennis
Elev 1,370 dna
API No 47–047–04165

59 Mingo County, W Va
United Fuel Gas Co
No 9416 Mingo and Wyoming Land Co
Elev 1,556 dna
API No 47–059–00001

60 Boone County, W Va
Consolidated Gas Supply Co
No 1021 Federal Coal Co
Elev 1,299 dna
API No 47–005–04008

61 Fayette County, W Va
Columbia Gas Transmission Corp
No 9793 Kanawha Gauley Coke and Coal Co
Elev 1,085 dna
API No 47–019–04041

62 Gilmer County, W Va
Westrans Petroleum Inc
No 1–1978 William J Mohr Heirs
Elev 959 dna
API No 47–021–06001

63 Lewis County, W Va
Freemans Creek District
Allegheny Land and Mineral Co
No A–455 Alfred Woofer
Elev 1,160 kb
Permit Lewis No 1864
API No 47–041–04189

64 Marion County, W Va
Phillips Petroleum Co
No 312–1 Ronald Robe
Elev 1,774 dna
API No 47–049–20312

65 Preston County W Va
United Fuels Producers Funds, Inc
No 137–1 George F Guthrie
Elev 1,982 dna
API No 47–077–00040

66 Somerset County, Pa
Shell Oil Co
No 1 R D Shumaker
Elev 2,494 dna
API No 37–111–00005

67 Somerset County, Pa
Winber Quadrangle, Quemahoning Township
Felmont Oil Corp and Peoples Natural Gas Co
No 1 (Ser F–146) Robert F Henninger
Elev 2,018 gl, 2,031 kb
API No 37–111–00004

68 Cambria County, Pa
Johnstown Quadrangle, H10

Pennzoil United
No 1 F W Heidingsfelder
Elev 2,232 kb
Permit No 13
API No 37–021–00017

69 Cambria County, Pa
Johnstown Quadrangle, C12
Peoples Natural Gas Co
No 4611 W Griffith
Elev 2,026 gl, 2,040 kb
Permit No 17

70 Cambria County, Pa
Patton Quadrangle, B1
Peoples Natural Gas Co
No 1–4361 H Leiden
Elev 1,913 kb
Permit No 3
API No 37–021–00007

71 Clearfield County, Pa
Houtzdale Quadrangle, D1
New York State Natural Gas Corp
No N–808 Mid Penn Coal Co
Elev 1,580 kb
Permit No 356
API No 37–033–00332

72 Clearfield County, Pa
Houtzdale Quadrangle, B4, Boggs Township
Manufacturers Light and Heat Co
No 1–4729 Haupt Heirs
TD 7,810, Elev 1,679 kb
Permit No 371
SPI No 37–033–00011

73 Clearfield County, Pa
New York State Natural Gas Corp
No 1 Clearfield Trust Co
Elev 1,437 dna
API No 37–033–20354

74 Potter County, Pa
Renovo West Quadrangle, C202
Consolidated Gas Supply Corp
No N–972 Pennsylvania Department of Fish and Waters
Elev 1,870 kb
API No 37–105–20182

75 Tioga County, Pa
Elkland Quadrangle, B36
New York State Natural Gas Corp
No 1 Linder
Elev 1,918 dna
API No 37–117–20017

76 Chemung County, N Y
Rio Oil, Inc
No 1 Richards
TD 4,126, Elev 1,243 df
API No 31–015–00003

77 Chemung County, N Y
Veteran Township
Rio Oil, Inc
No 1 Stephen Boor
TD 3,311, Elev 1,526 gl, 1,529 df
API No 31–015–00001

78 Tompkins County, N Y
Enfield Township
New York State Natural Gas Corp
No 1 Grund
TD 8,903, Elev 1,454 gl, 1,457 df
API No 31–109–00077

79 Cattaraugus County, N Y
Freedom Township
Columbia Gas Transmission Corp
No 20221T Robert J and Minnie Edmunds
Elev 1,744 gl, 1,756 kb
API No 31–009–11478

80 Allegany County, N Y
Hume Township
New York State Natural Gas Corp
No 1 D A Wolfer
TD 7,560, Elev 1,560 gl, 1,573 kb

81 Allegany County, N Y
Almond Township
New York State Natural Gas Corp
No 6213 Eastern Gas Shales Program, New York
Elev 1,840 gl, 1,853 kb

82 Steuben County, N Y
Howard Township
J V Pizza
No 1 Richardson Farm
API No 31–101–10880

83 Steuben County, N Y
Campbell Township
Richard W Harding and others
No 1 G D Scudder
TD 3,445, Elev 1,438 gl, 1,441 df
API No 31–101–00008

84 Mercer County, Pa
Shenango Quadrangle, A7, West Salem Township
Bert Fields
No 1 Lihan
TD 4,792, Elev 1,165 gl
API No 37–085–00024

85 Mercer County, Pa
Pymatuming Township
Melben Oil Co
No 1 Emma McKnight
TD 8,211, Elev 960 kb
API No 37–085–00021
(Wagner, 1958)

86 Mercer County, Pa
Stoneboro Quadrangle, I10
United Natural Gas Co

No 1 J V Johnson
TD 6,140, Elev 1,587 gl
API No 37–085–00012

87 Jefferson County, Pa
Punxsutawney Township, A62
Consolidated Gas Supply Corp
No 1 J I Zeedick
TD 7,429, Elev 1,539 gl

88 Ashland County, Ohio
Lake Township
Roy Stewart
No 1 Kenneth and Rex Masher
TD 5,480
Permit Ashland No 1762

89 Wayne County, Ohio
Paint Township
Management Central Corp
No 1 John L Cramer
API No 34–169–04096

90 Stark County, Ohio
Sandy Township
Texaco, Inc
No 1 William Rarrie
Elev 1,035 gl, 1,045 kb
Permit Stark No 2001

91 Carroll County, Ohio
Lee Township
East Ohio Gas Co
No 3265 Raymond M and Clara L Goddard
Elev 1,284 gl, 1,294 kb
API No 34–019–20901

92 Hancock County, W Va
Clay District
Humble Oil and Refining Co
No 1 Minesinger
TD 10,387, Elev 1,039 gl, 1,052 kb

93 Allegheny County, Pa
Forward Township
C E Power Systems
No 1 Fee
Elev 759 gl, 769 kb

94 Westmoreland County, Pa
Donegal Quadrangle, Mt Pleasant Township
Felmont Oil Corp
No 1 C E Heibal
Elev 1,495 gl, 1,506 kb
API No 37–129–00017

95 Bedford County, Pa
Phillips Petroleum Company
No 1 Penn Tract 26–B
Elev 2,394 gl, 2,409 kb
API No 37–009–00032

96 Perry County, Ohio
Hopewell Township
Irvine Producing Co
No 1 Lawrence and Delpha Mitchell
TD 2,940, Elev 808 df
Permit Perry No 2839
API No 34–127–06001

97 Perry County, Ohio
Harrison Township
Quaker State Oil Refining Corp
No 1 D W and M J Potts
TD 3,549, Elev 795 gl, 797 df
Permit Perry No 2597
API No 34–127–060012

98 Morgan County, Ohio
Morgan Township
Ohio Fuel Gas Co
No 1 Benjamin F Hammond
TD 4,898, Elev 1,041 kb
Permit Morgan No 1203
API No 34–115–04020

99 Morgan County, Ohio
Center Township
Texaco, Inc
No 12 Delbert McMannis Unit
TD 3,870, Elev 892 gl
Permit Morgan No 1282
API No 34–115–04162

100 Washington County, Ohio
Adams Township
Berry Holding Co
No 1 Cecil F Offenberger
TD 6,095, Elev 949 kb
Permit Washington No 3272
API No 34–167–04009

101 Pleasants County, W Va
Grant District
Commonwealth Gas Corp
No 1 William C Kerns and others
Elev 1,085 kb
Permit Pleasants No 667

102 Ross County, Ohio
Twin and Paxton Townships
Copperas Mountain Section
(Kepferle and Roen, 1981, p 294)

103 Scioto County, Ohio
Valley Township, Section 5
Continental Oil Company
No 1 Shisler
TD 1,075, Elev 531 kb
Permit Scioto No 194

104 Scioto County, Ohio
Green Township
U S S Chemical Division
No 1 Fee
TD 5,607, Elev 557 kb
Permit Scioto No 212
API No 34–145–06001

105 Boyd County, Ky
22–W–82
Inland Gas Co
No 537 C E Fannin Estate
TD 7,800, Elev 709 kb
106 Wayne County, W Va
Butler District—2 88 mi S 38°07′, 2 24 mi W 82°30′
Columbia Gas Transmission Corp
No 20060–T Fee
TD 3,598, Elev 647 kb
Permit Wayne No 1576
API No 47–099–21578
107 Lawrence County, Ky
10–S–83
Columbia Gas Transmission Corp
No 9557 Fieger
TD 4,037, Elev 802 df
API No 16–127–04023
108 Martin County, Ky
19–Q–84
United Fuel Gas Co
No 8610–T Jasper James and others
TD 13,172, Elev 659 kb
API No 16–159–00001
109 Pike County, Ky
3–K–87
Columbia Gas Transmission Corp
No 9697 Kentland Coal and Coke Co
TD 4,944, Elev 1,293 df
API No 16–195–04060
110 Buchanan County, Va
450 ft S 37°10′, 4,900 ft W 82°07′30″
Columbia Gas Transmission Corp
No 9722–T J W Pobst
TD 7,296, Elev 1,683 kb
API No 45–027–04032
111 Scott County, Va
6,400 ft S 36°40′, 4,500 ft E 82°20′
Tidewater Oil Co and Wolf's Head Oil Co
No 1 E D Smith
TD 7,222, Elev 1,468 kb
112 Scott County Va
Duffield Quadrangle, 13–C–81, 1,900 FNL, 1,200 FWL, Duffield Section
(Kepferle and Roen, 1981, p 308)
113 Hawkins County, Tenn
Kyles Ford Quadrangle, 21–A–78E, 1,600 FSL, 0 FEL, Little War Gap Section
(Kepferle and Roen, 1981, p 307)
114 Hawkins County, Tenn
Pressemens Home Quadrangle (now Camelot Quadrangle)—761,500 N , 2,855,050 E
Tennessee Division of Geology
Anthony Lucas Property
No 4 Core Hole, Eastern Gas Shales Project
TD 1,525 1, Elev 1,245 gl
API No 41–073–1002
115 Hawkins County, Tenn
Pressmens Home Quadrangle (now Camelot Quadrangle)—759,000 N , 2,855,900 E
Tennessee Division of Geology
Anthony Lucas Property
No 5 Core Hole, Eastern Gas Shales Project
TD 275, Elev 1,350 gl
API No 41–073–1001
116 Grainger County, Tenn
Bean Station Quadrangle—724,300 N , 2,783,400 E
Tennessee Division of Geology
No 8 Core Hole, Eastern Gas Shales Project
TD 915 6, Elev 1,080 gl
API No 41–057–1003
117 Grainger County, Tenn
Avondale Quadrangle—710,300 N , 2,762,000 E
Gury Federal
No 9 Core Hole, Eastern Gas Shales Project
TD 1,920, Elev 1,140 gl
118 Grainger County, Tenn
Joppa Quadrangle—682,500 N , 2,700,950 E
Tennessee Division of Geology
David Wilson Property
No 6 Core Hole, Eastern Gas Shales Project
TD 486 0, Elev 970+ gl
API No 41–057–1001
119 Campbell County, Tenn
Jacksboro Quadrangle—1,800 FSL, 2,100 FWL
Geo, Inc
No 2 Geo-Lindasy Land Company
Elev 1,660 gl, 1,678 kb
120 Roane County, Tenn
Harriman Quadrangle, 1–8S–59E—700 FNL, 3,200 FEL, Emory Gap Section
(Kepferle and Roen, 1981, p 301)
121 Bledsoe County, Tenn
Melvine Quadrangle, 9–10S–54E—1,100 FSL, 150 FEL, Lowe Gap Section
(Kepferle and Roen, 1981, p 296)
122 Bledsoe County, Tenn
Pikeville Quadrangle, 5–12S–53E—5,300 FSL, 1,000 FWL, Pikeville Section
(Kepferle and Roen, 1981, p 296)
123 Claiborne County, Tenn
Howard Quarter Quadrangle—767,150 N , 2,756,500 E
Tennessee Division of Geology
Fred Pearson Farm
No 1 Core Hole, Eastern Gas Shales Project
TD 254 0, Elev 1,100 gl
API No 41–025–6001

124 Hancock County, Tenn
Sneedville Quadrangle—803,150 N , 2,836,050 E
Tennessee Division of Geology
Calver Johnson Property
No 3 Core Hole, Eastern Gas Shales Project
API No 41–067–1001

125 Wise County, Va
Appalachia and Big Stone Gap Quadrangles, 12–E–81 E—3,100 FSL, 110 FWL, Big Stone Gap Section
(Kepferle and Roen, 1981, p 308–310)

126 Wise County, Va
Flat Gap Quadrangle, Gladeville Township
Columbia Gas Transmission Corp
No, 20338 Pennsylvania-Virginia Corp
TD 5,734, Elev 2,395 47 gl

127 De Kalb County, Tenn
Sligo Bridge Quadrangle, 8–7S–46E—700 FSL, 1,900 FWL, Sligo Bridge Section
(Kepferle and Roen, 1981, p 270)

128 De Kalb County, Tenn
Center Hill Dam Quadrangle, 20–6S–45E—200 FNL, 400 FWL, Hurricane Bridge Section
(Kepferle and Roen, 1981, p 272)

129 Clay County, Tenn
Dale Hollow Dam Quadrangle, 11–A–9E—1,900 FSL, 2,000 FEL, Pleasant Grove Section
(Kepferle and Roen, 1981, p 275)

130 Cumberland County, Ky
Burkesville Quadrangle, 21–D–50E—700 FNL, 1,400 FWL, Burkesville Section
(Kepferle and Roen, 1981, p 277)

131 Russell County, Ky
Creelsboro Quadrangle, 2–E–52E—1,800 FNL, 300 FWL, Creelsboro Section
(Kepferle and Roen, 1981, p 278)

132 Pulaski County, Ky
Delmer Quadrangle, 19–11–58E—3,200 FSL, 2,250 FEL, Ringgold Road Section
(Kepferle and Roen, 1981, p 279)

133 Madison County, Ky
Berea Quadrangle, 7–M–63E—575 FNL, 600 FWL, Berea Section
(Kepferle and Roen, 1981, p 281)

134 Estill County, Ky
Panola Quadrangle, 13–0–66E—1,900 FSL, 100 FEL, Good Shepherd Baptist Church Section
(Kepferle and Roen, 1981, p 283)

135 Powell County, Ky
Clay City Quadrangle, 12–Q–67E—925 FSL, 900 FWL, Clay City Section
(Kepferle and Roen, 1981, p 284)

136 Lewis County, Ky
Vanceburg Quadrangle, 25–Z–75E—700 FNL, 2,300 FEL, Vanceburg Section
(Kepferle and Roen, 1981, p 290)

Chapter C

New Albany Shale (Devonian and Mississippian) of the Illinois Basin

By NANCY R. HASENMUELLER

U.S. GEOLOGICAL SURVEY BULLETIN 1909
PETROLEUM GEOLOGY OF THE DEVONIAN AND MISSISSIPPIAN BLACK SHALE OF EASTERN NORTH AMERICA

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PLATE

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FIGURES

New Albany Shale (Devonian and Mississippian) of the Illinois Basin

By Nancy R. Hasenmueller[1]

Abstract

The New Albany Shale (Middle Devonian to Early Mississippian) is present in the Illinois basin areas of Illinois, Indiana, and western Kentucky, where it consists predominantly of brownish-black and greenish-gray shales Generally, the brownish-black shale is characterized by high concentrations of organic material, trace elements, and pyrite and is laminated The greenish-gray shale has low concentrations of organic material, trace elements, and pyrite and is bioturbated In addition to these two dominant lithologies, the New Albany contains lesser amounts of sandstone, siltstone, limestone, dolomite, and phosphate

In Illinois, the New Albany Shale is assigned group status, and, in Indiana and western Kentucky, the New Albany is regarded as a formation On the basis of variations in lithology, the New Albany is divided in the subsurface into formations in Illinois and members in Indiana and Kentucky

The New Albany attains a maximum thickness of more than 460 feet in the southern part of the Illinois basin in southeastern Illinois and adjacent Kentucky In this area of thick New Albany, the dominant lithology is brownish-black shale The shale thins toward the basin margins except in west-central Illinois, where bioturbated, greenish-gray shale more than 300 feet thick is present The two areas of thick New Albany are separated by a northeastward-southwestward-trending area of thinner shale in Illinois This band of thinner shale extends eastward into west-central Indiana

The distribution of the brownish-black and the greenish-gray shales indicates deposition in a stratified deep-water basin that is centered in southeastern Illinois and western Kentucky The development of a stratified water column, abundant organic material, and a slow rate of clastic sedimentation were necessary for preservation of high concentrations of organic material Bioturbated, greenish-gray shales reflect a slightly better oxygenated, but low-energy, environment Higher energy, aerobic, near-shore environments had only a limited distribution and are restricted to west-central Illinois

Brownish-black shale lithologies in the lower and the upper parts of the New Albany Shale have large amounts of organic carbon The greatest concentrations of organic carbon are in the upper part of the New Albany in southeastern Indiana and west-central Kentucky, where organic-carbon content is 12 to 13 percent by weight Limited data from the deeper part of the basin indicate that this interval contains 8 to 11 percent organic carbon The organic-carbon content of greenish-gray shale is low, commonly 1 to 2 percent by weight

INTRODUCTION

Although Devonian shales are an important source of natural gas in the Appalachian basin, gas has been produced only on a limited basis from the New Albany Shale in the Illinois basin in Indiana and western Kentucky In this basin, the brownish-black, organic-rich shales are probable source beds for younger Mississippian and Pennsylvanian oil pools, as well as underlying Silurian and Devonian pools (Stevenson and Dickerson, 1969, Barrows and Cluff, 1984), and someday may become a source of synthetic fuels in areas of southeastern Indiana and west-central Kentucky

In the last decade, the hydrocarbon potential of the New Albany has resulted in detailed studies that pertain to the stratigraphy, structure, petrography, composition, and physical properties of the shale and their relation to production of gas These studies were undertaken by the Illinois, Indiana, and Kentucky Geological Surveys as part of the Eastern Gas Shales Project (EGSP) and were supported in part by the Morgantown Energy Technology Center of the U S Department of Energy (DOE) Later, additional studies, which were partly funded by the DOE, were conducted to discern whether the shale near the outcrop area in southeastern Indiana and west-central Kentucky was a potential source of synthetic oil

This chapter provides information relating to the stratigraphy of the shale in the Illinois basin and summarizes the stratigraphic interpretations made by the Illinois, Indiana, and Kentucky Geological Surveys in the EGSP final reports (Bergstrom and others, 1980, Lineback, 1980, Schwalb and Norris, 1980e, Hasenmueller and Bassett,

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1981) and in other publications that resulted from the EGSP (Barrows and others, 1979, Cluff and others, 1981) It also includes information from several studies of the oil potential of the shale in Indiana and Kentucky (Beard, 1980, Hasenmueller, 1982, Robl and others, 1983, Hasenmueller and Leininger, 1987)

STRATIGRAPHY

General Discussion

The name "New Albany Black Slate" was first used by Borden (1874) for brownish-black shale exposed along the Ohio River at New Albany, Ind The New Albany consists predominantly of organic-rich, brownish-black and organic-poor, greenish-gray shale and is present in the subsurface throughout much of the Illinois basin in Illinois, southwestern Indiana, and western Kentucky (fig 1) Much of the brownish-black shale is characterized by high concentrations of organic material, trace elements, and pyrite The fauna is limited, and fossils are predominantly nektonic and planktonic The greenish-gray shale has low concentrations of organic material, trace elements, and pyrite The fauna is somewhat more diverse than that of the brownish-black shale In addition to these two dominant lithologies, the New Albany contains lesser amounts of sandstone, siltstone, limestone, dolomite, and phosphate beds The New Albany ranges in age from Middle Devonian to Early Mississippian, although most of the shale is Late Devonian in age

In Indiana and western Kentucky, the New Albany Shale is recognized as a formation In Illinois, it is given group status and is subdivided into nine formations (Lineback, 1980, Cluff and others, 1981) In ascending order, the formations are the Blocher Shale, the Sylamore Sandstone, the Selmier Shale, the Sweetland Creek Shale, the Grassy Creek Shale, the Saverton Shale, the Louisiana Limestone, the Horton Creek Formation, and the Hannibal Shale (fig 2)

In southeastern Indiana, the New Albany Shale has been divided on the basis of lithology into five members (Lineback, 1968) In ascending order, they are the Blocher, the Selmier, the Morgan Trail, the Camp Run, and the Clegg Creek Members (fig 2) These members also are recognized in Bullitt County in west-central Kentucky (Lineback, 1970, Beard, 1980) A sixth member, the Ellsworth Member, is composed of greenish-gray and interbedded, greenish-gray and brownish-black shales and has been recognized in the subsurface in the northern part of the Illinois basin in Indiana (Lineback, 1970) and in parts of central and southwestern Indiana (fig 2, Hasenmueller and Bassett, 1981)

In western Kentucky, the New Albany is divided into three members, which are, in ascending order, the Blocher Member, the Selmier Member, and the Grassy Creek Member (fig 2) A shale interval equivalent to the Saverton and the Hannibal Shales of Illinois is recognized in limited areas in the subsurface of western Kentucky, but it is not considered to be a part of the New Albany in Kentucky (Schwalb and Norris, 1980e) Rather, it is considered to be a lateral equivalent of the lower part of the New Providence Shale (Dever and McGrain, 1969)

The New Albany reaches its maximum thickness of more than 460 feet (ft) in an area in the southern part of the Illinois basin 20 miles (mi) south of the junction of the Wabash and the Ohio Rivers (fig 3) Thick New Albany extends eastward in Kentucky along the Moorman Syncline, a structure that was active during deposition of the shale (Schwalb and Norris, 1980e) The area of thick shale in the southern part of the basin represents the depositional center of the ancestral Illinois basin during the Middle and the Late Devonian, and, in this area, laminated, brownish-black shale is the dominant lithology A second depositional center is in southeastern Iowa and west-central Illinois, where thicknesses of more than 300 ft of bioturbated, greenish- and olive-gray shales are reported in Henderson and Hancock Counties (Lineback, 1980) The two depositional centers are separated by a northeastward-southwestward-trending area of thinner shale that extends eastward into west-central Indiana

In southeastern Illinois, southwestern Indiana, and western Kentucky, the New Albany conformably overlies Middle Devonian carbonate rocks Westward in Illinois, the lowest unit of the New Albany, the Blocher Shale, grades laterally into the argillaceous limestone, dolomite, and shale of the Lingle and the Alto Formations In areas where the Blocher is not present in Illinois, the Sylamore Sandstone marks the base of the New Albany, which unconformably overlaps Middle Devonian to Late Ordovician strata Eastward and northward in Indiana, the New Albany paraconformably overlies the Muscatatuck Group (Middle Devonian) In west-central Kentucky, the New Albany unconformably overlies strata ranging in age from Middle Devonian to Late Ordovician

Throughout much of the Illinois basin, the New Albany interval is overlain conformably by Mississippian strata In most of southern, central, and eastern Illinois, the New Albany is conformably overlain by the Chouteau Limestone of Kinderhookian age The Rockford Limestone, which is Kinderhookian and Valmeyeran in age, conformably overlies the New Albany in most areas in the subsurface of Indiana The Rockford is absent, however, along the Indiana-Illinois State line, in southern Indiana, and in other localized areas (Hasenmueller and Bassett, 1981) In areas where the Rockford is absent, the New Albany is directly overlain by greenish-gray shale that constitutes the deep-water bottomset beds of the Borden delta (Lineback, 1966) In Illinois, this shale is named the "Springville Shale," and, in Indiana and Kentucky, it is named the "New Providence Shale "

Figure 1. Locations of the wells in Illinois, Indiana, and western Kentucky that are used in stratigraphic cross sections and that penetrate the New Albany Shale (Group).

In extreme western Illinois, the McCraney Limestone conformably overlies the uppermost unit of the New Albany in this area, the Hannibal Shale (fig. 2). Across most of western Illinois, the New Albany and the Chouteau have been erosionally truncated and are overlain by strata of Valmeyeran age. The northern limit of the New Albany in

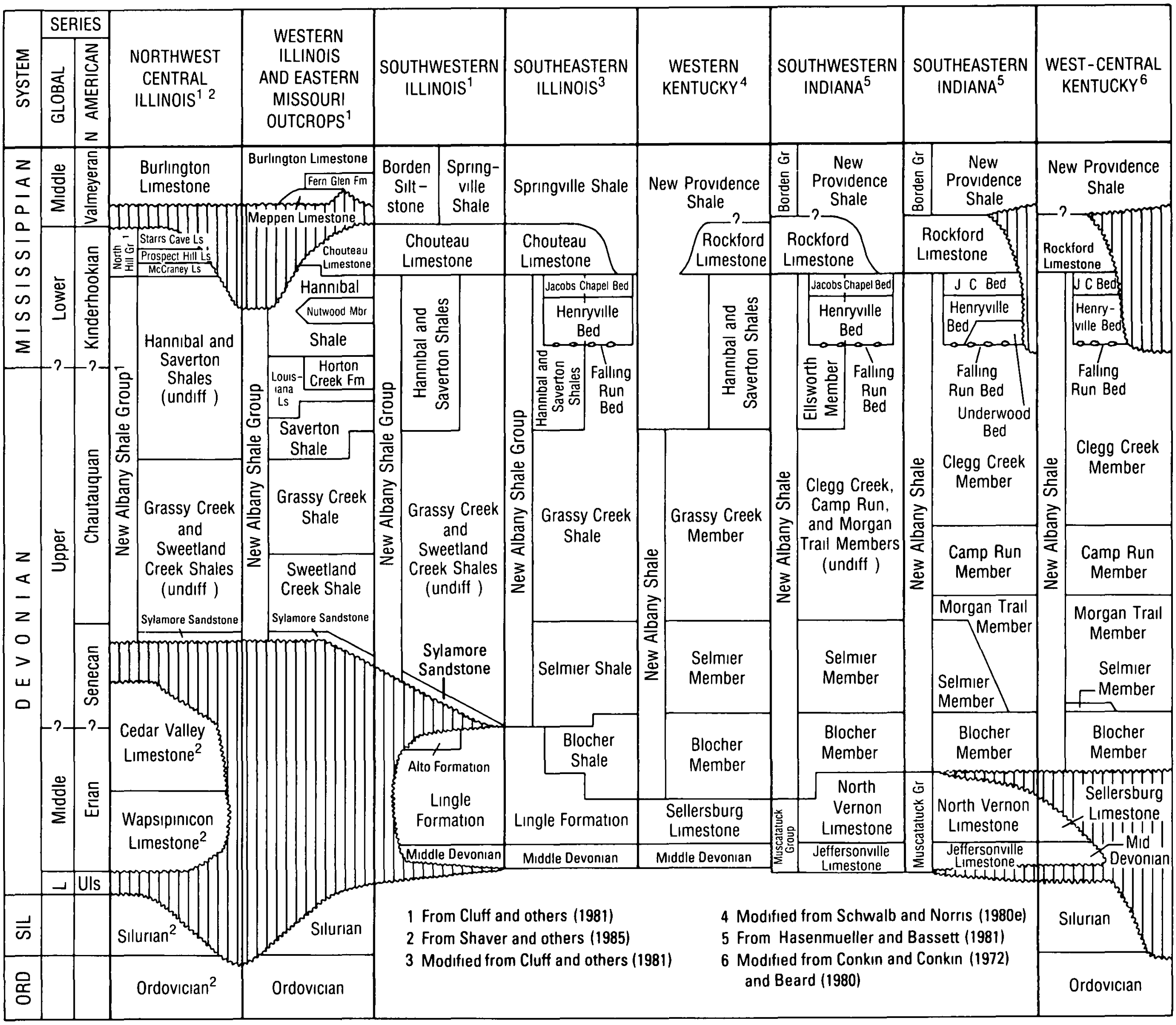

Figure 2. Correlation of the New Albany Shale (Group) in the Illinois basin

Illinois is in an area where it has been erosionally truncated and is overlain by Pennsylvanian strata (Cluff and others, 1981)

In limited areas of northwestern Kentucky, the New Albany is overlain by the Saverton and the Hannibal Shales Where these shale units and the overlying Rockford Limestone are absent, the New Albany is overlain by the New Providence Shale (Schwalb and Norris, 1980a) Generally, in west-central Kentucky, the New Albany is overlain by the New Providence Shale, but, in parts of Jefferson County and in Bullitt County, the New Albany is overlain by the Rockford Limestone (Conkin and Conkin, 1972, 1975, Kepferle, 1974)

Blocher Member (Blocher Shale in Illinois)

The name "Blocher Formation" was first used by Campbell (1946) for the basal unit of the New Albany Shale in Jefferson County, Ind , near Blocher The unit was later reduced in rank to member status by Lineback (1968) The Blocher is predominantly a finely laminated, organic-rich, calcareous, brownish- to grayish-black shale but contains a few thin beds of greenish-gray shale, fine-grained limestone, dolomite, calcareous quartz sandstone, and phosphatic sandstone The Blocher is distinct in that it is the only brownish-black shale unit that contains much calcite The carbonate is present as silt-sized rhombohedral grains,

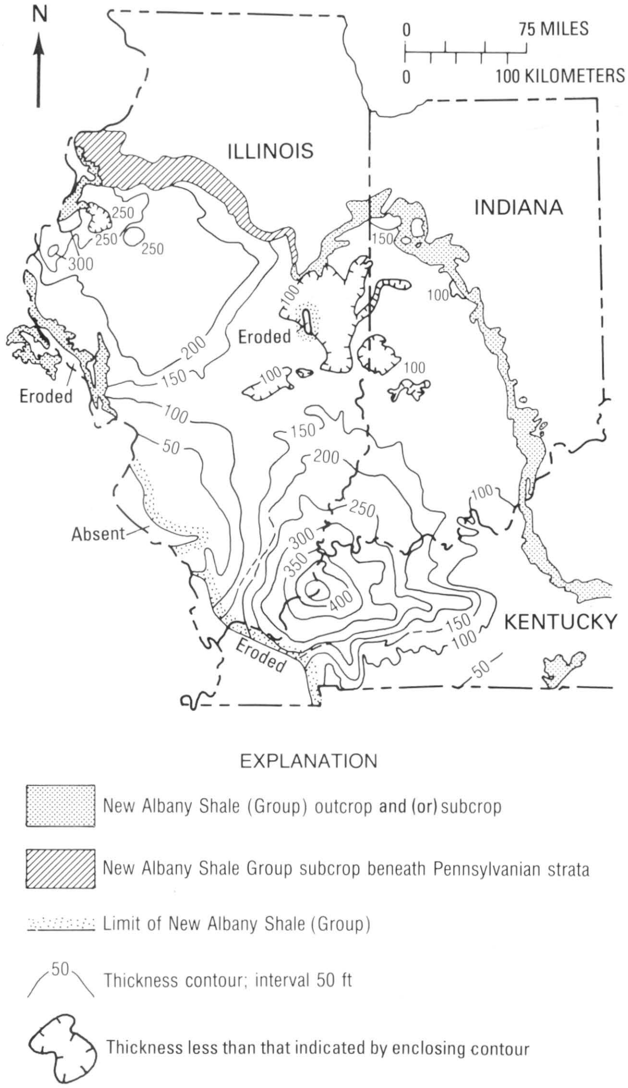

Figure 3. Thickness of the New Albany Shale (Group) in the Illinois basin. (Modified from Lineback, 1980.)

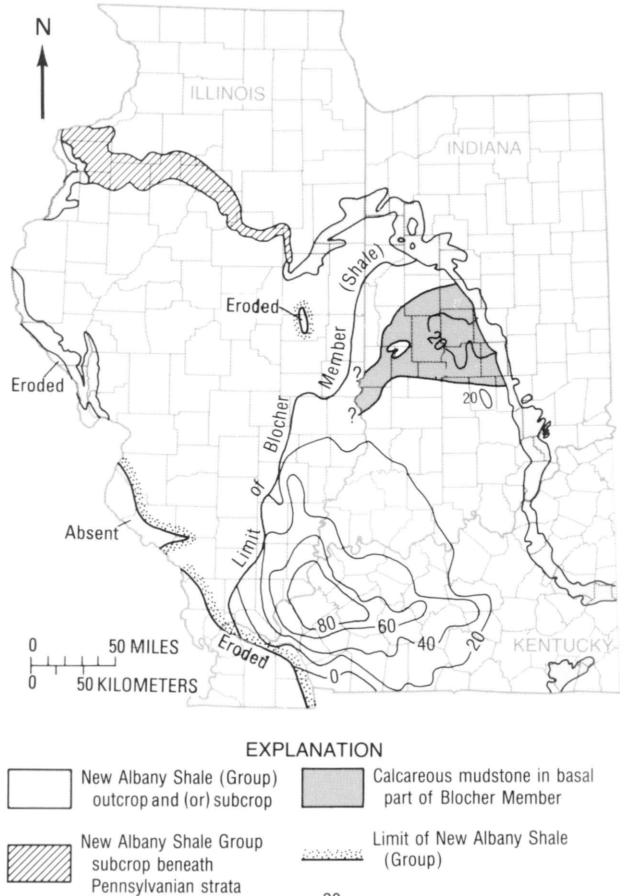

Figure 4. Thickness of the Blocher Member (Shale) in the Illinois basin. (Modified from Lineback, 1980.)

which are randomly distributed in the shale and concentrated in numerous laminae (Lineback, 1970). Small pyrite nodules and disseminated pyrite are associated with the carbonate in the laminae. The basal part of the Blocher in the outcrop area of southeastern Indiana contains the greatest concentrations of randomly distributed carbonate grains. Dark-grayish-brown carbonate concretions are also present in the lower part of this member in the outcrop area.

A thin phosphatic sandstone bed or bone bed at the base of the Blocher contains quartz, phosphatic nodules, rock fragments, fish bones and teeth, and conodonts and has been traced throughout much of southeastern Indiana. This basal bed contains abundant pyrite and marks the beginning of renewed sedimentation in a transgressive sequence (Pickering, 1979).

In central Indiana, a laminated, calcareous, dark-gray-brown mudstone occurs in the basal part of the Blocher. This relatively different mudstone lithology is vertically gradational into the calcareous, brownish-black shale of the Blocher.

The moderately high concentrations of carbonate minerals and the low concentrations of radioactive elements in the Blocher impart distinctive geophysical characteristics that make it possible to trace the unit from the type area in southeastern Indiana into the deeper part of the Illinois basin (pl. 1). The Blocher that is delineated on geophysical logs includes the entire calcareous brownish-black shale interval and is not restricted to the more calcareous interval at the base of the Blocher as proposed by Cluff and others (1981). In the deeper part of the Illinois basin, the restricted black shale interval of the Blocher as mapped by Cluff and others (1981) is basically equivalent to the interval mapped by Hasenmueller and Bassett (1981), but the restricted Blocher is not recognized as far to the north in Illinois as the Blocher is in Indiana (fig. 4).

In Indiana, the Blocher ranges in thickness from less than 5 ft along the outcrop belt in southeastern Indiana to 67 ft in the subsurface of Posey County in southwestern Indiana (fig. 4; Hasenmueller and Bassett, 1981). The Blocher reaches a maximum thickness of more than 80 ft in Hardin County in southeastern Illinois and in adjacent areas of western Kentucky (Lineback, 1980). The unit thins eastward in Kentucky, but it is recognized in the outcrop area of the New Albany in west-central Kentucky (Lineback, 1970; Beard, 1980).

The Blocher has not been strongly bioturbated, and fossils present are interpreted as being planktonic and nektonic. Conodonts, fish debris, *Tasmanites*, *Styliolina*, *Tentaculites*, linguloid brachiopods, and small calcareous brachiopods (*Leiorhynchus* and *Chonetes*) have been reported (Lineback, 1970). The occurrence of *Tentaculites* and *Styliolina* in the New Albany is limited to the Blocher, and that these fossils commonly have a preferred orientation in carbonate layers in the lower part of the unit indicates the existence of bottom currents during Blocher time (Lineback, 1968). Conodonts indicate that the Blocher is mostly Middle Devonian in age, although some beds are earliest Late Devonian (Collinson and others, 1967).

Sylamore Sandstone

The Sylamore Sandstone, which is named for Sylamore Creek in Stone County, Ark. (Penrose, 1891), is the basal formation of the New Albany Shale Group in central and western Illinois. Typically, the Sylamore consists of subrounded to rounded fine to medium quartz sand cemented with calcite, dolomite, or pyrite. In places, the matrix is silty or shaly and is commonly phosphatized. Phosphatic nodules, conodonts, fish teeth, and phosphatic brachiopods are common, and the bed is bioturbated in most areas (Cluff and others, 1981).

The sandstone is a continuous thin sheet in western and central Illinois (fig. 5), where it is rarely more than 5 ft thick and is generally only a few inches thick (Workman and Gillette, 1956). The thickness of the interval was not mapped by Cluff and others (1981) because the sandstone is commonly too thin to be recognized except in cores. In areas where closely spaced cores are available, the thickness of the sandstone is variable over short distances.

In western and central Illinois, the Sylamore unconformably rests on carbonate rocks ranging from Late Ordovician to Middle Devonian in age (Collinson and Atherton, 1975). Evidence is lacking to determine whether the unconformity represents a period of subaerial exposure or submarine nondeposition (Cluff and others, 1981). The sandstone grades upward into the Sweetland Creek Shale or the Sweetland Creek and Grassy Creek Shales undifferentiated. Because these overlying shales become younger northward and westward in Illinois, the subjacent Sylamore is interpreted as a time-transgressive unit (Cluff and others, 1981).

Figure 5. Distribution of the Sylamore Sandstone (shaded area) in Illinois. (From Lineback, 1980.)

Conodonts from the Sylamore are indicative of an early Late Devonian age. The Sylamore has been tentatively correlated with thin sandy beds in the upper part of the Blocher or the lower part of the Selmier Shale (Sweetland Creek) in southeastern Illinois (Collinson and others, 1967). Thin quartz sandstone beds at the base of the Selmier in southeastern Indiana may be correlative with the Sylamore (Hasenmueller and Bassett, 1981).

Selmier Member (Selmier Shale in Illinois)

The name "Selmier Member" of the New Albany Shale was first applied by Lineback (1968) to the greenish-gray shale that overlies the Blocher Member near the

Selmier State Forest in Jennings County, Ind. The shales of the Selmier have been traced from the outcrop area in southeastern Indiana into the subsurface of southwesternmost Indiana (Hasenmueller and Bassett, 1980b). The name "Selmier" for equivalent beds has been extended into southeastern Illinois, where it is ranked as a formation in the New Albany Shale Group, and into western Kentucky, where it is ranked as a member of the New Albany (Lineback, 1980). In Illinois, this interval had been assigned to the Sweetland Creek Shale by Collinson and others (1967), but, because the Sweetland Creek Shale of western Illinois is, at least in part, stratigraphically higher than the Selmier, the use of the name "Sweetland Creek" now is restricted to areas to the north and the west of the deeper parts of the basin (Reinbold and others, 1980). The Sweetland Creek is separated from the Selmier by an arbitrary vertical cutoff (fig. 6). The name "Selmier" also is applied to thin beds of greenish-gray shale in the outcrop area in west-central Kentucky (Lineback, 1970; Beard, 1980).

In the outcrop area in southeastern Indiana, the Selmier consists of greenish- to olive-gray shale and thin

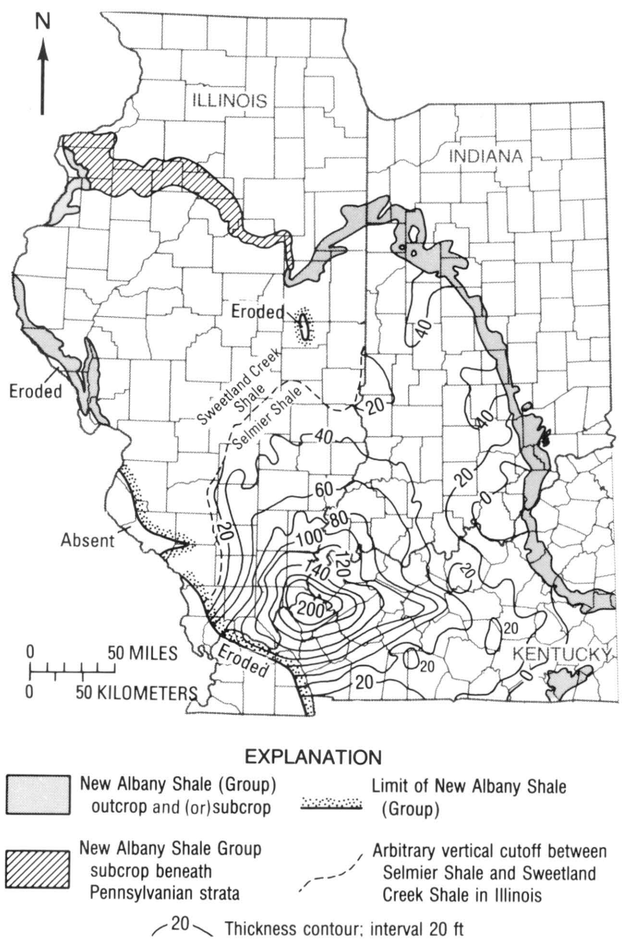

Figure 6. Thickness of the Selmier Member (Shale) in the Illinois basin. (Modified from Lineback, 1980.)

beds of olive-black shale, dolomite, and quartzose sandstone. At the type section, brownish-gray to olive-black shale beds are near the base of the member. In addition to numerous carbonate laminae, thin beds of concretions and large isolated septarian concretions composed of ferroan dolomite have been reported at several exposures (Lineback, 1970; Hasenmueller and others, 1983b).

In the deeper part of the Illinois basin in southwestern Indiana and southeastern Illinois, the Selmier generally contains greater concentrations of organic carbon and is darker in color than it is in the outcrop area. In cores from southeastern Illinois, the Selmier consists of alternating beds of brownish-black, grayish-black, and dark-greenish- to olive-gray shales and mudstone. The dark shales generally are poorly laminated and contain small burrows; the dark-greenish- to olive-gray shales are indistinctly bedded and commonly are burrowed (Cluff and others, 1981).

The Selmier is not recognized in most of Harrison, Floyd, and Clark Counties in southeastern Indiana (fig. 6; pl. 1). To the north, the Selmier thickens to more than 40 ft in central Indiana; this northward thickening appears to be partly the result of a facies relation with the overlying brownish-black shale of the Morgan Trail Member. In northwestern Indiana, the Selmier includes some shale that is assigned to the Sweetland Creek in adjacent Illinois. The Selmier thickens to the southwest in Indiana and is 126 ft thick in Posey County.

The maximum thickness of the Selmier (Sweetland Creek) that was mapped in northwestern Kentucky by Schwalb and Norris (1980c) was 170 ft; however, the thickness of the member in Kentucky was revised by Lineback (1980) to conform with the thickness of the shale mapped in southeastern Illinois, where the Selmier is more than 200 ft thick in places. The Selmier thins to 20 ft in central Illinois, where it is arbitrarily separated from the Sweetland Creek Shale (fig. 6).

In the outcrop area in Indiana, the Selmier is extensively burrowed, and the trace fossils *Chondrites*, *Zoophycos*, and *Planolites* have been identified. Conodonts, *Tasmanites*, *Callixylon*, and ammonoid anaptychi (Hasenmueller and others, 1983b), as well as a few gastropods and pelecypods (Lineback, 1970), are also present in the Selmier. The conodonts from the Selmier indicate a Late Devonian age (*to*I to *to*II; Collinson and others, 1967).

Sweetland Creek Shale

The name "Sweetland Creek beds" originally was used to describe the Devonian greenish-gray and brownish-black shales overlying the Cedar Valley Limestone along Sweetland Creek in southeastern Iowa (Udden, 1899). Collinson and others (1967) proposed that the name "Sweetland Creek Shale" be restricted to the greenish-gray shale and that the overlying brownish-black shale at the type section be assigned to the Grassy Creek. They extended the use of the name "Sweetland Creek" eastward in the Illinois basin, but Cluff and others (1981) restricted the use of the name to the western and the northern parts of Illinois.

The two dominant lithofacies of the Sweetland Creek Shale in Illinois are indistinctly bedded, bioturbated, greenish-gray to grayish-green shale and thickly laminated, olive-gray to olive-black shale that has a few burrows. Pronounced interbedding of greenish-gray and olive-black shales characterizes the Sweetland Creek. The bottom contact of each bed of laminated, olive-black shale is sharp, but the top contact is burrowed. The burrows are filled with lighter colored shale and extend only a few inches into the olive-black shale. The shallow depth of the burrows indicates that the olive-black sediment was relatively toxic to burrowing organisms. The trace fossils *Zoophycos*, *Planolites*, *Teichichmus*, and *Chondrites* commonly are found at the interface where greenish-gray shale beds overlie olive-black shale beds (Cluff and others, 1981).

The Sweetland Creek Shale is recognized as a distinct formation principally in the subsurface of central Illinois and in parts of southwestern Illinois. Strata equivalent to the Sweetland Creek are present in western and north-central Illinois, but, in these areas, the Sweetland Creek is not readily differentiated from the overlying Grassy Creek Shale.

On the basis of conodont faunas, an early to middle Late Devonian age (*to*I) has been assigned to the Sweetland Creek in the type area (Collinson and others, 1967); it is, therefore, of the same age as the Selmier Member in the outcrop area in southeastern Indiana. However, Cluff and others (1981) reported that, in the subsurface of northern and western Illinois, most of the Sweetland Creek is at a higher stratigraphic position and is, therefore, younger than the Selmier in the deeper part of basin and the Sweetland Creek at the type section. They suggested that the younger Sweetland Creek interval may have been included with the Grassy Creek at the type section by Collinson and others (1967) and that, although a thin interval of the Sweetland Creek might be equivalent to the upper part of the Selmier, most of the Sweetland Creek grades laterally into and is equivalent in age to the Grassy Creek Shale in southeastern Illinois. They concluded that the lack of data in northern and western Illinois makes it difficult to correlate the Sweetland Creek in the subsurface precisely with the Sweetland Creek type area, and they tentatively correlated the Sweetland Creek of western Illinois with the uppermost part of the Selmier Member, the entire Morgan Trail Member, and part of the Camp Run Member of Indiana.

Grassy Creek Shale (Grassy Creek Member in Kentucky)

The Grassy Creek Shale is named for Grassy Creek in Pike County, Mo. (Keyes, 1898), and, as currently defined by Collinson and Atherton (1975), includes the brownish-black shale interval of the middle and the upper parts of the New Albany Shale Group in Illinois (fig. 2). Originally, the formation was only recognized in the western part of the State; usage of the name was later extended into central and southwestern Illinois (Workman and Gillette, 1956) and into eastern Illinois (Collinson and others, 1967). The Grassy Creek is recognized in western Kentucky, where it is the uppermost member of the New Albany Shale.

In southern Illinois and western Kentucky, the Grassy Creek contains thinly laminated, pyritic, organic-rich, brownish- to gray-black shale. Northward in Illinois, the Grassy Creek grades into olive-black to olive-gray shale interbedded with grayish-olive- to grayish-green mudstone. Pyrite is common and occurs as fine crystals, framboids, thin lenses, and nodules of various sizes. The shale is thinly laminated and has closely spaced laminae composed of silt-sized quartz and feldspar cemented by carbonate and pyrite (Cluff and others, 1981). Little or no interparticle porosity is visible in thin sections. In western Illinois, the thin interbeds of greenish-gray shale may contain abundant small burrows; the brownish-black shales, however, are not burrowed.

The Falling Run, the Henryville, and the Jacobs Chapel Beds, which are lithologically and paleontologically distinct thin beds recognized near the top of the New Albany Shale in the outcrop area in southeastern Indiana, were identified at two unusual exposures in southeastern Illinois; consequently, use of these names has been extended into Illinois (Cluff and others, 1981). Only the Henryville Bed is thick enough to be recognized on geophysical logs, and the distribution of the bed has been mapped in Illinois and Indiana (fig. 7). These three beds overlie brownish-black shale in much of southeastern Illinois and are included in the Grassy Creek Shale. In some other areas, the beds overlie greenish-gray shale and are assigned to the undifferentiated Saverton and Hannibal Shales (Cluff and others, 1981).

The Grassy Creek reaches its maximum thickness of about 160 ft in Hardin County, Ill., and adjacent areas of Kentucky (fig. 8). The Grassy Creek gradually thins eastward to 30 ft in west-central Kentucky (Schwalb and Norris, 1980b). In northern and western Illinois, where the brownish-black shale of the Grassy Creek interfingers with the greenish-gray shale of the Sweetland Creek, the Grassy Creek is not differentiated from the Sweetland Creek. The undifferentiated interval has a maximum thickness of 140 ft in Warren and Henderson Counties (Cluff and others, 1981).

Fossils reported from the Grassy Creek are predominantly pelagic and include conodonts, skeletal fish debris, and inarticulate brachiopods. *Tasmanites* is common to abundant. The macrofauna of the Grassy Creek is sparse, and the conodont fauna is not well known (Collinson and others, 1967). Conodont faunas from the underlying Sweet-

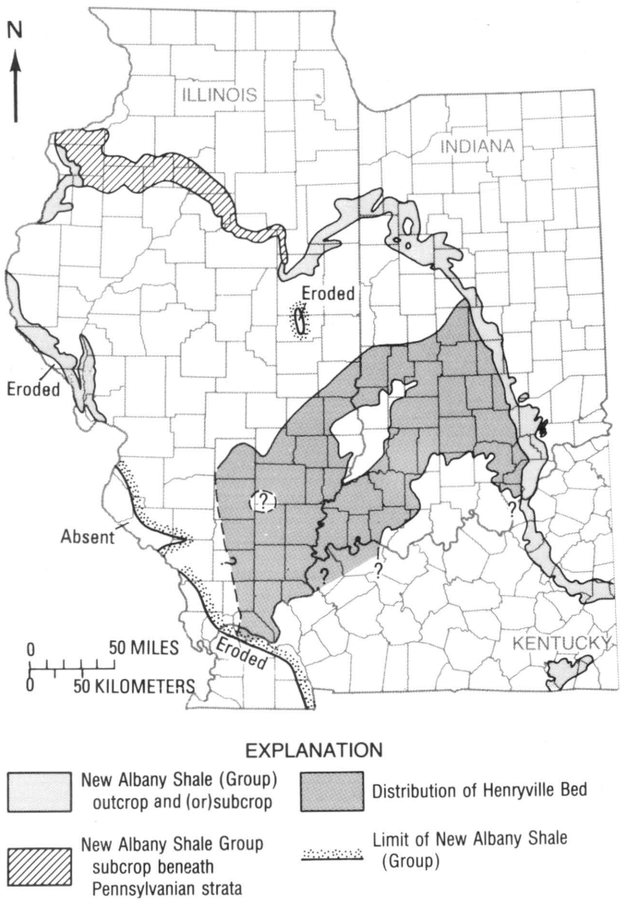

Figure 7. Distribution of the Henryville Bed in the Illinois basin. (Information on Illinois from Cluff and others, 1981.)

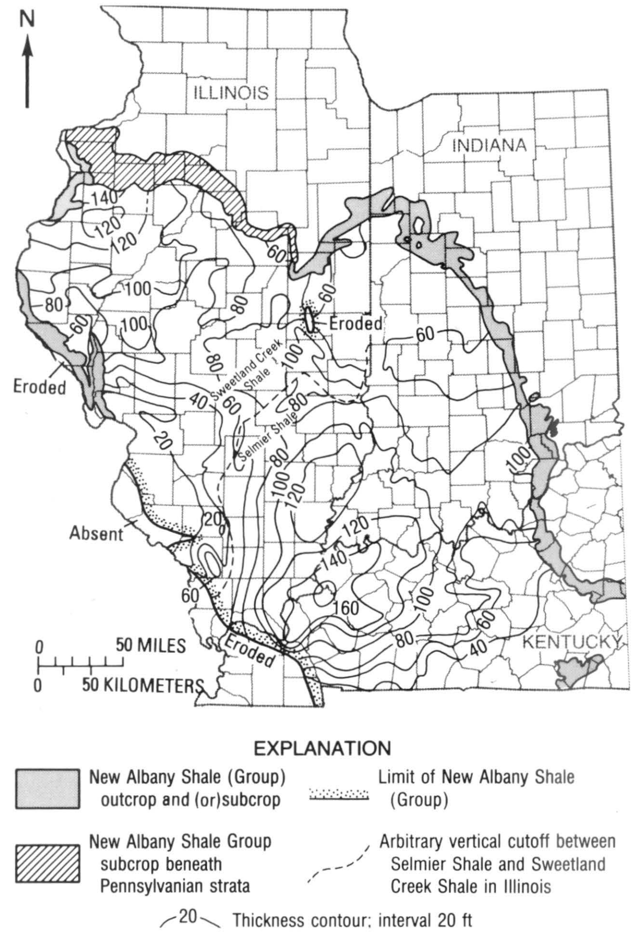

Figure 8. Thickness of the Grassy Creek Shale (Member) in Kentucky and east of the arbitrary vertical cutoff in Illinois; the thickness of the undifferentiated Morgan Trail, Camp Run, and Clegg Creek Members in Indiana; and the combined thickness of the Sweetland Creek and the Grassy Creek Shales west of the arbitrary vertical cutoff. (Modified from Lineback, 1980.)

land Creek and the overlying Saverton Shale in the type area indicate an early Late Devonian age (Collinson and others, 1962). The Grassy Creek of southeastern Illinois is probably equivalent to the Morgan Trail, the Camp Run, and the Clegg Creek Members of Indiana (fig. 2). The type Grassy Creek Shale of western Illinois represents a smaller interval of geologic time than the Grassy Creek of southeastern Illinois and is equivalent to the lower part of the Clegg Creek Member and perhaps the uppermost part of the Camp Run Member of Indiana (Cluff and others, 1981).

Morgan Trail, Camp Run, and Clegg Creek Members

In the outcrop area of the New Albany Shale in southeastern Indiana, three lithologically distinct members are differentiated above the Selmier Member (Lineback, 1968). In ascending order, these are the Morgan Trail, the Camp Run, and the Clegg Creek. These members are recognized in the outcrop area and in cores from the subsurface of southeastern Indiana and west-central Kentucky (Lineback, 1970; Beard, 1980; Robl and others, 1983). The members were not delineated in the subsurface by Hasenmueller and Bassett (1980a) but were mapped as an undifferentiated interval.

The undifferentiated interval, which is continuous with the Grassy Creek Shale (Member) of Illinois and western Kentucky, is 140 ft thick in the southernmost parts of Posey and Vanderburgh Counties in southwestern Indiana. This unit thins to about 60 ft in central and northern Indiana (fig. 8).

Morgan Trail Member

The Morgan Trail Member of the New Albany Shale was named for a roadside park near the type section, which is about 1.5 mi southeast of Blocher in Scott County, Ind. (Lineback, 1970). The Morgan Trail consists mainly of fissile, siliceous, brownish- to olive-black shale that has pyritic, calcareous laminae and beds, it may include a few thin beds of olive-gray shale. Thin, hard pyritic beds that are laterally persistent are characteristic of this member. In exposures, the shale is jointed. Linguloid brachiopods, conodonts, and silicified logs of the genus *Callixylon* are present but are generally rare in cores from the subsurface of southeastern Indiana. *Tasmanites* is locally common to abundant in the Morgan Trail, and some thin beds are composed predominantly of *Tasmanites*.

In the subsurface of Indiana, the Morgan Trail thins northward from 38 ft in northern Clark County to 7 ft in central Bartholomew County. The northward thinning appears, in part, to be the result of a facies relation with the underlying Selmier Member, which increases in thickness correspondingly. The Morgan Trail was not recognized in the subsurface because its lithology could not be readily differentiated from that of the overlying Camp Run Member on geophysical logs or in well cuttings.

Conodonts from the Morgan Trail have not been studied, but the member is presumed to be at about the same biostratigraphic position as Zone *to*II because the overlying Camp Run Member contains conodonts assignable to Zone *to*III (Lineback, 1970). The Morgan Trail Member is considered to be stratigraphically equivalent to the lower part of the Grassy Creek of Illinois and western Kentucky.

Camp Run Member

The type section of the Camp Run Member is on the southern side of Indiana Highway 311 at the Interstate Highway 65 overpass near Sellersburg in Clark County, Ind. (Lineback, 1968). The member consists of laminated, organic-rich, brownish-black shale interbedded with greenish- to olive-gray shale. The greenish-gray shale beds are bioturbated, and the upper contact of the underlying brownish-black shale beds commonly is burrowed. Carbonate laminae and bands are present in cores of the member from the subsurface, and dolomite concretions from 2 to 3 ft in diameter are found in the brownish-black shale beds at the type locality. *Tasmanites* is common to abundant, and linguloid brachiopods, conodonts, and carbonized plant remains are present, but rare, in cores of the Camp Run interval. Silicified *Callixylon* and a few small pyritized gastropods and pelecypods also were present (Lineback, 1970).

The thickness of the Camp Run is fairly uniform throughout the subsurface in southeastern Indiana, where it ranges from 24 to 28 ft (Hasenmueller, 1982). The greenish-gray shale beds range from 0.1 to about 1 ft in thickness, and the brownish-black shale beds range from 0.4 to 4.5 ft in thickness. The Camp Run Member is recognized in cores throughout central and southeastern Indiana; however, the interval is not differentiated on geophysical logs from wells in southwestern Indiana.

The Camp Run contains conodonts assignable to Zone *to*III (Lineback, 1970) and is correlated with part of the Grassy Creek of Illinois and western Kentucky (fig. 2).

Clegg Creek Member

The name "Clegg Creek," which is taken from a small stream of the same name, was proposed by Lineback (1968) for the uppermost member of the New Albany Shale in parts of Kentucky and Indiana. The section is exposed in a road cut 2 mi southeast of Henryville, Clark County, Ind., and approximately 2 mi downstream from the confluence of Clegg and Silver Creeks. The member is characterized by finely laminated, pyritic, brownish-black shale rich in organic material. The unit contains more quartz silt and less dolomite than the lower members of the New Albany (Lineback, 1970). In southeastern Indiana, the member contains intervals of carbonate laminae and large concretions as much as 3 ft in diameter and 1 ft in thickness. The brownish-black shale of the Clegg Creek is well jointed in outcrop.

In Jackson, Scott, and northern Clark Counties, the Clegg Creek is about 40 ft in thickness. The member thins southward from Clark County to 22 ft in Harrison County; this thinning is in the upper part of the member (Hasenmueller and others, 1983b). The Clegg Creek has not been mapped as a distinct unit throughout the subsurface of southwestern Indiana, but the interval has been recognized in cores from Sullivan, Greene, and Dubois Counties and on geophysical logs (pl. 1).

Although fossils are sparse in the brownish-black shale of the Clegg Creek, linguloid brachiopods, conodonts, *Tasmanites*, *Callixylon*, and *Protosalvinia* (*Foerstia*) have been found and are locally common. Articulate and inarticulate brachiopods, arthropods, fish remains, plant fossils, gastropods, pelecypods, conodonts, and scolecodonts have been reported from several lithologically distinct beds in the upper few feet of the member (Lineback, 1968).

A bed of greenish-gray shale 7.5 ft below the top of the Clegg Creek in northeastern Jackson County contains no conodonts but has been correlated with the Louisiana Limestone of western Illinois on the basis of the brachiopod fauna (Lineback, 1970). The Louisiana contains conodonts assigned to Zone *to*VI (Collinson, 1961). Thus, Zones *to*IV and *to*V are presumed to be represented by the lower part of the Clegg Creek. Conodont faunas indicate that the uppermost beds of the Clegg Creek are equivalent to the Hannibal Shale of western Illinois and Missouri (Lineback, 1970). Physical correlations indicate that the Morgan Trail-Camp Run-Clegg Creek interval of Indiana subsurface usage is equivalent to the Grassy Creek of southeastern Illinois (Hasenmueller and Bassett, 1980c; Lineback, 1980).

The recognition of the exact position of the *Protosalvinia*-bearing interval in the Clegg Creek Member in Indiana and in west-central Kentucky has facilitated correlation of the Devonian shales of the Illinois basin with those of the Appalachian basin The position of the *Protosalvinia* interval in the Clegg Creek indicates that the member is equivalent to part of the Huron Member, the Three Lick Bed, and the Cleveland Member of the Ohio Shale of the Appalachian basin (Kepferle, 1981, Hasenmueller and others, 1983a) Although *Protosalvinia* has not been recognized in Illinois, it has been found as far west as Sullivan County, Ind , and is likely to be present in southeastern Illinois

Falling Run Bed

The Falling Run was named by Campbell (1946), who designated the type section on Falling Run Creek in New Albany, Floyd County, Ind The bed is 0 2 ft thick and consists of sparsely fossiliferous, phosphatic nodules and phosphatic debris Throughout most of southern Indiana, the greenish-gray shale of the overlying Underwood Bed is not present, and the Henryville Bed rests directly on the Falling Run (fig 2) In the outcrop area and the subsurface in southeastern Indiana, the Falling Run Bed has been traced from Floyd County as far north as Jackson County Phosphate nodules are present at the same stratigraphic position in a core from Dubois County in southwestern Indiana The bed has been recognized in southeastern Illinois (Cluff and others, 1981) and Bullitt County in west-central Kentucky (Lineback, 1970, Conkin and Conkin, 1975) The nodules contain a fauna of inarticulate brachiopods and arthropods, a diverse flora of terrestrial plant debris, and abundant *Tasmanites* cysts The matrix contains fragmented inarticulate brachiopods and conodonts, the fragmented nature of the fossil debris indicates that it may be coprolitic in origin (Maliva, 1984) Although no conclusive evidence has been found, the Falling Run is considered to be earliest Mississippian in age (Lineback, 1970)

Underwood Bed

The Underwood originally was named "Underwood Formation" by Campbell (1946) The bed is recognized only in the immediate vicinity of the type section, which is 2 mi southeast of Underwood, Clark County, Ind , where it overlies the Falling Run Bed and underlies the Henryville Bed The Underwood consists of fossiliferous, greenish-gray shale and is 0 4 ft thick It contains a conodont and scolecodont fauna of Kinderhookian age and is the lowest bed of proved Mississippian age in the New Albany Shale On the basis of a conodont fauna indicative of the *Siphonodella sulcata* Assemblage Zone, the Underwood is correlated with the lower part of the Hannibal Shale of Missouri and Illinois (Lineback, 1970)

Henryville Bed

The name "Henryville" was used by Campbell (1946) for shale exposed along the bank of Lodge Creek (mistakenly identified as Caney Fork Creek by Campbell), 1 5 mi southwest of Henryville, Clark County, Ind The Henryville consists of fissile black shale that has high concentrations of organic matter and trace elements (Lechler and others, 1979) The bed is 0 4 to 1 7 ft thick in the outcrop area in southeastern Indiana and reaches a maximum of 4 ft in the subsurface Throughout much of southeastern Indiana, the Henryville is overlain by the greenish-gray shale of the Jacobs Chapel Bed and is underlain by the Falling Run Bed The Henryville is recognized in the subsurface as far north as Hendricks County in central Indiana and is present in Posey County in southwestern Indiana (fig 7) In a core from Dubois County, Ind , the Henryville is present and is underlain by phosphatic nodules of the Falling Run Bed The upper few inches of the Henryville commonly contains horizontal burrows filled with greenish-gray shale These burrows were made after the Henryville was deposited when more oxygenated conditions existed during the deposition of the overlying Jacobs Chapel The Henryville contains a conodont fauna similar to that found in the middle part of the Hannibal Shale of Missouri and western Illinois and is of Kinderhookian age (Lineback, 1970)

In southeastern Indiana, the Henryville and the Falling Run Beds cannot always be differentiated on geophysical logs from the rest of the underlying brownish-black shale of the Clegg Creek Member, and, in this area, the beds are part of the Clegg Creek In areas of southwestern Indiana, however, where the Henryville overlies the greenish-gray shale of the Ellsworth Member, the bed can be recognized on geophysical logs and is part of the Ellsworth (pl 1) The bed is recognized in the subsurface of Illinois (Cluff and others, 1981) It was not reported from the subsurface of western Kentucky but was recognized in Bullitt County in west-central Kentucky (Lineback, 1970, Conkin and Conkin, 1975)

Jacobs Chapel Bed

The name "Jacobs Chapel" was used by Campbell (1946) for soft, sparsely fossiliferous, glauconitic, greenish-gray shale exposed in the banks of Lewis Branch near Jacobs Chapel Church in Floyd County, Ind The Jacobs Chapel is the uppermost bed of the New Albany Shale

In the outcrop area in much of Scott, Clark, and Floyd Counties, the bed is 0 2 to 0 6 ft thick In the subsurface of southeastern Indiana, the Jacobs Chapel has been recognized in cores, however, it is too thin to be recognized on geophysical logs The bed was recognized in southeastern Illinois by Cluff and others (1981), and use of the name "Jacobs Chapel Bed" has been extended into that part of Illinois Although the Jacobs Chapel has not been reported in the subsurface of westernmost Kentucky, the bed is possibly present but too thin to be recognized. In west-central Kentucky, the Jacobs Chapel is present in southern Jefferson and northern Bullitt Counties (Conkin and Conkin, 1972, 1975). Conodonts from the Jacobs Chapel indicate that the bed correlates with the middle and the upper parts of the Hannibal Shale of the Mississippi Valley area (Rexroad, 1969).

Saverton Shale

The name "Saverton Shale" was used by Keyes (1912a, b) to describe gray shale lying above the Grassy Creek Shale and below the Louisiana Limestone. A specific type section was not designated by Keyes, but an exposure in the bluffs of the Mississippi River near Louisiana, Pike County, Mo., was later designated the type locality (Mehl, 1960). In the outcrop area, the Saverton is a bluish- to greenish-gray silty shale that contains thin sandstone beds and carbonate beds.

Cluff and others (1981) recognized lower and upper parts of the Saverton in the subsurface of Illinois. The lower part consists of greenish-gray shale interbedded with olive-black shale. Generally, the interbedding becomes thicker and less distinct upward in the section. The greenish-gray beds are nonlaminated, silty, organic poor, and commonly extensively bioturbated. The olive-black beds are laminated and less silty, and the amount of organic material varies from one lamina to the next. The upper part of the Saverton consists of massive, greenish-gray, bioturbated mudstones. These beds are generally unfossiliferous and contain less than 1 percent organic carbon.

In parts of western Illinois, the Saverton is overlain by the Louisiana Limestone or the Horton Creek Formation. In areas where these formations are absent, it is not possible to differentiate the shale of the Saverton from the greenish-gray shale of the overlying Hannibal Shale. Cluff and others (1981) mapped the combined thickness of the Saverton Shale, the Louisiana Limestone, the Horton Creek Formation, and the Hannibal Shale. The maximum thickness of these formations is more than 180 ft in Hancock County in western Illinois (fig. 9). In western and central Illinois, the Saverton is recognized as a distinct formation. In the northernmost part of this area, the Saverton reaches a maximum thickness of 120 ft; to the south and east, the interval thins.

Because the Saverton grades into the underlying and overlying formations, regional correlations are difficult (Cluff and others, 1981). Throughout its extent the Saverton conformably overlies the Grassy Creek, and, eastward and southward in Illinois, it grades laterally into the brownish-black shale of the Grassy Creek. In much of west-central Illinois, the Saverton is overlain by the Louisiana Limestone, but, where the Louisiana is absent, the Saverton and

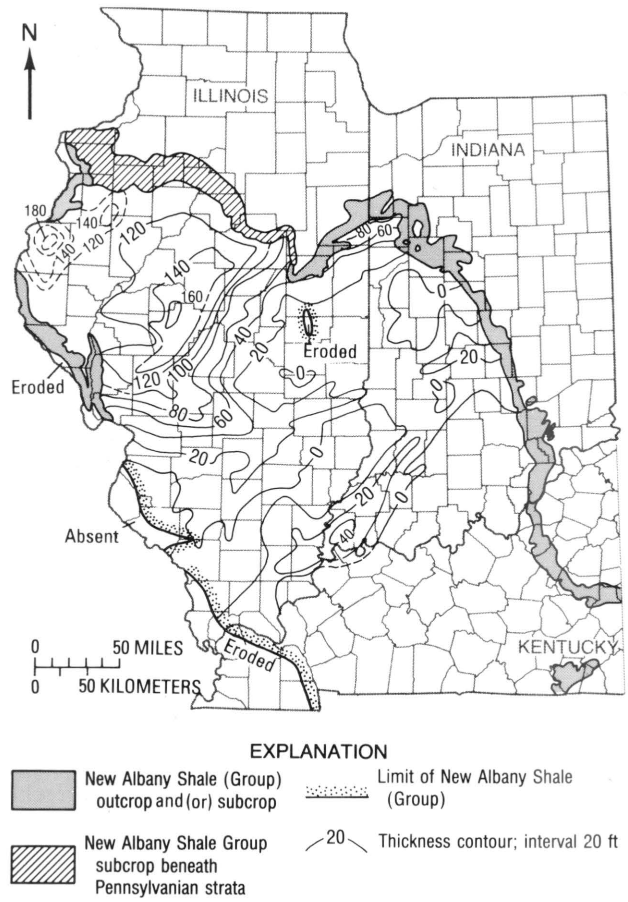

Figure 9. Thickness of the Saverton Shale, the Louisiana Limestone, the Horton Creek Formation, and the Hannibal Shale in Illinois; the Saverton and the Hannibal Shales in western Kentucky; and the Ellsworth Member in Indiana. (Modified from Lineback, 1980.)

the Horton Creek are not differentiated (pl. 1). In areas where the Louisiana and the Horton Creek are absent, the Saverton cannot be differentiated from the Hannibal.

Conodont faunas from the Saverton range from Zones *to*III through *to*IV (uppermost Devonian). On that basis, the Saverton is partly equivalent to the Louisiana Limestone, which is also latest Devonian in age. The basal part of the Saverton becomes younger to the south and the east where the Saverton grades into the Grassy Creek. The Saverton has been correlated with the Clegg Creek Member of Indiana by Collinson and others (1967).

Louisiana Limestone

The name "Louisiana Limestone" (Keyes, 1892) is taken from Louisiana in Pike County, Mo., where the limestone is exposed in the bluffs of the Mississippi River. At this exposure, the Louisiana is underlain by the Saverton Shale and overlain by the Hannibal Shale. The Louisiana is light-gray to tan micritic limestone that contains thin beds of shale and dolomite. In the areas where the limestone crops out, it is a very pure, texturally homogenous carbonate. In the subsurface, the Louisiana is commonly a fine-grained, micritic limestone, but, in many places, it is argillaceous and extensively burrowed (Cluff and others, 1981).

The Louisiana Limestone crops out in the Illinois and the Mississippi River valleys in northeastern Missouri and westernmost Illinois (Williams, 1943). In the subsurface, the Louisiana is present as a narrow band extending from central Iowa into west-central Illinois (Scott and Collinson, 1961). By using geophysical logs and well samples, Cluff and others (1981) found that the limestone was more extensive in the subsurface than was previously mapped. The maximum thickness of the Louisiana in Illinois is about 30 ft near the Mississippi River in Pike and Calhoun Counties. To the east, the Louisiana is less than 10 ft thick. Physical correlations suggest that the thin Louisiana in the subsurface is equivalent to only the middle part of the thicker Louisiana along the Mississippi River (Cluff and others, 1981).

The Louisiana conformably overlies and grades laterally into the Saverton Shale, except in a few areas in Jersey and Madison Counties where the Saverton is either absent or too thin to be recognized. In this area, the Louisiana directly overlies the Grassy Creek Shale. In much of western Illinois, the Louisiana is unconformably overlain by the Horton Creek Formation, but studies of conodont faunas indicate that the hiatus between Louisiana and Horton Creek deposition was short (Collinson and Atherton, 1975). In the subsurface of Illinois, Cluff and others (1981) found no evidence of a significant unconformity. Along the Mississippi, near the type area, the Louisiana is overlain by the Hannibal Shale.

Although they are nowhere abundant, a large variety of macrofossils, many of which are small or dwarfed individuals, are found in the Louisiana (Williams, 1943). The Louisiana contains a conodont fauna of latest Devonian age and correlates with Zones *to*V and *to*VI of European zonation (Collinson and others, 1967). The Louisiana Limestone has been correlated with the upper part of the Clegg Creek Member of the New Albany Shale in Indiana (Lineback, 1970).

Horton Creek Formation

The name "Horton Creek" Formation was introduced by Conkin and Conkin (1973) for strata in western Illinois previously included in the "Glen Park" Formation of Collinson (1961). The lithology of the Horton Creek varies considerably and may consist of siltstone, shale, sandy limestone, micritic limestone and dolomite, oolitic limestone, and limestone conglomerate. The siltstone and shale of the Horton Creek are greenish- to dark-greenish-gray, bioturbated, and sparsely fossiliferous and are similar to the shale of the Hannibal and the upper part of the Saverton. Gray to tan, argillaceous, sparsely fossiliferous, micritic limestone and dolomite are the dominant carbonate lithology, although oolitic limestone is common, especially in the upper part of the formation. The name "Hamburg Oolite," which originally was applied by Weller (1914) to a widespread distinctive oolitic limestone near the top of the Horton Creek, has been reinstated with the rank of bed (Cluff and others, 1981).

The Horton Creek is recognized as a distinct formation in central and west-central Illinois. The maximum thickness of the formation is more than 60 ft in Bond and Montgomery Counties, where it includes mostly siltstone (Cluff and others, 1981). In areas where the limestone of the Horton Creek is not present, the shale and the siltstone cannot be differentiated from the overlying Hannibal Shale, and a vertical cutoff marks the limit of the formation. Beyond the area of the underlying Louisiana Limestone, the shale of the Horton Creek cannot be differentiated from the Saverton Shale.

Conodont faunas of the Horton Creek in the outcrop area show that the formation is Mississippian in age and that the base of the formation marks the position of the Devonian-Mississippian boundary (Collinson and others, 1971). According to Cluff and others (1981), the age of the siltstone and the shale that lie between the Louisiana Limestone and the oolitic limestone in the upper part of the Horton Creek in the subsurface of Illinois is problematic. They suggest that the Horton Creek may be either Devonian or Devonian and Mississippian in age.

Hannibal Shale

The Hannibal Shale, which is named for Hannibal in Marion County, Mo., is well exposed in the bluffs along the Mississippi River (Keyes, 1892). In Illinois, the formation consists of highly bioturbated, nonlaminated, organic-poor, greenish- to dark-greenish-gray mudstone and shale. The silt content of the Hannibal is generally high, and argillaceous siltstone beds are prominent in places, particularly in the upper part of the formation.

The Nutwood Member of the Hannibal Shale is a thin (0–40 ft), silty, dark-brown to black shale in the lower part of the formation and is named for Nutwood in Jersey County in western Illinois (Workman and Gillette, 1956). The shale grades laterally and vertically into the gray shale of the Hannibal.

The Hannibal Shale is recognized as a distinct formation in part of central and west-central Illinois and reaches a maximum thickness of 110 ft in northeastern Macoupin County. The formation thins to the northwest of this area as a result of erosion, and it also thins to the southeast away from its source area (Cluff and others, 1981).

At the type section, the Hannibal overlies the Louisiana Limestone and is overlain by the Burlington Limestone (Atherton and others, 1975). In the type section and in nearby areas, the lower part of the Hannibal probably includes strata equivalent to the Horton Creek Formation (Cluff and others, 1981). In those areas of Illinois where the Horton Creek is present, the Hannibal conformably overlies it.

After considering the available conodont evidence, Collinson and others (1971) thought it likely that the base of the Mississippian System was at or near the base of the Hannibal Shale in the standard section. They decided, however, to maintain the lower boundary of the Mississippian at the top of the Louisiana Limestone until additional conodont evidence becomes available.

Saverton and Hannibal Shales Undifferentiated

Throughout that part of Illinois where the Louisiana Limestone and the Horton Creek Formation are absent, the Hannibal is not differentiated from the underlying greenish-gray shales of the Saverton (Cluff and others, 1981). The undifferentiated Saverton and Hannibal Shales reach a maximum thickness of 180 ft in Hancock County in western Illinois (fig. 9). The Falling Run, the Henryville, and the Jacobs Chapel Beds overlie the greenish-gray shale interval of the undifferentiated Saverton and Hannibal Shales in a core in Wayne County in southeastern Illinois and are assigned to the Saverton and Hannibal undifferentiated.

In areas where the Hannibal and the Saverton are not differentiated from one another, the exact position of the Devonian-Mississippian boundary is not known. The Hannibal is equivalent to the Falling Run, the Underwood, the Henryville, and the Jacobs Chapel Beds (Lineback, 1970). Where the Henryville and the Falling Run are at the top of the greenish-gray shale, most of the Saverton-Hannibal interval is probably Devonian in age. In areas of southeastern Illinois where the Falling Run, the Henryville, and the Jacobs Chapel overlie the Grassy Creek, the Hannibal equivalent is represented by these beds and possibly the upper few feet of the underlying Grassy Creek (Cluff and others, 1981).

Where the undifferentiated Saverton and Hannibal Shales are recognized in western Kentucky, they overlie the Grassy Creek Member of the New Albany Shale and are overlain by the Rockford Limestone. The Hannibal is recognized in the subsurface of western Kentucky (Schwalb and Norris, 1980e) and is considered to be a lateral equivalent of the basal part of the New Providence Shale rather than a part of the New Albany Shale (Dever and McGrain, 1969, fig. 6). The Hannibal Shale, as recognized in the subsurface of western Kentucky, probably includes strata equivalent to the undifferentiated Saverton and Hannibal Shales of Illinois, and the interval is referred to here as the undifferentiated Saverton and Hannibal Shales (fig. 2).

Although the distribution of the undifferentiated Saverton and Hannibal Shales is sporadic in Kentucky, the interval is present in Union, Henderson, Daviess, McLean, and Ohio Counties in northwestern Kentucky; it is about 10 ft thick in a drill hole in McLean County (Schwalb and Norris, 1980a, d). Basinwide mapping indicates that the undifferentiated Saverton and Hannibal interval is more than 20 ft thick in parts of northern Henderson and Union Counties (Lineback, 1980). In southwestern Kentucky, the thickness of the shale is about 10 and 35 ft in core holes from Calloway and Trigg Counties, respectively (Dever and McGrain, 1969, fig. 6). The Henryville Bed was not reported in the subsurface of northwestern Kentucky by Schwalb and Norris (1980e).

Ellsworth Member

The name "Ellsworth Shale" was used first by Newcombe (1932) for 30 to 40 ft of greenish-gray shale exposed in the Petoskey Portland Cement quarry 1.5 mi south of Ellsworth, Antrim County, Mich. Use of the name "Ellsworth" was extended into Indiana by Lineback (1968) for a unit that consists of a lower interval of interbedded, greenish-gray and brownish-black shale and an upper interval of predominantly greenish-gray shale. In the Illinois basin, the Ellsworth is a member of the New Albany Shale.

Tongues of greenish-gray shale that occupy the same stratigraphic position as the Ellsworth were recognized by Lineback (1970) in the central and the southwestern parts of Indiana, but he did not include these in the Ellsworth Member. The name "Ellsworth" was extended to include these rocks when physical continuity of the greenish-gray shale into central and southwestern Indiana was established by Hasenmueller and Bassett (1981).

Although the Ellsworth includes brownish-black and greenish- to medium-gray shale, gray shale is volumetrically the dominant lithology, particularly in the central and the southwestern parts of Indiana. In central Indiana, the greenish- to dark-greenish-gray shale is noncalcareous to slightly calcareous and contains carbonate lenses and small amounts of pyrite. Calcareous brachiopods are common. To the southwest in Posey County, the Ellsworth consists of medium- to medium-dark-gray shale. In the northern part of the Illinois basin, the member consists of a lower part of interbedded, greenish-gray and brownish-black shale and an upper part of greenish-gray shale that contains articulate brachiopods.

The Henryville and the Jacobs Chapel Beds overlie the greenish-gray shales of the Ellsworth Member in central Indiana and are included in the Ellsworth. Phosphate nodules indicative of the Falling Run Bed are not present in the area.

In central Indiana, the Ellsworth, which includes the Henryville Bed, ranges in thickness from 7 ft in Bartholomew County to about 21 ft in Morgan County (fig 9) The member is 16 to 22 ft thick in areas of Vigo and Sullivan Counties in western Indiana Along a northeastward-southwestward linear trend in southwestern Indiana, the Ellsworth thickens to more than 40 ft, and the underlying undifferentiated Morgan Trail, Camp Run, and Clegg Creek Members thin slightly The thinning is confined to the upper part of the undifferentiated interval, and the Clegg Creek grades laterally into the lower part of the Ellsworth (Hasenmueller and Bassett, 1981) In the northernmost part of the Illinois basin in Indiana, the greenish-gray shale of the Ellsworth grades into the upper part of the underlying Clegg Creek Member In this area, the Ellsworth thickens rapidly northwestward and is more than 80 ft thick in a core from northwestern Benton County

The Henryville Bed is not recognized in northern Indiana, but a thin greenish-gray shale is present immediately below the Rockford Limestone in cores from Fountain and Warren Counties This greenish-gray shale bed is not as soft as the Jacobs Chapel in southern Indiana, but their lithology is similar, and it is in the same stratigraphic position as the Jacobs Chapel Bed

The Ellsworth Member of Indiana is equivalent to the Saverton Shale, the Louisiana Limestone, the Horton Creek Formation, and the Hannibal Shale of Illinois (Cluff and others, 1981) and to the undifferentiated Saverton and Hannibal Shales in western Kentucky

DEPOSITIONAL ENVIRONMENT

The two dominant lithofacies of the New Albany Shale in the Illinois basin are organic-rich, brownish-black shale and organic-poor, greenish- to olive-gray shale The distribution of these lithofacies indicates deposition of the shale in a deep-water, stratified basin centered in southeastern Illinois and western Kentucky (Cluff and others, 1981) Although covering a large area geographically, the Devonian-Mississippian sea was essentially an enclosed cratonic sea that had only limited communication with the open ocean (Lineback, 1970, Ettensohn and Barron, 1981) This restricted communication enabled the development of an environment where organic-rich muds were preserved

The sea has been interpreted as being equatorial and deep enough for development of a stratified water column that prevented oxygenation of bottom waters The anaerobic conditions on the bottom were toxic to benthic organisms and allowed preservation of the organic material High concentrations of organic material in the brownish-black shale reflect not only an abundance of organic matter, but also a slow rate of clastic sedimentation (Ettensohn and Barron, 1981)

The source of much of the quartz silt and clay in the New Albany was the erosion of highlands to the east in the present Appalachian area The abundance of coarser siltstone beds and the thickness of these clastic units in the upper part of the New Albany sequence in west-central Illinois suggest the existence of another source area for sediments during latest Devonian and earliest Mississippian time (Cluff, 1980)

Aerobic, highly agitated, near-shore environments had a limited distribution in the Illinois basin and were restricted to west-central Illinois, where crossbedded, oolitic limestone and limestone conglomerate of the Horton Creek Formation were deposited The bioturbated, micritic limestone beds of the Louisiana Limestone and the Horton Creek probably were deposited in an aerobic, lower energy, shallow-water environment (Cluff and others, 1981) Because the carbonate units are thin and limited in distribution, this shallow-water environment did not exist for very long (Cluff, 1980)

Most of the mudstone and the shale of the New Albany was deposited in low-energy environments that ranged from dysaerobic to anaerobic The dysaerobic zone is characterized by a rapid decrease in oxygen with depth and is restrictive to most benthic invertebrates Only soft-bodied burrowing organisms and micro-organisms (mostly bacteria) are common in this zone (Cluff, 1980) Because of metabolic requirements for abundant oxygen, calcified faunas are generally unable to survive in dysaerobic environments (Cluff and others, 1981)

In the Illinois basin, greenish-gray shales, which are formed in dysaerobic environments, have been subdivided by Cluff (1980) into a highly bioturbated lithofacies and an indistinctly bedded, moderately burrowed, unfossiliferous lithofacies The highly bioturbated lithofacies includes silty, greenish-gray shale that grades into argillaceous siltstone or relatively silt-free, greenish-gray shale, and it is representative of a dysaerobic, quiet-water, offshore environment Bioturbated shale and siltstone are the dominant facies in west-central Illinois and suggest that this area was a broad shelf region during New Albany deposition (fig 10) This lithology is typical of the upper part of the Saverton Shale, part of the Horton Creek Formation, and the Hannibal Shale of west-central Illinois, the Hannibal of southeastern Illinois and northwestern Kentucky, the Selmier Member in central and southern Indiana, the Ellsworth Member of central and southwestern Indiana, and the upper part of the Ellsworth in the northern part of the Illinois basin in Indiana The presence of calcareous brachiopods in the Ellsworth in central Indiana indicates more oxygenated waters were present in this area during Late Devonian time

The indistinctly bedded, moderately burrowed, unfossiliferous, dark-greenish to olive-gray shale lithofacies is representative of a dysaerobic, quiet-water environment This shale was deposited in an environment that was slightly less oxygenated and, therefore, less hospitable to a benthic burrowing fauna than the environment of highly bioturbated, greenish-gray shale The shale contains little

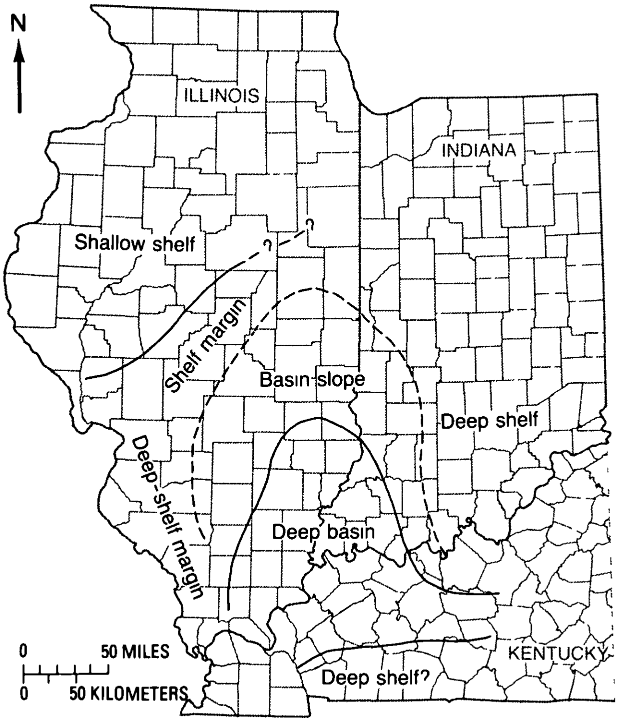

Figure 10. Generalized paleogeography of the Illinois basin during the New Albany deposition (From Lineback, 1980)

silt-sized material and may be interbedded with brownish-black shale Indistinctly bedded, greenish-gray shale interbedded with brownish-black shale is typical of the Selmier in the deep part of the basin, the Sweetland Creek Shale in Illinois, the Camp Run Member in southeastern Indiana, the lower part of the Saverton Shale of Illinois, and the lower part of the Ellsworth Member in the northern part of the basin in Indiana These interbedded shale sequences reflect changes in the oxygen content of the sea water and resultant fluctuations in the position of the dysaerobic/anaerobic boundary in the basin

Cluff (1980) subdivided the organic-rich, brownish-black shales into a thickly laminated lithofacies and a thinly laminated lithofacies The thickly laminated shale is characteristic of an anaerobic, quiet-water environment The shale is typically not burrowed and contains only nektonic and planktonic faunal elements Thickly laminated, brownish-black shale occurs in the Selmier in the deeper part of the basin and, to a lesser extent, in the Sweetland Creek and the Grassy Creek Shales in western and west-central Illinois The thickly laminated, brownish-black shale commonly is interbedded with the indistinctly laminated, greenish-gray shale

The thinly laminated, organic-rich, brownish-black shale represents an anaerobic, quiet-water environment that has low clastic input Pelagic sedimentation was dominant, and the fauna is predominantly planktonic and nektonic No evidence has been found of a benthic fauna, and the shale is not burrowed (Cluff, 1980) Finely laminated shale of this type is found in the Grassy Creek, the Morgan Trail, and the Clegg Creek

Although the mudstones and the shales in the New Albany were deposited in a low-energy environment, evidence has been found of sporadic gentle currents during deposition of the shale in parts of southeastern Indiana during late Middle Devonian and early Late Devonian time Beds in the lower part of the Blocher Member that contain abundant *Styliolina* shells and have a preferred orientation and cross-laminated, fine-grained sandstone and siltstone beds in the Selmier Member indicate current activity (Lineback, 1970, Cluff, 1980) Progressive deepening of the inland sea probably precluded development of current-related sedimentary structures in younger shale beds in much of the basin

As the cratonic sea deepened during the Late Devonian, upwelling caused phosphate- and nitrogen-rich, oxygen-poor, deep, oceanic water to enter the cratonic sea (Ettensohn and Barron, 1981) Sediments deposited during upwelling characteristically have high concentrations of organic material, phosphate, and heavy metals (Ettensohn and Barron, 1981) The widespread distribution of the Falling Run Bed, which contains phosphatic material, indicates a major influx of phosphate-rich water in conjunction with an absence of clastic materials in southeastern Illinois, southern Indiana, and part of west-central Kentucky

ORGANIC MATTER

The major part (90–95 percent) of the organic material in the brownish-black shale facies is amorphous (sapropelic) organic matter (Barrows and others, 1979) Recognizable organic material of terrestrial origin is present as carbonized logs in the brownish-black shale, and Cross and Hoskins (1951) reported a terrestrial flora near the top of the New Albany The amount of organic material in the greenish-gray shale is low, and the dominant type of material is humic The humic material is preserved in the greenish-gray shale because it is resistant to destruction by the benthic fauna and the aerobic bacteria that are present in the dysaerobic environment (Barrows and Cluff, 1984) Fragments of carbonized logs are also present in greenish-gray intervals

The brownish-black shale from the Blocher Member (Shale), the Grassy Creek Shale, and the Clegg Creek Member has high concentrations of organic carbon The black shale of the Henryville Bed contains the highest concentrations of organic matter

In southeastern Indiana, the Blocher interval contains an average of 7 8 percent organic carbon by weight (Hasenmueller and Leininger, 1987), and, in west-central Kentucky, the mean organic-carbon content ranges from 7 4 to 9 9 percent (Robl and others, 1983) Westward in Indiana, the organic carbon drops to 5 2 percent in a core in Sullivan County In the deeper part of the basin, selected samples contain averages of 4 and 8 percent organic carbon in Wayne and White Counties, Ill , respectively, and 6 percent in Christian County, Ky (Frost, 1980)

The organic-carbon content of the Grassy Creek Shale (Member) ranges from an average of 2 8 percent for selected samples from Henderson County in western Illinois to 9 percent for samples from White County, Ill , and 7 6 percent for samples from Christian County, Ky (Frost, 1980)

The Clegg Creek Member contains the highest concentrations of organic carbon and averages 12 6 percent organic carbon by weight in southeastern Indiana (Hasenmueller and Leininger, 1987) In west-central Kentucky, the mean organic-carbon content ranges from 9 3 to 13 0 percent (Robl and others, 1983) To the north and west in Indiana, the organic carbon decreases to 9 percent in Marion County in central Indiana and Sullivan County in western Indiana To the southwest in Dubois County, Ind , the organic-carbon content is 11 percent The organic-carbon content is greater than 20 percent by weight in the Henryville Bed in areas of Clark County Where the bed overlies the greenish-gray shale of the Ellsworth in central Indiana, the organic carbon averages 15 percent

The organic-carbon content of samples of greenish-gray shale from the Selmier Member (Shale), the Sweetland Creek Shale, the Camp Run Member, the Saverton Shale, the Hannibal Shale, and the Ellsworth Member is low, commonly 1 to 2 percent by weight Interbedded darker shale beds may contain 7 to 8 percent organic carbon, and some brownish-black shale beds in the Camp Run contain slightly more than 11 percent organic carbon

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Chapter D

Review and Revision of the Devonian-Mississippian Stratigraphy in the Michigan Basin

By R. DAVID MATTHEWS

U.S. GEOLOGICAL SURVEY BULLETIN 1909
PETROLEUM GEOLOGY OF THE DEVONIAN AND MISSISSIPPIAN BLACK SHALE OF EASTERN NORTH AMERICA

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Review and Revision of the Devonian-Mississippian Stratigraphy in the Michigan Basin

By R. David Matthews[1]

Abstract.

Stratigraphic and characterization work dealing with the Devonian-Mississippian shale sequence in the Michigan basin accelerated in the late 1970's as a result of funding by the U S Department of Energy Antrim cores were cut for study in Sanilac and Otsego Counties, Mich In addition, cuttings were collected from 35 drilling wells, and samples were collected from 7 surface locations More than 40 reports were issued as a result of the project funded by the Department of Energy, including two major reports A review of both studies suggests that existing formational names, as traditionally defined by lithology and color, are inadequate to describe fully a stratigraphic framework that is based on gamma-ray log correlations In this chapter, new informal terminology based on gamma-ray correlations is advocated to recognize the facies relation between the western Ellsworth Shale and the upper part of the eastern Antrim Shale The combined new informal unit is called the "Ellsworth/upper Antrim" and conforms to J M Forgotson's concept of a "format " The term "lower Antrim" is suggested not only for the western Antrim but also for the lower part of the eastern Antrim that comprises Garland D Ells' Units 1 A, 1 B, 1 C, and generally part or all of Unit 2 The contact between the Ellsworth/upper Antrim and the lower Antrim occurs at the known or predicted position of the time-stratigraphic marker *Foerstia* (*Protosalvinia*) Isopach maps and cross sections based on this interpretation suggest an erosional episode ranging from post-Sunbury to pre-"Coldwater Red Rock" time in southwestern Michigan Because the contour patterns on several isopach maps do not conform to present basin margins, the shale units are treated as remnants of much more widespread shales Five east-west gamma-ray cross sections and 162 well data sheets were prepared and serve to define and clarify the upper and the lower boundaries of the new informal units described Several disconformities and paraconformities are postulated within the Devonian-Mississippian shale sequence The Antrim Shale has twice the quartz of the average shale and 10 times the amount of polycrystalline quartz The hydrogen to carbon ratios of kerogen and the bitumen content of the organic shale increase with depth

INTRODUCTION

Purpose and Areal Extent of the Study

In response to the energy shortages of the 1970's, the Federal Government instituted research into the feasibility of using oil shale and other unconventional energy sources One of those programs, the Eastern Gas Shales Project (EGSP), was initiated in 1976 by the Energy Research and Development Administration, now the U S Department of Energy (DOE), to study the Devonian-Mississippian black shales in the three major eastern basins—the Appalachian, the Illinois, and the Michigan—as potential sources of natural gas The EGSP, which was directed by the Morgantown Energy Research Center (now the Morgantown Energy Technology Center [METC]), in Morgantown, W Va , sought to determine the magnitude of potential shale gas reserves, to characterize the shales, and to develop new stimulation techniques and to improve existing ones (Overbey, 1978) Early emphasis was placed on studies in the Appalachian basin where more than 10,000 shale gas wells had been drilled The Illinois and the Michigan basins, which have relatively minor shale gas production, received less emphasis in the shale characterization study

In Michigan, where the Antrim Shale had been under experimental investigation as an oil shale by the Dow Chemical Company since the mid-1950's (Matthews and Humphrey, 1977), the DOE entered into a 4-year contract in 1976 with Dow as the prime contractor for a test of the feasibility of in-situ processing as a means of producing hydrocarbons from the Antrim The Michigan investigation by Dow was administered through the DOE's Laramie Technology Research Center (LETC) in Wyoming A list of the resulting publications is given in Appendix A

The purpose of this report on the Devonian-Mississippian shale sequence in the Michigan basin is to present new stratigraphic interpretations and to summarize and call attention to recent work on the black shales,

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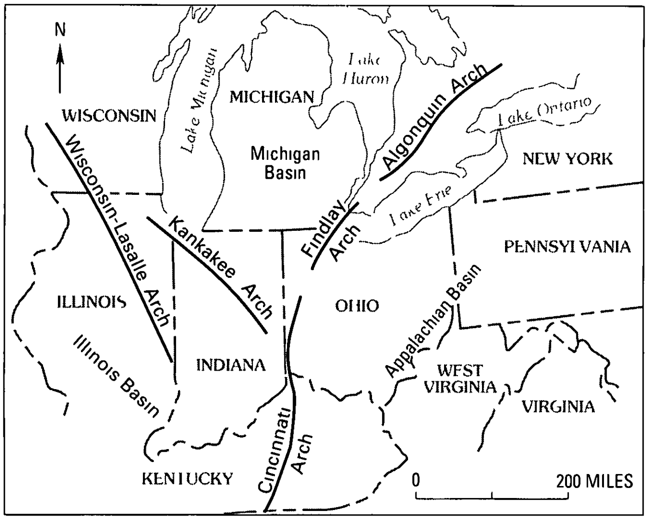

Figure 1. Major structural features outlining the Michigan basin

including reports that may have been overlooked owing to the administrative division within the DOE or because of the incomplete publication of maps, open-file material, and computer-stored data The geographic extent of this Michigan basin study includes the southern peninsula of Michigan, parts of northern Indiana and Ohio, and southern Ontario

Acknowledgments

This report does not pretend to be one of original research Rather, it is a compilation of work by others concurrent with my own involvement with the Antrim Shale since 1956 and, in particular, with the several subcontracted investigations that were a part of the Dow/Antrim project from 1976 to 1980 I have relied heavily upon the work of former coworkers and associates, in particular, Garland D Ells' 1979 report and the 1980 Dow Final Summary Report by David C Young

GEOLOGIC SETTING

The Michigan basin, which is intracratonic and roughly circular, covers about 122,000 square miles (mi^2) and is bounded on the west by the Wisconsin arch and the Wisconsin Dome, on the north and northeast by the Canadian Shield, on the east and southeast by the Algonquin arch in Ontario and the Findlay arch in northwestern Ohio, respectively, and on the southwest by the Kankakee arch in northern Indiana and Illinois (fig 1) The basin has been filled with more than 17,000 feet (ft) of sedimentary rocks (Ells and Champion, 1976) deposited during flexure rather than as the result of faulting (Cohee, 1945, Hinze and others, 1975, Sleep and Sloss, 1978, Lidiak, 1982) The more than 100,000 cubic miles (mi^3) of rock that eventually filled the basin has been divided (de Witt, 1960) into four general lithologic sequences—clastics (Cambrian), carbonate-evaporites (Early Ordovician through Middle Devonian), shale-sandstone (Late Devonian and Mississippian), and coal-bearing rocks (Pennsylvanian, Permian, and Jurassic) The Antrim Shale and associated Devonian-Mississippian rocks in Michigan form the initial deposits of the shale-sandstone sequence These rocks attain an aggregate thickness of nearly 900 ft in the northwestern quadrant of the basin (figs 2, 3)

Near the center of the modern structural basin, the base of the Antrim, as defined by Fisher (1980), is more than 2,400 ft below sea level (fig 4) The Antrim Shale and associated rocks rise toward the margins of the basin where their truncated edges subcrop under a cover of glacial drift on land or under lake sediment in Lakes Michigan, Huron, and St Clair They crop out at the surface in several small exposures in the northern lower peninsula and in Ontario A list of 21 selected Devonian shale exposures in northern Michigan and in Ontario is included in Appendix B Black shales of Upper Devonian age are found in pockets on top of the Silurian dolomite, about 20 miles (mi) west of Chicago, Ill , a thickness of 500 ft of Ellsworth Shale equivalent is preserved in the fault blocks of the Des Plaines Disturbance, which is about 30 mi south of the Illinois-Wisconsin State line (Willman, 1971)

The absence of Devonian-Mississippian shales across the basin margins is the result of the erosion of extensive deposits that covered much of the continental interior during the Late Devonian (Conant and Swanson, 1961, Ettensohn and Barron, 1981) The evidence for the removal of missing Paleozoic rocks that ranged in thickness from 2,000 to 3,280 ft and that were once present over the Michigan basin and its bounding arches is found in the elevated organic maturity observed in rocks in Michigan (Hathon and others, 1980a, Wold and others, 1981, Cercone, 1984), Ontario (Uyeno and others, 1982), and Illinois (Thomas and Frost, 1980) These data are shown in table 1 The presence of 700 ft of late Devonian-Mississippian rocks in some of the fault blocks near Des Plaines, Ill , suggests that "more than 1000 feet of younger Paleozoic rocks could have been present" (Willman, 1971, p 37) Additional evidence of continuous deposition between the Illinois and the Michigan basins across the area of the present Kankakee arch during the Late Devonian is provided by surviving lithofacies patterns and unit thicknesses (Matthews, 1983a, Matthews and Feldkirchner, 1983)

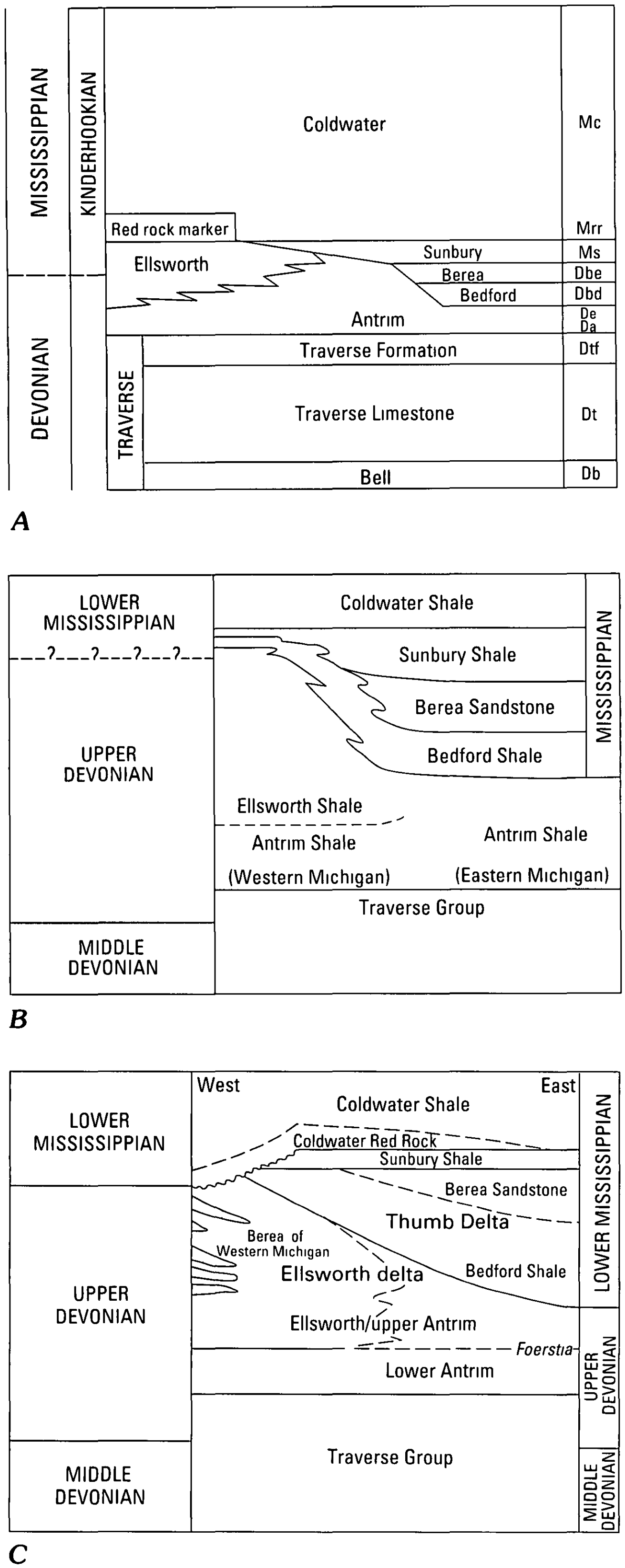

Figure 2. Devonian-Mississippian subsurface stratigraphic nomenclature for eastern and western Michigan *A*, Michigan Basin Geological Society Stratigraphic Committee (1969) *B*, Ells (1979, p 2, fig 2) *C*, This study

WORK BEFORE DEPARTMENT OF ENERGY FUNDING

Stratigraphy

The bituminous black shales of the Antrim were recognized as a rock type in Michigan as early as 1838 They were known by various names—Portage, Huron, Ohio-Black, and St Clair—before the St Clair was renamed the Antrim from surface exposures in that county in 1901 (Martin and Straight, 1956) The type localities for the Bedford Shale, the Berea Sandstone, and the Sunbury Shale, which were named in the 1870's, are in Ohio They were identified initially in Michigan in two wells in Washtenaw County—the Bedford and the Berea in 1876 and the Sunbury in 1900 The Ellsworth Shale was named by Newcombe (1932) from a well in Muskegon County, in 1933, he selected an outcrop near the town of Ellsworth in Antrim County as an appropriate type section

The sequence of rocks from the base of the Antrim Shale (Late Devonian) up to the base of the Coldwater Shale (Early Mississippian) poses several stratigraphic problems that have challenged investigators since the above-mentioned formations were first described This sequence of black shales and associated rocks is preserved in an intracratonic basin where it overlaps rocks of the Traverse Group, which includes beds "unquestionably Upper Devonian" (Ehlers and others, 1970, p 31) The sequence underlies a thick basinwide Lower Mississippian shale, thus, the sequence includes the Devonian-Mississippian boundary Because neither the base (the Traverse-Antrim contact) nor the top (the Ellsworth-Coldwater contact) of the sequence in western Michigan is easily identified in well cuttings, it has not been defined with any consistency in past studies Several informal unit names, such as "Traverse Formation," "Traverse Limestone," and "Coldwater Red Rock," have been used widely in subsurface work for many years (fig 2) Although basinwide correlations can be based on gamma-ray logs (Wallace and others, 1977, Lilienthal, 1978, Ells, 1979, Roen, 1980), paleontological evidence in the subsurface is scarce, and, therefore, time lines are uncertain (Cross and Bordner, 1980, Fisher, 1980) The multiple deltaic depositional system is probably responsible for the significant differences in the eastern and the western lithologic sections

One of the earliest writers to divide the Antrim in terms of upper and lower units and to recognize the consistent nature of the lower beds was LeMone (1964) In his study, which involved 700 gamma-ray logs, he stated, "The Lower Antrim is continuous throughout the entire basin " Our incomplete understanding of Devonian-Mississippian black shale stratigraphy was summed up by Ells (1979, p 12, 13), when he stated, "The general relationship between the Ellsworth and Antrim Formations is established either as an intertonguing, interfingering,

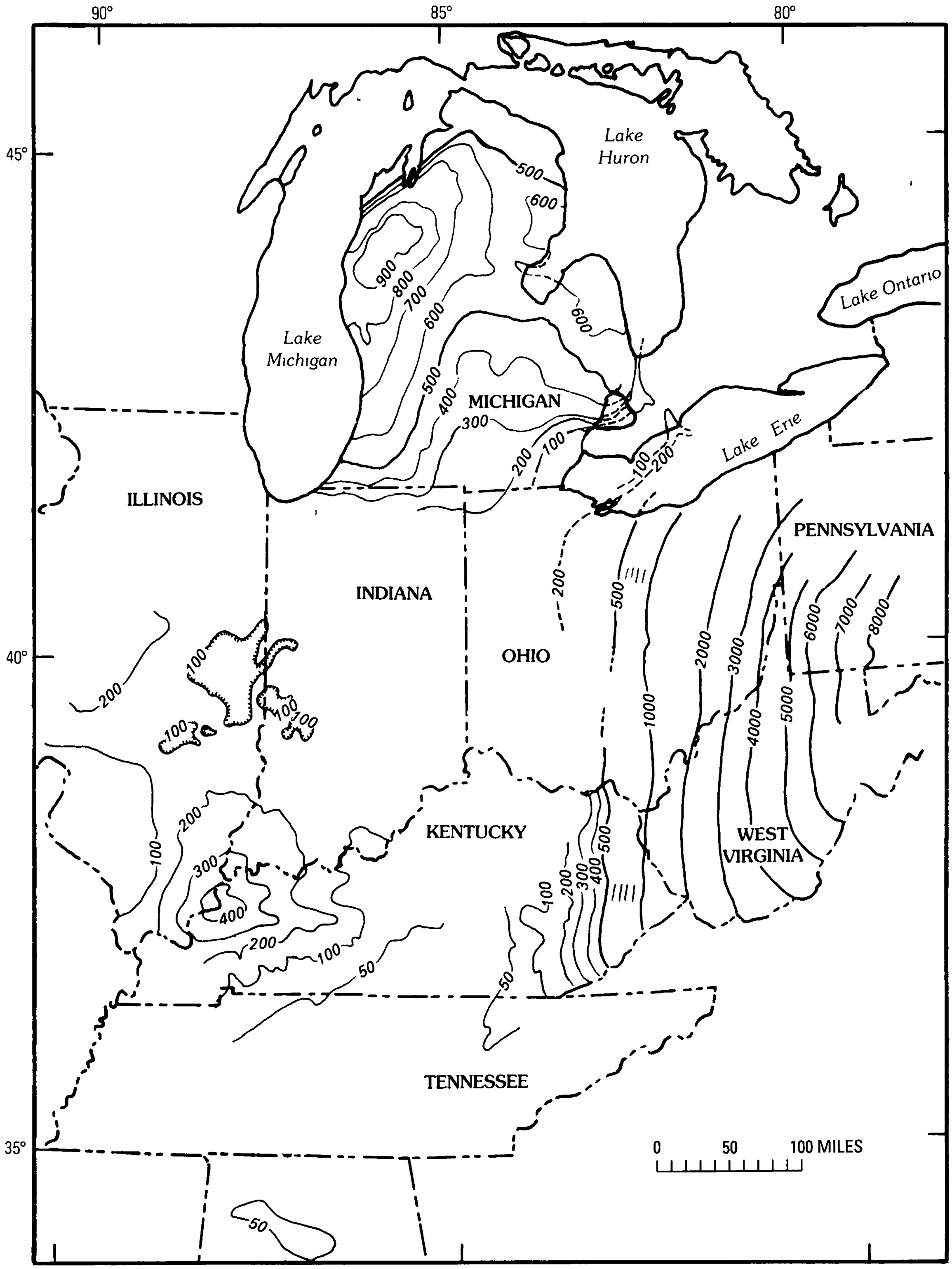

Figure 3. Preserved thickness of the Devonian-Mississippian shale in the Eastern United States (From Matthews, 1983a)

lateral transition or facies relationship" and "The entire interval—from basal Antrim upward to the top of the Sunbury Shale—is stratigraphically related in a complicated way" (fig 2)

Sedimentation

The total black shale sequence thins along a north-south zone through the center of the modern structural

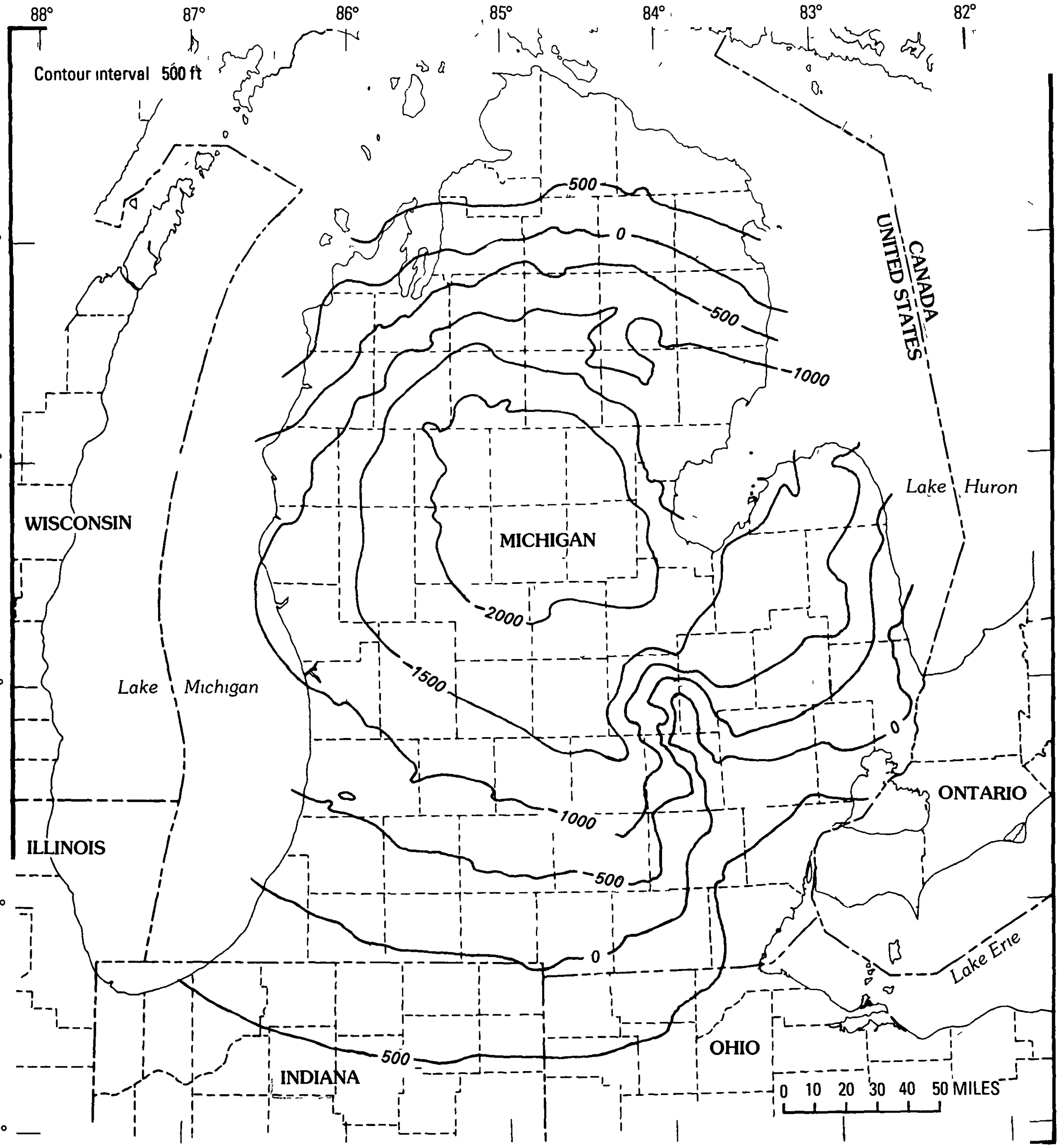

Figure 4. Structure of the "Traverse Limestone" This surface forms the base of the Antrim Shale, it is the top of the first locally important limestone in the upper part of the Traverse Group (Modified from Fisher, 1980, pl. 4.)

basin, the aggregate thickness increases to the northwest and to the east This elongated "thin" in the center of the basin, which is evident in early basin isopach maps (Newcombe, 1933, fig 15) and cross sections (Tarbell, 1941, fig 1), challenges us to clarify the structural inferences that can be drawn from the isopach data The hazards of postulating paleoarches based solely on the thinning or absence of strata were elucidated by Kay (1945) and Calvert (1974), and their warnings are appropriate here Early researchers in Michigan called upon structural or topographic barriers to separate Ellsworth-type rocks from Antrim lithology

Newcombe (1933) called the thin area an axis of "tilting" and of "uplift" that separated the two basins by an upwarping trend In a study limited to southwestern Michigan, Bishop (1940, p 2160) concluded that " a low barrier originated at the end of Traverse limestone deposition, becoming gradually more pronounced throughout

Antrim-Ellsworth time " Hale (1941, p 713) suggested that a shallow axial area acted as a barrier through central Michigan Tarbell (1941, p 724) constructed two basin-wide cross sections that were based on well cuttings, but, because she included the thickness in the central basin, her working interval was "a shale series of somewhat uniform thickness (about 1,500 feet thick) " If one subtracts the Coldwater Shale, then the east-west cross section (Tarbell, 1941, p 726, fig 1) shows a thick eastern Traverse to Sunbury interval of about 630 ft, a thin central Traverse to base of Coldwater interval of 510 ft, and a thick western Traverse to "Coldwater Red Rock" interval of 790 ft Although the Ellsworth had been described as having been limited by a barrier, Weller (1948, p 157) concluded that " more probably it grades laterally into the upper part of the Antrim shale and overlying formations "

The concept of a central nonemergent arch was revived by McGregor (1954) and was later used by de Witt (1960, p 62) Both thought that the Antrim was deposited in a silled basin The barrier concept remained in the first of the modern studies to use gamma-ray logs (LeMone, 1964) Although LeMone (1964, p 31, 37) wrote about an alternate solution of nondeposition of sediments, he chose to interpret his "B" interval (Traverse to Coldwater) isopach thin as a barrier or axis separating "two distinct areas of accumulation", locally, along that axis the shales change character "in only seven miles distance " LeMone's "B" interval corresponded closely to McGregor's "A unit" minus the transition zone in the upper part of the Traverse Group

Asseez (1967, 1969) considered a lack of sedimentation in the center of the basin as a possible explanation for the thinning of the Bedford-Berea at a distance from its source, however, he denied that the same argument was tenable for the Ellsworth He concluded that an "environmental barrier" seemed to be the most plausible explanation for the apparent separation of the Ellsworth and the Bedford-Berea (Asseez, 1969, p 133) and that the localization of rock types on opposite sides of the basin "was not effected by a structural or topographic barrier but by an environment in which all sediments deposited were primarily or secondarily black" (Asseez, 1969, p 127) He considered the Antrim to have been deposited in a reducing and shallow-water environment that was displaced basinward by the encroachment of eastern and western deltas

Different eastern and western deltas have been advocated by others, including Newcombe (1933), Baltrusaitis and others (1948), Cohee and others (1951), Cross and Bordner (1980), Fisher (1980), and Matthews (1983a) The deltaic nature of the Bedford-Berea section and its correlation with Appalachian formations has long been recognized (Cohee and Underwood, 1944, Cohee and others, 1951, de Witt, 1960), the Bedford-Berea deposit was given the name Thumb delta by Cohee (1965) Recognition of a deltaic origin for the Ellsworth in western Michigan has been slower to find acceptance, although the Ellsworth sediments were shown to be thickest in the northwest (Newcombe, 1933) and to have come from the north and the west (Hale, 1941) The term "Ellsworth Delta" has been used by Asseez (1969), Gardner (1974), and Fisher (1980)

Of the many interpretations of time relations between eastern and western deltaic deposits, one of the earliest descriptions of the true facies relation was contained in the summary by Baltrusaitis and others (1948, p 17), who stated, "The greenish gray Ellsworth shale of the western half of Michigan overlying the black shale of Antrim is contemporaneous with and interfingers with the upper Antrim of central and eastern Michigan "

WORK DURING AND SUBSEQUENT TO DEPARTMENT OF ENERGY FUNDING

Garland D. Ells' Stratigraphic Study

When interest in the energy potential of the eastern black shales led to federally funded research, one of the first subcontracts awarded by the Dow/Antrim project went to the Geological Survey Division of the Michigan Department of Natural Resources to support Garland D Ells' ongoing stratigraphic studies into the relation of the eastern Antrim Shale, the Bedford Shale, the Berea Sandstone, and the Sunbury Shale and their corresponding intervals in different parts of the basin

Ells' (1979) work was a major contribution to the regional black shale stratigraphy in Michigan, and he succeeded in providing the framework for future studies His investigation was essentially limited to the construction of six basinwide stratigraphic cross sections covering the interval between the base of the Antrim Shale and the base of the "Coldwater Red Rock " The six cross sections (A–F) involving 99 gamma-ray logs formed a network of sections in which 16 logs were common control points at intersections These 16 wells received dual identification, the first well in the A cross section is A 1, which also begins the C section as C 1 Ells divided the eastern Antrim into six units based on gamma-ray patterns, his basal Unit 1 was divided into 1 A, 1 B, and 1 C, in descending stratigraphic order The overlying Bedford was divided into Units 7 and 8, in ascending order, and the Berea was labeled Unit 9 (fig 5) Ells claimed no formal status for his designated units, rather he suggested that they could be useful aids in helping to decipher the regional stratigraphy of the basin Each cross section was discussed in his text, and anomalous logs and problematic correlations were noted He was unable to identify all the subunits in the Ellsworth

In his summary, Ells (1979) noted the following east-to-west stratigraphic relations

- A facies relation between the upper part of the Antrim Shale in the east and the Ellsworth Shale to the west

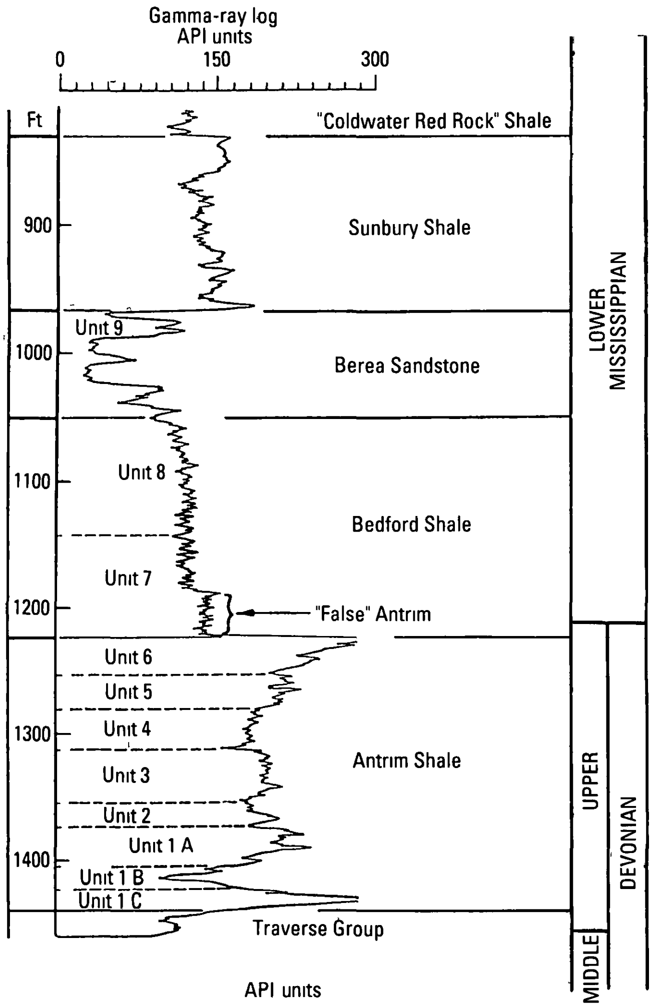

Figure 5. Unit subdivisions based on gamma-ray log characteristics The log is from the Dow Chemical Company No 1 Rhoburn well, Sanilac County, Mich API, American Petroleum Institute (From Ells, 1979, p 27, fig 3)

- A facies relation between the Bedford Shale in the east and the upper part of the Ellsworth to the west
- A westward pinch out of the Berea Sandstone
- A westward thinning of the Sunbury Shale in some areas and a merging of the Sunbury into the uppermost Ellsworth in other areas to the west

Ells accepted de Witt's (1970, p 610) assignment of Early Mississippian for the Berea, the Bedford, and the Sunbury of the Michigan basin On the basis of his Antrim correlations, Ells (1979, p 54) stated that "most" of the Ellsworth appears to be of Devonian age but that part of the Bedford (Mississippian) extends into the upper part of the Ellsworth in a facies relation

No geological data were mapped as a part of Ells' published study He did not attempt to explain depositional environments, to identify disconformities, or to suggest sediment source areas The regional sequence of events was not made a part of his reported work, except for the time equivalency and facies relations implicit in a number of his unit correlations

James H. Fisher's Studies

A stratigraphic and structural mapping program of the black shale interval was begun by Louis I Briggs, University of Michigan, who died before the work was completed A detailed description of the core samples was prepared subsequently by R Douglas Elmore, University of Michigan (Briggs and Elmore, 1980) Later, the mapping program was undertaken by James H Fisher, Michigan State University, who constructed a series of 25 maps and 1 cross section

Fisher's (1980) basinwide structure and isopach maps were contoured on 1 250,000- and 1 1,000,000-scale base maps The 1 250,000-scale quadrangles were used to allow the inclusion of a large number of data points Fisher plotted approximately 2,200 wells for which he had gamma-ray logs on a base map These logs provided the basis for Fisher's structure and isopach maps

Fisher's (1980) published report contains only his maps of the basin at the 1 1,000,000 scale, these do not show his numerous data points and, because of printing problems, were poorly reproduced Because of the large number (over 150) and the bulk of the more detailed maps, it was not feasible to include them, even as folded maps, in his report All his 1 250,000-scale map segments were placed in the library of the LETC at the end of his study During the restructuring of the DOE Technology Centers, those maps were shipped first to Morgantown, W Va , and later to the U S Geological Survey (USGS) in Reston, Va (John Roen, USGS, oral commun , 1985)

At the termination of the Dow/Antrim project, Fisher's gamma-ray logs were donated to Michigan State University The data derived from those gamma-ray logs included Fisher's assigned formation tops, thicknesses, intervals, location coordinates, well identifications, elevations, and other data necessary to his computer mapping The data were stored on a seven-track tape that was subsequently damaged, unfortunately, duplicates are unavailable (J H Fisher, Michigan State University, written commun , 1986)

Fisher's lithofacies maps were based on an examination of approximately 99 sets of drill cutting samples obtained from the Michigan Geological Survey, Michigan State University, and the University of Michigan Data for the six bedrock maps were obtained from oil and gas drillers' logs, core hole records, geophysical logs, and water well records

At the top of the Traverse Group (fig 6), Fisher (1980) included the transition zone, which is a series of gray and black shales and limestones informally called the

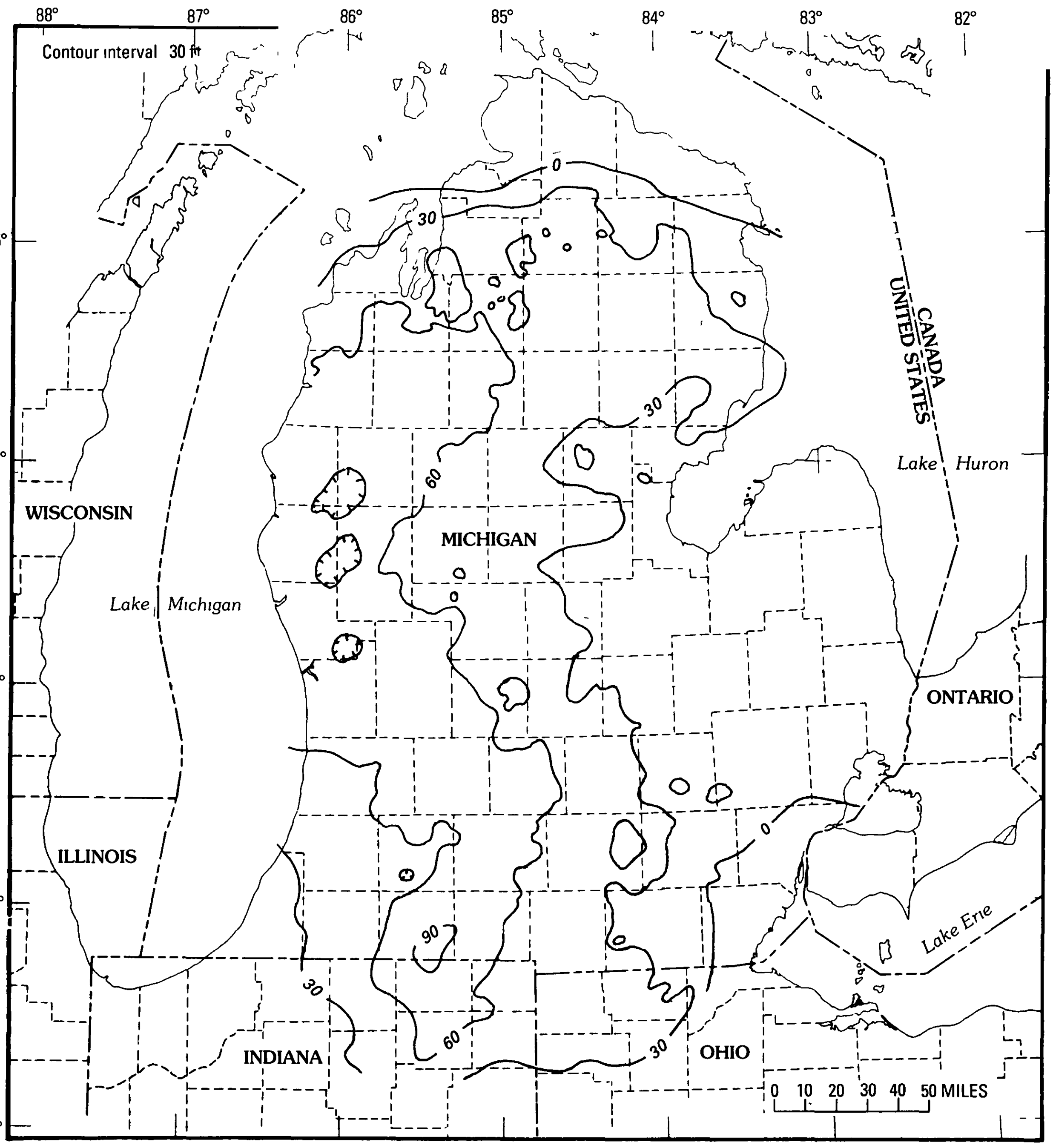

Figure 6. Isopach map of "Traverse Formation " This unit, which contains calcareous gray shale and sporadic stringers of limestone and black shale, forms a transition zone between the "Traverse Limestone" and the overlying massive black shale of the Antrim Shale The "Traverse Formation" is considered to be a part of the basal Antrim Shale by Fisher, (1980), however, in this study, the unit is assigned to the underlying Traverse Group, which is in agreement with Ells (1979) (Modified from Fisher, 1980, pl 13)

"Traverse Formation" or "Traverse Shale" by petroleum industry geologists, within his black shale sequence, Ells (1979) omitted these same transition beds from the black shale sequence Fisher (1980, p 14) maintained that the "Traverse Formation" is "gradational with and has far more affinities with the Antrim than it does with the underlying Traverse limestone " These transition beds, according to Fisher, overlie a minor unconformity in southwestern Michigan that is the probable boundary between Middle and Upper Devonian In his interpretation of events, the "Traverse Formation" indicates deepening water conditions before stagnant water, "perhaps to 100 feet" (Fisher, 1980, p 19), prevailed basinwide Following a period of black shale deposition, the Ellsworth delta invaded from the west, but only prodelta sediments extended into the western part of the Michigan basin Later, the influence of the delta waned, and black shale conditions returned to cover some of the Ellsworth deposits in the west-central part of the basin Fisher recognized the Bedford-Berea delta from the east as a second separate event Fisher followed the subjective custom in Michigan of using shale color as the primary feature to distinguish between the Antrim and the Ellsworth He suggested that the occasional dark shale in the basal Bedford may be reworked Antrim

Paxton Quarry Studies

The Paxton Quarry, Alpena County, Mich , which was deepened in 1979, exposes 139 ft of the basal Antrim and the uppermost Traverse Group, although the highest 33 ft of the exposure is now covered Descriptions of the upper quarry were published by Ehlers and Kesling (1970) and Hathon and others (1978), the expanded quarry section has been included in a lithostratigraphic and biostratigraphic study by Gutschick (1987)

In 1987, a 152-ft core was cut through the exposed quarry section into the underlying "Traverse Formation," and gamma-ray, neutron, density, sonic, resistivity, and caliper logs were obtained The subsurface units that have produced shale gas in northern Michigan—1 A, 1 B, 1 C, and 2—were identified in the quarry face, and the Traverse Group-lower Antrim contact was recognized (fig 7, Matthews, 1988) The core and the logs were donated to the University of Michigan Core Laboratory in Ann Arbor

PALEONTOLOGY AND PALYNOLOGY

Paleontological evidence that would assist in establishing time lines through the Devonian-Mississippian black shale sequence in the Michigan basin is scarce (Cross and Bordner, 1980, Fisher, 1980), and, as a consequence, time lines, including the placement of the Devonian-Mississippian boundary, are uncertain Fossils that are present in the Antrim and the Sunbury Shales are the ubiquitous sporomorphs *Tasmanites*, wood fragments, the tree branch impression *Callixylon newberryi* (Dawson), *Sporangites*, conodonts, fish fragments (scales, plates, jaws), brachiopods (*Lingula*, *Orbiculoidea*), and the remains of *Foerstia* (*Protosalvinia*) Many of these are described in Hoover's (1960) review of the Ohio Shale Bioturbation occurs but is not universal, it provides evidence of burrowing organisms in the form of "worm trails" and preserved burrows at some of the contacts where gray or greenish-gray shale overlies organic-rich black shale Of the fossils known, only *Foerstia* has significance as a biostratigraphic marker (Hasenmueller and others, 1983) Unfortunately, it has been documented in only one site in Michigan (Matthews, 1983b)

Sanford (1967) noted a lack of megascopic fossils and suggested that detailed micropaleontological investigations were needed to establish more precise stratigraphic relations from the east to the west across the Michigan basin within the Devonian-Mississippian black shale sequence A study of *Tasmanites* failed to provide regional correlations (Boneham, 1967) A study of the Kettle Point Shale that used drill cuttings is of interest because the microfossils recognized can be related to the biostratigraphic marker *Foerstia* that occurs "just below the lowest level of *Radiolaria*, coincides with a notable decline in conodont abundance, and would seem to be just above the *quadrantinodosa* conodont zone" (Winder, 1966, p 1293) Depositional conditions apparently were changing while *Foerstia* lived

Because of *Foerstia*, a more precise time line has been established across Ontario (Russell and Barker, 1983, Russell, 1985) and over the Cincinnati arch (Kepferle, 1981, Hasenmueller and others, 1983) Because two earlier mentions of *Foerstia* in Michigan went unnoticed, the importance of the fossil's presence was overlooked (LeMone, 1964, Cliffs Minerals, Inc , 1981b) LeMone (1964, p 34) mentioned foerstian remains in core samples from Bay County in his thesis but did not include well names, depths, photographs, or stratigraphic conclusions The Cliffs Minerals, Inc (1981b, p B–6, B–7, 23), core description of Dow No 103 in Sanilac County mentioned *Foerstia* in Unit 2 Neither LeMone nor Cliffs Minerals, Inc , drew any conclusions concerning the stratigraphic nature or impact of the fossil

Later, the discovery of and publications concerning *Foerstia* in Michigan (Matthews, 1982, 1983b) provided stratigraphers with a single time line linking the Michigan basin with the Appalachian and the Illinois basins Ells' (1979) Unit 2 of the lower Antrim in eastern Michigan is now known to correlate with the middle Huron Member of the Ohio Shale (Matthews, 1982, 1983b, Hasenmueller and others, 1983)

As part of the Dow/Antrim project, Michigan State University received a subcontract for a palynological study of drill cuttings from five wells located on an east-west line through the center of the Michigan basin (Cross and Bordner, 1980) Thirty-seven plant spores, which are probably terrestrial forms, and eighteen acritarchs, which represent marine organisms, were differentiated and photographed The study involved 150 samples of drill cuttings of which 70 were from the Antrim and 25 were from the Ellsworth The contacts at the base and the top of the Antrim were clearly discernible by changes in populations Cross and Bordner (1980, p 6, 7) concluded that the wells were some distance from the paleoshorelines and noted that "land plant spores increase slightly in relative frequency upwards from base to top of the Antrim—this alone is an indication of increasingly close approach or proximity of the source of supply " and " the presence of a few terrestrial palynomorphs in the upper part of [the western

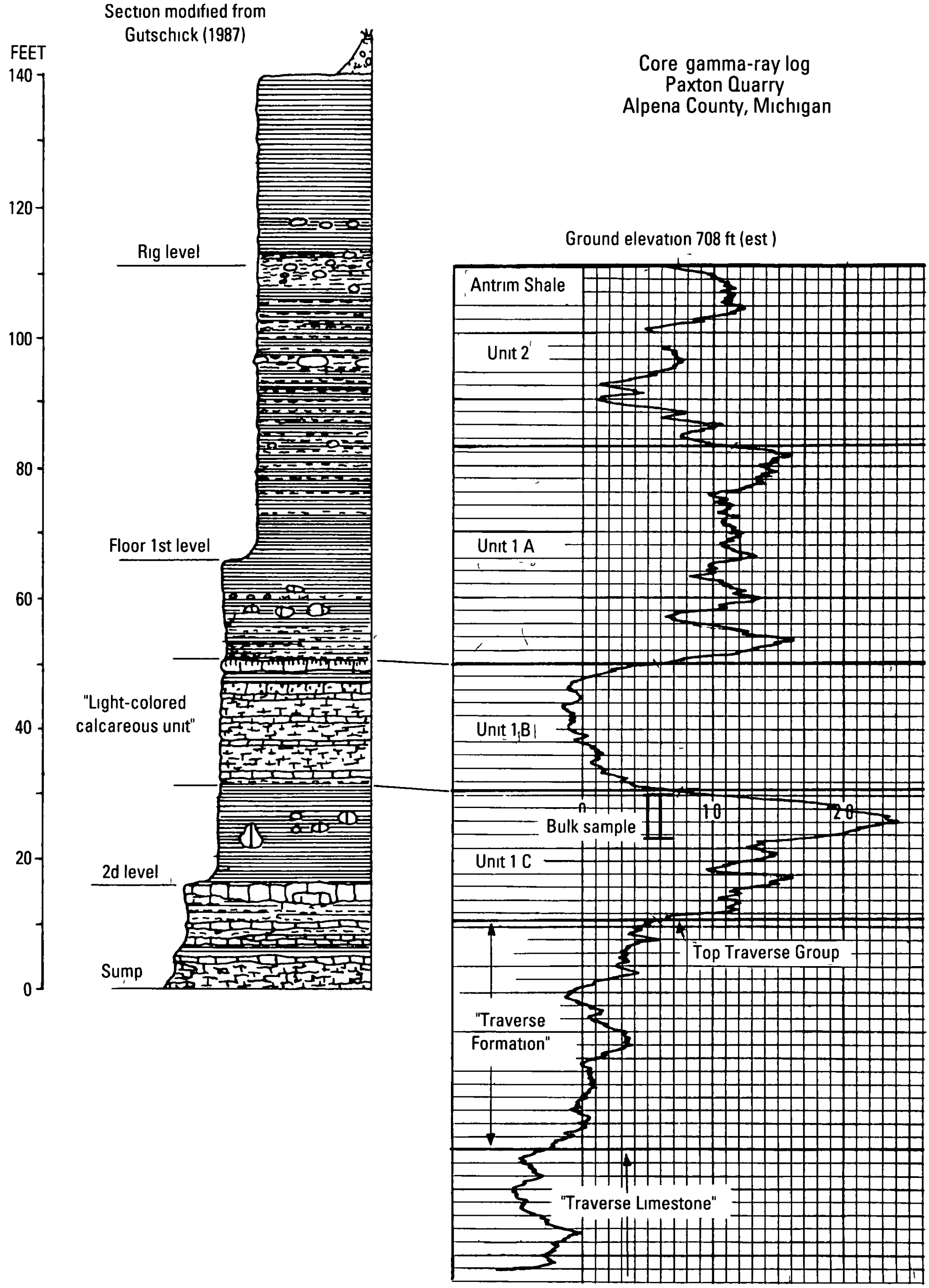

Figure 7. Correlation of the Paxton Quarry section and subsurface units (From Matthews, 1988)

two wells] not seen in the east may indicate a western source for the basin in later Antrim time " They concluded that they knew of no clear paleontological markers definable within the Antrim Because definition of age determinations in the subsurface formations in Michigan is in the initial stage, stratigraphers have had to develop a subsurface terminology based on lithology, color, and mechanical log characteristics that conforms to petroleum industry usage

STRATIGRAPHY

Discussion of Stratigraphic Units

Traverse Group

The formation divisions within the Traverse Group were defined from surface studies along the basin margins, and few of them are recognized in the subsurface In the east, these divisions include, in ascending order of deposition, the Bell Shale, the Rockport Quarry Limestone, the Ferron Point Formation, the Genshaw Formation, the Newton Creek Limestone, the Alpena Limestone, the Four Mile Dam Formation, the Norway Point Formation, the Potter Farm Formation, the Thunder Bay Limestone, and the Squaw Bay Limestone, in the west, the uppermost formation, the Jordan River, is equivalent to or younger than the Squaw Bay (Ells, 1979)

The Squaw Bay Limestone is overlain by a sequence of gray shales, gray shaly limestones, and shaly dolomites that form a transition zone between the brown crystalline limestone of the Squaw Bay and the solidly black shale of the Antrim This sequence may contain thin Antrim-type black shales as well as gray shales and shaly limestones typical of the Traverse Group Riggs (1938) termed this transition zone the "Traverse Formation " This transition zone, which is informally referred to as the "Traverse Formation" or "Traverse Shale," was assigned by Ells (1979) to the Traverse Group, he used the lowest major radioactive shale as the base of the Antrim I have followed Ells' practice, unlike Ells, Fisher (1980, pl 14) included the transition zone in his total shale interval The "Traverse Formation" averages about 50 ft thick in western Michigan and thins to about 10 ft in the east (fig 6)

Antrim Shale

The Antrim is a radioactive, hard, brittle, pyritic, carbonaceous, black to dark-gray shale that has occasional thin gray shales and thin stringers of limestone in the lower part The Antrim also contains concretions composed of bituminous limestone up to 3 ft or more in diameter The larger concretions can be thick enough to cause a negative gamma-ray deflection, thus creating an anomalous log pattern that can cause false correlations According to Ruotsala (1980) the relatively high radioactive response that makes the Antrim readily apparent on gamma-ray logs is due to the presence of thorium (up to 10–12 parts per million [ppm]) and uranium (up to 40 ppm) *Tasmanite* spores, fish scales *Lingula*, and the tree branch impression *Callixylon newberryi* are fairly common, other small fossils and fragments are also present The Antrim is unusual in that it has a high percentage of quartz—up to 50 percent or more by weight (Bennett, 1978, Hathon and others, 1980a, Ruotsala, 1980), this is about twice the amount of quartz in most shales (Shaw and Weaver, 1965) The remaining major components are clays (mostly illite) and kerogen, kaolinite, chlorite, and pyrite are minor constituents

Traditionally, the top of the Antrim Shale has been picked at the top of the first black shale beneath the gray shales of the Bedford in eastern Michigan or under the greenish-gray shales of the Ellsworth in western Michigan Because of the facies change between the Ellsworth and its equivalent beds in the upper part of the Antrim, the top of the Ellsworth/Antrim unit rises stratigraphically about 550 ft from east to west across the basin (fig 2*C*, see also fig 8) Also, using the first black shale encountered in drilling can cause confusion in recognizing the Antrim top in those parts of the basin where the Antrim is overlain by the black Sunbury or the dark Bedford The top of the Antrim in eastern Michigan is easily recognized because it is marked by an abrupt deflection of the gamma-ray curve to the right The top few feet of the Antrim exhibit the highest radiation levels in the upper part of the Antrim Even in areas where the overlying Bedford is a dark radioactive shale—exceeding 20 American Petroleum Institute (API) units above the normal gray shale base line—the typical abrupt deflection to the right of the eastern Antrim can be noted (fig 5) I have used this deflection to define the top of the Antrim Shale in this study

The Antrim Shale lies on eroded Traverse beds in the western and the southwestern areas of the basin (Bishop, 1940), in the central and the northern areas, the contact appears to be conformable (Baltrusaitis and others, 1948) In southeastern Michigan, the Antrim unconformably overlies an eroded Traverse surface (Gardner, 1974, Rickard, 1984) In Ontario, the contact of the Kettle Point Shale, which is the Antrim equivalent, with the underlying Hamilton (Traverse) Formation is disconformable (Russell, 1985)

The physical geometry of the Antrim Shale, in combination with the Ellsworth Shale, conforms to an idealized black shale sequence repeated in several black shales in the Appalachian, the Illinois, and the Michigan basins (Matthews, 1983a, Matthews and Feldkirchner, 1983) The idealized black shale sequence occurs in the Sunbury of Michigan and Ohio and in the Hannibal-Saverton/upper Clegg Creek in Indiana, it also occurs in the lower Huron/Chagrin in Ohio and Pennsylvania and in the Dunkirk/Perrysburg of New York An idealized black shale sequence (fig 8) consists of shales deposited during two different episodes of deposition The first shale, "A," is black, organic rich, and widespread It is then overlain by a wedge of shale, "B/C," which is composed of two distinctly different facies—an organic-poor prodelta gray or green-gray shale "C" that forms the thickest part of the wedge nearest to the source and its more distal, deeper water facies, an organic-rich black shale, "B," that forms the thin portion of the wedge Different yet time-related rocks that can be defined by log markers (such as the "B/C" wedge)

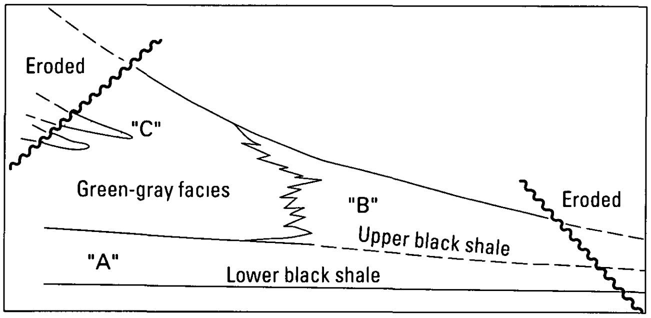

Figure 8. Idealized black shale sequence (From Matthews, 1983a)

have been proposed as mappable units by Forgotson (1957), who suggested that such units be called "formats "

Shales "A" and "B" are so similar in appearance that they can be differentiated only by using gamma-ray or other log markers, and, if they are mapped as a single unit, then unusual and artificial patterns result Fisher (1980, p 15, pl 12) noted the "odd looking anomaly" on his isopach map of the Antrim that includes "A" and "B" of this report He pointed out that it was "entirely synthetic "

Ellsworth Shale

The Ellsworth Shale of western Michigan is an organic-poor, gray to green-gray shale that has less pyrite and quartz and slightly more dolomite than typical black Antrim (Ruotsala, 1980) It is shale "C" of the idealized black shale sequence in Michigan (fig 8) Its source lay to the west and the northwest The occasional sandstones and siltstone bed found in the more westerly parts of the Ellsworth delta are similar in origin and relative position —but in mirror image—to the sandstones and siltstones within the eastern part of the Chagrin Shale of Pennsylvania, Ohio, and West Virginia

When the Ellsworth is mapped as a formational lithotype, as Fisher (1980, pl 11) did, it appears as a shale up to 850 ft thick, existing only in the western half of the basin (fig 9) It terminates abruptly to the east as the result of loss of identity at the north-south-trending facies change through the center of the basin The artificial anomaly that was created by the cutoff was the result of the Dow/DOE requirement that Fisher use traditional Michigan stratigraphic terminology when mapping his data

Within the "B/C" wedge (fig 8), the lateral facies change between the Ellsworth and the upper Antrim is frequently abrupt and can occur over short distances, but depositional conditions early in the formation of the wedge resulted in a transition of black and green gray at the base of the traditional Ellsworth A transitional period also occurred at the close of the "B/C"-wedge-building process that resulted in black shale depositional conditions returning to parts of the western side of the basin Black shale forms a top over much of the wedge This black shale is Fisher's (1980) suggested "Upper Antrim " I consider that the top of this black shale at the top of the Ellsworth/upper Antrim wedge marks the contact of the Upper Devonian with the overlying Mississippian

Bedford Shale and Berea Sandstone

The Bedford Shale and the Berea Sandstone are deltaic deposits described by Cohee and Underwood (1944), Baltrusaitis and others, (1948), Asseez (1969), de Witt (1970), Ells (1979), and Fisher (1980) The Bedford Shale is a gray prodelta facies lateral to and underlying the sandstones and the siltstones of the Berea The shale represents the forward, progressive building of the prodelta, the sand records the peak of delta development In eastern Michigan, the Bedford lies disconformably on the Antrim and has sharp contacts characterized by the presence of glauconite observed in Dow cores in the central and the eastern parts of the basin The Devonian-Mississippian boundary is probably at that contact

The Berea Sandstone is thickest in Sanilac and Lapeer Counties, Mich , and pinches out in the central part of the basin Fisher's (1980, pl 10) map of the Bedford shows some notable thickenings in the far reaches of the delta in Kent and Kalamazoo Counties, Mich , and in Steuben County, Ind The combined Bedford-Berea interval, which I have based on my interpretation of Ells' (1979) data, also shows thick areas in Kent and Stuben Counties (fig 10) Control wells for maps drawn for this study are identified in figure 11 and described in Appendix C The question of extent of the Bedford Shale and its relation to the upper beds in the Ellsworth in western Michigan is unsettled Ells (1979) placed some western black shales within the basal Bedford, as can be seen in his cross sections D, E, and F, specifically in his correlations for individual wells D 8 to D 13, E 12, and F 7 and F 8 These same black shales were called the "Upper Antrim" by Fisher (1980) and the "Upper-Radioactive Zone" by Tetra Tech, Inc (1981)

Because dark shales occasionally occur in the base of the Bedford, I thought that I had encountered the top of the Antrim when I first observed this lithology in a well cored in Sanilac County in 1972, however, there was no mistaking the true top of the Antrim when the next core was recovered 10 hours later The Bedford became glauconitic and lightened in color at the base, the Antrim top was black, sharp, and abrupt I assigned the informal term "false Antrim" to the 33 ft of dark basal Bedford (fig 5) When I mapped the extent of the "false Antrim" in Sanilac County by using gamma-ray logs, I found that it ranged in thickness from 8 to 48 ft across a three-township area of about 100 mi^2 It is a facies of the basal Bedford, but the origin of such a limited black shale is puzzling Fisher (1980) suggested that the dark basal Bedford shales may be reworked Antrim, but I believe that the small Sanilac County deposit and other dark

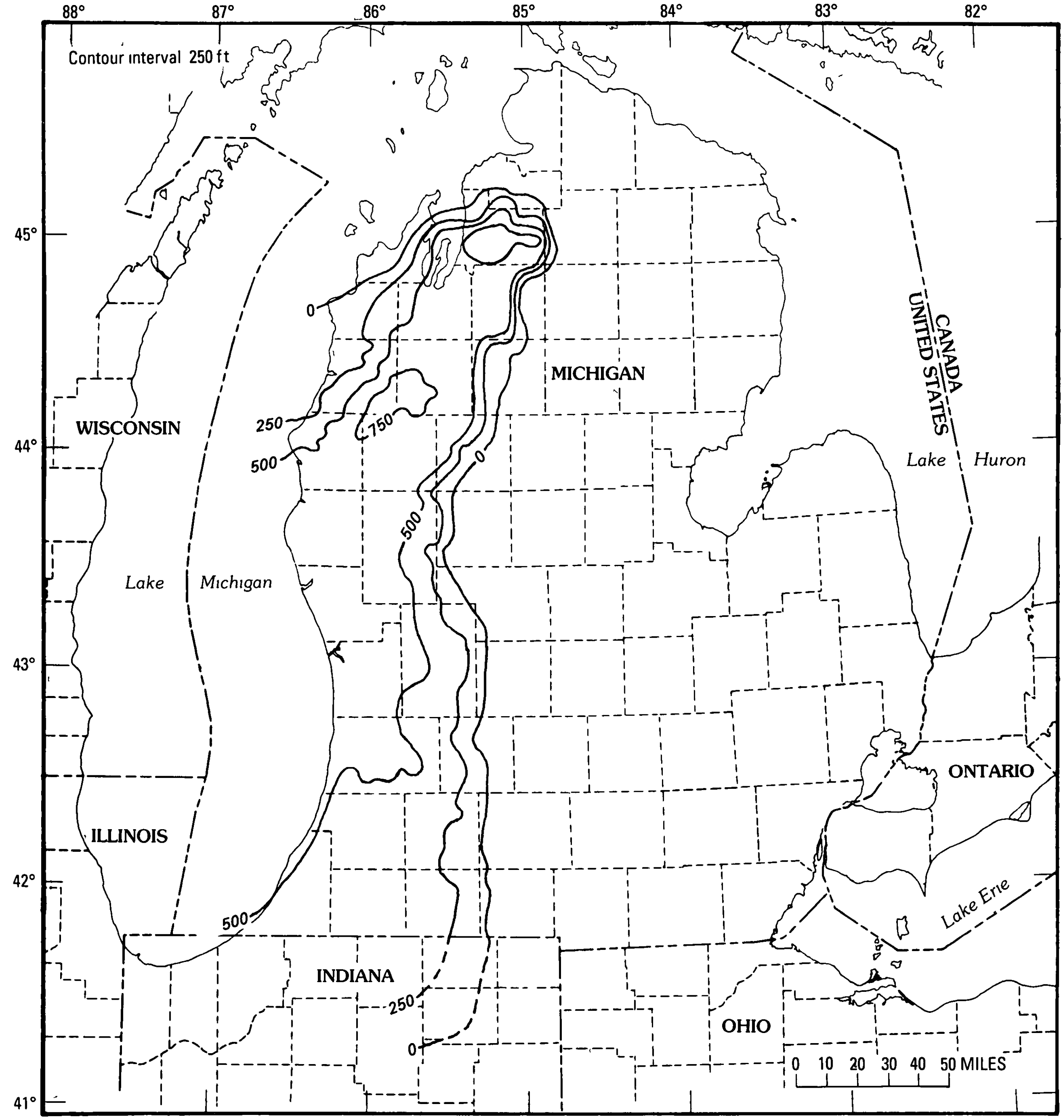

Figure 9. Isopach map of Ellsworth Shale (Modified from Fisher, 1980, pl 11)

basal Bedford shales in central and western Michigan were deposited in relatively deeper water areas where the euxinic environment of the Antrim persevered into Bedford time Thus, a black or dark shale facies of the Bedford does occur beyond the limits of the Bedford-Berea deltaic deposits, as they are generally recognized Ells (1979) was correct to identify some Bedford as black

Sunbury Shale

The Lower Mississippian Sunbury Shale is dark gray to black, brittle, and carbonaceous It is widespread and averages from 30 to 40 ft across most of the basin, although, locally in western Michigan, it exceeds 50 ft (fig 12) It is absent in the southwest

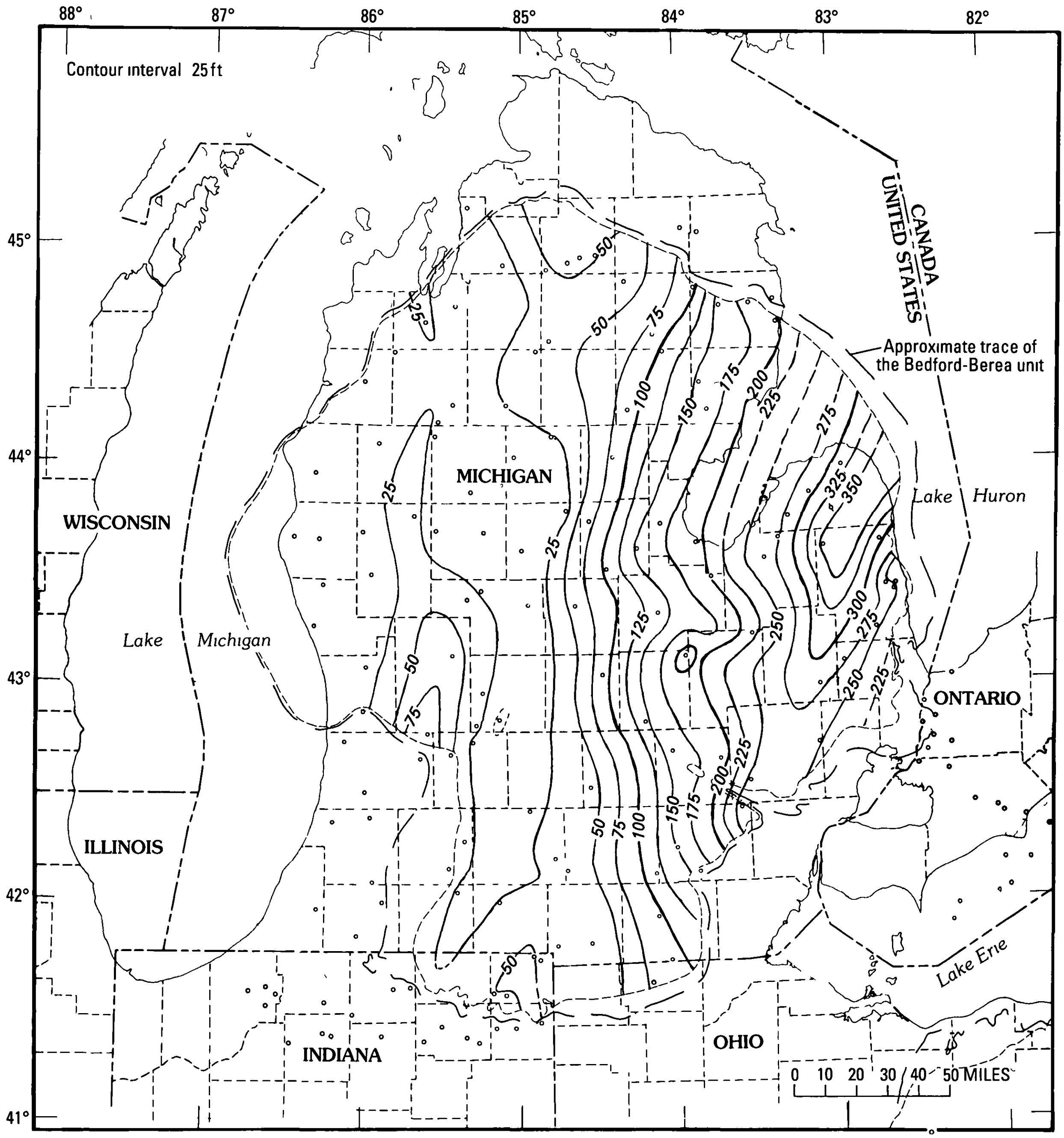

Figure 10. Isopach map of Bedford-Berea unit

A rapid change in thickness occurs in the Sunbury in eastern Michigan where the formation reaches 165 ft or more In northern Sanilac County, a nearly normal 66 ft expands to 124 ft across a distance of 18 mi Such a change in thickness suggests a facies relation between the abnormally thick part of the upper Sunbury and part of the lower Coldwater Shale The radioactive patterns of the basal Coldwater in eastern Michigan have not been studied in detail At this stage, it is not possible to verify the postulated upper boundary of a "B/C" wedge (fig 8) that increases in thickness westward into the basal Coldwater Shale Because of the nearness to Lake Huron and the absence of subsurface control to the east under the lake, it is also not possible to show a postulated decrease in black shale thickness in an eastward direction as the postulated "B/C" wedge of upper Sunbury would predict The pattern is, however, similar to that of an idealized black shale sequence—a widespread 40-ft-thick black shale (that is, the "normal" Sunbury)—overlain by an apparent black shale facies shale "B " The similarity to the physical geometry of

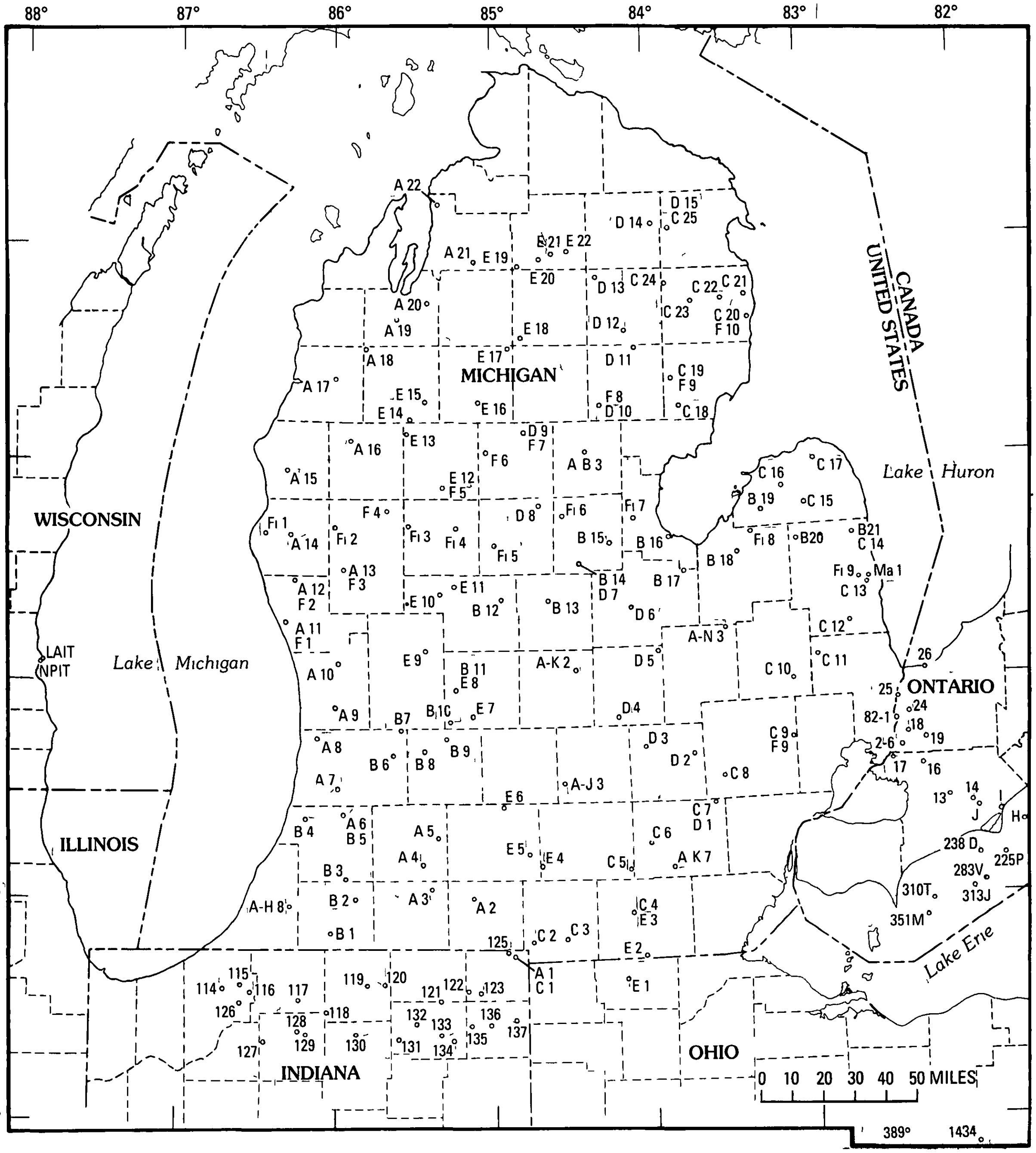

Figure 11 Locations of wells used in this study Some wells were assigned dual identification numbers, for example, A 1 and C 1 are the same well

the "upper Sunbury" and the gray Orangeville Shale in northern Ohio, as described by Pepper and others (1954), is noteworthy (fig 13) The recognition of two genetic types of Sunbury Shale in the Appalachian basin by Van Beuren (1981, p 12) supports the concept, he described a "characteristically thin and widespread" black shale (the "A" shale of my model) overlain by a black shale ("B") that is more laterally restricted and is a "distal facies" of laterally adjacent nonblack clastics ("C")

The Sunbury is absent in the southwestern part of the Michigan basin, whether this is due to depositional pinch out (Baltrusaitis and others, 1948) or to erosional truncation is debatable The formation is less than 10 ft thick near its western zero line in Barry, Kalamazoo, and St Joseph Counties, Mich , and in parts of Indiana A pinch-out there is certainly plausible In its southern terminus through Ottawa, Kent, and Allegan Counties, however, the loss is abrupt and unlike the consistent depositional pattern seen

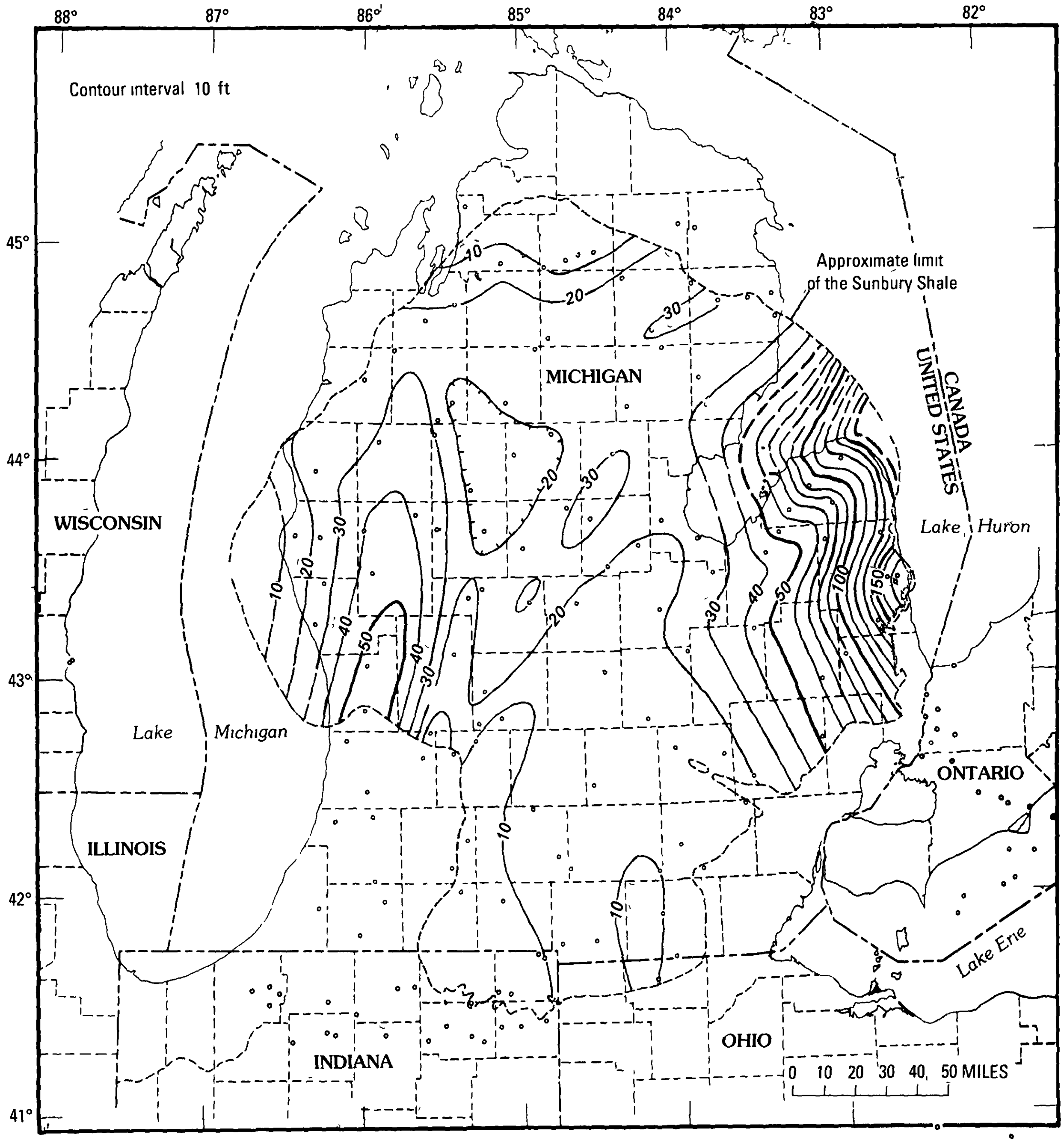

Figure 12. Isopach map of Sunbury Shale

throughout most of the basin The Sunbury in central Ottawa County is 56 ft thick in one well and absent in another well 14 mi away The Bedford Shale, which is not covered by the Sunbury, is present in a strip through Kalamazoo and St Joseph Counties beyond the zero line of the Sunbury, in that area, it appears that the Bedford has been truncated by an episode of post-Sunbury–pre-"Coldwater Red Rock" erosion West and south of the Bedford limit, I believe the Ellsworth also has been truncated It increases in thickness to the west, through Barry County, at a rate of about 11 feet per mile (ft/mi), and, west of the Bedford zero line, where the Ellsworth is overlain by "Coldwater Red Rock," it continues to thicken but at the much lower rate of about 3 ft/mi I attribute the reduction in the rate of thickening to erosional loss

A core of the Sunbury from Midland County contained occasional brachiopods and a *Callixylon* impression Because the upper contact of the black Sunbury with the gray Coldwater Shale in the core was sharp and the shale immediately above contained glauconite, I believe that

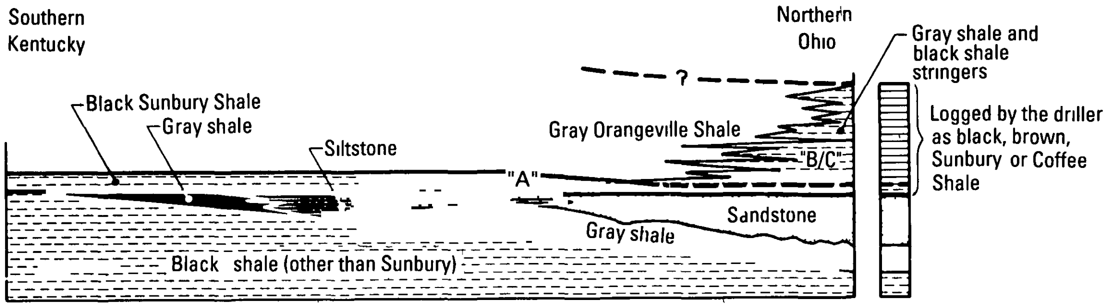

Figure 13. Physical geometry of the Sunbury Shale and related rocks in Ohio as it conforms to the idealized black shale sequence shown in figure 8 The shale labeled "Black Sunbury Shale" is a widespread deposit of the "A" type A lower portion of the "gray Orangeville Shale" exists in a facies relation to "gray shale and black shale stringers", these time-equivalent rocks have the characteristics of a "B/C" wedge (Modified from Pepper and others, 1954)

the top of the Sunbury marks a paraconformity or disconformity

The base of the Sunbury is an erosional unconformity in Ontario, according to Sanford (1967) In cores in Midland and Sanilac Counties, the Berea-Sunbury contact is sharp, and the upper few inches of sandstone are greenish (glauconitic?) and pyritic Because Sunbury deposition appears to have been a much later event than the cessation of the deposition of the Berea, the contact at the base of the Sunbury also marks a disconformity or an erosional unconformity

Coldwater Shale

The basal Coldwater Shale (Mississippian) contains an informal marker called the "Coldwater Red Rock," which consists of one or more thin beds of red shale and red shaly limestone The red rock marker is present over most of the basin but is best developed in western Michigan At its base, it includes a distinctive deflection to the left on gamma-ray logs that is used for lack of a better device to indicate the base of the Coldwater Shale where the Sunbury is difficult to identify or is absent

The core of the basal Coldwater Shale in Sanilac County above the Sunbury consisted of almost 19 ft of a gray shale overlain by almost 5 ft of sandstone that looks like a younger Bedford-Berea delta in miniature This thin 19-ft sequence of beds completes a second repetitive ascending sequence of black shale, gray shale, and sandstone Included in the first sequence are the Antrim Shale (black), the Bedford Shale (gray), and the Berea Sandstone This sequence is followed by a second one composed of the Sunbury Shale (black), the "Coldwater shale" (gray), and the "Coldwater sandstone " The basal Coldwater Shale may contain the distal remnants of a unrecognized delta overlying the Sunbury Shale

The basal 1 inch of Coldwater Shale is greenish in color, probably because of the glauconite This is similar to the glauconite observed immediately above the Sunbury-Coldwater contact in Midland County cores The sharpness of the upper contact of the Sunbury and the presence of glauconite duplicate the pattern observed in several Dow cores at the Antrim-Bedford contact, this pattern of a sharp contact with glauconite is advanced as evidence of disconformity at both contacts

Discussion of Proposed Informal Units

In the construction of the maps presented here, the Michigan basin was approached regionally, and shales preserved in the basin were considered to be only remnants of larger deposits that once extended across the eastern midcontinent With this in mind, the thinning of a unit along present basin margins was as likely to be the result of one or more Late Paleozoic or post-Paleozoic erosional truncations as it was to be of depositional pinch-out I assumed that black shale characteristics observed in other basins, such as common patterns of depositional wedges, abrupt facies changes, frequent paraconformities, and erosional truncations, had application in Michigan

I projected contour lines into and, in some cases, beyond the area where a mapped unit had been eroded to suggest a once-continuous deposition over the arches Contours were not closed off to indicate actual preserved thickness near the zero line where partial sections were covered by glacial drift Thicknesses were aggregated to support the thickness of units projected across the Michigan-Ontario border In Ohio, total shale interval thickness was based on Hoover's (1960, pl 3) map and conforms to the three Ohio control wells in my data set

The complexities of a shale-to-shale facies change and apparent time lines based on gamma-ray correlation lines crossing lithologic boundaries based on color make the traditional stratigraphic nomenclature confusing and inadequate to describe properly the stratigraphic relations within the Devonian-Mississippian sequence in the Michigan basin The boundaries of the Antrim Shale cannot be based correctly on the occurrence of a black shale lithotype Because of the widespread availability of gamma-ray logs, the black shale sequence is best described through the use of log patterns However, this offers little guidance to the well-site geologist who is trying to describe drill cuttings before the well is logged or to the researcher who is attempting subsurface work using only data from drillers' logs or scout tickets Formational "tops" that are based on the occurrence of a black shale in the geologic column have no regional validity across large parts of the Michigan basin, although black shale "tops" may serve informally as useful working units locally

My 1982 maps were based on the well data sheets appended to Ells' (1979) study In updating those maps for this report, I have increased Ells' original 99 control wells to 162 (fig 11) by adding new wells selected from literature sources and reproductions, not from original logs, to fill in gaps, to identify faulted areas (that is, missing sections or abnormal thicknesses), and to clarify basin margins Consequently, the geographic scope of his maps has been enlarged The 162 wells used for control in this report are shown in detail on the well data sheets in Appendix C, any deviations from Ells' data are explained in the individual well data sheets All control wells used in the study (fig 11) are identified by Ells' designation or by other codes, for example, A–K 7 is from Lilienthal's (1978) section A–K The various authors' lines of cross section are omitted, however, each published line of section can be determined—E 1, E 2, and E 3 for Ells' (1979) E section and Fi 1, Fi 2, and so forth for Fisher's (1980)

The best way to illustrate the complexities of the Devonian-Mississippian stratigraphy in Michigan is to show east-west sections that cross the facies change in midbasin at right angles to depositional dip In this way the most rapid change in lithology can be documented In Michigan, lines of stratigraphic cross section (fig 14) that run north and south are generally parallel to depositional strike, and, if far enough to the west or to the east, then the individual wells will present few problems in correlation However, the lines of section that run north and south along the zone of facies change (for example, along the eastern "edge" of the Ellsworth [fig 9]) will present misleading patterns that will be exaggerated by changes in direction as the line "zig zags" back and forth across the facies change

Four of the five east-to-west cross sections (figs 15, 16) are composites of tracings of individual well logs and data from Ells' (1979) report The lines of section for the five cross sections are shown on an index map (fig 14) Ells' unit designations are shown only where those units involve my correlations at the top or the base of the Ellsworth/upper Antrim Differences between my correlations and those of Ells can be seen on four of the gamma-ray log sections, for example, in the "Southern" section of figure 16, my correlation line at the base of the Ellsworth/upper Antrim at the western end (B 4–B 2) differs from the top or the base of Ells' Unit 2 Differences are also shown at the top of the Ellsworth/upper Antrim, as in the "South-Central" section of figure 16 between B 9 and C 8, where my correlation line moves from the base of Ells' Unit 7 (B 9), to the base of Unit 6 (D 4), to a split of Unit 5 (D 2), and back to Unit 7 (C 9)

Two east-to-west gamma-ray stratigraphic cross sections in northern Indiana were published as part of the EGSP (Hasenmueller and Bassett, 1980) The shale-to-shale facies change from nonradioactive Ellsworth-type shales in the west to radioactive Antrim-type shales in the east is depicted by Hasenmueller and Bassett between wells 120 and 121 (fig 11) In their sections, the Antrim was considered to include the "Traverse Formation" of informal Michigan usage (fig 17) The sequence identified as the Bedford Shale by Ells (1979) is called the Ellsworth Shale in the Indiana sections The Indiana sections are composed of closely spaced logs, which resulted in an informative document that I have adapted to the nomenclature used in this chapter Twenty-three Indiana wells from the Hasenmueller and Bassett (1980) sections are included in the individual well data sheets (Appendix C)

The rationale for the separation of the Antrim into upper and lower units, as suggested by LeMone (1974), Fisher (1980), and Matthews (1983a, b), was based primarily on the consistent basinwide gamma-ray pattern of the lower beds of the Antrim generally below Ells' Unit 2 rather than on the more complex spatial geometry found in the Antrim and the Ellsworth Shales above Unit 2 It was not until the discovery of the time-stratigraphic marker fossil *Foerstia* (*Protosalvinia*) within Unit 2 that paleontological evidence became a part of the rationale for division (Matthews, 1983b) I postulated a hiatus at the point of the suggested division similar to the reported paraconformity developed as the result of a study of the *Foerstia* zone in southern Indiana and northwestern Kentucky (Conkin and Conkin, 1974, 1982) I have observed reddish-brown shale in drill cuttings near the base of the Ellsworth/upper Antrim in Otsego County, the extent and significance of this "redrock marker" is unknown, but it occurs at or near the stratigraphic position of the postulated depositional hiatus above the lower Antrim

Because the Ellsworth Shale, as a recognizable lithotype based mainly on color, and a part of the dark shale of the eastern Antrim are time-equivalent facies, I have treated them as one mappable unit, the Ellsworth/upper Antrim (fig 18) The Bedford-Berea also is treated as a single mapping unit of genetically related rocks (fig 10)

I have mapped the lower Antrim (fig 19) separately from the Ellsworth/upper Antrim (fig 18) The contact between the two is based on gamma-ray log correlations within or close to Ells' Unit 2 The relation of the top of the lower Antrim to Ells' informal units is indicated on the individual data sheets (Appendix C) Any differences in the Ellsworth/upper Antrim–Bedford contact also are noted on the data sheets

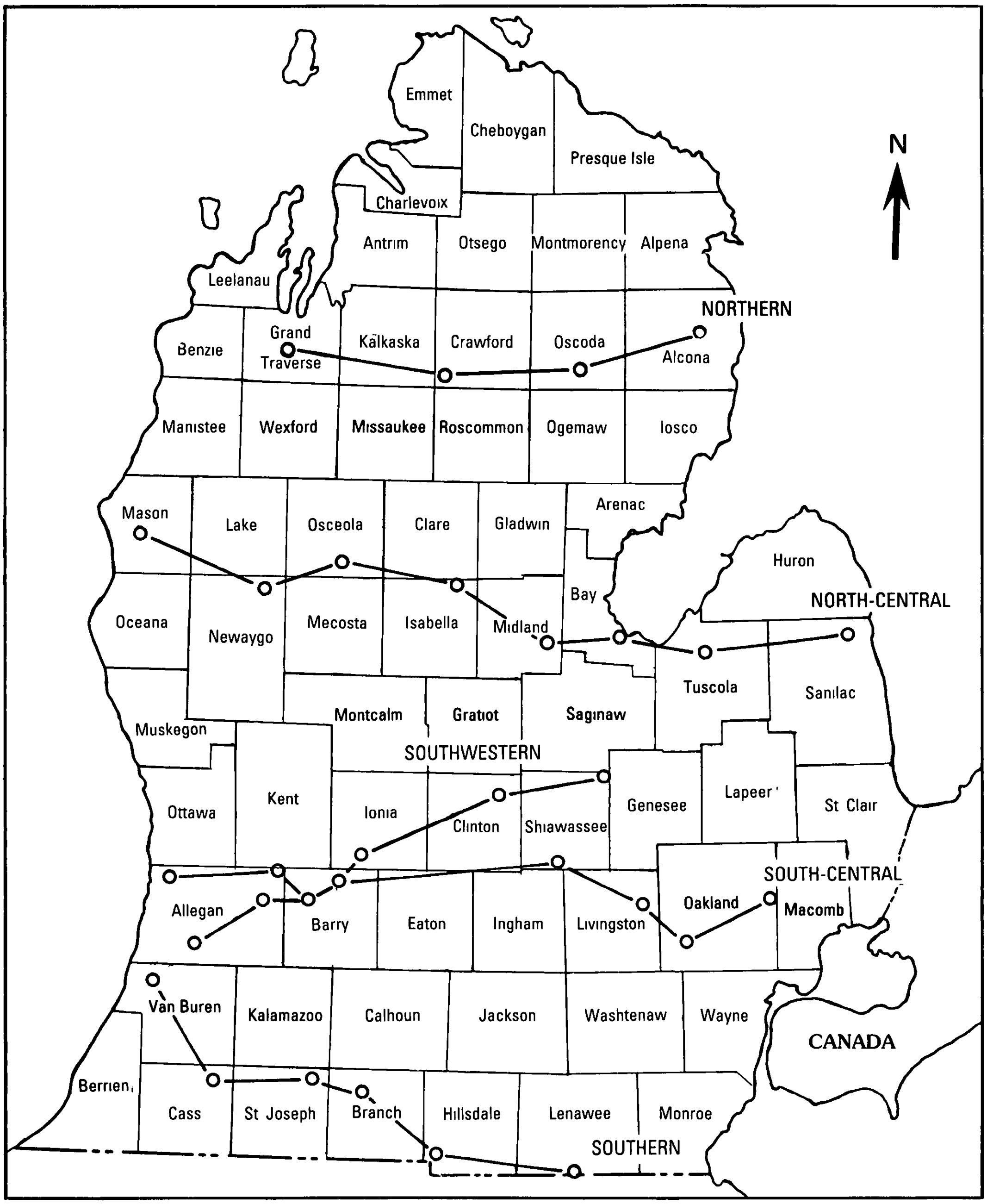

Figure 14. County names in the Lower Peninsula of Michigan and lines of cross section used in this study (figs 15, 16, 22)

In Ontario, the lower Antrim was considered to be that part of the Kettle Point Shale found below the published position of *Foerstia* (Russell, 1985) In Michigan, the contact between the lower Antrim and the Ellsworth/upper Antrim is placed at the known or predicted zone of *Foerstia* This zone has been projected across the basin by using Ells' logs in many combinations The contact, which is based on the projection and best correlations of the *Foerstia* zone, falls within or slightly above or below Ells' Unit 2

The positions of the subcrop traces and zero isopach lines for the several mapped units shown on the geologic map shown in figure 20 are my interpretations that were based on the published sources listed in the caption Because the contact between the lower Antrim and the Ellsworth/upper Antrim is based on log correlations, it was not possible to mark the map trace of that contact The top and the base of the Antrim (Da) in the east and the Ellsworth (De) and the Antrim (Dla) in the west are conventional in subcrop treatment

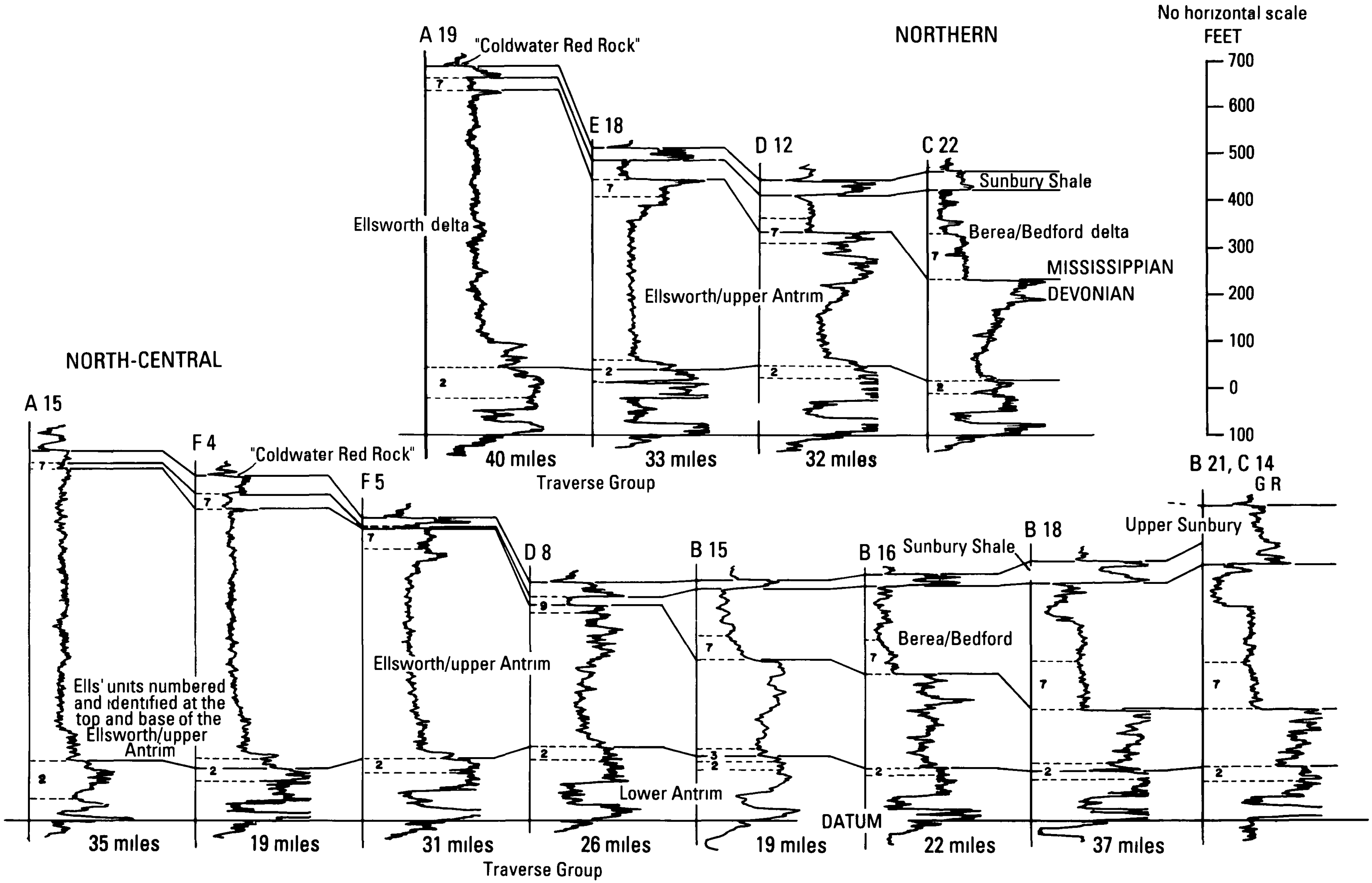

Figure 15. Northern and north-central stratigraphic cross sections based on gamma-ray logs traced from Ells' (1979) report Numbered segments identify some of his units Boundaries of the major informal units used in this study are shown as they relate to his unit correlations

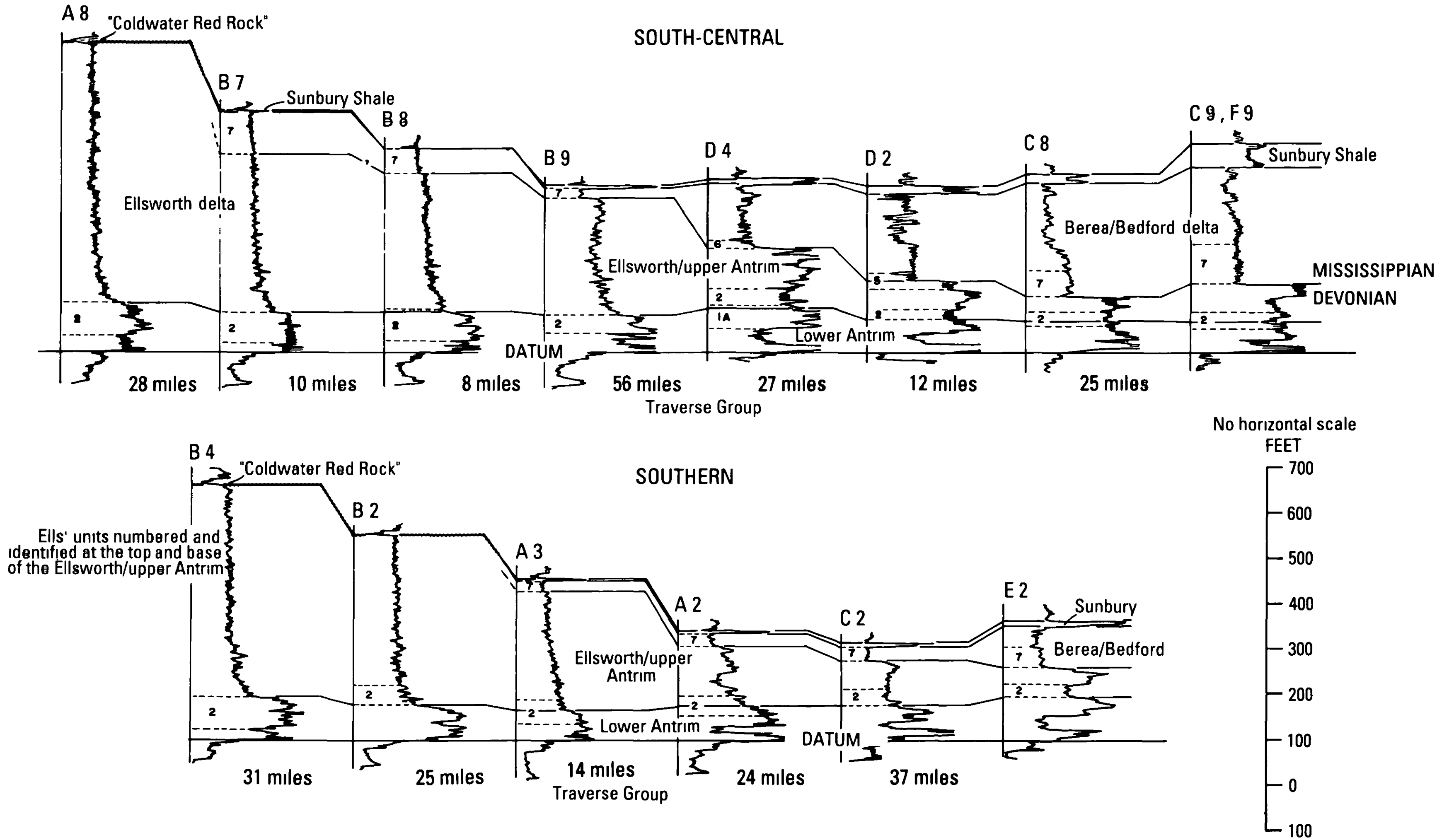

Figure 16. South-central and southern stratigraphic cross sections based on gamma-ray logs traced from Ells' (1979) report Numbered segments identify some of his units Boundaries of the major informal units used in his study are shown as they relate to his unit correlations

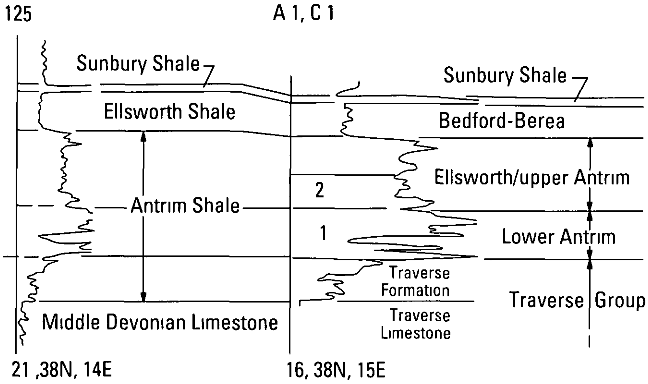

Figure 17. Differences in nomenclature and gamma-ray log correlations between Indiana usage, which is shown in well No 125 (Hasenmueller and Bassett, 1980), and Michigan usage, which is illustrated by a well that has dual identification numbers, A 1 and C 1 (Ells, 1979) The two wells in this section are in Steuben County, Ind , approximately 6 mi apart The terminology shown in well A 1/C 1 is that used in this study Ells' (1979) Units 1 and 2 are designated

Interpretation

The stratigraphic relations within the Devonian-Mississippian shale sequence can be clarified if one considers depositional units embracing genetically related sediments These informal units—the lower Antrim, the Ellsworth/upper Antrim, and the Bedford-Berea—can be delineated by gamma-ray log correlations Depositional hiatuses of varying severity, including one major erosional truncation, are postulated to mark the boundaries of these units

The thinning in the basin center of the total Devonian-Mississippian shale interval, which was of such concern to earlier writers, is apparent whether one includes the transition zone in the top of the Traverse Group (fig 20), as Fisher (1980, pl 14) did, or excludes it, as I did (fig 21) The central thin zone represents the aggregate thickness of two separate depositional wedges entering the basin initially from the west and later from the east As noted by McGregor (1954, p 2335), isopach lines do not follow the circular configuration of the basin, thus "implying the extent of the basin is greater than shown" on a map of the present structural basin The Devonian-Mississippian shale sequence in Michigan must be considered to be made up of small remnants of once larger regional deposits

The informal unit at the base of the sequence in my analysis is the lower Antrim, which has a consistent gamma-ray pattern of nearly uniform thickness across most of the basin (fig 19) It changes gradually in thickness from over 175 ft in north-central Michigan to less than 50 ft in northern Indiana and in Ontario It does not seem unreasonable to postulate a continuous deposition across the Algonquin and the Findlay arches (fig 1) by connecting the 100-ft thickness in Ohio with the 100-ft thickness in Ontario and projecting 125- and 150-ft contour lines to bridge the gap (fig 19) An overall thickening trend to the southeast into the Appalachian basin is suggested from a minimum of 53 ft (C 1, D 1) in northeastern Washtenaw County, Mich

The Ellsworth/upper Antrim has been described as a single unit of time-equivalent rocks that forms a wedge thinning away from its source (Matthews, 1983a, Matthews and Feldkirchner, 1983) The Ellsworth/upper Antrim (fig 18) shows a broad axis of thin shale that extends south-southwest from Huron County in the Thumb delta through Lapeer and Oakland Counties on into Ohio I once referred to this thin zone as "a previously unrecognized arch or platform" (Matthews, 1983a, p 6), but I now believe it is better explained as a basinal plain far enough from the northwestern source of the Ellsworth delta to receive little sediment from either the Ellsworth or the Catskill deltas in the east The Catskill delta and other eastern clastic sources in the Appalachian basin probably contributed to the material east of this thin zone in eastern Michigan

Two other features of the Ellsworth/upper Antrim unit deserve comment—a rapid east-to-west thickening in north-central Michigan that changes abruptly to a relatively constant thickness in Wexford and Mason Counties and an abrupt shift in spacing and direction of contour lines that occurs in Allegan and Barry Counties in western Michigan (fig 18) By my analysis, the northwestern columnar section includes the Sunbury and the Bedford Shales, although I do not place as much of the highly radioactive black shale within the Bedford as Ells (1979) did (see data sheets for wells D 8–D 13, E 12, F 7, and F 8 in Appendix C) Any erosional truncation of the Ellsworth/upper Antrim overlain by the Bedford would have to have been pre-Bedford Erosion at that time is possible The upper contact of the Ellsworth/upper Antrim with the overlying Bedford in central and eastern Michigan is abrupt where it has been cored several times by Dow It appears to be disconformable That this surface experienced a severe hiatus resulting in erosional truncation in the west can be conjectured The leveling off may be simply a depositional feature related to the deltaic origin of the unit

The thickness changes in Allegan and Barry Counties are puzzling, and several interpretations were considered In general, I concurred with Ells' (1979) tops, and my map is the result of contouring thicknesses based on his top of the Ellsworth under the Bedford equivalent or below the "Coldwater Red Rock" where no Bedford was present Ells implied a facies relation between the Bedford equivalent and the upper part of the Ellsworth, and, in that analysis, the shift in contours would mark the "cutoff" at the facies change I considered another solution that postulates a loss of the Bedford and the Sunbury Shales by pre-"Coldwater Red Rock" erosional truncation as shown in the cross section "Southwestern" in figure 22 A rapid thickening of

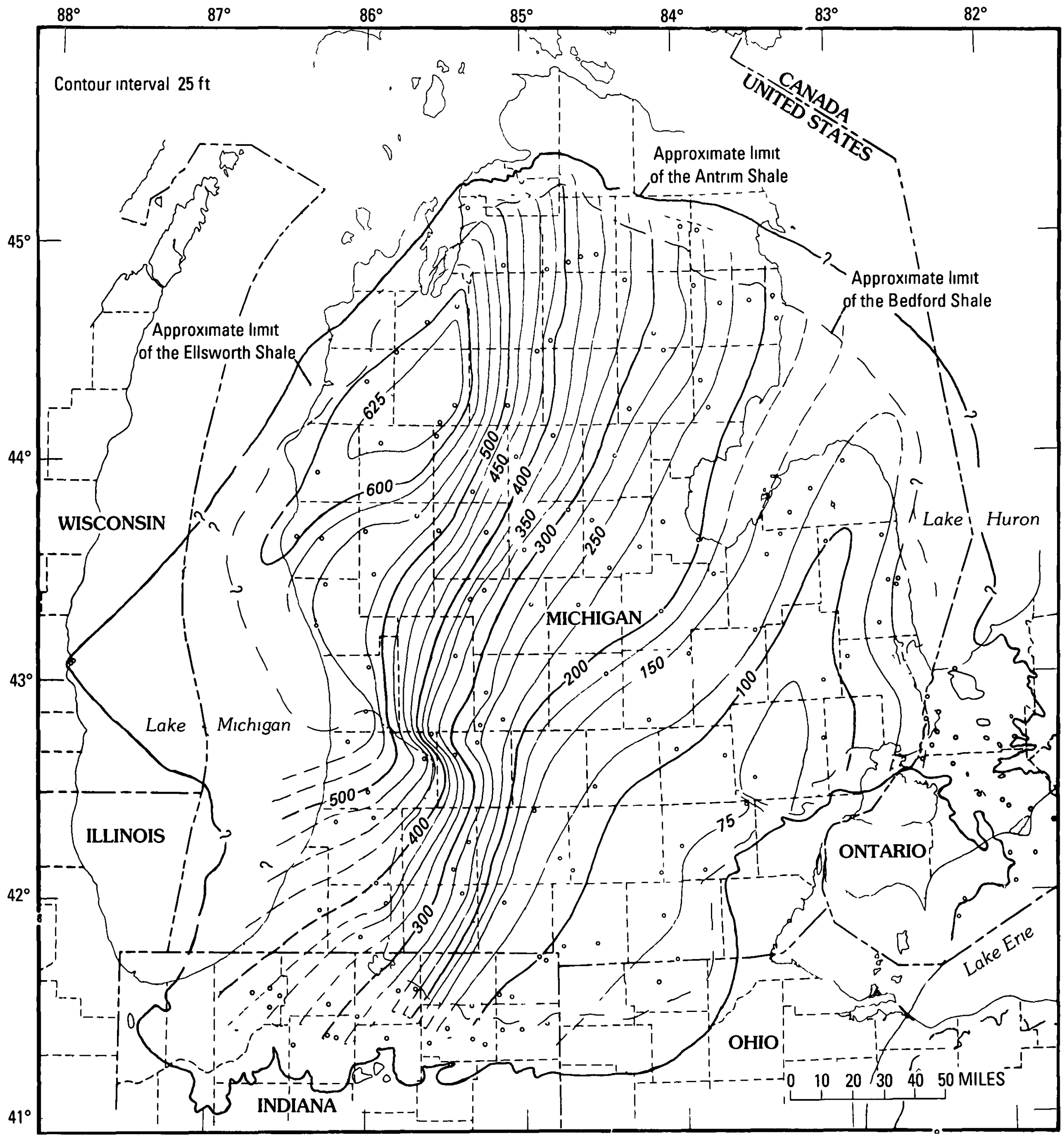

Figure 18. Isopach map of Ellsworth/upper Antrim Shale

an apparent Ellsworth equivalent shale in the Illinois basin and its truncation (fig 23) appear to be similar in geometry to the Ellsworth/upper Antrim The truncations in both basins may be time related, the Hannibal "is truncated by erosion below the Burlington Limestone in western Illinois" (Reinbold and others, 1980, p 32), the Burlington is Mississippian (Atherton and others, 1975) According to the Illinois Geological Survey, the Devonian-Mississippian boundary is "probably occurring near the base of the Hannibal Shale" (Atherton and others, 1975, p 125) Thus, two similar shales that thicken to the northwest in neighboring basins appear to have been truncated by Late Devonian or early Mississippian erosion

When the widespread lower Antrim is combined with the overlying informal unit made up of the different facies of the Ellsworth delta (fig 24), a massive wedge of shale more than 800 ft thick is formed in the northwest and thins to less than 150 ft along an axis in southeastern Michigan This thin axis, which extends from the eastern Thumb delta south-southeast into Ohio and Indiana, appears to separate

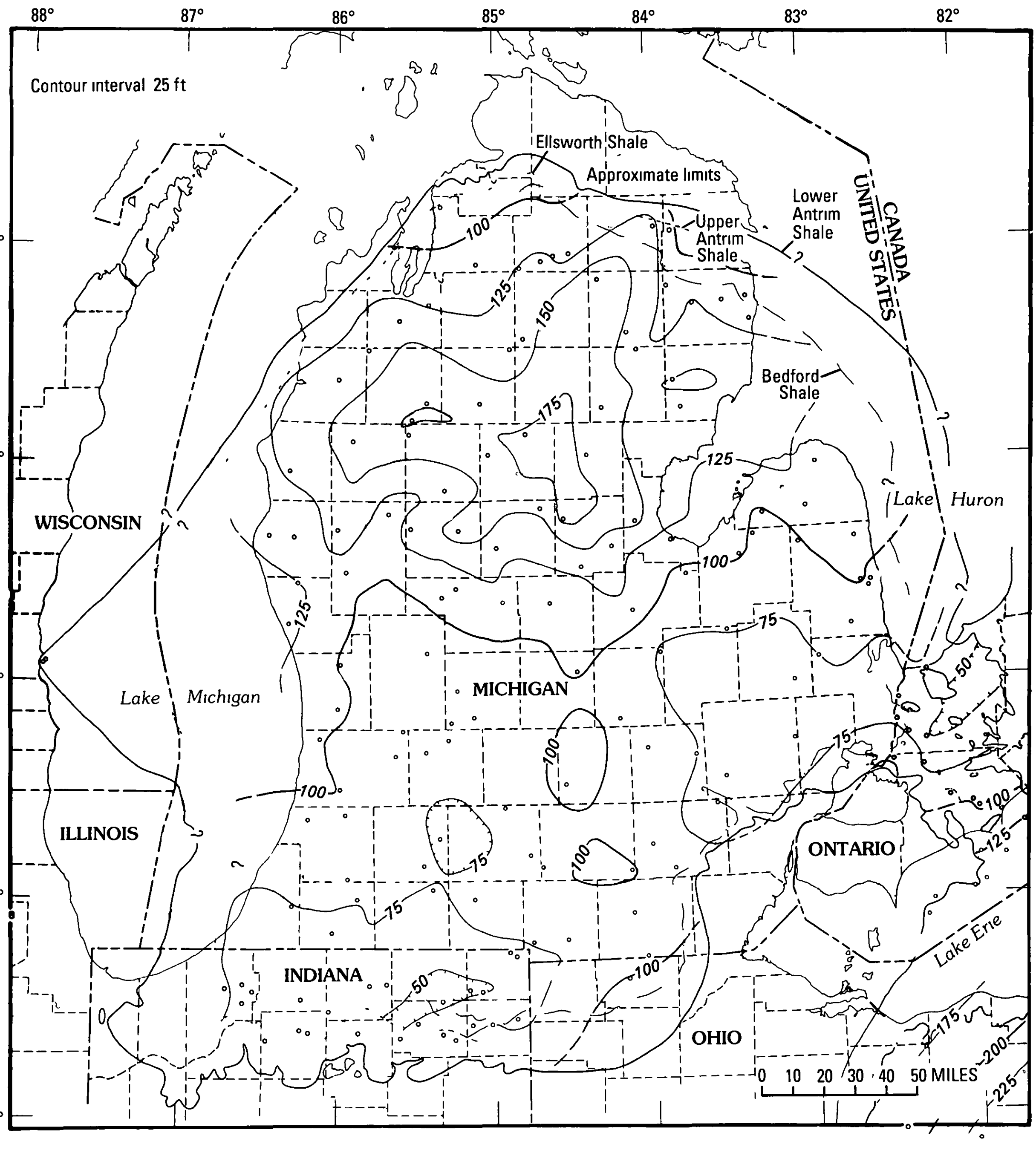

Figure 19. Isopach map of lower Antrim Shale

the bulk of the Michigan deposit from an Appalachian Devonian shale wedge that is independent of the present positions of the Algonquin and the Findlay arches (fig 1) Based on the three Ohio wells posted, contours in Ohio show a postulated westward thinning to about 450 ft The projected thickness in the Michigan-Ontario border area increases gradually to about 250 ft southeast of the thin axis toward Ohio Bridging this thickness gap of 200 ft across the Chatham sag in Ontario seems plausible, although it is certainly conjectural

The thick area in the northwestern part of the Michigan basin shows a northeast-to-southwest trend, if this trend is extended into the Illinois basin, then it would pass through the Western Depocenter shown on the isopach map of the total New Albany Shale Group (Reinbold and others, 1980, p 22, fig IB–2) and on the regional isopach in this chapter (fig 3) The Western Depocenter in the Illinois basin shows more than 200 ft of thickness preserved It may be that during the late Devonian these two western areas were part of a single Devonian shale thickness trend

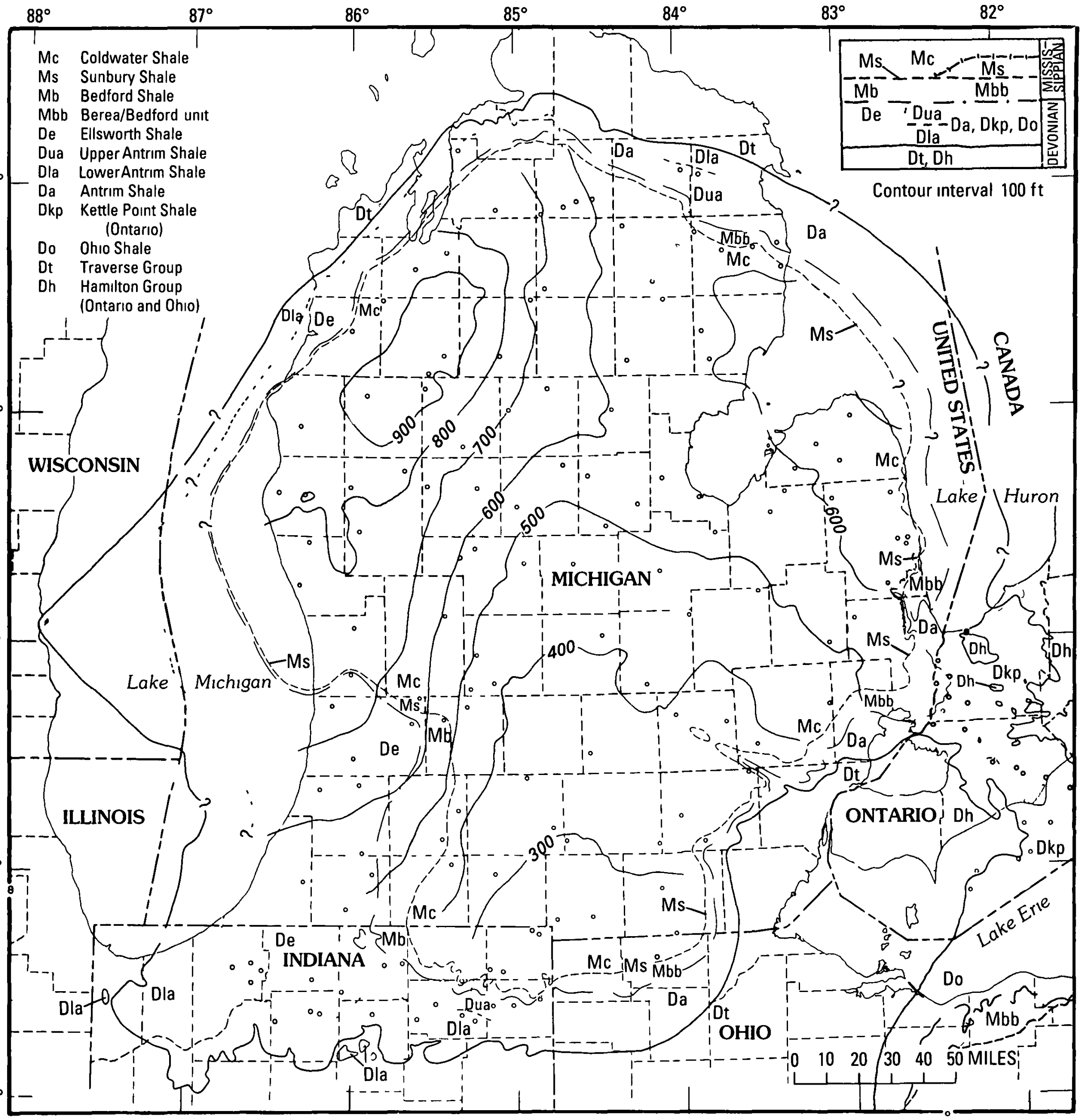

Figure 20 Total Devonian-Mississippian shale interval ("Traverse Formation"-Sunbury Shale) modified from Fisher (1980, pl 14) and geologic map The geologic map is based on the following authors Bird (1983), Brigham (1971), Brown (1963), Carlton (1982), de Witt (1960), Edwards and Raasch (1921), Ehlers and Kesling (1970), Fisher (1973, 1980), Gardner (1974), Hasenmueller and Bassett, (1979), Janssens and de Witt (1976), Kesling and others (1974), Martin (1936), Matthews (1973), Ostrom and others (1970), Pepper and others (1954), Russell (1985), Uyeno and others (1982), and Wold and others (1981)

The Bedford-Berea delta, which prograded from the east and the northeast, was a separate event from the Ellsworth delta and followed a gap in time at the top of the Ellsworth/upper Antrim The western delta contributed not only to the Ellsworth Shale in the west but also to most of the time-equivalent black upper Antrim facies in the east Both shale facies of the Ellsworth delta were in place across the basin before the Bedford-Berea sediments entered the Michigan basin In northern Ohio, Bedford muds covered the black sediment of the Cleveland, which was soft enough to be deformed (Lewis, 1982), however, the Bedford-Berea entrance into Michigan occurred later than in Ohio (Pepper and others, 1954) Judging from several cores of the Antrim-Bedford contact I have examined in Midland and

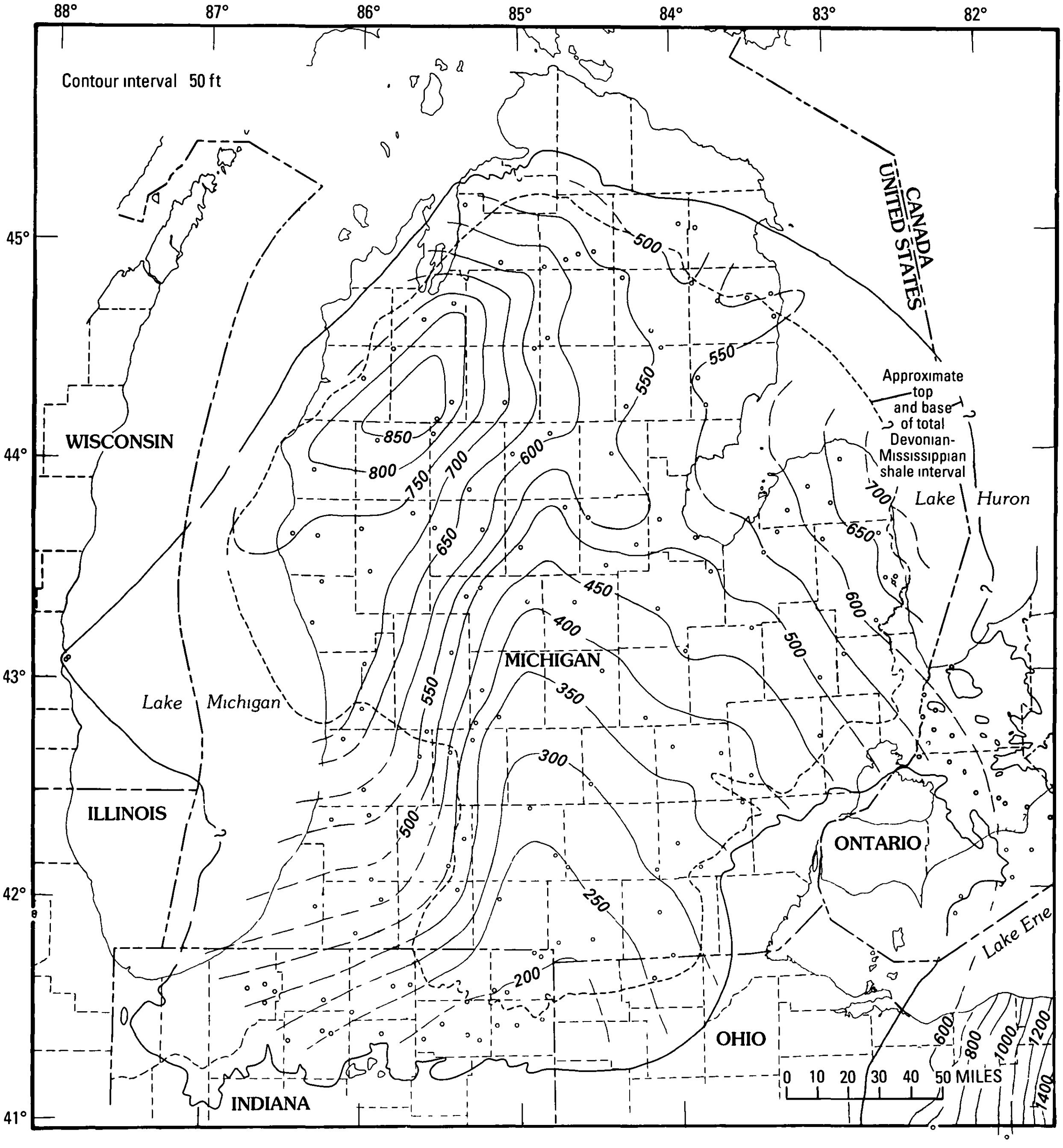

Figure 21. Isopach map of total Devonian-Mississippian shale interval as defined in this study

Sanilac Counties, the uppermost Antrim beds show no evidence of similar soft deformation I believe that the Bedford and the Ellsworth in western Michigan are also separate noncorrelative shales The Bedford is younger and overlies the Ellsworth Based on my correlations, they are not facies of one another

The westward thinning of the Bedford-Berea was expected, as was its thick axis through the Thumb delta, however, the thinning eastward from that axis was not so expected (fig 10) In my interpretation, the northern edge of the thick area of Bedford-Berea in Newaygo County was assumed to have been truncated by erosion along its southern edge and not to have been terminated by depositional pinch-out because it changes from 94 ft to zero in less than 8 mi This curious feature requires further study The western edge of the Bedford-Berea, which extends from LaGrange County, Ind , to Barry County, Mich , does not show the same abrupt loss, however, the Bedford-Berea is

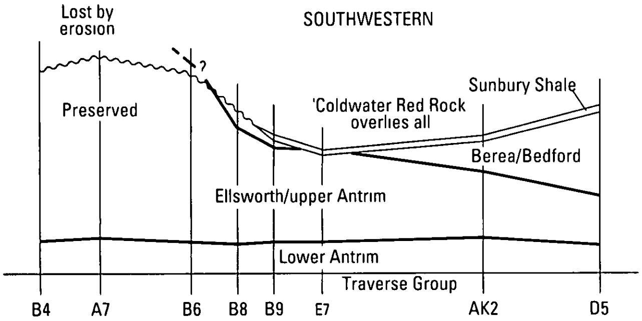

Figure 22. Postulated pre-"Coldwater Red Rock" erosional truncation of the Sunbury, Bedford, and part of the Ellsworth Shales. See appendix C for dimensions.

overlain by the "Coldwater Red Rock" in an area about 15 mi wide. I have interpreted this to be an area of truncation by pre-"Coldwater Red Rock" erosion (fig. 2*C*).

In southwestern Michigan, Bishop (1940, p. 2161) recognized an unconformable surface at the top of the Traverse Limestone and "an even more apparent nonconformity at the top of the Ellsworth." I agree and suggest that the complexity at the top of the Ellsworth in western Michigan is explained by post-Sunbury–pre-"Coldwater Red Rock" erosional truncation, possibly concurrent with the pre-Burlington truncation of the Hannibal-Saverton Shale interval in the northwestern Illinois basin (fig. 23, Cluff and others, 1981).

The Sunbury Shale (fig. 12) also shows a thick north-to-south axis in western Michigan, which is similar to the one in the Bedford-Berea, but it is offset by about 10 mi to the west. The Sunbury also is truncated abruptly. Explanations based on depositional thinning or facies change in the west are not as satisfactory as those based on an erosional truncation (fig. 2*C*). At certain control points in the east, the Sunbury is thick—165 ft seen in Fisher's (1980) Fi 9 and 172 ft in a well (Ma 1) in Sanilac County. Ells' (1979) nearest well (C 13) to these two controlling thick wells is anomously thin as the result of a loss of section caused by faulting. The anomalous well (C 13), which showed only 65 ft of the Sunbury, was not included on my map (fig. 12).

In my analysis, a wide area of southwestern Michigan has lost the Sunbury, the Bedford-Berea, and part of the Ellsworth/upper Antrim to pre-"Coldwater Red Rock" erosional truncation or an unconformity; in that area, contours are based on Ells' (1979) total thickness (fig. 21). The Ellsworth/upper Antrim sequence is a product of the Ellsworth delta. The Bedford-Berea, which is a later event, is the product of the Thumb delta. The postulated angular unconformity that truncated the Sunbury, the Bedford-Berea, and part of the Ellsworth/upper Antrim is shown by a wavy line in figure 2*C*; other hiatuses are not given special line treatment. Disconformities or unconformities, however, do occur in four other stratigraphic positions—

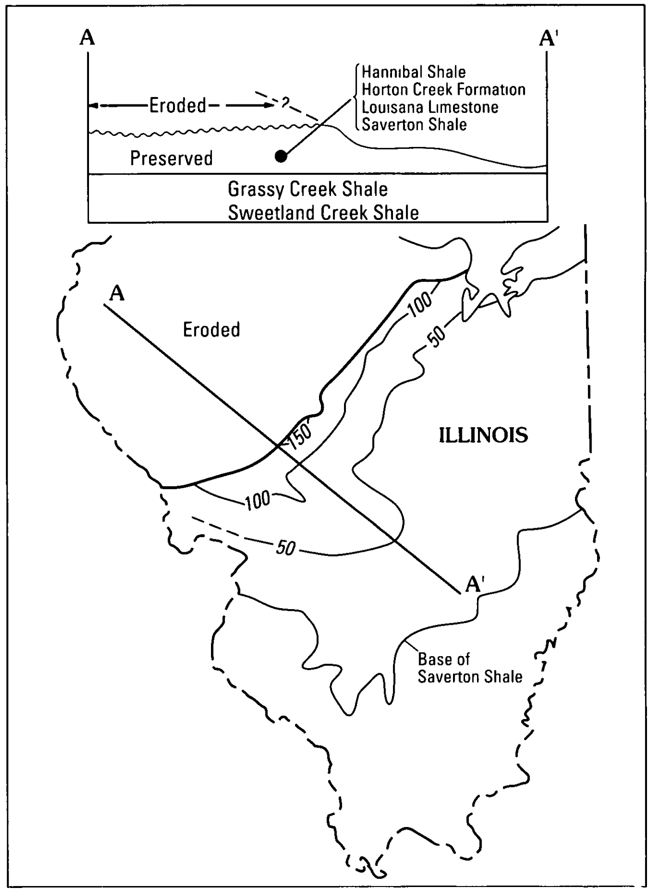

Figure 23. Saverton/Louisiana/Horton Creek/Hannibal interval in Illinois. Modified from Reinbold and others (1980, p. 28, fig. IV–7).

between the "Traverse Limestone" and the "Traverse Formation" in the eastern and the western parts of the basin, between the Ellsworth/upper Antrim and the overlying Bedford-Berea, between the Bedford-Berea and the overlying Sunbury, and between the Sunbury and the overlying Coldwater Shale. Paraconformities, which are small-scale disconformities, are thought to exist between the lower Antrim and the overlying Ellsworth/upper Antrim within the *Foerstia* zone during a time when tectonic influences altered the depositional setting of the region. A paraconformity also is postulated in eastern Michigan between the "Upper Sunbury" and the Sunbury.

The Devonian-Mississippian boundary is placed between the Ellsworth/upper Antrim and the overlying Bedford-Berea or at the base of the "Coldwater Red Rock" where the Bedford-Berea is not present.

DEPOSITIONAL ENVIRONMENT

The layered water model that was espoused by Rhoads and Morse (1971) and Byers (1977) and reviewed

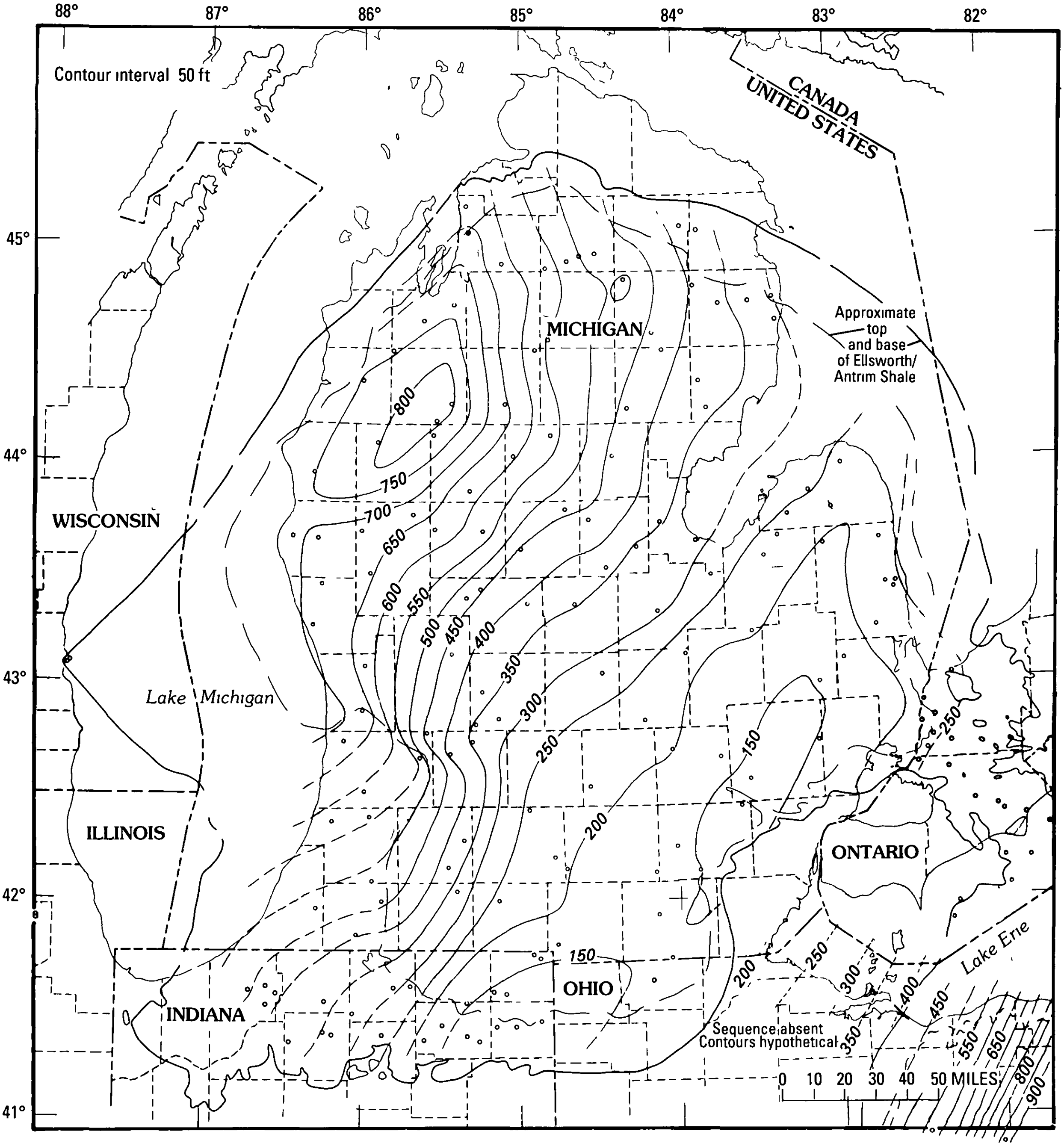

Figure 24. Isopach map of combined lower Antrim Shale and Ellsworth/upper Antrim Shale

by Cluff and others (1981) remains the best explanation for the deposition of the black Antrim-, the Ohio-, and the New Albany-type shales and their organic-poor facies of the Ellsworth and Chagrin type In such a stratified water model (fig 25), a mixed layer, the aerobic zone, which contains oxygen greater than 1 0 milliliter per liter (mL/L), overlies a transition layer, the dysaerobic zone, which has oxygen in the range of 0 1 to 1 0 mL/L, the deepest layer, the anaerobic zone, which is deficient in oxygen, has less than 0 1 mL/L Although water depths are conjectural, wave action can, by definition, influence only the upper layer The upper and the lower layers are referred to as the epilimnion and the hypolimnion, respectively A number of factors, including rate of organic or clastic deposition or both and changes in the wave base, can raise or depress the interface between the layers without necessarily changing sea level On a gently sloping sea floor, changes in the elevation of the interface will result in submarine transgressions or regressions of that interface across the sea floor Organic-rich sediments will accumulate in the deeper water

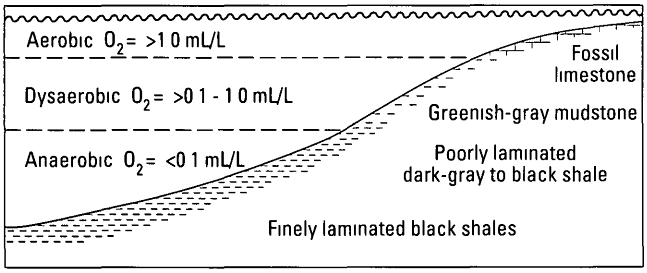

Figure 25. Model of an idealized stratified anoxic basin (Modified from Rhoads and Morse, 1971)

within the anaerobic environment, however, an organic-poor, time-equivalent facies will be deposited in the shallower water within the aerobic environment A series of transgression-regression movements of the layered water interface will result in the interbedding of the two lithotypes Because oxygenated water is involved during part of this process, the occurrence of bottom-dwelling life forms and bioturbated sediments is possible part of the time Interbedding also can be the result of turbidity currents that transport organic-poor shales and siltstones into the euxinic part of the basin to form turbidites Presumably, these currents also entrain burrowing organisms and dissolved oxygen, but whether either can survive to develop a bioturbated sediment is, in my opinion, debatable

The above model of submarine transgression and regression of layered water and the resulting lithotypes is represented by the Antrim Shale of the Michigan basin The widespread lower Antrim, which consists of Ells' (1979) Units 1 C, 1 B, 1 A (in ascending order), and sometimes part or all of Unit 2, is considered to have been deposited on a basin plain The basin plain environment is similar to that proposed by Potter and others (1980) for the lower Huron of Ohio, which is correlative with the lower Antrim The conditions of the basin plain environment were sufficient to provide an anaerobic water layer under which Units 1 C, 1 A, and 2 were deposited The entire Michigan basin was influenced by anaerobic bottom conditions while the organic-rich sediments of Units 1 C, 1 A, and 2 were accumulating

Unit 1 B represents an uplift or shallowing of all but the southwestern part of the basin that allowed oxygenated water to reach large areas of the sea bottom The consistent gamma-ray patterns within Unit 1 B across most of the basin rule out sea-floor tilting and suggest a very widespread controlling mechanism, possibly a decrease in sea level or a lowering of the layered water interface or both The southwestern part of the basin, however, remained relatively deep, and euxinic bottom conditions continued uninterrupted throughout the deposition of Units 1 C, 1 B, and 1 A The sources of clastics and organics must have been very distant A slight increase in the thickness of the total lower Antrim occurs in the northwest, but it would be highly conjectural to suggest a northwestern source on that evidence alone

I postulate a hiatus associated with the *Foerstia* zone, although I have never observed in numerous cores any apparent breaks in lithology or the presence of glauconite so characteristic of the hiatuses that mark other contacts in the Devonian-Mississippian shale sequence The nature of sedimentation and the geometry of the resulting shale above the general level of Unit 2 suggested a shift in the proximity of the sediment source and, possibly, in its direction as well Because these changes required an unknown span of time, I suggest a depositional hiatus from these data Following the development of a closer sediment source, the Ellsworth prodelta beds prograded into Michigan from the west and the northwest Paleontological evidence for depositional change at that time also appears in the Michigan basin portion of Ontario, where Winder (1966) described different fossil populations above and below the *Foerstia* zone in the Kettle Point Shale, which is the Antrim equivalent Tentative evidence in support of differing depositional conditions is suggested by the results of the pyrolysis-gas chromatography of three Antrim core samples from Sanilac County—two samples above and one below the stratigraphic position of *Foerstia* The lowest sample contained more marine organic matter than the upper two (J S Leventhal, USGS, written commun , 1984)

The Ellsworth/upper Antrim forms a wedge of shale that is thickest toward the western or the northwestern source of the Ellsworth delta The organic-poor Ellsworth was deposited on the sea floor that had been elevated by tilting into the aerobic zone, while its organic-rich facies, the upper Antrim, was accumulating at a slower rate farther east under the anaerobic bottom conditions that continued largely unchanged from those that prevailed during the deposition of Units 1 A and 2

SHALE CHARACTERIZATION

Sources

Historically, the natural gas potential of the Antrim, as suggested by gas shows in many counties, including Jackson, St Clair, and Alcona, and by production in Otsego County, was responsible for the early and current interest shown by the petroleum industry (Matthews and Humphrey, 1977, Matthews, 1980), but little characterization data resulted Recent industry interest has dealt with the Antrim Shale as an oil shale (Matthews and others, 1980) or as a potential source rock, vitrinite reflectance as high as 1 30 and a thermal alteration index (TAI) of 3 2 have been reported in central Michigan (table 1)

From 1976 through 1980, DOE-funded projects generated new data concerning shale characterization as well as stratigraphic knowledge The Antrim was partially cored in two Otsego County wells through funding by the METC, detailed reports describing these cores (Cliffs Minerals,

Table 1. Maturity and estimated burial depths of Antrim Shale and other rocks
[R_o%, vitrinite reflectance in percent, TAI, thermal alteration index, —, no data]

Site	R_o%	TAI	Estimated Depth		Reference
			Feet	Meters	
Northwestern Illinois basin, Henderson Co , Ill	—	—	2,000	610	Thomas and Frost (1980, p 149)
Michigan	—	—	3,280	1,000	Wold and others (1981, p 1630)
	0 46	—	4,593	1,400	Hathon and others (1980a, p 25)
Central Michigan	1 30	3 2	3,280	1,000	Cercone (1984, p 135)
Southern Michigan	40	2 2	—	—	Do
Southwestern Ontario "Devonian rocks"	—	—	7,200	2,195	Uyeno and others (1982, p 25)
Saginaw coal, Mich (Pennsylvanian)	54–60	2 6	7 600	2,300	Cercone (1984, p 133)

Inc , 1980c, 1981a) and three Antrim cores from Dow/DOE wells in Sanilac County (Cliffs Minerals, Inc , 1981b) were published Several reports were published as part of the EGSP—a screening report (Tetra Tech, Inc , 1981), an analysis of shales (Cliffs Minerals, Inc , 1982), and two final reports (Cobb and Miles, 1982, Struble, 1982) Appendix A lists additional reports

Cores were cut at the Dow site in Sanilac County, and fresh drill cuttings were collected from 35 drilling wells across the basin (fig 26, Appendix D) to supply samples for the Dow/DOE/Antrim project Nine surface samples also were studied from six localities in Michigan and one in Ontario (Hathon and others, 1980b)

Since the 1950's, the Antrim Shale has been cored by several oil companies, including Shell (Otsego County), AMOCO (Otsego and Grand Traverse Counties), Sun (Midland County), McClure (Sanilac County), and the former Atomic Energy Commission Dow cored more than 5,000 ft of the Antrim and its associated rocks in Otsego, Midland, Bay, and Sanilac Counties in Michigan and in Lambton County in Ontario between 1956 and 1976 Results of these private industry investigations seldom were made public

Geochemical

Inorganic elemental and organic analyses were conducted by Dow/DOE subcontractors on sample sets from 28 wells and on 22 core samples by using neutron activation analysis (Young, 1980) Elemental analyses revealed that sulfur varied proportionately with carbon and that calcium values varied inversely with organic carbon (Leddy and others, 1980) The uranium was as much as 40 ppm, but the thorium tended to be uniform at 10 to 12 ppm (Ruotsala, 1980) The illitic character and the high quartz content of the Antrim Shale and the finely disseminated nature (less than 0 5–15 micrometers) of the bulk of the pyrite were mentioned in an early Dow report (Matthews and Humphrey, 1977)

The kerogen in the Antrim was found to consist of roughly equal amounts of aromatic and aliphatic carbons The paraffins had the same constituents in differing amounts, the aromatic fractions appeared to have significant compositional differences (Leddy and others, 1980)

Fischer assay oil yields have been reported to range from 4 to 22 gallons per ton (gal/ton) (Humphrey and Wise, 1977) and up to 16 9 gal/ton (Swanson, 1960) A large-scale retorting (over 7 tons) of Antrim Shale from the Paxton Quarry in Alpena County by the LETC yielded almost 10 gal/ton (Martel and Harak, 1977) In the late 1950's, the Antrim was experimentally burned in situ at the Paxton Quarry (Matthews and Humphrey, 1977), where the organic content is high enough to have caused spontaneous combustion in the crushed shale stockpile on a few occasions (Dennis Lane, National Gypsum Company, oral commun , 1983) The total carbon content of the Antrim Shale is variable, the sample shown in figure 27 ranges from 4 to 12 weight percent A bulk sample taken from a high-grade zone in the upper part of Unit 1 C in the Paxton Quarry yielded 14 0 gal/ton (Matthews, 1987)

Total organic carbon in three Antrim cores from Sanilac County was related to oil yield by dividing Fischer assay results by percent organic matter, the results of this calculation suggested that the lower half of the Antrim "will yield more oil than shale equally rich in organic matter in the upper half" (Leddy and others, 1980, p 39) Because Fischer assay results are improved as the content of aliphatic carbon increases (Miknis and Netzel, 1982), this observation may indicate a shift in the aliphatic to aromatic ratio that favors a depositional setting more distant from land The hydrogen to carbon ratios of the kerogen increased with depth (Leddy and others, 1980)

The bitumen content (toluene-extractable material) was determined by Leddy and others (1980, p 33), and, to make the mapping easier, I multiplied the reported values by 1,000 As shown in figure 28, bitumens increase with depth, and a possible concentration appears to occur along the Ellsworth/upper Antrim facies change (compare with fig 9) Such a concentration reminds one of Potter's (1980, p 60) observation regarding Appalachian samples "Some gray and greenish-gray shale samples particularly those near beds of black shale have too much extractable material for the amount of carbon present "

Hydrocarbon components were determined by pyrochromatographic analyses for 35 wells and 9 outcrop

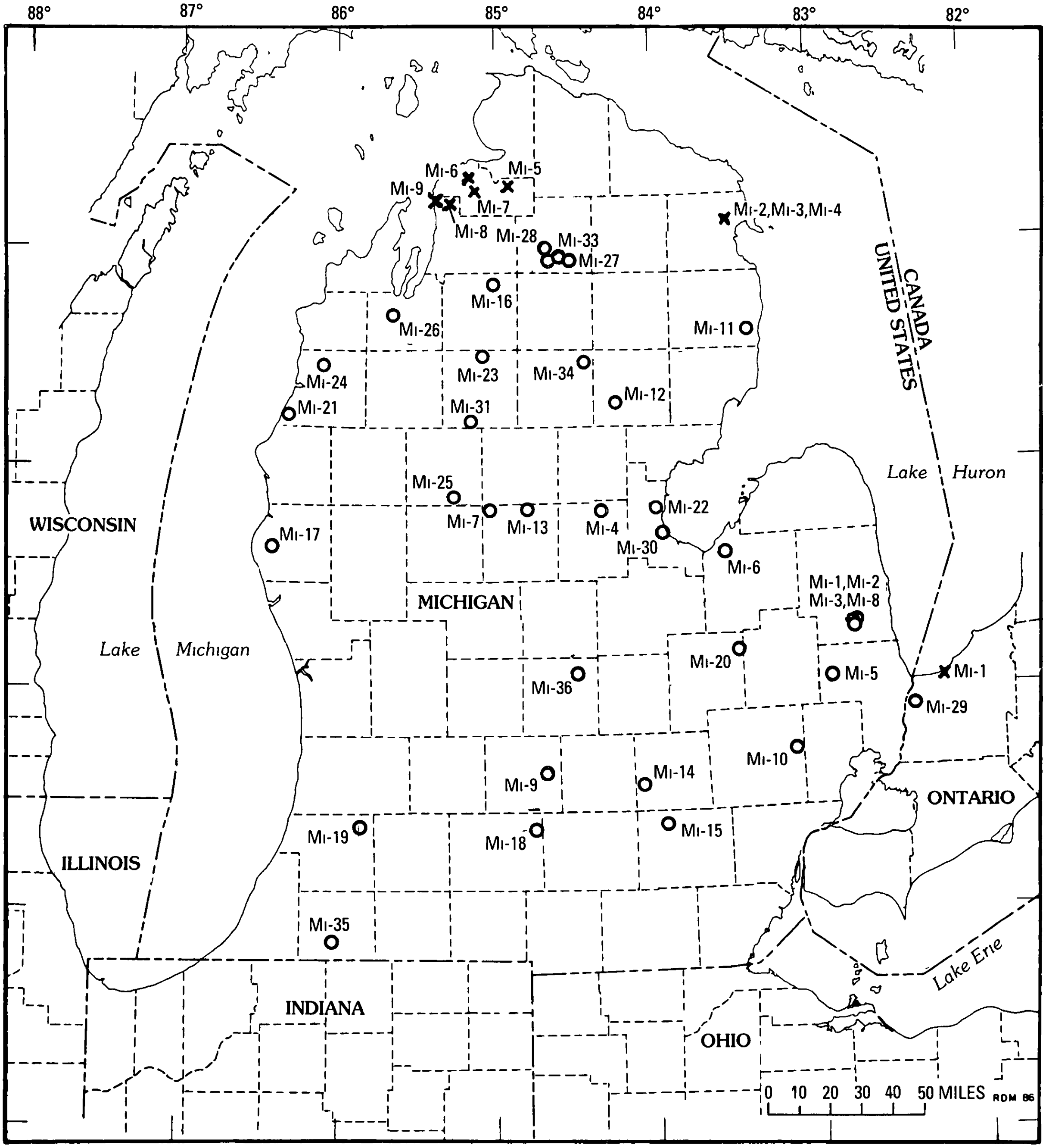

Figure 26. Locations of wells (open circles) and outcrops (crosses) sampled for the Dow/Department of Energy/Antrim project See appendix D for well identification

samples (Snyder and Maness, 1980, p 6) Their data show that, when expressed as "hydrocarbon count per sample, the greater values of hydrocarbon counts are generally located near the central deeper part of the Michigan Basin "

Lithological

X-ray mineralogical determinations were made of 12 outcrop, 104 core, and 707 well cuttings samples (Young, 1980) The black Antrim Shale averaged 65 percent quartz, 30 percent illite, and 5 percent kaolinite, as well as some chlorite (Ruotsala, 1980), "no clay minerals of expandable type were found" (Ruotsala, 1978, p 4) Hathon and others (1980a) determined that the shale contained approximately 50 percent quartz by weight and that, in the less than 500-mesh-sized fraction, 56 percent of that quartz was polycrystalline, they noted that this is twice the amount of quartz in the average shale and 10 times the amount of

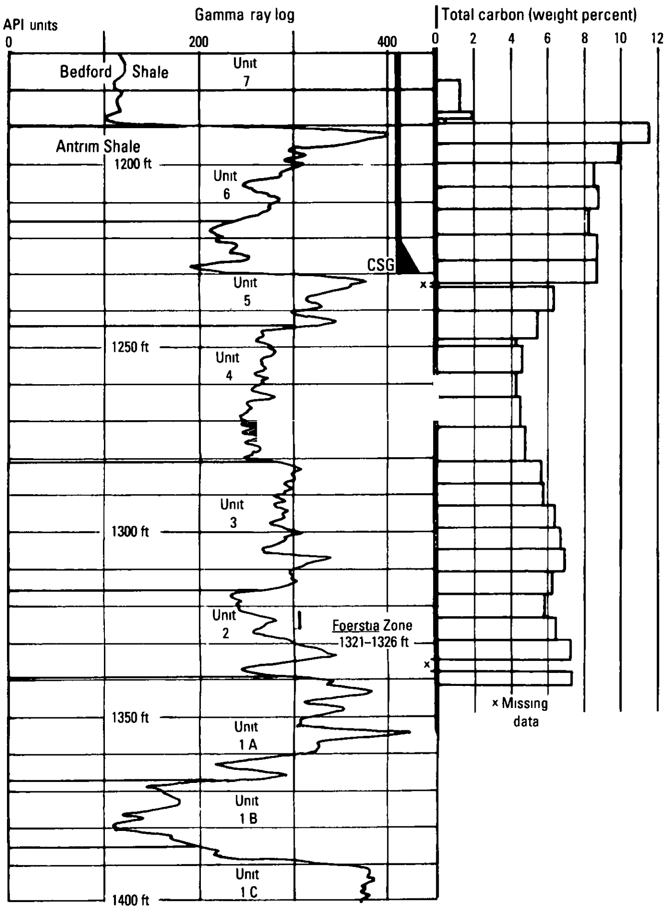

Figure 27 Total carbon in core related to the gamma-ray log of Dow/Department of Energy well No 110, Sanilac County, Mich Units are from Ells (1979) API, American Petroleum Institute

polycrystalline quartz in the silt-sized fraction of sandstones and shales They stated, " much of the quartz is authigenic Also, this quartz precipitated from formation waters less saline than normal sea water" (Hathon and others, 1980a, p 1) Their interpretation of the observed isotopic data is, as they stated, "difficult to rationalize with the presumed marine origin of the shale" (Hathon and others, 1980a, p 29)

Physical

Physical property tests were conducted on oriented core from the first three DOE wells drilled at the Dow site in Sanilac County After the cores had been described and photographed, strength and deformation properties were studied in quasi-static uniaxial compression, point load strength, and surface hardness tests (Kim, 1978) Fracture toughness was measured (Kim and Mubeen, 1980), and ultrasonic velocity and elastic constants were investigated (Wallace and others, 1980) Thirty core samples were tested for dynamic Young's modulus, Poisson's ratio, and damping ratio (Somogyi, 1980) Diffusivity of the Antrim samples was undertaken by Cannon and others (1980) The data derived from these analyses will be found in the various reports listed in Appendix A

UNRESOLVED QUESTIONS

The true significance of thinning and the appropriate choice of boundaries for units that are to be considered for thickness study remain debatable points for the Devonian-Mississippian shale sequence in Michigan I have combined units I believe were genetically related, the Ellsworth/upper Antrim is such a unit, as is the Bedford-Berea If the layered water model is correct, and I believe it is, then the highly radioactive, organic black shales were formed in water deeper than their correlative lighter colored and organic-poor shale facies If the choice of a genetically related mapping unit is correct, then a thin area or axis of black shale represents a deeper water site of minimal deposition (that is, approaching the conditions of a sediment-poor basin)

The recognition of depositional hiatuses within the Devonian-Mississippian shales in Michigan has received little attention I have relied on the visual evidence from cores of abrupt, sharp contacts associated with glauconite to postulate breaks in sedimentation at the tops of the Sunbury and the Antrim Shales and at the top of the Berea Sandstone The postulated paraconformity at the top of the lower Antrim is based on three observations—the known and predicted position of *Foerstia*, an underlying gamma-ray pattern consistent across most of the basin, and the postulated tectonic movements necessary to alter the depositional setting between the lower Antrim and the overlying beds Additional finds of *Foerstia* and the recognition of other biostratigraphic markers are badly needed, perhaps the thin layers of conodont "hash" and bone beds occasionally observed in cores may serve that purpose

More precise mapping to better define the zone of shale-to-shale facies change in central Michigan can be accomplished and quantified by the application of the 20 API units greater than the normal shale base line rule (Roen, 1980) Similar facies changes have been mapped in Ohio, Pennsylvania, and West Virginia, where they have been associated with the occurrence of shale gas (Matthews, 1985)

The lateral abruptness of the facies change from organic-poor to organic-rich shale through a vertical section of more than 200 ft is not clearly understood The layered water model explains interfingering of black and gray shales by a submarine transgression-regression across a sloping sea floor, however, a remarkable dynamic equilibrium is required to build a section of these intercalated beds that is more than 200 ft thick and to limit the lateral extent of the zone of facies change to distances as short as 10 mi

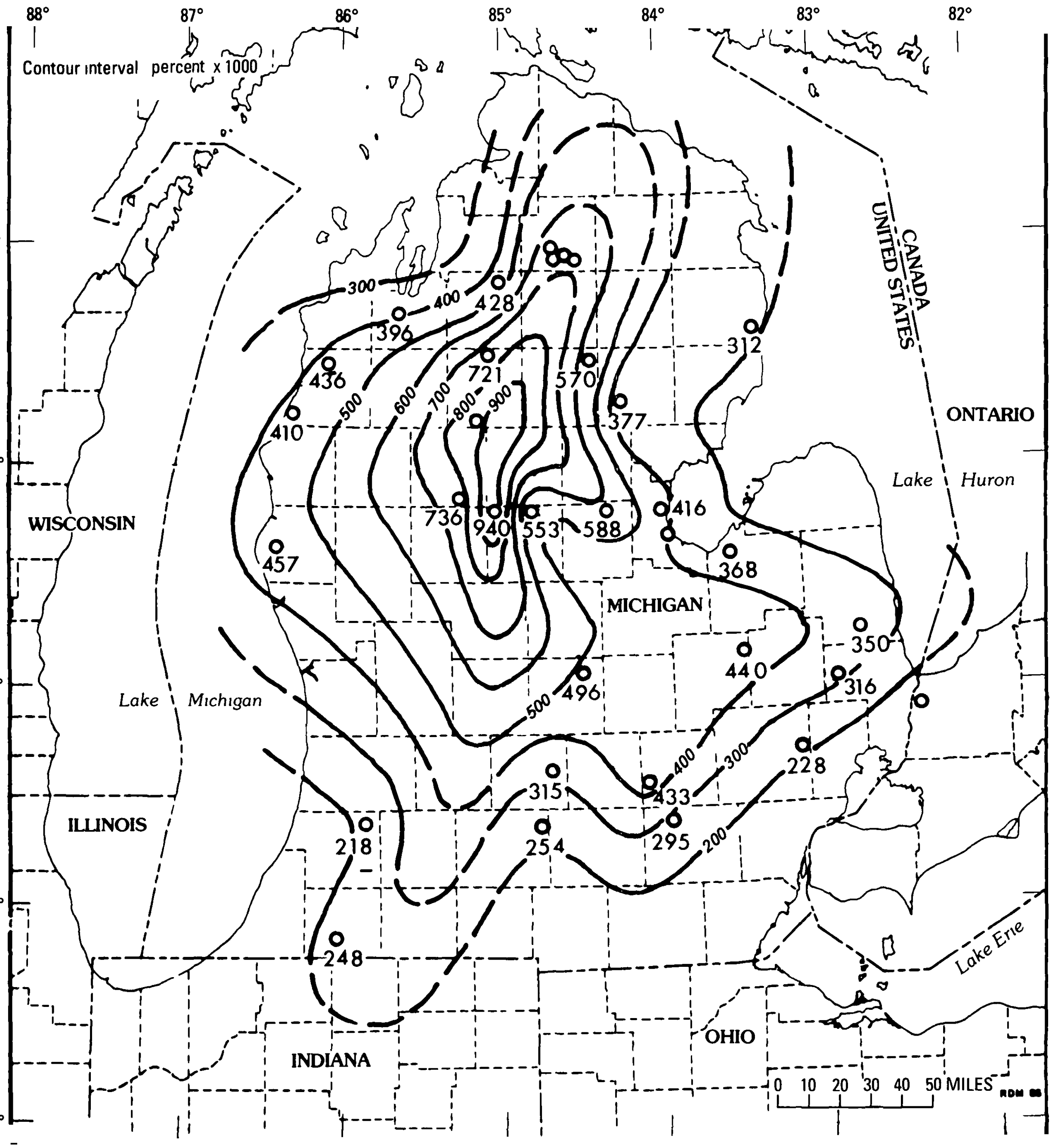

Figure 28. Bitumin (toluene-extractable material) distribution (in percent ×1,000) The averages were determined from 26 locations (open circles) and from well cuttings and cores (Leddy and others, 1980, p 33), "overall average" and "highest 28 percent" were reported, the latter values were posted at ×1,000

The thinning of units may be the result of three different causes—depositional pinch-out, loss of identity as the result of facies change, or erosional truncation The last has not been examined closely for thinning near-basin margins Pre-Pleistocene erosion is readily apparent, however, Paleozoic erosional surfaces near the basin margins are not as apparent A regional approach to mapping is helpful if we are to understand original depositional patterns

More stratigraphic data are needed to link the detailed surface stratigraphy to the simplified stratigraphy used in the subsurface at the top and the base of the Antrim, for example, a 1987 core hole in the Paxton Quarry enabled Units 1 A, 1 B, 1 C, and 2 and the Traverse Group-lower

Antrim contact to be identified in the quarry (fig 7, Matthews, 1988)

The apparent post-Sunbury–pre-"Coldwater Red Rock" erosional truncation in southwestern Michigan needs further clarification Little work has been done in regard to faulting that may have altered the thickness of the shale section The abundance and origin of quartz in the Antrim and the role of the Antrim as a source rock are also worthy of further study The potential for natural gas production (and oil?) from the Antrim Shale has been underestimated because it has yet to be understood Many of these questions will not be answered until new cores are cut and the black shales again become a matter of economic interest

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APPENDIXES

APPENDIX A: DEPARTMENT OF ENERGY REPORTS CONCERNING MICHIGAN RESULTING FROM THE DOW/ANTRIM PROJECT AND REPORTS BY OTHER CONTRACTORS

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APPENDIX B: LOCALITIES OF DEVONIAN SHALE EXPOSURES IN NORTHERN MICHIGAN

[List was abstracted from 112 localities, dated February 1940, which had been recorded by the Geological Survey of Michigan in summer 1926, by expeditions of the Museum of Paleontology, University of Michigan From Michigan Geological Society (1956) and Ehlers and Kesling (1970) Mile, mi, feet, ft]

Shore and bluffs on Lake Michigan, approximately 1 mi south of Norwood, Charlevoix County, but in Antrim County Eastern side of SE 1/4 sec 3, T 32 N , R 9 W Antrim Shale, type locality

Shale pit, Petoskey Portland Cement Company, 1 mi south of Ellsworth, Antrim County SE 1/4 sec 23, T 32 N , R 8 W Ellsworth Shale, type locality

Abandoned quarry at Kamp Kairphree on the shore of Charlevoix Lake (Pine Lake) about 5 mi southeast of Charlevoix, Charlevoix County NW 1/4 sec 3, T 33 N , R 7 W Norwood Shale

Abandoned shale pit, Boyne City Brick Company, in northeastern corner of Boyne City, Charlevoix County SW 1/4 sec 25, T 33 N , R 6 W Ellsworth Shale

Ditch beside north-south road parallel to Pennsylvania Railroad and 1/4 mi south of Walloon Lake station, Charlevoix County Near northern boundary of NW 1/4 sec 15, T 33 N , R 5 W Antrim Shale

Rock cut on scenic road adjacent to Lake Michigan about 1 mi north of pier at Norwood, Charlevoix County NE 1/4 sec 27, T 33 N , R 9 W Norwood Shale, type locality

Pit along road leading west from Lake Garden on northern arm of Walloon Lake, Emmet County Southern line, sec 36, T 34 N , R 6 W Antrim or Norwood Shale

Abandoned shale pit on southern side of east-west road 1/3 mi west of the Beebe School located 1/2 mi west and 2 1/2 mi south of Afton, Cheboygan County NW 1/4 SE 1/4 sec 14, T 34 N , R 2 W Norwood Shale

Huron Portland Cement Company shale quarry at Paxton about 8 mi west of Alpena County NE 1/4 sec 30, T 31 N , R 7 E Antrim Shale and "Traverse Formation "

Ditch along Highway M65 (Leer Road) 1/8 mi south of Lachine and north of Morrison Creek, Alpena County About 1/8 mi south of northwestern corner of sec 21, T 31 N , R 6 E Norwood Shale

Small rock cut on Lancaster Truck Trail (Glennie Road, between Highway M32 and Herron Road) 1/2 mi east and 1 1/2 mi north of Huron Portland Cement Co shale pit at Paxton, Alpena County 1/8 mi south of center of sec 17, T 31 N , R 7 E Norwood Shale

Point on Alpena-Hillman road at northern edge of Paxton Quarry (locality 34) Alpena County, 1/8 mi west of northeastern corner of sec 30, T 31 N , R 7 E Antrim Shale

Bluff on Lake Michigan shore about 1 mi southwest of Eastport, Antrim County West of center of sec 12, T 31 N , R 9 W Ellsworth Shale

Abandoned shale pit about 1 mi northeast of center of East Jordan, Charlevoix County NW 1/4 sec 24, T 32 N , R 7 W Ellsworth Shale

Exposures on both sides of road along south shore of Charlevoix Lake about 3/4 mi northwest of Advance, Charlevoix County NE 1/4 SE 1/4 sec 30, T 33 N , R 6 W Antrim Shale

Ravine about 3/4 mi southeast of Kamp Kairphree extending from bridge on County Highway 630 to shore of Lake Charlevoix, Charlevoix County Eastern side of sec 3, T 33 N , R 7 W Norwood Shale

Dump pile by old "gold" mine shaft on northern side of an east-west road (Taylor-Hawks Road) about 3/4 mi northeast of Herron, Alpena County Less than 1 mi east of southeastern corner of sec 36, T 31 N , R 6 E Squaw Bay Limestone and Norwood and Antrim Shales

Ledges along U S 23 and Lake Huron shore about 6 mi south of Alpena and just south of Squaw Bay, Alpena County NE 1/4 sec 22, T 30 N , R 8 E Antrim Shale

Shoreline of Sulphur Island in Thunder Bay, over 5 mi south of Alpena and about 1 1/2 mi east of the shore of Lake Huron Sec 24 (east), T 30 N , R 8 E , Alpena County Antrim Shale

Cut of Detroit and Mackinac Railroad (abandoned section) Southwest and southeast of sec 15, just east of Bean Creek Road, over 1 mi east of Lachine, Alpena County Antrim Shale

Shoreline at Kettle Point (Cape Ipperwash) at western edge of Ipperwash Beach on Lake Huron shore about 3 mi west of Government Park, Stoney Point, Lambton County, Ontario, Canada Kettle Point (Antrim), 10 ft exposed with 1956 lake levels

APPENDIX C: WELL DATA SHEET INDEX

This list should be used to locate data sheets for wells located in the study area The map identification codes (alphabetic, numeric, or both) are from figure 11 The well data sheets follow ABS, absent, NL, original not legible, NA, not available, ND, not differentiated

Map I D	Sheet No	Map I D	Sheet No	Map I D	Sheet No	Map I D	Sheet No
A 1, C 1	1	B 21, C 14	42	E 7	83	16	124
A 2	2	C 2	43	E 9	84	17	125
A 3	3	C 3	44	E 10	85	18	126
A 4	4	C 4, E 3	45	E 11	86	19	127
A 5	5	C 5	46	E 12, F 5	87	24	128
A 6,B 5	6	C 6	47	E 13	88	25	129
A 7	7	C 7, D 1	48	E 14	89	26	130
A 8	8	C 8	49	E 15	90	82–1	131
A 9	9	C 9, F 9	50	E 16	91	H	132
A 10	10	C 10	51	E 17	92	I	133
A 11, F 1	11	C 11	52	E 18	93	J	134
A 12, F 2	12	C 12	53	E 19	94	2–6	135
A 13, F 3	13	C 13	54	E 20	95	1434	136
A 14	14	C 15	55	E 21	96	389	137
A 15	15	C 16	56	E 22	97	114	138
A 16	16	C 17	57	F 4	98	115	139
A 17	17	C 18	58	F 6	99	116	140
A 18	18	C 19, F 9	59	Fi 1	100	117	141
A 19	19	C 20, F 10	60	Fi 2	101	118	142
A 20	20	C 21	61	Fi 3	102	119	143
A 21	21	C 22	62	Fi 4	103	120	144
A 22	22	C 23	63	Fi 5	104	121	145
B 1	23	C 24	64	Fi 6	105	122	146
B 2	24	C 25, D 15	65	Fi 7	106	123	147
B 3	25	D 2	66	Fi 8	107	125	148
B 4	26	D 3	67	Fi 9	108	126	149
B 6	27	D 4	68	A-B 3	109	127	150
B 7	28	D 5	69	A-H 8	110	128	151
B 8	29	D 6	70	A-J 3	111	129	152
B 9	30	D 8	71	A-K 2	112	130	153
B 10	31	D 9, F 7	72	A-K 7	113	131	154
B 11, E 8	32	D 10	73	A-N 3	114	132	155
B 12	33	D 11	74	Ma 1	115	133	156
B 13	34	D 12	75	351 M	116	134	157
B 14, D 7	35	D 13	76	310 T	117	135	158
B 15	36	D 14	77	313 J	118	136	159
B 16	37	E 1	78	238 D	119	137	160
B 17	38	E 2	79	283 V	120	LAIT	161
B 18	39	E 4	80	225 P	121	NPIT	162
B 19	40	E 5	81	13	122		
B 20	41	E 6	82	14	123		

Map I D	A-1, C-1
Permit No	None
Section, Township, Range	16, 38 N , 15 E
County, State	Steuben, Ind

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	790	10
Bedford-Berea	800	42
Ellsworth-upper Antrim	842	93
Lower Antrim	935	65
Traverse Group	1,000	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	158
Top Sunbury to top Traverse Group	210

COMMENTS
Lower Antrim—Same as top of Unit 1A

1

Map I D	A-2
Permit No	23214
Section, Township, Range	33, 5 S , 7 W
County, State	Branch, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	905	7
Bedford-Berea	912	26
Ellsworth-upper Antrim	938	130
Lower Antrim	1,068	82
Traverse Group	1,150	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	212
Top Sunbury to top Traverse Group	245

COMMENTS
Lower Antrim—Top is 20 ft within the 45 ft of Unit 2, which is split 20 ft/25 ft

2

Map I D	A-3
Permit No	22242
Section, Township, Range	17, 5 S , 9 W
County, State	St Joseph, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	704	6
Bedford-Berea	710	23
Ellsworth-upper Antrim	733	262
Lower Antrim	995	73
Traverse Group	1,068	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	335
Top Sunbury to top Traverse Group	364

COMMENTS
Lower Antrim—Top is 20 ft within the 55 ft of Unit 2, which is split 20 ft/35 ft

3

Map I D	A-4
Permit No	23044
Section, Township, Range	11, 4 S, 10 W
County, State	Kalamazoo, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (feet)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	760	46
Ellsworth-upper Antrim	806	274
Lower Antrim	1,080	80
Traverse Group	1,166	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	360
Top Sunbury to top Traverse Group	400

COMMENTS
Bedford-Berea—Eroded top under "Coldwater Red Rock "
Lower Antrim—Same as top of Unit 2

4

Map I D	A-5
Permit No	24033
Section, Township, Range	27, 2 S , 9 W
County, State	Kalamazoo, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,072	8
Bedford-Berea	1,080	33
Ellsworth-upper Antrim	1,113	261
Lower Antrim	1,374	69
Traverse Group	1,443	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	330
Top Sunbury to top Traverse Group	371

COMMENTS
Lower Antrim—Same as top of Unit 2

5

Map I D	A-6, B-5
Permit No	28590
Section, Township, Range	16, 1 S , 14 W
County, State	Van Buren, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	615	469
Lower Antrim	1,084	96
Traverse Group	1,180	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	565
Top Sunbury to top Traverse Group	565

COMMENTS
Ellsworth/upper Antrim—Eroded top under "Coldwater Red Rock "
Lower Antrim—Same as top of Unit 2

6

Map I D	A-7
Permit No	24130
Section, Township, Range	5, 1 N , 14 W
County, State	Allegan, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	650	495
Lower Antrim	1,145	98
Traverse Group	1,243	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	593
Top Sunbury to top Traverse Group	593

COMMENTS
Ellsworth/upper Antrim—Eroded top under "Coldwater Red Rock "
Lower Antrim—Same as top of Unit 2

7

Map I D	A-8
Permit No	23462
Section, Township, Range	17, 4 N , 15 W
County, State	Allegan, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	719	573
Lower Antrim	1,292	107
Traverse Group	1,399	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	680
Top Sunbury to top Traverse Group	680

COMMENTS
Ellsworth/upper Antrim—Eroded top under "Coldwater Red Rock "
Lower Antrim—Same as top of Unit 2

8

Map I D	A-9
Permit No	23002
Section, Township, Range	32, 6 N , 14 W
County, State	Ottawa, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	895	578
Lower Antrim	1,473	106
Traverse Group	1,579	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	684
Top Sunbury to top Traverse Group	684

COMMENTS
Ellsworth/upper Antrim—Eroded top under "Coldwater Red Rock "
Lower Antrim—Same as top of Unit 2

9

Map I D	A-10
Permit No	24751-DP1453
Section, Township, Range	21, 8 N , 14 W
County, State	Ottawa, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,100	56
Bedford-Berea	1,156	16
Ellsworth-upper Antrim	1,172	536
Lower Antrim	1,708	99
Traverse Group	1,807	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	635
Top Sunbury to top Traverse Group	707

COMMENTS
Lower Antrim—Top is 8 ft within the 70 ft of Unit 2, which is split 8 ft/62 ft

10

Map I D	A-11, F-1
Permit No	26353
Section, Township, Range	15, 10 N , 17 W
County, State	Muskegon, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	907	25
Bedford-Berea	932	17
Ellsworth-upper Antrim	949	551
Lower Antrim	1,500	130
Traverse Group	1,630	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	681
Top Sunbury to top Traverse Group	723

COMMENTS
Lower Antrim—Same as top of Unit 2

11

Map I D	A-12, F-2
Permit No	23266
Section, Township, Range	8, 12 N , 16 W
County, State	Muskegon, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,052	29
Bedford-Berea	1,081	10
Ellsworth-upper Antrim	1,091	544
Lower Antrim	1,635	127
Traverse Group	1,762	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	671
Top Sunbury to top Traverse Group	710

COMMENTS
Lower Antrim—Same as top of Unit 2

12

Map I D	A-13, F-3
Permit No	22866
Section, Township, Range	26, 13 N , 14 W
County, State	Newaygo, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,569	46
Bedford-Berea	1,615	15
Ellsworth-upper Antrim	1,630	548
Lower Antrim	2,178	112
Traverse Group	2,290	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	660
Top Sunbury to top Traverse Group	721

COMMENTS
Lower Antrim—Top is 48 ft within the 51 ft of Unit 3, which is split 48 ft/3 ft

13

Map I D	A-14
Permit No	24087
Section, Township, Range	36, 15 N , 17 W
County, State	Oceana, Mich

FORMATION UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,092	23
Bedford-Berea	1,115	17
Ellsworth-upper Antrim	1,132	573
Lower Antrim	1,705	100
Traverse Group	1,805	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	673
Top Sunbury to top Traverse Group	713

COMMENTS
Lower Antrim—Same as top of Unit 2

14

Map I D	A-15
Permit No	23956
Section, Township, Range	14, 18 N , 17 W
County, State	Mason, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	800	25
Bedford-Berea	825	14
Ellsworth-upper Antrim	839	619
Lower Antrim	1,458	130
Traverse Group	1,588	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	749
Top Sunbury to top Traverse Group	788

COMMENTS
Lower Antrim—Same as top of Unit 2

15

Map I D	A-16
Permit No	26832
Section, Township, Range	32, 20 N , 13 W
County, State	Lake, Mich

FORMATION, UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,318	31
Bedford-Berea	1,349	17
Ellsworth-upper Antrim	1,366	630
Lower Antrim	1,996	164
Traverse Group	2,160	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	794
Top Sunbury to top Traverse Group	842

COMMENTS
Lower Antrim—Same as top of Unit 2

16

Map I D	A-17
Permit No	28825
Section, Township, Range	27, 23 N , 14 W
County, State	Manistee, Mich

FORMATION UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	702	25
Bedford-Berea	727	5
Ellsworth-upper Antrim	732	613
Lower Antrim	1,345	139
Traverse Group	1,484	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	752
Top Sunbury to top Traverse Group	782

COMMENTS
Lower Antrim—Same as top of Unit 2

17

Map I D	A-18
Permit No	30295
Section, Township, Range	6, 24 N , 12 W
County, State	Wexford, Mich

FORMATION, UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	982	27
Bedford-Berea	1,009	8
Ellsworth-upper Antrim	1,017	603
Lower Antrim	1,620	137
Traverse Group	1,757	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	740
Top Sunbury to top Traverse Group	775

COMMENTS
Lower Antrim—Same as top of Unit 2

18

Map I D	A-19
Permit No	28954
Section, Township, Range	23, 26 N , 11 W
County, State	Grand Traverse, Mich

FORMATION UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	595	23
Bedford-Berea	618	29
Ellsworth-upper Antrim	647	593
Lower Antrim	1,240	141
Traverse Group	1,381	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	734
Top Sunbury to top Traverse Group	786

COMMENTS
Lower Antrim—Same as top of Unit 2

19

Map I D	A-20
Permit No	28817
Section, Township, Range	28, 27 N , 9 W
County, State	Grand Traverse, Mich

FORMATION, UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	790	20
Bedford-Berea	810	15
Ellsworth-upper Antrim	825	620
Lower Antrim	1,445	122
Traverse Group	1,567	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	742
Top Sunbury to top Traverse Group	777

COMMENTS
Lower Antrim—Same as top of Unit 2

20

Map I D	A-21	
Permit No	27483	
Section, Township, Range	24, 29 N , 7 W	
County, State	Antrim, Mich	
FORMATION, UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	727	18
Bedford-Berea	745	19
Ellsworth-upper Antrim	764	509
Lower Antrim	1,273	110
Traverse Group	1,383	NA
INTERVALS		Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)		619
Top Sunbury to top Traverse Group		656

COMMENTS
Lower Antrim—Same as top of Unit 2

21

Map I D	A-22	
Permit No	22639	
Section, Township, Range	19, 32 N , 8 W	
County, State	Antrim, Mich	
FORMATION UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	311	56
Lower Antrim	367	90
Traverse Group	457	NA
INTERVALS		Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)		146
Sunbury to top Traverse Group		146

COMMENTS
Ellsworth/upper Antrim—Eroded top under glacial drift
Lower Antrim—Same as top of Unit 2

22

Map I D	B-1	
Permit No	23290	
Section, Township, Range	26, 7 S , 15 W	
County, State	Cass, Mich	
FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	276	319
Lower Antrim	595	70
Traverse Group	665	NA
INTERVALS		Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)		389
Top Sunbury to top Traverse Group		389

COMMENTS
Ellsworth/upper Antrim—Top eroded under glacial drift
Lower Antrim—Same as top of Unit 2 Thickness greater than 319 ft

23

Map I D	B-2	
Permit No	23668	
Section, Township, Range	31, 5 S , 13 W	
County, State	Cass, Mich	
FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	578	377
Lower Antrim	955	78
Traverse Group	1,033	NA
INTERVALS		Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)		455
Top Sunbury to top Traverse Group		455

COMMENTS
Ellsworth/upper Antrim—Eroded top under "Coldwater Red Rock "
Lower Antrim—Same as top of Unit 2

24

Map I D	B-3
Permit No	23524
Section, Township, Range	34, 4 S , 14 W
County, State	Van Buren, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	585	399
Lower Antrim	984	88
Traverse Group	1,072	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	487
Top Sunbury to top Traverse Group	487

COMMENTS
Ellsworth/upper Antrim—Eroded top under "Coldwater Red Rock "
Lower Antrim—Same as top of Unit 2

25

Map I D	B-6
Permit No	24003
Section, Township, Range	17, 3 N , 11 W
County, State	Allegan, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	1,151	461
Lower Antrim	1,612	88
Traverse Group	1,700	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	549
Top Sunbury to top Traverse Group	549

COMMENTS
Ellsworth/upper Antrim—Eroded top under "Coldwater Red Rock "
Lower Antrim—Same as top of Unit 2

27

Map I D	B-4
Permit No	21900
Section, Township, Range	28, 1 S , 16 W
County, State	Van Buren, Mich

FORMATION, UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	417	466
Lower Antrim	883	90
Traverse Group	973	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	556
Top Sunbury to top Traverse Group	556

COMMENTS
Ellsworth/upper Antrim—Eroded top under "Coldwater Red Rock "
Lower Antrim—Same as top of Unit 2

26

Map I D	B-7
Permit No	21779
Section, Township, Range	2, 4 N , 11 W
County, State	Allegan, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,309	4
Bedford-Berea	1,313	94
Ellsworth-upper Antrim	1,407	343
Lower Antrim	1,750	87
Traverse Group	1,837	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	430
Top Sunbury to top Traverse Group	528

COMMENTS
Lower Antrim—Same as top of Unit 2

28

Map I D	B-8	
Permit No	24504	
Section, Township, Range	12, 3 N , 10 W	
County, State	Barry, Mich	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	1,287	56
Ellsworth-upper Antrim	1,343	307
Lower Antrim	1,650	84
Traverse Group	1,734	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	391
Top Sunbury to top Traverse Group	447

COMMENTS
Lower Antrim—Top 8 ft within the 68 ft of Unit 2, which is split 8 ft/60 ft

29

Map I D	B-9	
Permit No	23573	
Section, Township, Range	20, 4 N , 8 W	
County, State	Barry, Mich	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,610	10
Bedford-Berea	1,620	22
Ellsworth-upper Antrim	1,642	258
Lower Antrim	1,900	85
Traverse Group	1,985	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	343
Top Sunbury to top Traverse Group	375

COMMENTS
Lower Antrim—Same as top of Unit 2

30

Map I D	B-10	
Permit No	23482	
Section, Township, Range	28, 5 N , 8 W	
County, State	Ionia, Mich	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,647	12
Bedford-Berea	1,659	33
Ellsworth-upper Antrim	1,692	260
Lower Antrim	1,952	86
Traverse Group	2,038	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	346
Top Sunbury to top Traverse Group	391

COMMENTS
Lower Antrim—Top is 3 ft within the 39 ft of Unit 2, which is split 3 ft/36 ft

31

Map I D	B-11, E-8	
Permit No	24619	
Section, Township, Range	34, 7 N , 8 W	
County, State	Ionia, Mich	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,779	21
Bedford-Berea	1,800	30
Ellsworth-upper Antrim	1,830	288
Lower Antrim	2,118	82
Traverse Group	2,200	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	370
Top Sunbury to top Traverse Group	421

COMMENTS
Lower Antrim—Top is 23 ft within the 41 ft of Unit 2, which is split 23 ft/18 ft

32

Map I D	B-12
Permit No	24011
Section, Township, Range	8, 11 N , 5 W
County, State	Montcalm, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	2,523	30
Bedford-Berea	2,553	8
Ellsworth-upper Antrim	2,561	260
Lower Antrim	2,821	119
Traverse Group	2,940	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	379
Top Sunbury to top Traverse Group	417

COMMENTS
Lower Antrim—Same as top of Unit 2

33

Map I D	B-13
Permit No	23347
Section, Township, Range	14, 11 N , 3 W
County, State	Gratiot, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	2,260	18
Bedford-Berea	2,278	55
Ellsworth-upper Antrim	2,333	245
Lower Antrim	2,578	108
Traverse Group	2,686	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	353
Top Sunbury to top Traverse Group	426

COMMENTS
Lower Antrim—Same as top of Unit 2

34

Map I D	B-14, D-7
Permit No	23849
Section, Township, Range	21, 13 N , 1 W
County, State	Midland, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	2,280	20
Bedford-Berea	2,300	102
Ellsworth-upper Antrim	2,402	227
Lower Antrim	2,629	131
Traverse Group	2,760	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	358
Top Sunbury to top Traverse Group	480

COMMENTS
Lower Antrim—Same as top of Unit 2

35

Map I D	B-15
Permit No	None (#8 Salt)
Section, Township, Range	21, 14 N , 2 E
County, State	Midland, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	2,415	19
Bedford-Berea	2,434	152
Ellsworth-upper Antrim	2,586	206
Lower Antrim	2,792	138
Traverse Group	2,930	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	344
Top Sunbury to top Traverse Group	515

COMMENTS
Lower Antrim—Top is 14 ft within the 27 ft of Unit 3, which is split 14 ft/13 ft

36

Map I D	B-16
Permit No	BD 125
Section, Township, Range	10, 14 N , 5 E
County, State	Bay, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,625	24
Bedford-Berea	1,649	189
Ellsworth-upper Antrim	1,838	200
Lower Antrim	2,038	112
Traverse Group	2,150	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	312
Top Sunbury to top Traverse Group	525

COMMENTS
Lower Antrim—Same as top of Unit 2

37

Map I D	B-17
Permit No	22270
Section, Township, Range	5, 12 N , 6 E
County, State	Saginaw, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,995	25
Bedford-Berea	2,020	201
Ellsworth-upper Antrim	2,221	165
Lower Antrim	2,386	96
Traverse Group	2,482	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	261
Top Sunbury to top Traverse Group	487

COMMENTS
Lower Antrim—Top is 11 ft within the 20 ft of Unit 2, which is split 11 ft/9 ft

38

Map I D	B-18
Permit No	23890
Section, Township, Range	8, 13 N , 9 E
County, State	Tuscola, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,565	45
Bedford-Berea	1,610	269
Ellsworth-upper Antrim	1,879	131
Lower Antrim	2,010	104
Traverse Group	2,114	NA

INTERVALS	Thickness (ft)
Ellsworth/upper Antrim/lower Antrim inclusive	235
Top Sunbury to top Traverse Group	549

COMMENTS
Lower Antrim—Top is 15 ft within the 35 ft of Unit 2, which is split 15 ft/20 ft

39

Map I D	B-19
Permit No	24699
Section, Township, Range	10, 15 N , 10 E
County, State	Huron, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,423	64
Bedford-Berea	1,487	280
Ellsworth-upper Antrim	1,767	139
Lower Antrim	1,906	96
Traverse Group	2,002	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	235
Top Sunbury to top Traverse Group	579

COMMENTS
Lower Antrim—Top is 16 ft within the 26 ft of Unit 2, which is split 16 ft/10 ft

40

Map I D	B-20
Permit No	23583
Section, Township, Range	28, 14 N , 12 E
County, State	Sanilac, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,327	66
Bedford-Berea	1,393	358
Ellsworth-upper Antrim	1,751	101
Lower Antrim	1,852	97
Traverse Group	1,949	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	198
Top Sunbury to top Traverse Group	622

COMMENTS
Lower Antrim—Top is 8 ft within the 28 ft of Unit 2, which is split 8 ft/20 ft Possible faulted section showing repeated Sunbury

41

Map I D	B-21, C-14
Permit No	24047
Section, Township, Range	21, 14 N , 15 E
County, State	Sanilac, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	795	124
Bedford-Berea	919	307
Ellsworth-upper Antrim	1,226	121
Lower Antrim	1,347	113
Traverse Group	1,460	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	234
Top Sunbury to top Traverse Group	665

COMMENTS
Lower Antrim—Same as top of Unit 2

42

Map I D	C-2
Permit No	23973
Section, Township, Range	10, 8 S , 4 W
County, State	Hillsdale, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	812	12
Bedford-Berea	824	28
Ellsworth-upper Antrim	852	98
Lower Antrim	950	78
Traverse Group	1,028	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	176
Top Sunbury to top Traverse Group	216

COMMENTS
Lower Antrim—Top is the same as Unit 1A

43

Map I D	C-3
Permit No	22298
Section, Township, Range	4, 8 S , 2 W
County, State	Hillsdale, Mich

FORMATION UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	867	13
Bedford-Berea	880	29
Ellsworth-upper Antrim	909	87
Lower Antrim	996	84
Traverse Group	1,080	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	171
Top Sunbury to top Traverse Group	213

COMMENTS
Lower Antrim—Same as top of Unit 1A

44

Map I D	C-4, E-3
Permit No	23751
Section, Township, Range	25, 6 S , 2 E
County, State	Lenawee, Mich

FORMATION UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	570	10
Bedford-Berea	580	91
Ellsworth-upper Antrim	671	81
Lower Antrim	752	88
Traverse Group	840	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	169
Top Sunbury to top Traverse Group	270

COMMENTS
Lower Antrim—Same as top of Unit 1A

45

Map I D	C-5
Permit No	23656
Section, Township, Range	24, 4 S , 2 E
County, State	Jackson, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,190	10
Bedford-Berea	1,200	115
Ellsworth-upper Antrim	1,315	85
Lower Antrim	1,400	104
Traverse Group	1,504	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	189
Top Sunbury to top Traverse Group	314

COMMENTS
Lower Antrim—Same as top of Unit 1A

46

Map I D	C-6
Permit No	21903
Section, Township, Range	6, 3 S , 4 E
County, State	Washtenaw, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	683	14
Bedford-Berea	697	150
Ellsworth-upper Antrim	847	79
Lower Antrim	926	89
Traverse Group	1,015	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	168
Top Sunbury to top Traverse Group	332

COMMENTS
Lower Antrim—Same as top of Unit 1A

47

Map I D	C-7, D-1
Permit No	23743
Section, Township, Range	3, 1 S , 7 E
County, State	Washtenaw, Mich

FORMATION UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	400	17
Bedford-Berea	417	237
Ellsworth-upper Antrim	654	76
Lower Antrim	730	53
Traverse Group	783	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	129
Top Sunbury to top Traverse Group	383

COMMENTS
Lower Antrim—Same as top of Unit 1A

48

Map I D	C-8
Permit No	23312
Section, Township, Range	30, 2 N , 8 E
County, State	Oakland, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	410	20
Bedford-Berea	430	252
Ellsworth-upper Antrim	682	56
Lower Antrim	738	66
Traverse Group	804	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	122
Top Sunbury to top Traverse Group	394

COMMENTS
Lower Antrim—Top is 21 ft within the 31 ft of Unit 2, which is split 21 ft/10 ft

49

Map I D	C-10
Permit No	24048
Section, Township, Range	6, 6 N , 12 E
County, State	Lapeer, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	963	62
Bedford-Berea	1,025	280
Ellsworth-upper Antrim	1,305	94
Lower Antrim	1,399	72
Traverse Group	1,471	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	166
Top Sunbury to top Traverse Group	508

COMMENTS
Lower Antrim—Top is 5 ft within the 35 ft of Unit 1A, which is split 5 ft/30 ft

51

Map I D	C-9, F-9
Permit No	23407
Section, Township, Range	1, 3 N , 11 E
County, State	Oakland, Mich

FORMATION UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	278	53
Bedford-Berea	331	254
Ellsworth-upper Antrim	585	90
Lower Antrim	675	65
Traverse Group	740	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	155
Top Sunbury to top Traverse Group	462

COMMENTS
Lower Antrim—Top is 25 ft within the 35 ft of Unit 2, which is split 25 ft/10 ft

50

Map I D	C-11
Permit No	24478
Section, Township, Range	33, 8 N , 13 E
County, State	St Clair, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	893	90
Bedford-Berea	983	277
Ellsworth-upper Antrim	1,260	105
Lower Antrim	1,365	75
Traverse Group	1,440	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	180
Top Sunbury to top Traverse Group	547

COMMENTS
Lower Antrim—Top is within the 38 ft of Unit 1A, which is split 3 ft/35 ft

52

Map I D	C-12
Permit No	369–731-474
Section, Township, Range	8, 9 N , 15 E
County, State	Sanilac, Mich

FORMATION UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	828	139
Bedford-Berea	967	257
Ellsworth-upper Antrim	1,224	140
Lower Antrim	1,364	80
Traverse Group	1,444	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	220
Top Sunbury to top Traverse Group	616

COMMENTS
Lower Antrim—Top is 11 ft within the 22 ft of Unit 2, which is split 11 ft/11 ft

53

Map I D	C-13
Permit No	24609
Section, Township, Range	7, 11 N , 16 E
County, State	Sanilac, Mich

FORMATION, UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	550	65
Bedford-Berea	615	252
Ellsworth-upper Antrim	867	152
Lower Antrim	1,019	88
Traverse Group	1,107	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	240
Top Sunbury to top Traverse Group	557

COMMENTS
Lower Antrim—Top is within the 31 ft of Unit 2, which is split 15 ft/16 ft Sunbury is anomalously thin, probably the result of faulting

54

Map I D	C-15
Permit No	24789
Section, Township, Range	36, 16 N , 12 E
County, State	Huron, Mich

FORMATION, UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,280	80
Bedford-Berea	1,360	412
Ellsworth-upper Antrim	1,772	43
Lower Antrim	1,815	112
Traverse Group	1,927	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	155
Top Sunbury to top Traverse Group	647

COMMENTS
Lower Antrim—Same as top of Unit 2 This appears to be a faulted section that has repeated and missing sections

55

Map I D	C-16
Permit No	29926
Section, Township, Range	35, 17 N , 11 E
County, State	Huron, Mich

FORMATION, UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,540	91
Bedford-Berea	1,631	288
Ellsworth-upper Antrim	1,919	131
Lower Antrim	2,050	123
Traverse Group	2,173	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	254
Top Sunbury to top Traverse Group	633

COMMENTS
Lower Antrim—Same as top of Unit 2

56

Map I D	C-17
Permit No	23899
Section, Township, Range	21, 18 N , 13 E
County, State	Huron, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	943	117
Bedford-Berea	1,060	310
Ellsworth-upper Antrim	1,370	122
Lower Antrim	1,492	116
Traverse Group	1,608	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	238
Top Sunbury to top Traverse Group	665

COMMENTS
Lower Antrim—Same as top of Unit 2

57

Map I D	C-18
Permit No	23084
Section, Township, Range	11, 21 N , 5 E
County, State	Iosco, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,648	32
Bedford-Berea	1,680	160
Ellsworth-upper Antrim	1,840	215
Lower Antrim	2,055	145
Traverse Group	2,200	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	360
Top Sunbury to top Traverse Group	552

COMMENTS
Lower Antrim—Same as top of Unit 2

58

Map I D	C-19, F-9
Permit No	23420
Section, Township, Range	28, 23 N , 5 E
County, State	Iosco, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,805	25
Bedford-Berea	1,830	155
Ellsworth-upper Antrim	1,985	228
Lower Antrim	2,213	150
Traverse Group	2,363	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	378
Top Sunbury to top Traverse Group	558

COMMENTS
Lower Antrim—Same as top of Unit 2

59

Map I D	C-20, F-10
Permit No	23208
Section, Township, Range	22, 26 N , 9 E
County, State	Alcona, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	340	23
Bedford-Berea	363	198
Ellsworth-upper Antrim	561	188
Lower Antrim	749	114
Traverse Group	863	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	302
Top Sunbury to top Traverse Group	523

COMMENTS
Lower Antrim—Same as top of Unit 2

60

Map I D	C-21
Permit No	23274
Section, Township, Range	16, 27 N , 9 E
County, State	Alcona, Mich

FORMATION UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	346	133
Lower Antrim	479	108
Traverse Group	587	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	241
Top Sunbury to top Traverse Group	241

COMMENTS
Lower Antrim—Top is 4 ft within the 22 ft of Unit 2, which is split 4 ft/18 ft
Ellsworth/upper Antrim—Thickness is greater than 133 ft, top eroded under the glacial drift

61

Map I D	C-23
Permit No	23265
Section, Township, Range	27, 27 N , 6 E
County, State	Alcona, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	739	33
Bedford-Berea	772	155
Ellsworth-upper Antrim	927	234
Lower Antrim	1,161	126
Traverse Group	1,287	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	360
Top Sunbury to top Traverse Group	548

COMMENTS
Lower Antrim—Top is 22 ft within the 27 ft of Unit 3, which is split 22 ft/5 ft

63

Map I D	C-22
Permit No	24359
Section, Township, Range	20, 27 N , 8 E
County, State	Alcona, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	478	39
Bedford-Berea	517	193
Ellsworth-upper Antrim	710	215
Lower Antrim	925	116
Traverse Group	1,041	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	331
Top Sunbury to top Traverse Group	563

COMMENTS
Lower Antrim—Same as top of Unit 2

62

Map I D	C-24
Permit No	27060
Section, Township, Range	30, 28 N , 5 E
County, State	Alcona, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	723	22
Bedford-Berea	745	99
Ellsworth-upper Antrim	844	265
Lower Antrim	1,109	116
Traverse Group	1,225	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	381
Top Sunbury to top Traverse Group	502

COMMENTS
Top of Ellsworth/upper Antrim is 64 ft below top of unit 7 Top of lower Antrim is 20 ft below top of Unit 3

64

Map I D	C-25, D-15
Permit No	28583
Section, Township, Range	32, 31 N , 5 E
County, State	Alpena, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	222	169
Lower Antrim	391	109
Traverse Group	500	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	278
Top Sunbury to top Traverse Group	278

COMMENTS
Ellsworth/upper Antrim—Eroded top under the glacial drift, thickness greater than 169 ft
Lower Antrim—Same as top of Unit 2

65

Map I D	D-2
Permit No	24029
Section, Township, Range	22, 3 N , 6 E
County, State	Livingston, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	627	18
Bedford-Berea	645	190
Ellsworth-upper Antrim	835	88
Lower Antrim	923	75
Traverse Group	998	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	163
Top Sunbury to top Traverse Group	371

COMMENTS
Ellsworth/upper Antrim—Top of upper Antrim is 15 ft within the 35 ft of Unit 5, which is split 15 ft/20 ft
Lower Antrim—Top is the same as top of Unit 1A

66

Map I D	D-3
Permit No	28175
Section, Township, Range	1, 3 N , 3 E
County, State	Livingston, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	254	14
Bedford-Berea	268	164
Ellsworth-upper Antrim	432	118
Lower Antrim	550	83
Traverse Group	633	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	201
Top Sunbury to top Traverse Group	379

COMMENTS
Ellsworth/upper Antrim—Top is same as top of Unit 5
Lower Antrim—Top is same as top of Unit 1A

67

Map I D	D-4
Permit No	23376
Section, Township, Range	22, 5 N , 2 E
County, State	Shiawassee, Mich

FORMATION UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,599	12
Bedford-Berea	1,611	141
Ellsworth-upper Antrim	1,752	137
Lower Antrim	1,889	91
Traverse Group	1,980	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	228
Top Sunbury to top Traverse Group	381

COMMENTS
Ellsworth/upper Antrim—Top of upper Antrim is same as top of Unit 5
Lower Antrim—Top is 10 ft within the 51 ft of Unit 1A, which is split 10 ft/41 ft

68

Map I D	D-5	
Permit No	27549	
Section, Township Range	12, 8 N , 4 E	
County, State	Shiawassee, Mich	
FORMATION UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,652	22
Bedford-Berea	1,674	226
Ellsworth-upper Antrim	1,900	139
Lower Antrim	2,039	73
Traverse Group	2,112	NA
INTERVALS		Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)		212
Top Sunbury to top Traverse Group		460

COMMENTS
Ellsworth/upper Antrim—Same as top of Unit 5
Lower Antrim—Top is 16 ft within the 53 ft of Unit 1A, which is split 16 ft/37 ft

69

Map I D	D-6	
Permit No	23429	
Section, Township, Range	33, 11 N , 3 E	
County, State	Saginaw, Mich	
FORMATION, UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,918	19
Bedford-Berea	1,937	133
Ellsworth-upper Antrim	2,070	200
Lower Antrim	2,270	114
Traverse Group	2,384	NA
INTERVALS		Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)		314
Top Sunbury to top Traverse Group		466

COMMENTS
Lower Antrim—Top is 14 ft within the 24 ft of Unit 2, which is split 14 ft/10 ft

70

Map I D	D-8	
Permit No	BD 127	
Section, Township, Range	17, 16 N , 3 W	
County, State	Isabella, Mich	
FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	2,475	29
Bedford-Berea	2,504	22
Ellsworth-upper Antrim	2,526	299
Lower Antrim	2,825	156
Traverse Group	2,981	NA
INTERVALS		Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)		455
Top Sunbury to top Traverse Group		506

COMMENTS
Ellsworth/upper Antrim—Top is 22 ft within the 36 ft of Unit 9, which is split 22 ft/14 ft
Lower Antrim—Top is the same as top of Unit 2

71

Map I D	D-9, F-7	
Permit No	22345	
Section, Township, Range	21, 20 N , 4 W	
County, State	Clare, Mich	
FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	2,678	19
Bedford-Berea	2,697	22
Ellsworth-upper Antrim	2,719	386
Lower Antrim	3,105	180
Traverse Group	3,285	NA
INTERVALS		Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)		566
Top Sunbury to top Traverse Group		607

COMMENTS
Ellsworth/upper Antrim—Top is the same as Unit 7
Lower Antrim—Top is same as top of Unit 2

72

Map I D	D-10
Permit No	27006
Section, Township, Range	10, 21 N , 1 E
County, State	Ogemaw, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,921	26
Bedford-Berea	1,947	87
Ellsworth-upper Antrim	2,034	285
Lower Antrim	2,319	157
Traverse Group	2,476	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	442
Top Sunbury to top Traverse Group	555

COMMENTS
Ellsworth/upper Antrim—Top of upper Antrim is 41 ft within the 75 ft of Unit 7, which is split 41 ft/34 ft
Lower Antrim—Same as top of Unit 2

73

Map I D	D-11
Permit No	23711
Section, Township, Range	4, 24 N , 3 E
County, State	Ogemaw, Mich

FORMATION UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,672	26
Bedford-Berea	1,698	102
Ellsworth-upper Antrim	1,800	291
Lower Antrim	2,091	127
Traverse Group	2,218	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	418
Top Sunbury to top Traverse Group	546

COMMENTS
Ellsworth/upper Antrim—Top of upper Antrim is 48 ft within the 78 ft of Unit 7, which is split 48 ft/30 ft
Lower Antrim—Top is 5 ft within the 27 ft of Unit 2, which is split 5 ft/22 ft

74

Map I D	D-12
Permit No	28294
Section, Township, Range	12, 25 N , 2 E
County, State	Oscoda, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,843	31
Bedford-Berea	1,874	81
Ellsworth-upper Antrim	1,955	286
Lower Antrim	2,241	147
Traverse Group	2,388	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	433
Top Sunbury to top Traverse Group	545

COMMENTS
Ellsworth/upper Antrim—Top of upper Antrim is 30 ft within the 52 ft of Unit 7, which is split 30 ft/22 ft
Lower Antrim—Top is same as top of Unit 2

75

Map I D	D-13
Permit No	28546
Section, Township, Range	16, 28 N , 1 E
County, State	Oscoda, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,430	23
Bedford-Berea	1,453	33
Ellsworth-upper Antrim	1,486	331
Lower Antrim	1,817	174
Traverse Group	1,991	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	505
Top Sunbury to top Traverse Group	561

COMMENTS
Ellsworth/upper Antrim—Top is the same as top of Unit 7
Lower Antrim—Top is the same as top of Unit 2

76

Map I D	D-14
Permit No	28866
Section, Township, Range	21, 31 N , 4 E
County, State	Montmorency, Mich

FORMATION UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	196	172
Lower Antrim	368	128
Traverse Group	496	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	300
Top Sunbury to top Traverse Group	300

COMMENTS
Ellsworth/upper Antrim—Eroded top of upper Antrim directly under glacial drift
Lower Antrim—Top is 8 ft within the 23 ft of Unit 3, which is split 8 ft/15 ft
Ellsworth/upper Antrim—Thickness is greater than 172 ft

77

Map I D	E-1
Permit No	None
Section, Township, Range	34, 9 S , 2 E
County, State	Fulton, Ohio

FORMATION UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	233	10
Bedford-Berea	243	80
Ellsworth-upper Antrim	323	64
Lower Antrim	387	102
Traverse Group	489	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	166
Top Sunbury to top Traverse Group	256

COMMENTS
Ellsworth/upper Antrim—Top is same as top of Unit 4
Lower Antrim—Top is same as top of Unit 1A

78

Map I D	E-2
Permit No	23295
Section, Township, Range	3, 9 S , 3 E
County, State	Lenawee, Mich

FORMATION, UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	215	13
Bedford-Berea	228	92
Ellsworth-upper Antrim	320	67
Lower Antrim	387	95
Traverse Group	482	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	162
Top Sunbury to top Traverse Group	267

COMMENTS
Lower Antrim—Top same as top of Unit 1A

79

Map I D	E-4
Permit No	22583
Section, Township, Range	7, 4 S , 3 W
County, State	Jackson, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,208	15
Bedford-Berea	1,223	31
Ellsworth-upper Antrim	1,254	110
Lower Antrim	1,364	93
Traverse Group	1,457	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	203
Top Sunbury to top Traverse Group	249

COMMENTS
Lower Antrim—Top is same as top of Unit 1A

80

Map I D	E-5
Permit No	22657
Section, Township, Range	22, 3 S , 4 W
County, State	Calhoun, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,270	19
Bedford-Berea	1,289	33
Ellsworth-upper Antrim	1,322	113
Lower Antrim	1,435	82
Traverse Group	1,517	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	195
Top Sunbury to top Traverse Group	247

COMMENTS
Lower Antrim—Top is same as top of Unit 1A

81

Map I D	E-6
Permit No	22489
Section, Township, Range	6, 1 S , 5 W
County, State	Calhoun, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,515	16
Bedford-Berea	1,531	21
Ellsworth-upper Antrim	1,552	148
Lower Antrim	1,700	82
Traverse Group	1,782	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	230
Top Sunbury to top Traverse Group	267

COMMENTS
Lower Antrim—Top is 12 ft within the 27 ft of Unit 2, which is split 12 ft/15 ft

82

Map I D	E-7
Permit No	23574
Section, Township, Range	15, 5 N , 7 W
County, State	Ionia, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,852	8
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	1,860	240
Lower Antrim	2,100	85
Traverse Group	2,185	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	325
Top Sunbury to top Traverse Group	333

COMMENTS
Lower Antrim—Top is 18 ft within the 31 ft of Unit 2, which is split 18 ft/13 ft

83

Map I D	E-9
Permit No	24826
Section, Township, Range	6, 8 N , 9 W
County, State	Kent, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,913	13
Bedford-Berea	1,926	62
Ellsworth-upper Antrim	1,988	342
Lower Antrim	2,330	92
Traverse Group	2,422	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	434
Top Sunbury to top Traverse Group	509

COMMENTS
Lower Antrim—Top is 21 ft within the 41 ft of Unit 2, which is split 21 ft/20 ft

84

Map I D	E-10
Permit No	29812
Section, Township, Range	1, 11 N , 9 W
County, State	Montcalm, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	2,265	17
Bedford-Berea	2,282	38
Ellsworth-upper Antrim	2,320	355
Lower Antrim	2,675	105
Traverse Group	2,780	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	460
Top Sunbury to top Traverse Group	515

COMMENTS
Lower Antrim—Top is the same as top of Unit 2

85

Map I D	E-11
Permit No	24594
Section, Township, Range	23, 12 N , 8 W
County, State	Montcalm, Mich

FORMATION UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	2,402	23
Bedford-Berea	2,425	22
Ellsworth-upper Antrim	2,447	338
Lower Antrim	2,785	115
Traverse Group	2,900	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	453
Top Sunbury to top Traverse Group	498

COMMENTS
Lower Antrim—Top is the same as top of Unit 2

86

Map I D	E-12, F-5
Permit No	27122
Section, Township, Range	18, 17 N , 8 W
County, State	Osceola, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	2,540	18
Bedford-Berea	2,558	4
Ellsworth-upper Antrim	2,562	486
Lower Antrim	3,048	132
Traverse Group	3,180	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	618
Top Sunbury to top Traverse Group	640

COMMENTS
Ellsworth/upper Antrim—Top of upper Antrim is 4 ft within the 47 ft of Unit 7, which is split 4 ft/43 ft
Lower Antrim—Same as top of Unit 2

87

Map I D	E-13
Permit No	23216
Section, Township, Range	19, 20 N , 10 W
County, State	Osceola, Mich

FORMATION UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	2,108	30
Bedford-Berea	2,138	23
Ellsworth-upper Antrim	2,161	621
Lower Antrim	2,782	163
Traverse Group	2,945	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	784
Top Sunbury to top Traverse Group	837

COMMENTS
Lower Antrim—Same as top of Unit 2

88

Map I D	E-14
Permit No	23636
Section, Township, Range	33, 21 N , 10 W
County, State	Wexford, Mich

FORMATION, UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	2,150	27
Bedford-Berea	2,177	23
Ellsworth-upper Antrim	2,200	638
Lower Antrim	2,838	177
Traverse Group	3,015	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	815
Top Sunbury to top Traverse Group	865

COMMENTS
Lower Antrim—Top is same as top of Unit 2

89

Map I D	E-15
Permit No	22890
Section, Township, Range	32, 22 N , 9 W
County, State	Wexford, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	2,233	17
Bedford-Berea	2,250	15
Ellsworth-upper Antrim	2,265	633
Lower Antrim	2,898	172
Traverse Group	3,070	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	805
Top Sunbury to top Traverse Group	837

COMMENTS
Lower Antrim—Top is same as top of Unit 2

90

Map I D	E-16
Permit No	24501
Section, Township, Range	31, 22 N , 6 W
County, State	Missaukee, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	2,393	22
Bedford-Berea	2,415	25
Ellsworth-upper Antrim	2,440	497
Lower Antrim	2,937	163
Traverse Group	3,100	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	660
Top Sunbury to top Traverse Group	707

COMMENTS
Ellsworth/upper Antrim—Top is same as top of Unit 7
Lower Antrim—Top is same as top of Unit 2

91

Map I D	E-17
Permit No	30610
Section, Township, Range	2, 24 N , 5 W
County, State	Missaukee, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,853	26
Bedford-Berea	1,879	37
Ellsworth-upper Antrim	1,916	432
Lower Antrim	2,348	133
Traverse Group	2,481	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	565
Top Sunbury to top Traverse Group	628

COMMENTS
Ellsworth/upper Antrim—Top is same as top of Unit 7
Lower Antrim—Top is 20 ft within the 42 ft of Unit 2, which is split 20 ft/22 ft

92

Map I D	E-18
Permit No	27187
Section, Township, Range	21, 25 N , 4 W
County, State	Crawford, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,575	25
Bedford-Berea	1,600	42
Ellsworth-upper Antrim	1,642	410
Lower Antrim	2,052	139
Traverse Group	2,191	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	549
Top Sunbury to top Traverse Group	616

COMMENTS
Ellsworth/upper Antrim—Top is same as top of Unit 7
Lower Antrim—Top is 22 ft within the 45 ft of Unit 2, which is split 22 ft/23 ft

93

Map I D	E-19
Permit No	28886
Section, Township, Range	32, 29 N , 4 W
County, State	Otsego, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,120	10
Bedford-Berea	1,130	47
Ellsworth-upper Antrim	1,177	445
Lower Antrim	1,622	127
Traverse Group	1,749	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	572
Top Sunbury to top Traverse Group	629

COMMENTS
Ellsworth/upper Antrim—Top is 10 ft within the 45 ft of Unit 7, which is split 10 ft/35 ft
Lower Antrim—Top is 27 ft within the 52 ft of Unit 2, which is split 27 ft/25 ft

94

Map I D	E-20
Permit No	26216
Section, Township, Range	16, 29 N , 3 W
County, State	Otsego, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,158	7
Bedford-Berea	1,165	55
Ellsworth-upper Antrim	1,220	395
Lower Antrim	1,615	133
Traverse Group	1,748	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	528
Top Sunbury to top Traverse Group	590

COMMENTS
Ellsworth/upper Antrim—Top is 20 ft within the 55 ft of Unit 7, which is split 20 ft/35 ft
Lower Antrim—Top is 25 ft within the 50 ft of Unit 2, which is split 25 ft/25 ft

95

Map I D	E-21
Permit No	None
Section, Township, Range	7, 29 N , 2 W
County, State	Otsego, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,102	8
Bedford-Berea	1,110	68
Ellsworth-upper Antrim	1,178	362
Lower Antrim	1,540	60+
Traverse Group	NA	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	422+
Top Sunbury to top Traverse Group	498+

COMMENTS
Ellsworth/upper Antrim—Top is 21 ft within the 33 ft of Unit 7, which is split 21 ft/12 ft
Lower Antrim—Top is same as top of Unit 1A Total depth of 1,600 ft is within Unit 1A

96

Map I D	E-22	
Permit No	28837	
Section, Township, Range	1, 29 N , 2 W	
County, State	Otsego, Mich	
FORMATION UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,070	8
Bedford-Berea	1,078	52
Ellsworth-upper Antrim	1,130	353
Lower Antrim	1,483	117
Traverse Group	1,600	NA
INTERVALS		Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)		470
Top Sunbury to top Traverse Group		530

COMMENTS
Ellsworth/upper Antrim—Top is same as top of Unit 7
Lower Antrim—Top is 23 ft within the 43 ft of Unit 2, which is split 23 ft/20 ft

97

Map I D	F-4	
Permit No	27480	
Section, Township, Range	30, 16 N , 11 W	
County, State	Newaygo, Mich	
FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	2,130	39
Bedford-Berea	2,169	31
Ellsworth-upper Antrim	2,200	550
Lower Antrim	2,750	110
Traverse Group	2,860	NA
INTERVALS		Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)		660
Top Sunbury to top Traverse Group		730

COMMENTS
Ellsworth/upper Antrim—Same as base of Unit 7
Lower Antrim—Top is 17 ft within the 47 ft of Unit 2, which is split 17 ft/30 ft

98

Map I D	F-6	
Permit No	26649	
Section, Township, Range	21, 19 N , 6 W	
County, State	Clare, Mich	
FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	2,549	13
Bedford-Berea	2,562	12
Ellsworth-upper Antrim	2,574	439
Lower Antrim	3,013	168
Traverse Group	3,181	NA
INTERVALS		Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)		607
Top Sunbury to top Traverse Group		632

COMMENTS
Ellsworth/upper Antrim—Same as top of Unit 7
Lower Antrim—Same as top of Unit 2

99

Map I D	F1 1	
Permit No	30169	
Section, Township, Range	27, 15 N , 18 W	
County, State	Oceana, Mich	
FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	NL	14
Bedford-Berea	NL	22
Ellsworth-upper Antrim	NL	621
Lower Antrim	NL	114
Traverse Group	NL	NA
INTERVALS		Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)		735
Top Sunbury to top Traverse Group		771

COMMENTS
Thickness scaled from a poor reproduction from Fisher (1980), depths were not legible

100

Map I D	Fi 2	
Permit No	26662	
Section, Township, Range	20, 15 N , 14 W	
County, State	Newaygo, Mich	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	NL	40
Bedford-Berea	NL	18
Ellsworth-upper Antrim	NL	537
Lower Antrim	NL	140
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	677
Top Sunbury to top Traverse Group	735

COMMENTS
Thickness scaled from a poor reproduction from Fisher (1980), depths were not legible

101

Map I D	Fi 3	
Permit No	27489	
Section, Township, Range	17, 15 N , 10 W	
County, State	Mecosta, Mich	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	NL	34
Bedford-Berea	NL	10
Ellsworth-upper Antrim	NL	503
Lower Antrim	NL	135
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	638
Top Sunbury to top Traverse Group	682

COMMENTS
Thickness scaled from a poor reproduction from Fisher (1980), depths were not legible

102

Map I D	Fi 4	
Permit No	24101	
Section, Township, Range	23, 15 N , 8 W	
County, State	Mecosta, Mich	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	NL	18
Bedford-Berea	NL	8
Ellsworth-upper Antrim	NL	416
Lower Antrim	NL	163
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	579
Top Sunbury to top Traverse Group	605

COMMENTS
Thickness scaled from a poor reproduction from Fisher (1980), depths were not legible

103

Map I D	Fi 5	
Permit No	30519	
Section, Township, Range	14, 14 N , 6 W	
County, State	Isabella, Mich	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	NL	22
Bedford-Berea	NL	15
Ellsworth-upper Antrim	NL	316
Lower Antrim	NL	130
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	446
Top Sunbury to top Traverse Group	483

COMMENTS
Thickness scaled from a poor reproduction from Fisher (1980), depths were not legible

104

Map I D	Fi 6
Permit No	30126
Section, Township, Range	4, 15 N , 2 W
County, State	Midland, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	NL	33
Bedford-Berea	NL	70
Ellsworth-upper Antrim	NL	266
Lower Antrim	NL	183
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	449
Top Sunbury to top Traverse Group	552

COMMENTS
Thickness scaled from a poor reproduction from Fisher (1980), depths were not legible

105

Map I D	Fi 7
Permit No	31191
Section, Township, Range	10, 15 N , 3 E
County, State	Bay, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	NL	24
Bedford-Berea	NL	162
Ellsworth-upper Antrim	NL	201
Lower Antrim	NL	156
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	356
Top Sunbury to top Traverse Group	543

COMMENTS
Thickness scaled from a poor reproduction from Fisher (1980), depths were not legible

106

Map I D	Fi 8
Permit No	23485
Section, Township, Range	12, 14 N , 9 E
County, State	Tuscola, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,447	53
Bedford-Berea	1,500	273
Ellsworth-upper Antrim	1,773	142
Lower Antrim	1,915	95
Traverse Group	2,010	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	237
Top Sunbury to top Traverse Group	563

COMMENTS
Scaled from a poor reproduction

107

Map I D	Fi 9
Permit No	24544
Section, Township, Range	35, 12 N , 15 E
County, State	Sanilac, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	NL	165
Bedford-Berea	NL	252
Ellsworth-upper Antrim	NL	142
Lower Antrim	NL	103
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	245
Top Sunbury to top Traverse Group	662

COMMENTS
Thickness scaled from a poor reproduction from Fisher (1980), depths were not legible

108

Map I D	A-B3
Permit No	29066
Section, Township, Range	26, 19 N , 1 W
County, State	Gladwin, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	2,283	30
Bedford-Berea	2,313	82
Ellsworth-upper Antrim	2,395	275
Lower Antrim	2,670	170
Traverse Group	2,840	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	445
Top Sunbury to top Traverse Group	557

COMMENTS
Data from Lilienthal (1978, pl 10)

109

Map I D	A-H8
Permit No	26112
Section, Township, Range	10, 6 S , 17 W
County, State	Berrien, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	292	384
Lower Antrim	676	74
Traverse Group	750	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	458
Top Sunbury to top Traverse Group	458

COMMENTS
Data from Lilienthal (1978, pl 45)
Ellsworth/upper Antrim—Eroded top under glacial drift

110

Map I D	A-J3
Permit No	28929
Section, Township, Range	33, 2 N , 2 W
County, State	Ingham, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,793	19
Bedford-Berea	1,812	47
Ellsworth-upper Antrim	1,859	121
Lower Antrim	1,980	110
Traverse Group	2,090	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	231
Top Sunbury to top Traverse Group	297

COMMENTS
Data from Lilienthal (1978, pls 56, 57)

111

Map I D	A-K2
Permit No	27811
Section, Township, Range	6, 7 N , 1 W
County, State	Clinton, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	2,000	15
Bedford-Berea	2,015	85
Ellsworth-upper Antrim	2,100	175
Lower Antrim	2,275	103
Traverse Group	2,378	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	278
Top Sunbury to top Traverse Group	378

COMMENTS
Data from Lilienthal (1978, pls 61, 62)

112

Map I D	A-K7
Permit No	26856
Section, Township, Range	17, 4 S , 5 E
County, State	Washtenaw, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	178	131
Ellsworth-upper Antrim	309	61
Lower Antrim	370	89
Traverse Group	459	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	150
Top Sunbury to top Traverse Group	281

COMMENTS
Data from Lilienthal (1978, pls 61, 62)
Berea/Bedford—Eroded top under glacial drift

113

Map I D	Ma 1
Permit No	NA
Section, Township, Range	32, 12 N , 16 E
County, State	Sanilac, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	445	172
Bedford-Berea	617	257
Ellsworth-upper Antrim	874	NA
Lower Antrim	ND	NA
Traverse Group	1,066	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	192
Top Sunbury to top Traverse Group	621

COMMENTS
Data scaled from maps and sections in Matthews (1973)
Lower Antrim not differentiated

115

Map I D	A-N3
Permit No	24079
Section, Township, Range	4, 9 N , 8 E
County, State	Genesee, Mich

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	1,479	42
Bedford-Berea	1,521	219
Ellsworth-upper Antrim	1,740	134
Lower Antrim	1,874	77
Traverse Group	1,951	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	211
Top Sunbury to top Traverse Group	472

COMMENTS
Data from Lilienthal (1978, pl 77)

114

Map I D	351 M
Permit No	NA
Location	Lake Erie, Ontario, Canada (LE 351 M)

FORMATION UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	ABS	0
Lower Antrim	NL	16
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	16
Top Sunbury to top Traverse Group	16

COMMENTS

116

Map I D	310 T
Permit No	NA
Location	Lake Erie, Ontario, Canada (LE 310 T)

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	ABS	0
Lower Antrim	NL	29
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	29
Top Sunbury to top Traverse Group	29

COMMENTS
Estimated from isopach map by Bird (1983, fig 8)

117

Map I D	313 J
Permit No	NA
Location	Lake Erie, Ontario, Canada (LE 313 J)

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	NL	NA
Lower Antrim	NL	NA
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	62
Top Sunbury to top Traverse Group	62

COMMENTS
Estimated from isopach map by Bird (1983, fig 8)

118

Map I D	238 D
Permit No	NA (TM 1A)?
Location	Lake Erie, Ontario, Canada (LE 238 D)

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	NL	NA
Lower Antrim	NL	NA
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	52
Top Sunbury to top Traverse Group	52

COMMENTS
Estimated from isopach map by Bird (1983, fig 8)

119

Map I D	283 V
Permit No	NA (C13355) ?
Location	Lake Erie, Ontario, Canada (LE 283 V)

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	NL	NA
Lower Antrim	NL	NA
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	43
Top Sunbury to top Traverse Group	43

COMMENTS
From Bird (1983, p 42)

120

Map I D	225 P
Permit No	NA (V R 1) ?
Location	Lake Erie, Ontario, Canada (LE 225 P)

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	NL	NA
Lower Antrim	NL	NA
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	125
Top Sunbury to top Traverse Group	125

COMMENTS
From Bird (1983, p 42)

121

Map I D	14
Ontario Geological Society borehole	14
Location	Kent, Ontario, Canada

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	NL	20
Lower Antrim	NL	98
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	118
Top Sunbury to top Traverse Group	118

COMMENTS
From Russell (1985, fig 17)
Upper Antrim—Top of upper Antrim (Kettle Point) eroded No *Foerstia* reported Thickness scaled off a poor reproduction, and depths were not legible

123

Map I D	13
Ontario Geological Society borehole	13
Location	Kent, Ontario, Canada

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	ABS	0
Lower Antrim	NL	66
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	66
Top Sunbury to top Traverse Group	66

COMMENTS
From Russell (1985, fig 17)
Lower Antrim—Top of lower Antrim (Kettle Point) eroded No *Foerstia* reported Thickness scaled off a poor reproduction, and depths were not legible

122

Map I D	16
Ontario Geological Society borehole	16
Location	Kent, Ontario, Canada

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	72	144
Lower Antrim	216	72
Traverse Group	288	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	216
Top Sunbury to top Traverse Group	216

COMMENTS
Ellsworth/upper Antrim—Eroded top under glacial drift
Lower Antrim thickness—Determined by position of *Foerstia* from table 2 of Russell (1985)

124

Map I D	17	
Ontario Geological Society borehole	17	
Location	Kent, Ontario, Canada	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	ABS	0
Lower Antrim	NL	98
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	98
Top Sunbury to top Traverse Group	98

COMMENTS
Lower Antrim thickness—From table 2 of Russell (1985)

125

Map I D	18	
Ontario Geological Society borehole	18	
Location	Lambton, Ontario, Canada	

FORMATION UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	154	135
Lower Antrim	289	69
Traverse Group	358	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	204
Top Sunbury to top Traverse Group	204

COMMENTS
Ellsworth/upper Antrim—Eroded top under glacial drift
Lower Antrim thickness—From table 2 of Russell (1985)

126

Map I D	19	
Ontario Geological Society borehole	19	
Location	Lambton, Ontario, Canada	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	ABS	0
Lower Antrim	NL	52
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	52
Top Sunbury to top Traverse Group	52

COMMENTS
Lower Antrim thickness—From table 2 of Russell (1985)

127

Map I D	24	
Ontario Geological Society borehole	24	
Location	Lambton, Ontario, Canada	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	NA	20
Ellsworth-upper Antrim	154	161
Lower Antrim	315	75
Traverse Group	390	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	236
Top Sunbury to Top Traverse Group	256

COMMENTS
Bedford/Berea (Port Lambton)—Top is not shown but is known to be eroded and under the glacial drift
Lower Antrim thickness—From table 2 of Russell (1985)

128

Map I D	25	
Ontario Geological Society borehole	25	
Location	Lambton, Ontario, Canada	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	105	135
Lower Antrim	240	66
Traverse Group	306	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	201
Top Sunbury to top Traverse Group	201

COMMENTS
Ellsworth/upper Antrim—Eroded top under glacial drift
Lower Antrim thickness—From table 2 of Russell (1985)

129

Map I D	26	
Ontario Geological Society borehole	26	
Location	Lambton, Ontario, Canada	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	ABS	0
Lower Antrim	NL	72
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	72
Top Sunbury to top Traverse Group	72

COMMENTS
Lower Antrim thickness—From table 2 of Russell (1985)

130

Map I D	82–1	
Ontario Geological Society borehole	82-1	
Location	Lambton, Ontario, Canada	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	ABS	0
Lower Antrim	NL	62
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	62
Top Sunbury to top Traverse Group	62

COMMENTS
Lower Antrim thickness—From table 2 of Russell (1985)

131

Map I D	H	
Permit No	13243	
Location	Lake Erie, Ontario Canada (LE 175 D)	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	NL	3
Lower Antrim	NL	125
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	128
Top Sunbury to top Traverse Group	128

COMMENTS
From figure 17 of Russell (1985)
Depths are not legible, thickness scaled from a small reproduction

132

Map I D	I
Permit No	NA
Location	Kent, Ontario, Canada (lot 7, concession 97–STR)

FORMATION UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	NL	20
Lower Antrim	NL	105
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	125
Top Sunbury to top Traverse Group	125

COMMENTS
From figure 17 of Russell (1985) Depths are not legible, thickness scaled from a small reproduction

133

Map I D	J
Permit No	NA
Location	Kent, Ontario, Canada (lot 14, concession 9)

FORMATION UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	NL	7
Lower Antrim	NL	98
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	105
Top Sunbury to top Traverse Group	105

COMMENTS

134

Map I D	2–6
Permit No	NA
Location	Lambton, Ontario, Canada (lot 2, concession 6)

FORMATION UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	NA	161
Lower Antrim	NA	98
Traverse Group	NA	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	259
Top Sunbury to top Traverse Group	259

COMMENTS
Data from Winder (1966)

135

Map I D	1434
Permit No	1434
Section, Township	15, Chester
County, State	Wayne, Ohio

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	NL	135
Ellsworth-upper Antrim	NL	695
Lower Antrim	NL	235
Traverse Group	NL	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	930
Top Sunbury to top Traverse Group	1,065

COMMENTS
Data from Janssens and deWitt (1976)

136

Map I D	389
Permit No	389
Section, Township	30, Butler
County, State	Richland, Ohio

FORMATION, UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	425	14
Bedford-Berea	439	150
Ellsworth-upper Antrim	589	379
Lower Antrim	968	189
Traverse Group	1,157	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	568
Top Sunbury to top Traverse Group	732

COMMENTS
Data from Wallace and others (1977)

137

Map I D	114
Permit No	NA
Section, Township, Range	13, 36 N , 3 W
County, State	Laporte, Ind

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	218	114
Lower Antrim	332	81
Traverse Group	413	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	195
Top Sunbury to top Traverse Group	195

COMMENTS
Ellsworth/upper Antrim—Eroded top

138

Map I D	115
Permit No	NA
Section, Township, Range	1, 36 N , 2 W
County, State	Laporte, Ind

FORMATION UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	177	64
Lower Antrim	241	64
Traverse Group	305	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	128
Top Sunbury to top Traverse Group	128

COMMENTS
Ellsworth/upper Antrim—Eroded top under glacial drift

139

Map I D	116
Permit No	NA
Section, Township, Range	16, 36 N , 1 W
County, State	Laporte, Ind

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	144	78
Lower Antrim	222	65
Traverse Group	287	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	143
Top Sunbury to top Traverse Group	143

COMMENTS
Ellsworth/upper Antrim—Eroded top under glacial drift
"Traverse Formation" thickness 7 ft
"Traverse Lime"—depth to top 294 ft

140

Map I D	117
Permit No	NA
Section, Township, Range	32, 36 N , 3 E
County, State	St Joseph, Mich

FORMATION UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	192	219
Lower Antrim	411	59
Traverse Group	470	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	278
Top Sunbury to top Traverse Group	278

COMMENTS
Ellsworth/upper Antrim—Eroded top under glacial drift
"Traverse Formation" thickness 20 ft
"Traverse Lime"—depth to top 490 ft

141

Map I D	118
Permit No	NA
Section, Township, Range	23, 35 N , 4 E
County, State	Elkhart, Ind

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	243	144
Lower Antrim	387	64
Traverse Group	451	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	208
Top Sunbury to top Traverse Group	208

COMMENTS
Ellsworth/upper Antrim—Eroded top under glacial drift
"Traverse Formation" thickness 19 ft
"Traverse Lime"—depth to top 470 ft

142

Map I D	119
Permit No	NA
Section, Township, Range	14, 36 N , 6 E
County, State	Elkhart, Ind

FORMATION UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	180	243
Lower Antrim	423	64
Traverse Group	487	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	316
Top Sunbury to top Traverse Group	316

COMMENTS
Ellsworth/upper Antrim—Eroded top under glacial drift
"Traverse Formation" thickness 46 ft
"Traverse Lime"—depth to top 533 ft

143

Map I D	120
Permit No	NA
Section, Township, Range	14, 36 N , 7 E
County, State	Elkhart, Ind

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	284	194
Lower Antrim	478	63
Traverse Group	541	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	257
Top Sunbury to top Traverse Group	257

COMMENTS
Ellsworth/upper Antrim—Eroded top under glacial drift
"Traverse Formation" thickness 51 ft
"Traverse Lime"—depth to top 592 ft

144

Map I D	121	
Permit No	NA	
Section, Township, Range	2, 35 N , 10 E	
County, State	Noble, Ind	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	357	5
Bedford-Berea	362	41
Ellsworth-upper Antrim	403	108
Lower Antrim	511	44
Traverse Group	555	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	152
Top Sunbury to top Traverse Group	198

COMMENTS
"Traverse Formation" thickness 74 ft
"Traverse Lime"—depth to top 629 ft

145

Map I D	122	
Permit No	NA	
Section, Township, Range	20, 36 N , 12 E	
County, State	Steuben, Ind	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	418	6
Bedford-Berea	424	48
Ellsworth-upper Antrim	472	99
Lower Antrim	571	48
Traverse Group	619	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	147
Top Sunbury to top Traverse Group	201

COMMENTS
"Traverse Formation" thickness 71 ft
"Traverse Lime"—depth to top 690 ft

146

Map I D	123	
Permit No	NA	
Section, Township Range	25, 36 N , 12 E	
County, State	Steuben, Ind	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	461	8
Bedford-Berea	469	46
Ellsworth-upper Antrim	515	92
Lower Antrim	607	50
Traverse Group	657	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	142
Top Sunbury to top Traverse Group	196

COMMENTS
"Traverse Formation" thickness 63 ft
"Traverse Lime"—depth to top 720 ft

147

Map I D	125	
Permit No	NA	
Section, Township, Range	21, 38 N , 14 E	
County, State	Steuben, Ind	

FORMATION, UNIT OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	783	9
Bedford-Berea	792	50
Ellsworth-upper Antrim	842	100
Lower Antrim	942	65
Traverse Group	1,007	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	165
Top Sunbury to top Traverse Group	224

COMMENTS
Bedford/Berea—Called Ellsworth by Hasenmueller and Bassett (1980), called Bedford by Ells (1979)
Ellsworth/upper Antrim—Same as top of Unit 4
Lower Antrim—Same as Unit 1A (see fig 16)

148

Map I D	126	
Permit No	NA	
Section, Township, Range	6, 35 N , 1 W	
County, State	Laporte, Ind	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	175	6
Lower Antrim	181	67
Traverse Group	248	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	73
Top Sunbury to top Traverse Group	73

COMMENTS
Ellsworth/upper Antrim—Eroded top under glacial drift

149

Map I D	127	
Permit No	NA	
Section, Township, Range	5, 33 N , 1 E	
County, State	Marshall, Ind	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	ABS	0
Lower Antrim	182	45
Traverse Group	227	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	45
Top Sunbury to top Traverse Group	45

COMMENTS
Lower Antrim—Eroded top under glacial drift
Traverse Group—"Traverse Formation" (transition beds) absent, Antrim lies on "Traverse Lime "

150

Map I D	128	
Permit No	NA	
Section, Township, Range	13, 34 N , 2 E	
County, State	Marshall, Ind	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	160	115
Lower Antrim	275	60
Traverse Group	335	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	175
Top Sunbury to top Traverse Group	175

COMMENTS
Ellsworth/upper Antrim—Eroded top under glacial drift
"Traverse Formation" thickness 21 ft
"Traverse Lime"—depth to top 356 ft

151

Map I D	129	
Permit No	NA	
Section, Township, Range	21, 34 N , 3 E	
County, State	Marshall, Ind	

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	170	27
Lower Antrim	197	56
Traverse Group	253	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	83
Top Sunbury to top Traverse Group	83

COMMENTS
Ellsworth/upper Antrim—Eroded top under glacial drift
"Traverse Formation" thickness 20 ft
"Traverse Lime"—depth to top 273 ft

152

Map I D	130
Permit No	NA
Section, Township, Range	19, 34 N , 6 E
County, State	Kosciusko, Ind

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	ABS	0
Lower Antrim	210	61
Traverse Group	271	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	61
Top Sunbury to top Traverse Group	61

COMMENTS
Lower Antrim—Eroded top under glacial drift
"Traverse Formation" thickness 39 ft
"Traverse Lime"—depth to top 310 ft

153

Map I D	131
Permit No	NA
Section, Township, Range	33, 34 N , 8 E
County, State	Noble, Ind

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	ABS	0
Lower Antrim	367	53
Traverse Group	420	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	53
Top Sunbury to top Traverse Group	53

COMMENTS
Lower Antrim—Eroded top under glacial drift
"Traverse Formation" thickness 59 ft
"Traverse Lime"—depth to top 479 ft

154

Map I D	132
Permit No	NA
Section, Township, Range	9, 34 N , 9 E
County, State	Noble, Ind

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	300	26
Lower Antrim	326	55
Traverse Group	381	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	81
Top Sunbury to top Traverse Group	81

COMMENTS
Ellsworth/upper Antrim—Eroded top under glacial drift
"Traverse Formation" thickness 68 ft
"Traverse Lime"—depth to top 449 ft

155

Map I D	133
Permit No	NA
Section, Township, Range	35, 34 N , 10 E
County, State	Noble, Ind

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	ABS	0
Lower Antrim	423	42
Traverse Group	465	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	42
Top Sunbury to top Traverse Group	42

COMMENTS
Lower Antrim—Eroded top under glacial drift
"Traverse Formation" thickness 65 ft
"Traverse Lime"—depth to top 530 ft

156

Map I D	134
Permit No	NA
Section, Township, Range	8, 33 N , 11 E
County, State	Noble, Ind

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	ABS	0
Lower Antrim	288	70
Traverse Group	358	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	70
Top Sunbury to top Traverse Group	70

COMMENTS
Lower Antrim—Eroded top under glacial drift
"Traverse Formation" thickness 61 ft
"Traverse Lime"—depth to top 419 ft

157

Map I D	135
Permit No	NA
Section, Township, Range	17, 34 N , 12 E
County, State	DeKalb, Ind

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	392	27
Lower Antrim	419	71
Traverse Group	490	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	98
Top Sunbury to top Traverse Group	98

COMMENTS
Ellsworth/upper Antrim—Eroded top under glacial drift
"Traverse Formation" thickness 62 ft
"Traverse Lime"—depth to top 552 ft

158

Map I D	136
Permit No	NA
Section, Township, Range	16, 34 N , 13 E
County, State	DeKalb, Ind

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	345	14
Lower Antrim	359	75
Traverse Group	434	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	89
Top Sunbury to top Traverse Group	89

COMMENTS
Ellsworth/upper Antrim—Eroded top under glacial drift
"Traverse Formation" thickness 56 ft
"Traverse Lime"—depth to top 490 ft

159

Map I D	137
Permit No	NA
Section, Township, Range	35, 35 N , 14 E
County, State	DeKalb, Ind

FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	370	12
Lower Antrim	382	70
Traverse Group	452	NA

INTERVALS	Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)	82
Top Sunbury to top Traverse Group	82

COMMENTS
Ellsworth/upper Antrim—Eroded top under glacial drift
"Traverse Formation" thickness 59 ft
"Traverse Lime"—depth to top 511 ft

160

Map I D	LAIT No 12	
Permit No	None	
Section, Township, Range	NA	
County, State	Off Milwaukee, Wisc	
FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	ABS	0
Lower Antrim	NL	24
Traverse Group	NL	NA
INTERVALS		Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)		24
Top Sunbury to top Traverse Group		24

COMMENTS

Borehole about 1,900 ft offshore along Linwood Avenue Intake Tunnel Thickness estimated from undimensioned drawing

161

Map I D	NPIT	
Permit No	None	
Section, Township, Range	NA	
County, State	Milwaukee, Wisc	
FORMATION, UNIT, OR SUBUNIT	Depth to top (ft)	Thickness (ft)
Sunbury	ABS	0
Bedford-Berea	ABS	0
Ellsworth-upper Antrim	ABS	0
Lower Antrim	NL	15
Traverse Group	NL	NA
INTERVALS		Thickness (ft)
Lower Antrim-Ellsworth-upper Antrim (inclusive)		15
Top Sunbury to top Traverse Group		15

COMMENTS

Shaft for North Point Intake Tunnel on shore at eastern end of North Avenue, Milwaukee Fifteen feet of black shale under glacial drift "Kenwood Formation "

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APPENDIX D: WELLS SAMPLED FOR THE DOW/DEPARTMENT OF ENERGY/ANTRIM OIL SHALE PROJECT

[ERDA, Energy and Research Development Administration From Young (1980)]

Well number	Permit number	Company name	Well name	Location
Mi-1	624-771-474	Dow Chemical	Dow/ERDA 100	NE 8, 9 N , 15 E
Mi-2	622-771-474	do	Dow/ERDA 101	NE 8, 9 N , 15 E
Mi-3	621-771-474	do	Dow/ERDA 102	NE 8, 9 N , 15 E
Mi-4	32029	Consumers Power	Marsh No 1	NE 15, 16 N , 1 E
Mi-5	31937	Michigan Consolidated Gas	C C 770	SE 30, 7 N , 13 E
Mi-6	32055	E E Brehm	Cosens 1-36	NE 36, 14 N , 7 E
Mi-7	32035	Merrill Drilling	L Bazaire 2-5	SE 5, 16 N , 6 W
Mi-8	684-771-474	Dow Chemical	Dow/ERDA 105	NE 8, 9 N , 15 E
Mi-9	32291	Kulka & Schmidt	Round-Jones 1-7	NE 7, 2 N , 3 W
Mi-10	32931	Reef Petroleum	Smitha 4-1	NE 1, 3 N , 11 E
Mi-11	32413	Elek & Barlett	Schrade No 1	SW 2, 25 N , 8 E
Mi-12	32452	Marathon Oil	Baumchen K-6	NW 27, 22 N , 2 E
Mi-13	32562	Hunt Energy	Wild 1-3	SE 3, 16 N , 4 W
Mi-14	32427	Amoco	Patrick 1-28	NW 28, 2 N , 3 E
Mi-15	32581	Hunt Energy	Weber 1-26	SW 26, 1 S , 4 E
Mi-16	32292	Amoco	Fawcett 3-24	SW 24, 28 N , 6 W
Mi-17	32514	do	Tompkins 1-2	SE 2, 14 N , 18 W
Mi-18	32720	Scott Drilling	Collier 1-12	NE 12, 2 S , 4 W
Mi-19	32744	Kulka & Schmidt	Guldemond 1-21	SW 21, 1 S , 13 W
Mi-20	32787	Crystal Exploration	Ulrich No 1	NW 13, 9 N , 8 E
Mi-21	32622	Aztec	State 3-2	SE 2, 21 N , 17 W
Mi-22	32150	ATE-Dart et al	Broderick	NE 9, 16 N , 4 E
Mi-23	32827	Dart	Bruggers 1-7	NW 7, 24 N , 6 W
Mi-24	32847	Reef	Wussow 1-1	SW 1, 23 N , 15 W
Mi-25	32705	Richard Beeson	Turner 1-17	NW 17, 17 N , 8 W
Mi-26	32716	Northern Michigan Exploration	State Blair 3-21	NE 21, 26 N , 11 W
Mi-27	31171	M Welch	St Otsego Lake 1-15	SW 15, 29 N , 3 W
Mi-28	31401	Amoco	Swift 1-28	SE 28, 30 N , 3 W
Mi-29	(4335-Ont)	Dow Chemical	Dow Moore 3-21 XII	Lambton Co , Ontario
Mi-30	31386	Michigan Natural Resources	Staudacher-Shwa 1-2	SE 2, 14 N , 4 E
Mi-31	31448	Dart Oil & Gas	L Hemming 1-22	NE 22, 21 N , 7 W
Mi-32	31175	M Welch	St Otsego Lake 1-16	SE 16, 29 N , 3 W
Mi-33	31174	do	St Otsego Lake 1-22	NW 22, 29 N , 3 W
Mi-34	33037	Sun Oil	St Helen 15-35	SE 28, 24 N , 1 W
Mi-35	32768	Vernon East	Woods No 1	SE 18, 7 S , 14 W

Chapter E

Stratigraphy of the Kettle Point Formation (Upper Devonian of Southwestern Ontario, Canada)—Implications for Depositional Setting and Resource Potential

By D.J. RUSSELL

U.S. GEOLOGICAL SURVEY BULLETIN 1909
PETROLEUM GEOLOGY OF THE DEVONIAN AND MISSISSIPPIAN BLACK SHALE OF EASTERN NORTH AMERICA

CONTENTS

PLATE

[Plate is in pocket]

FIGURES

Stratigraphy of the Kettle Point Formation (Upper Devonian of Southwestern Ontario, Canada)—Implications for Depositional Setting and Resource Potential

By D.J. Russell[1]

Abstract

In southern Ontario, Canada, the Kettle Point Formation is the equivalent of the widespread Upper Devonian black and gray shales of the Eastern United States Because of its potential as an oil shale, it has been studied in that context by the Ontario Geological Survey, which drilled several fully cored and logged boreholes and conducted stratigraphic, sedimentological, and geochemical analyses

The gamma-ray log can be used for lithostratigraphic analysis and resource evaluation of the Kettle Point Formation because the prime lithologic variable and the control on oil shale potential is the organic-carbon content This parameter is a direct control on the gamma radiation from the unit An area close to the St Clair River in Lambton County has the best potential for oil shale exploitation In this area, the upper 10-meter section of the formation has total organic-carbon values of over 12 percent and correspondingly high Fischer assay yields

The lithostratigraphic systems, which are based on the gamma-ray log, for equivalent units in Ohio (the Ohio Shale) and Michigan (the Antrim Shale) can be extended into the Kettle Point Formation in neighboring parts of Ontario The sixfold division used for the Antrim Shale is best suited for use in Ontario Complications in the lithostratigraphy of the formation over the Algonquin arch (the positive feature separating the Appalachian and the Michigan basins) and an indication of Late Devonian submarine topography are revealed by using the incoming of the algal microfossil *Foerstia* as a stratigraphic datum

Processes affecting the pre-*Foerstia* Kettle Point Formation as it was deposited near the Algonquin arch were northward thinning of units against the arch, northward onlap, and change in characteristics, notably a lower organic-carbon content and more green shale over the arch The observed variations in stratigraphy can be explained by postulating movements in the boundary between oxygenated, relatively agitated water and anoxic, stagnant water interacting with the submarine topography Changes in water depth are not necessary to explain the stratigraphic variations present in the Kettle Point Formation

INTRODUCTION

The Upper Devonian black shales of eastern North America are important as potential unconventional sources of hydrocarbons In southwestern Ontario, a small area is underlain by the Kettle Point Formation, which is the equivalent of the volumetrically more significant Ohio, New Albany, Chattanooga, and Antrim Shales of the United States The Kettle Point Formation subcrops the Quaternary glacial deposits over most of its geographic extent and occurs at depths of no more than 160 meters (m) Consequently, it is not as good a potential source of gas as are the equivalents in the deeper parts of the Appalachian basin However, the high organic-carbon content of the Kettle Point Formation prompted the Ontario Geological Survey (OGS) to study its potential as an oil shale Some results of this study are presented here The voluminous data generated cover the gross stratigraphic, sedimentological, organic-geochemical, mineralogic, inorganic-geochemical, rock mechanical, and paleontological aspects of the unit (Barker and others, 1983b, Delitala, 1984, Loftsson, 1984, Johnson, 1985, Armstrong, 1986, Harris, 1986, Johnson and others, in press) Interpretations of the stratigraphic data and some of the geochemical data (Barker and others, 1983b, Russell and Barker, 1983, Russell, 1985) are synthesized in this chapter It is hoped that the concepts presented will aid in the interpretation of the equivalent sequences in the neighboring basins and other similar units regardless of age and will provide a framework for the resource assessment of the Kettle Point Formation

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GEOGRAPHIC AND GEOLOGICAL SETTING

The geographic extent of the Kettle Point Formation is shown in figure 1. Its position relative to the town of Sarnia, which is a major petrochemical center, may be fortuitous if the unit is ever exploited as an oil shale.

In the context of the Upper Devonian stratigraphy of the area, the formation is located geographically between the Ohio Shale of the Appalachian basin and the Antrim Shale of the Michigan basin, thus straddling the divide between these two major depocenters. This divide, the Algonquin-Findlay arch complex in Ontario (here called the Algonquin arch for brevity), has undergone reactivation at several times during and probably after Paleozoic time (Sanford and others, 1985), which gave it varying degrees of control over the patterns of sedimentation and erosion. The preservation of the Kettle Point Formation is the result of a synclinal feature formed by the opposing plunges of the Algonquin and the Findlay arches (fig. 1). The Algonquin arch formed first as a peripheral bulge to a foredeep caused by crustal loading of the Taconic Orogen. The Middle-Late Devonian Acadian orogeny may have reactivated the arch as a peripheral bulge to the trough in which the Middle Devonian black shales of Ohio and New York were deposited. Platform shales and carbonates (Hamilton and Traverse Groups) were deposited on this elevated area at that time, at least in part, contemporaneously with black shales to the southeast. The apparent lack of deep water sediments in the late Middle Devonian sequence of the Michigan basin suggests that the Algonquin arch was a distinctly asymmetric feature. That this morphology persisted into Late Devonian time is clear from the study of the Kettle Point Formation.

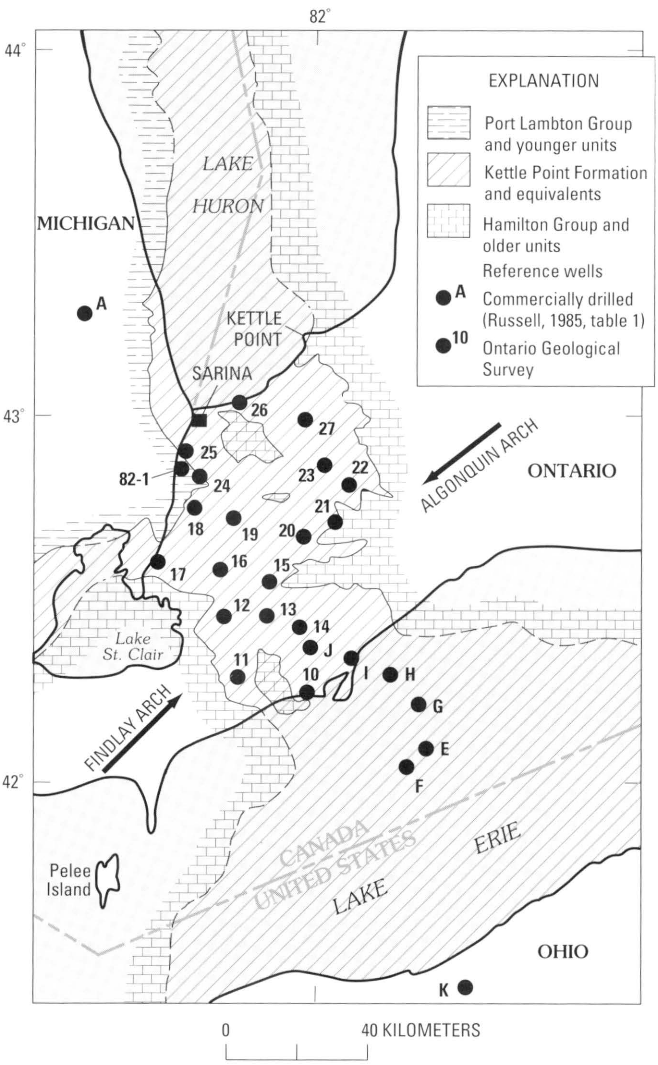

Figure 1. Area of outcrop-subcrop of the Kettle Point Formation showing locations of pertinent wells.

During Late Devonian time, it is likely that black shale was being deposited regionally—from the present area of outcrop-subcrop in southern Ontario and Michigan north to the Moose River basin of northern Ontario (fig. 2*D*). In this area, the Long Rapids Formation is an exact lithostratigraphic and near chronostratigraphic equivalent of the Kettle Point and the Antrim Formations. However, in Hudson Bay, which is to the north of the Moose River basin, the Late Devonian strata are evaporitic red beds (Sanford and Norris, 1975). Nevertheless, given the striking lithological similarities in all Devonian strata in this and the Appalachian basins and the continuity of the Devonian tectonism to the northeast, it is likely that Upper Devonian sediments once extended many hundreds of kilometers to the east and northeast of the present extent of the Kettle Point Formation.

STRATIGRAPHY OF THE KETTLE POINT FORMATION

Lithostratigraphy

At the only location of outcropping Late Devonian shale in Ontario, the concretions common in the lower part of those shales are well exposed. It is not known when these concretions were termed "kettles," but the location became known as Kettle Point (fig. 1), and the unit was named the Kettle Point Formation (Caley, 1943; Sanford and Brady, 1955). The Kettle Point Formation is defined (Russell, 1985) as the black, brown, and green shales lying between the Hamilton Group below and the Port Lambton Group above (fig. 2*C*).

In the Michigan and the Appalachian basins, significant differences in the internal stratigraphy of the gross black shale sequence are reflected in differences in terminology. In northern Ohio (fig. 2*A*), the Ohio Shale lies disconformably on the Prout Limestone and the Plum Brook Shale, which are correlative with the Hamilton Group of Ontario. The Ohio Shale is divided into, in ascending order,

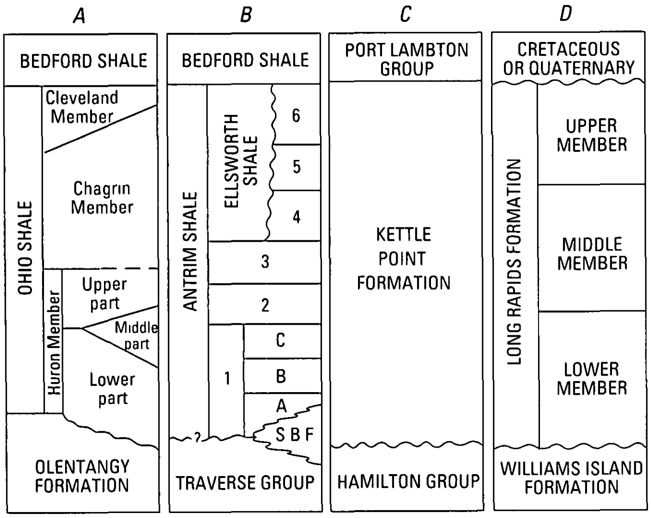

Figure 2. Stratigraphic subdivisions of some Late Devonian black shales of northeastern North America. *A*, Subdivisions in the eastern Kentucky, Ohio, and western West Virginia parts of the Appalachian basin. *B*, Subdivisions in the Michigan basin; S.B.F., Squaw Bay Formation. *C*, Major stratigraphic subdivisions in southwestern Ontario, Canada. *D*, Nomenclature for equivalent beds in the Moose River basin in the Hudson Bay area.

the Huron, the Chagrin, and the Cleveland Members. The Huron and the Cleveland Members are predominantly black shales. The Chagrin Member, which is composed of green and gray siltstones and shales, thins from east to west, eventually becoming the Three Lick Bed (Honeycutt, 1982). In the subsurface, the Huron Member is further subdivided into three units. A generally less radioactive middle part separates more radioactive upper and lower parts. The Ohio Shale is overlain conformably by the red, green, and gray Bedford Shale.

The nature of the basal contact of the Antrim Shale (Michigan basin) with the underlying carbonates is thought to be unconformable by Rickard (1984). Ells (1979, p. 7) included the underlying Squaw Bay Formation in the Traverse Group but agreed with previous workers (Hake and Maebius, 1938; Bishop, 1940; Cohee, 1951) that these "gray shales and gray and brown argillaceous limestones and dolomites" may be transitional between the carbonates of the Traverse Group and the Antrim Shale. Sanford (1968) stated that the Squaw Bay Formation intertongues with the basal parts of the Antrim and the Kettle Point Formations.

The Antrim Shale sequence in Michigan has been divided into six units (fig. 2*B*; Ells, 1979) on the basis of their gamma-ray log signatures. The lowermost unit is divided into three subunits. These numbered units and lettered subunits can be traced in the subsurface across many thousands of square kilometers in the eastern part of Michigan. Most of the section is radioactive black shale, with green shale of low radioactivity making up Units 1.B and 4. However, on the western side of the basin, the upper three units merge to become the Ellsworth Shale, which is a nonorganic green shale. Because of this change in lithology, the conformable upper contact with gray-green colored Bedford Shale is difficult to identify in western Michigan. In the eastern part, there is a sharp drop in gamma-ray intensity, but the upper contact apparently remains conformable.

As with most other studies of the Upper Devonian shales of eastern North America, the gamma-ray log has been the main tool in lithostratigraphic analysis of the Kettle Point Formation. The Paleozoic red, green, and gray shales in southern Ontario (that is, those poor in organic carbon) generally have maximum gamma-ray readings between 150 and 200 American Petroleum Institute units. Virtually all this radiation emanates from the unstable isotope potassium-40, which is a significant component of illite and is, in turn, a major component of the shales. This source of gamma radiation from the Kettle Point Formation is swamped by that from the uranium isotopes associated with organic matter. Swanson (1960) showed the direct ratio of uranium and organic carbon in the Chattanooga Shale. Similarly, Schmoker (1981) and Russell and Barker (1983) established the link between gamma radiation and organic-carbon contents for the Ohio Shale and for the Kettle Point Formation, respectively. Russell (1985) concluded that, at the regional level of correlation and at the level of detail required for resource assessment, the gamma-ray log served to reflect the significant changes in lithofacies and oil shale potential.

Several hundred wells have been drilled in the area of the Kettle Point Formation subcrop, many of which have gamma-ray logs. To provide a complete set of high-quality data points across the whole area, 20 fully cored and logged boreholes were drilled through the formation. The data from these wells have allowed the use of the older lower resolution variable quality logs in regional stratigraphic interpretation and resource evaluation. Surface casing is usually set at some point in the Kettle Point Formation because it is the first competent strata to be drilled; this casing produces an offset in the gamma-ray log and very poor resolution above the casing point. Despite these problems, the older logs have been of critical use in this study, espeically in the area south of the Algonquin arch. Figure 1 shows the locations of the 26 wells dicussed in this chapter—the wells designated by a number are from the OGS, and those designated by a letter are commercially drilled wells (Russell, 1985, table 1).

Core-Log Correlation

The following three distinct gross lithological associations make up the Kettle Point Formation.

Black shale.—The most volumetrically significant lithology is consistently commonly finely laminated micromicaceous silty noncalcareous pyrite-rich black shale. Calcareous shelled fossils or fossils of animals that originally had calcareous tests are absent The microfossil *Tasmanites* is abundant, as are various conodont forms, occasional fish scales and lingulid brachiopods occur

Green shale —Beds of variable, but generally less than 1 m, thickness of green and greenish-gray shales occur in the lower 75 percent of the formation These shales are variably bioturbated, the more affected examples have no fissility Bioturbated beds have burrowed bases The tops are usually conformable, eroded tops are rarely observed Calcite content is variable, variation apparently is not systematic Pyrite is present in minor amounts, as well as gypsum, Delitala (1984) reported an example of gypsum rimmed by pyrite in the upper part of a green bed

Black shale with silt laminae —In the lower one-half of the unit, the black shale lithology described above is modified in some sections by the presence of numerous thin (0 5- to 10-millimeter) white quartz silt and fine sand bands, which are occasionally slightly calcareous The calcareous concretions, which are common in the lower part of the unit, were formed during early diagenesis because the enclosing shales (always black) are contorted around them

A typical example of the correspondence among these lithologies, the gamma-ray log and total organic-carbon (TOC) content, is shown in figure 3 for borehole OGS 82–1 At the base of the Kettle Point Formation, all three lithologies are interbedded These rock types are found in disconformable contact with limestones of the Hamilton Group at various locations, but no clear geographic variation was noted At locations where black shale overlies the Hamilton Group, the underlying limestones had significant pyrite in the top meter From about 15 to 40 m above the base of the formation in OGS 82–1 is a sequence of black shale and black shale with siltstone above which is an interval of green shales The topmost 5 to 10 m of the formation (9 m in OGS 82–1) are consistent fissile to massive black shale

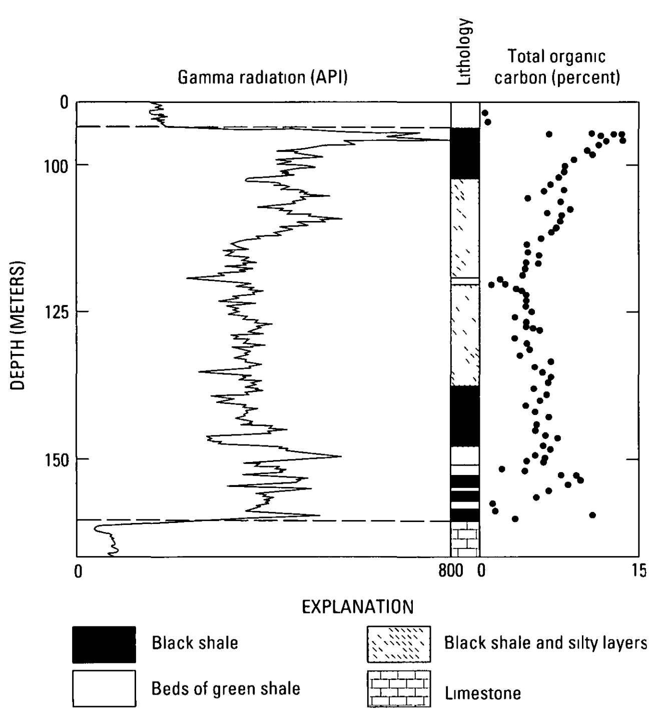

Figure 3. Correlation among gamma radiation, lithology, and total organic-carbon content for Ontario Geological Survey borehole 82–1 API, American Petroleum Institute

The only significant variations in mineralogy between the various lithologies discovered by Delitala (1984) were the presence of pyrite in black shale and its absence in the green and the gray units, which had variable calcite content Visual assessment of organic-carbon content was not attempted in this study In this regard, the only reliable criteria were the absence of organic carbon in the green units and the apparent lack of fissility in the sections of extremely high organic-carbon content Armstrong (1986) reported significant fissility in these highly organic units This contradiction may be caused by the time-dependent nature of fissility as it appears in core, that is, the longer the core sits in a core box, the more fissile the shale appears

Chronostratigraphy

The Kettle Point Formation represents the whole of Late Devonian sedimentation in southern Ontario (Winder, 1966, Uyeno and others, 1982) However, the absence of useful macrofossils and the inability of the available microfossils to provide a refined temporal subdivision of the Late Devonian black shales of eastern North America, in particular the Kettle Point Formation, present problems in interbasinal chronostratigraphic correlation Thus, the comparison of conditions in neighboring basins is hindered, as is understanding of paleogeography (or paleobathymetry) This problem has been lessened to some extent by the recognition of the fossil *Foerstia* as a consistent time marker in North America Hasenmueller and others (1983) and Russell (1985) summarized the data supporting this assertion, Kepferle (1981) and Matthews (1983) gave examples of its use in interbasinal correlations Broadhead and others (1982) used it to define variations in internal stratigraphy of the Ohio Shale Winder (1968) made the first observation of *Foerstia* in Ontario Russell (1985) reported an additional eight occurrences, which are restricted to the northern part of the formations area All those occurrences and those reported from the Antrim Shale (Matthews, 1983) are from about 30 m above the base of the shales Detailed gamma-ray correlations below this datum have been used to interpret the depositional setting of the Antrim-Kettle Point-Ohio Shales (Russell, 1985)

Correlation from the Antrim Shale to the Kettle Point Formation

A cross section of gamma-ray logs from Michigan to just north of the trace of the Algonquin arch shows that the six unit divisions of the Antrim defined by Ells (1979) can be used for the Kettle Point Formation with no adjustment in that area (pl. 1, sections *A–B*, *C–C'*). Log character and subunit thicknesses are similar in all wells until the arch is approached. The following changes in log character and thickness are present in wells OGS 18 and OGS 16, which are interpreted in terms of the position of the wells relative to the Late Devonian manifestation of the Algonquin arch.

- The tops of Unit 1 black shales are truncated by low radioactive green-gray shale in near-arch locations (wells OGS 16, 22, 23).
- The changes affecting Unit 1 also alter the log character of Unit 2 so that it is unrecognizable as such over the arch. In that area, the top of Unit 2 is poorly defined. At all locations where Unit 2 is recognized on the gamma-ray log, *Foerstia* was found in the core in equivalent strata. In well OGS 16, where the log character is atypical of Unit 2, *Foerstia* was found in the expected stratigraphic position.
- Unit 4 increases in thickness toward the arch as a function of the greater volumes of green shale in the middle of the formation. Total thickness of the formation is virtually constant; green and gray lithologies are developed preferentially over the arch as lateral equivalents of off-arch black shale.

Correlation from the Ohio Shale to the Kettle Point Formation

From the northern shore of Ohio to central Lake Erie, little change occurs in log character for the section preserved. However, only the lower part and some of the middle part of the Huron Member of the Ohio Shale have survived the erosion that formed Lake Erie. Plate 1 (section *B–B'*) shows the changes in stratigraphy of the Kettle Point Formation in moving from the immediate southern side of the Algonquin arch southward to northern Ohio. Within the Lake Erie boreholes, the formation is subdivided into as many as 13 informal units (A–M) that are characterized by increasing and then decreasing gamma-ray intensities, which presumably are caused by increases and decreases in organic-carbon content. Parallel to the Algonquin arch, these units are very consistent in thickness and log character (Russell, 1985). However, the following significant changes occur in log characteristics as the unit is traced from south to north.

- In a 35-kilometer (km)-wide zone south of the northern shore of Lake Erie, units A through K suffer a total thickness reduction by a factor of about 45 percent from south to north. It is believed that all units are present throughout the area and that thinning has occurred without omission of units.
- In the area from just south of the Lake Erie shoreline to the arch, the detailed subdivision possible in Lake Erie wells is not possible in this area because of the poorer quality of logs. As shown in plate 1 (section *B–B'*), the basal part of the formation is redivided into units X and Y, which, in turn, pinch out and are overstepped by younger shale units.

The base of the Kettle Point Formation over and north of the Algonquin arch (and, thus, the base of the Antrim Shale) is, therefore, significantly younger than the base of the Ohio Shale. The Kettle Point Formation in the area south of the arch appears to be assignable to Unit 1 (and, perhaps, to Unit 2) of the Antrim Shale; these units have greater thicknesses than those in the Michigan basin.

DEPOSITIONAL SETTING OF THE KETTLE POINT FORMATION

Plate 1 (sections *A–B*, *C–C'*) uses the base of the black shale sequence as the stratigraphic datum. The conclusion regarding ages of the base of the Ohio and Antrim Shales (see above) implies that the base of the shales is not a timeline and thus is not a useful datum in analyzing variation in rates and styles of deposition. If the position of *Foerstia* is accepted as a timeline, then sections with that as a datum will be more revealing. However, because *Foerstia*-bearing units are eroded to the south of the Algonquin arch (that is, just north of Lake Erie) and the Kettle Point Formation is not sampled in Lake Erie wells, a cross section that uses the *Foerstia* zone as a datum cannot be constructed. Plate 1 (section *A–A'*) is the next best thing—in the absence of *Foerstia* in adjacent wells, a series of the highest possible correlative log picks were used as local datum planes. This technique causes the difference in elevation of the *Foerstia* zone of 6 m between each end of the section. Therefore, units that are now eroded and that were originally between the local datums and the *Foerstia* level were not of constant thickness. The degree of apparent distortion implies a thinning of an additional 6 m from the Ohio Shale to the Antrim Shale; the location and nature of that thinning are not constrained by the data available.

Plate 1 (section *A–A'*) shows that the thinning of the shale sequence from the Appalachian to the Michigan basins is caused by the thinning of units and by unit omission and onlap against the submarine topographic expression of the Algonquin arch. The Late Devonian arch was manifested as a south-facing submarine rise. If compaction of the shale was assumed to be 50 percent, then the total relief across this feature was about 50 m in a lateral extent of 100 km. The northern part of the rise was steeper—about 30 m in 25 km. No significant deepening of water in the Michigan basin (that is, from the arch northward) is detected.

The preservation of organic carbon in sediments clearly requires that little or no oxygen be available to the sediments, this would allow oxidation of the organic matter. Equally clear is that if the oxygen, which most animals require, is absent from the sediments or bottom waters, then no such fauna will survive, consequently, little or no burrowing will occur, and bioturbation will not be a feature in the preserved sediments. Based on these tenets, Byers (1977) and Cluff (1980), as well as many subsequent authors, have interpreted the Late Devonian black shales of eastern North America to be the result of deposition in anoxic waters. The presence of an oxygenated atmosphere in Late Devonian times compels the interpretation of a decline in oxygen content between the wave-agitated oxygenated photic zone and the sea floor. This reduction may occur over a large vertical range or across an interface, for example, the Black Sea (Degens and Stoffer, 1980). In the Black Sea and other semienclosed environments, the change in oxygen content coincides with changes in other physical and chemical properties of the water, for example, temperature and salinity. Consequently, the interface can be termed the "thermocline" *and* the "halocline", because the change in salinity causes an increase in density, the change is also referred to as the "pycnocline" ("pyknos" is Greek for dense), which is the term used in this chapter. The lower waters in such a situation also will have a lower pH than the upper layer and may have a significant dissolved H_2S content. A further implication of the stratification of the water column is a division into an upper oxygenated agitated circulating layer (capped by a photic zone in which organic matter is generated) and a lower anoxic stagnant layer. As such, the interface between these two layers is as chemically and physically significant as that between water and air, which is an indeterminate number of meters above.

If the pycnocline in the Late Devonian sea had been gradual rather than sharp, then one might expect a significant thickness of sediments of intermediate organic carbon and a gradation of degrees of bioturbation. However, the extreme variations in organic-carbon content in the Kettle Point Formation (from 0 to 10 percent TOC through a few centimeters in some examples in the lower part) and the presence of eroded tops and the relative ubiquity of burrowed bases of green beds imply a very clear (albeit not razor sharp) distinction between the two environments of deposition. Sediments deposited in a "dysaerobic zone" of intermediate oxygen content are not recognized in the Kettle Point Formation. The apparent onlap of the formation over the Algonquin arch is interpreted as being a function of the pycnocline moving up and over this feature. Below the pycnocline, very fine terrigenous material and organic matter are allowed to settle to the sea floor. Above it, this material is kept in suspension, especially over "exposed" highs, which are swept clean by currents or, perhaps, by internal waves. Some of the silt, clay, and organic matter will cross the pycnocline. This may occur as the result of seasonal changes in rates of input or water conditions leading to discrete pulses of sediment, which give the fissility characteristic of the shales. It is likely that most of the terrigenous material was the finest constituent of dilute turbidity currents that traveled *along* the pycnocline before settling as a rain of sediment.

Once organic matter has crossed the pycnocline, it is virtually assured of reaching the sediment-water interface. Russell and Barker (1983) concluded that the kerogen of the Kettle Point Formation was dominantly the type II of Tissot and Welte (1978), that is, rich in marine organic matter. The controls on flux of organic matter across the pycnocline are, therefore, the rate of generation of organic matter in the photic zone and the thickness of oxygenated water between the photic zone and the pycnocline, that is, the zone in which organic matter is vulnerable to oxidation. The rate of generation of organic matter is controlled by many features, such as climate and oceanic circulation conditions. If a change in such a factor causes the pycnocline to move up, then an apparently transgressive sequence of black shales is deposited. However, this configuration of strata is not necessarily related to a genuine transgressive event (that is, the air-water interface moving upward relative to the substrate), but to movement by the interface between waters of differing oxygen contents.

The lithological variability of the lower part of the Kettle Point Formation suggests that the rise of the pycnocline was not a steady process, but rather involved significant oscillations. The presence of the large calcareous concretions in black shales of the lower part of the unit is also significant. Because these were probably formed by diffusion of ions through unconsolidated mud, the water overlying the mud could not have been anoxic or have had a low pH, such water cannot contain carbonate ions in solution. The concretions must have formed when the pycnocline was at or below the sediment-water interface, that is, the water column was not stratified. In this condition, organic matter and pyrite will be oxidized, thus causing green or gray mud to be formed in situ. More significantly, if the oxygen content of the water is high enough for a long enough time, then organisms will bioturbate the mud, thus enhancing the permeability and enabling more mud to be oxidized. The cohesion of clayey materials enables them to resist resuspension after deposition. However, given prolonged exposure above the pycnocline, green beds will have undergone some subaqueous erosion to give the sharp disconformable tops.

Because no evidence of deposition from turbidity currents is known in the Kettle Point Formation, it is likely that all the green beds, at least below Unit 4, were formed in place on the sea floor. Unit 4 is correlated with the Three Lick Bed, which is a regional green shale marker that can be traced eastward (up depositional slope) into the Chagrin Member of the Ohio Shale. This is a thick silty unit deposited by distal lobes of turbidity currents generated at a prograding shoreline located in New York State. This episode of enhanced turbidity current activity is interpreted here as having caused a widespread turnover of the stratified water column. The ubiquitous nonorganic lithologies present at this level (Three Lick Bed, Unit 4 of the Antrim and the Kettle Point), therefore, reflect the basinwide consequences of advancing turbidity currents in areas beyond the general range of their distal lobes.

In summary, the elevation of the pycnocline affects the lithology of the Kettle Point Formation in the following ways:

- Above it, fine sediment tends to be kept in suspension, and organic and inorganic material, which falls below it, settles to the sea floor;
- If it is deflected to the sediment-water interface, then the green shale is formed from black shale by in situ oxidation and bioturbation; and
- The distance from the photic zone to the pycnocline is a major control on the flux of organic matter across the pycnocline and, consequently, on the organic-carbon content of black mud deposited.

These principles are used to interpret the overall depositional conditions for the various units of the Kettle Point Formation (fig. 4). The stratigraphy of the formation is thus a result of the interaction of the pycnocline and the submarine topography. The enhanced amount of green shale over the arch is due to the greater likelihood of oxidizing conditions at the sea floor in this relatively elevated location.

No mention has been made of absolute water depth for deposition of these shales because no direct evidence of that parameter can be gained from this study of stratigraphy and lithofacies. The association with turbidite facies suggests deposition in water depths of at least tens of meters. The lack of karst features in the Hamilton Group limestones implies its continued submergence through Middle and Late Devonian time. Given the topography on the Algonquin arch, a minimum water depth of 50 m can be estimated. However, given that deposition is below the storm wave base, the actual depth of water is irrelevant. The depth of water relative to the pycnocline is the most important factor controlling deposition or nondeposition,

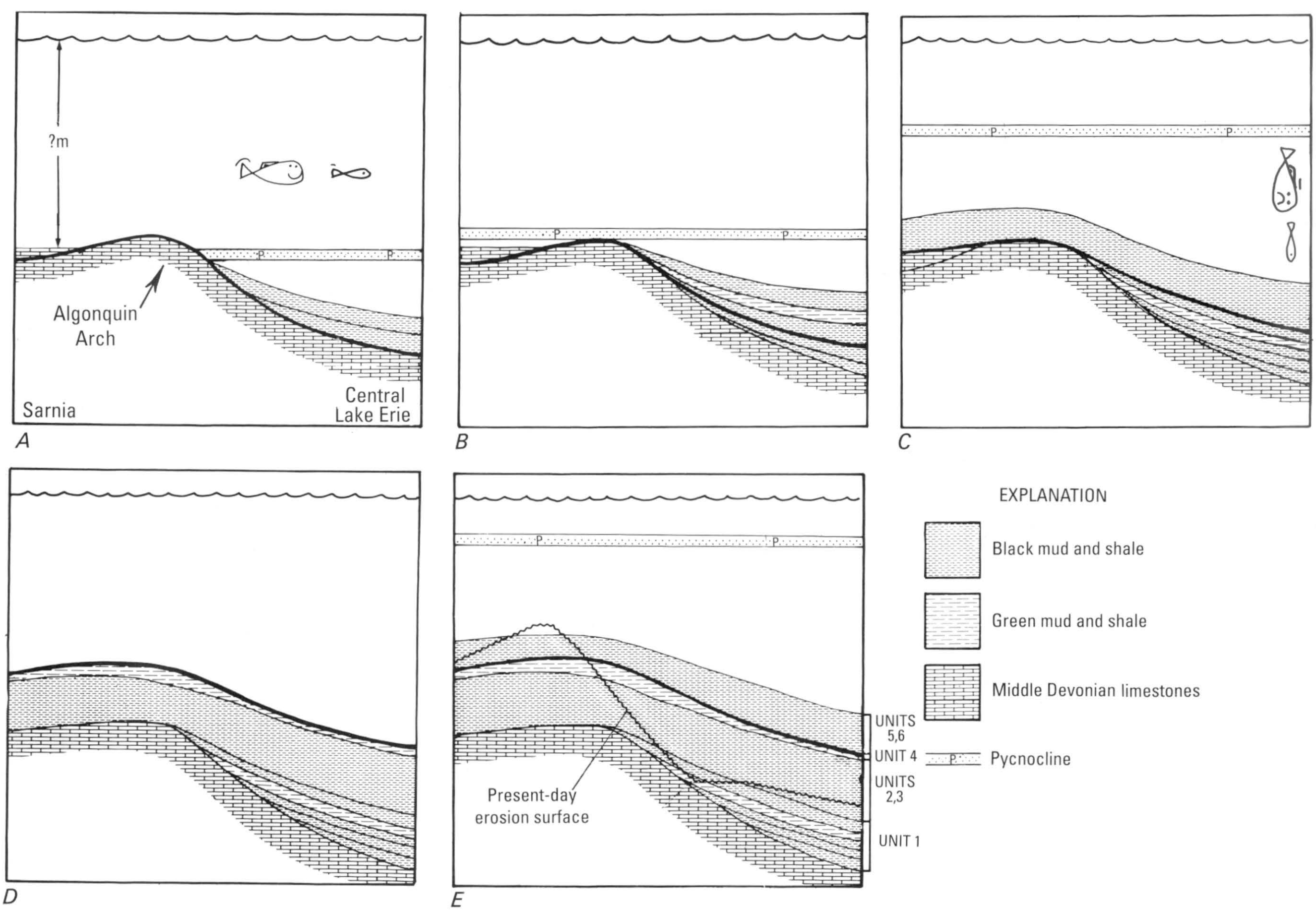

Figure 4. Depositional setting of the Kettle Point Formation in southern Ontario showing upward movement of the pycnocline and the products of sedimentation. *A* through *E* indicate the sequence of sedimentation from oldest to youngest, respectively.

the proportions of organic and nonorganic beds, and the stratigraphic relations between them

A further implication of the model discussed above concerns interpretation of apparently transgressive sequences As Hallam and Bradshaw (1979) pointed out, black shales often are interpreted as being associated with transgressions If the stratigraphic relation shown in figure 4 was resolvable on a seismic section, then it would appear as seismic reflectors steadily onlapping an erosional surface, which is a geometry that might be interpreted as being the result of a transgressive event (Vail and others, 1977) The pycnocline that is actually doing the transgressing may well have been "dragged up" by a sea-level rise However, the possibility of other processes causing a similar response should be considered, for instance, if a midoceanic oxygen minimum layer impinges on a continental rise and shelf, as shown by Demaison and Moore (1980) for the Indian Ocean to the south of India, then an apparent transgressive sequence may be generated that has no direct relation to a rise in sea level

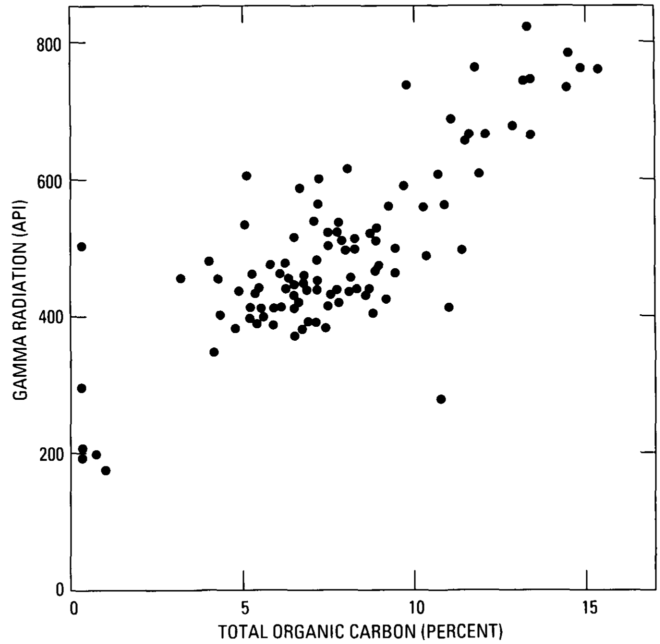

Figure 5. Correlation between gamma radiation and total organic-carbon content for Ontario Geological Survey borehole 24 API, American Petroleum Institute

IMPLICATIONS OF STRATIGRAPHY FOR RESOURCE ASSESSMENT OF THE KETTLE POINT FORMATION

A full analysis of the resource potential is not within the scope of this chapter Readers should refer to Johnson and others (in press) for a summary of all the data concerning the oil shale potential of the formation, including an estimate of the total oil shale resource However, the above discussion of the stratigraphy holds several significant implications for the oil shale potential of the unit

Figure 5 shows the extremely good correlation between the TOC of small samples (splits of 10-centimeter lengths of core) and the gamma-ray intensity picked at the sample point for borehole OGS 24 On the basis of this plot and considerations of detection of thin green beds and sensitivity of the gamma-ray log to variation of TOC in organically lean shales, Russell (1985) concluded that the gamma-ray log was capable of detection and quantification of zones of high TOC, that is, those of economic interest Consequently, Unit 6 of the Kettle Point Formation is the richest in organic carbon, followed by Unit 5 These units correlate with the Cleveland Member of the Ohio Shale, which has consistently high TOC Although Unit 1 has high values of TOC, it also has many low and zero values and is also likely to have the lowest continuity of black or green lithologies, the presence of large (up to 1-m) concretions in Unit 1 further decreases the attraction of those organic-rich beds Units 2 and 3 have intermediate TOC, Unit 4 is defined by the absence of organic-rich beds

A detailed map based on all available well control data showing the areas most prospective for oil-shale-grade Kettle Point Formation is given in Johnson and others (in press) On the basis of on the geological map of Uyeno and others (1982), the OGS boreholes, and the above discussion of the stratigraphy of the formation, it is possible to indicate where attention should be focused in the future (fig 6) Units 5 and 6 are limited in geographic extent to a triangular area bordering the St Clair River The limiting structural features to the northeast and the south are the Kimball-Colinville monocline and the Electric fault, respectively (fig 6) Locally, anomalously thick sections of organic shale may have been preserved, however, because of the effects of post-Devonian dissolution of Silurian salts (McDonald, 1960) Within the high-graded area, the resource potential will also vary rapidly according to the depth of overburden (assuming that surface mining is the preferred extraction technique) and the thickness of organic shale remaining below the glacial erosion surface However, the high-graded area is one of intensive land use for high-quality farmland or by the petrochemical industry Underground extraction methods, therefore, will need to be considered

That TOC is a good indicator of the oil shale potential of the unit was shown by Barker and others (1983a), who determined that the Fischer assay (FA) yield, in liters per tonne, was related to TOC as follows

$$FA = 4\ 6\ TOC - 0\ 73$$

and had yields up to 72 liters per tonne (L/tonne), or 17 U S gallons per ton (gal/ton), of oil In comparison, the yield for the Ordovician Collingwood Shale of southwestern Ontario is as follows

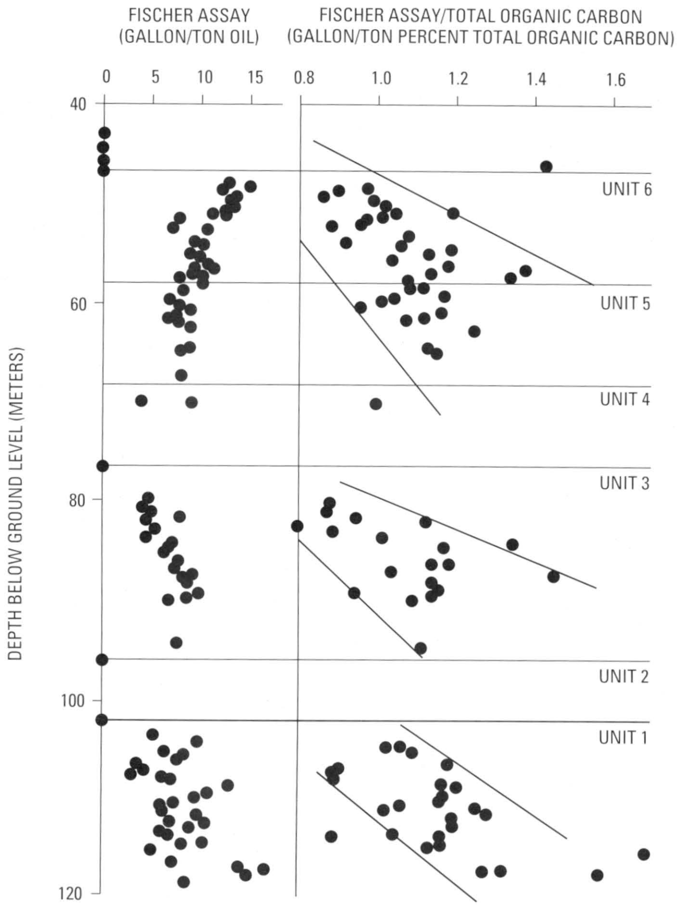

Figure 6. Variation in the ratio of the Fischer assay to the total organic-carbon content for samples from Ontario Geological Survey borehole 24.

$$FA = 5.6\ TOC - 3.9.$$

The larger negative intercept on the FA axis for the line described by this equation implies that a larger amount of organic carbon will produce no more liquid hydrocarbons upon pyrolysis than that in the Kettle Point Formation. This may be related to variations in the original type of kerogen or in the levels of the maturity of the kerogen. The apparently more labile nature of kerogen of the Kettle Point Formation than that of the Collingwood is probably the result of enhanced thermal maturity of the latter. From the visual observations of kerogen macerals and conodonts, the reflectance of vitrinitelike macerals, and the percentage of hydrocarbons in bitumen extracted from the shales, Barker and others (1983b) concluded that the Kettle Point Formation in onshore southern Ontario is immature to marginally mature, whereas the Collingwood is marginally mature to mature. Thus, the more labile kerogen of the Collingwood has been matured to the stage of hydrocarbon generation, which leaves a significant percentage of refractory or inert kerogen. The Kettle Point Formation, in contrast, remains in a state such that the maturation can be done under controlled industrial conditions (that is, retorting) to get a better yield per unit volume.

Barker and others (1983a) suggested that some input of terrestrial organic matter occurred in the Kettle Point Formation, which likely had lower yields of oil on pyrolysis, based on relative values of aliphatic to aromatic ratios in kerogen pyrolysates. That fluctuations in type of kerogen input did occur during Late Devonian time is indicated by a plot of the FA yield normalized to TOC, under the assumption that terrestrial organic matter will be more refractory than marine organic matter and, thus, will have a lower normalized FA yield. Figure 7 shows the variation in this

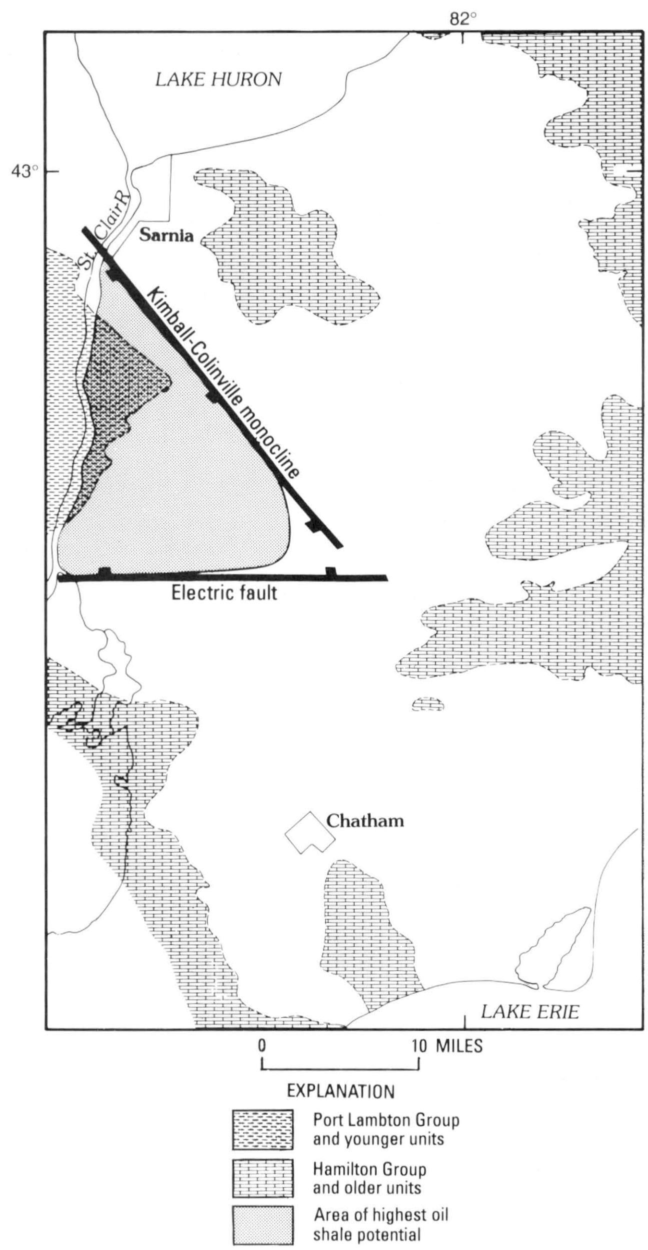

Figure 7. Area of best potential for oil shale in the Kettle Point Formation.

parameter for well OGS 24 Unfortunately, only those samples that have TOC over 5 percent were analyzed by FA Despite the gaps caused by this selection, there appear to be three zones of decreasing FA to TOC ratio The lower two zones are characterized by an upward decrease in TOC as well as FA/TOC, whereas the upper zone displays the opposite trend The lowest FA to TOC ratios are determined on samples just below the thick green shales of Unit 4 and of the Bedford Shale, that is, below zones regarded as being the result of basinwide overturn and oxygenation Whether a common process links these phenomena can be determined only by detailed kerogen characterization and geochemistry of the relevant zones

CONCLUSIONS

During Late Devonian time, the Algonquin arch, which marked the division between the Michigan and the Appalachian basins, was a south-facing submarine rise of about 50-m relief Variations in the stratigraphy of the Kettle Point Formation record the migration of the pycnocline The effects of the interaction of the pycnocline and the Late Devonian arch are recorded in the following types of changes in log character and subunit thickness, as reflected in the gamma-ray log

- Northward thinning away from the source of terrigenous material,
- Northward pinchout and overlap, and
- Change in characteristics, especially reduction in TOC over the arch

The onlap of the lowest part of the Kettle Point Formation onto the Middle Devonian carbonates of the Hamilton Group is the result of the upward movement of the pycnocline, below it, terrigenous material and organic matter are allowed to settle to the sea floor, and above it, they are kept in suspension With this model, the depth of water above the sea floor is not a primary control on facies deposited Given that deposition is below the storm wave base, depth relative to the pycnocline is the most important factor controlling the distribution and the abundance of organic and nonorganic shales Movements of the pycnocline may be related to rises in sea level However, many processes exist that may cause a rise in the pycnocline relative to the sea floor, independent of a eustatic sea-level rise A black shale sequence onlapping an unconformity, therefore, should not be automatically labeled a "transgressive black shale" unless independent evidence exists in more marginal deposits of a rise in sea level

As a consequence of the elevation of the pycnocline relative to the sea-floor topography, the topmost 15 m of the Kettle Point Formation is the richest in organic carbon and, thus, holds the most oil shale potential This interval is preserved only in an area bounded by the St Clair River, the Kimball-Colinville monocline, and the Electric fault TOC ranges of between 10 and 15 percent and FA yields of up to 70 L/tonne (20 U S gal/ton) give this unit a potential yield of at least 10 million barrels per square kilometer (Johnson and others, in press)

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Chapter F

A Depositional Model and Basin Analysis for the Gas-Bearing Black Shale (Devonian and Mississippian) in the Appalachian Basin

By ROY C. KEPFERLE

U.S. GEOLOGICAL SURVEY BULLETIN 1909
PETROLEUM GEOLOGY OF THE DEVONIAN AND MISSISSIPPIAN BLACK SHALE OF EASTERN NORTH AMERICA

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FIGURES

TABLE

A Depositional Model and Basin Analysis for the Gas-Bearing Black Shale (Devonian and Mississippian) in the Appalachian Basin

By Roy C. Kepferle[1]

Abstract

The gas-bearing organic-rich shale and related rocks of Devonian and Mississippian age in the Appalachian basin can be better understood as a result of physical and chemical characterizations These characterizations have led to the recognition of at least eight cycles of deposition, each of which began with the widespread accumulation of organic-rich mud, followed by overlying greenish-gray and gray muds and siltstones and culminating in limestone or yellowish and reddish siltstone, sandstone, and local conglomerate These sediments accumulated beneath a density-stratified water column in which the deeper layer was anaerobic, the intermediate layer was dysaerobic, and the uppermost layer was aerobic

The widespread recognition of each of the black shale units and of the deep-water origin postulated for such accumulation has contributed to the concept of the coincidence of black shale deposition accompanied by a eustatic rise in sea level A comparison of the episodes of high stands of sea level that had biostratigraphic markers, such as *Foerstia*, and chronostratigraphic markers, such as turbidites and volcanic ash beds, provide additional data for more precise intra- and interbasinal correlation of rock units and tectonic events

INTRODUCTION

The gas-bearing organic-rich shale and the related rocks of Devonian and Mississippian age in the Appalachian basin can be better understood as a result of the physical and the chemical characterizations made possible through the relatively recent studies by many individuals and organizations As expected, our understanding of the stratigraphy of the shale was greatly enhanced by the cooperative efforts of the individual stratigraphers from various States and universities and from the U S Geological Survey (Roen, 1980a, de Witt and Roen, 1985, de Witt and others, this volume When the stratigraphy is better understood, the physical and the chemical characteristics can be related to a general sequence of space and time in a basin analysis for this sequence of rocks

A cyclic pattern of stratigraphic succession was recognized in outcrop studies in New York (Pepper and de Witt, 1950, 1951, Pepper and others, 1956, Colton and de Witt, 1958, de Witt and Colton, 1959, 1978, Rickard, 1964, 1975) These cycles have now been traced stratigraphically throughout the black shale sequences of the Appalachian basin by means of gamma-ray stratigraphy (Wallace and others, 1977, 1978, Kepferle and others, 1978, Roen and others, 1978a, b, West, 1978) A tectonoclimatic origin of the black shale basin was discussed by Ettensohn and Barron (1981) Other models for the origin of black shale and the associated rocks for the Upper Devonian delta include those proposed by Barrell (1913, 1914a, b), Rich (1951a, b), Kuenen (1956), Sutton (1963), Sutton and others (1970), Rhoads and Morse (1971), Heckel (1973, 1977), Byers (1977, 1979), Schwietering (1979), and Jenkyns (1980) Cluff (1980) and Cluff and others (1981) applied the model of Rhoads and Morse (1971) to the Devonian shale of the Illinois basin

Geologic modeling is an attempt to simplify complex relations to better understand our observations in relation to the general geologic setting The Appalachian basin has supplied the framework for establishing several such models The tectonic studies of Kay (1944, 1951) incorporated the Appalachian basin as a prime example of the geosyncline In the Appalachian basin, a flysch and molasse couplet in sedimentation has been described as a cycle in the Ordovician-Silurian-Devonian-Mississippian depositional sequence (Potter and Pettijohn, 1963) Since these earlier tectonic models were developed, the need for refinement according to different facies has been met, in part, by the clastic wedge (Sloss, 1962, Colton, 1963), the turbidite

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model (Walker, 1967, McIver, 1970), the muddy shelf (Walker, 1971, Walker and Harms, 1971), and, more recently, the anoxic basin (Byers, 1977, Ettensohn, 1985a), the Brallier model of shelf-edge turbidites (Lundegard and others, 1980), and the Sunbury cycle of black shale deposition (Van Beuren, 1980, Van Beuren and Pryor, 1981)

The depositional cycle of the black shale sequence of the Devonian and Mississippian rocks in the Appalachian basin is presented as the basis on which the sedimentary fill of the basin can be analyzed and discussed in this chapter The description, classification, origin, and interpretation of the sediments involve all the aspects of a depositional sequence The rocks of the organic-matter (OM)-rich Devonian shale sequence and the related rocks have been described according to the major constituents recognized in outcrops, cores, drill cuttings, hand specimens, thin sections, thin-slab X-radiography, and scanning electron microscope The results indicate the ways mineral grains and cements relate to lithologies, laminae and beds relate to facies, facies relate to stratigraphic units, and the stratigraphic units relate to basin fill

The eight major lithologic cycles with which our model cycle will be compared in a basin analysis are named for the basal black shale unit that initiates the respective cycle The rocks included in the cycle are those for which distribution maps have been prepared—the Marcellus-Hamilton Group, the Genesee Formation, the Sonyea Formation, the West Falls Formation, the Java Formation, the Huron Member of the Ohio Shale-Dunkirk Shale Member of the Perrysburg Formation, the Cleveland Member of the Ohio Shale, and the Sunbury Shale The cycle beginning with the Sunbury Shale (Mississippian) was studied by Van Beuren (1980) because it was the only cycle not truncated by an overlying black shale unit For this reason, the Sunbury cycle is most nearly complete and is less subject to stratigraphic aberration However, it was not the object of concerted study by others cooperating with the Department of Energy in the Eastern Gas Shales Project (EGSP) Major stratigraphic units used in this report are shown in the correlation chart (fig 1) (equivalent to fig 4 in de Witt and others (this volume))

The controls of the source and the sedimentation rate of the basin fill, syn- and postdepositional tectonic movement within the basin, and the presence, maturation, migration, and accumulation of hydrocarbons within the basin are more subtle than the economic considerations These, however, presuppose some knowledge of the character of the basin fill The discussion following the "Acknowledgments" examines a typical cycle for black shale deposition in the Appalachian basin from the consideration of such factors as the character of the water column, the depth and the slope of the sediment-water interface, and the facies distribution

Acknowledgments

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BLACK SHALE CYCLE

Black organic-rich muds may be deposited in a variety of major environments and will remain black if oxygen is insufficent to remove the black pigment (Potter and others, 1980b, p 262) Lateral and vertical successions

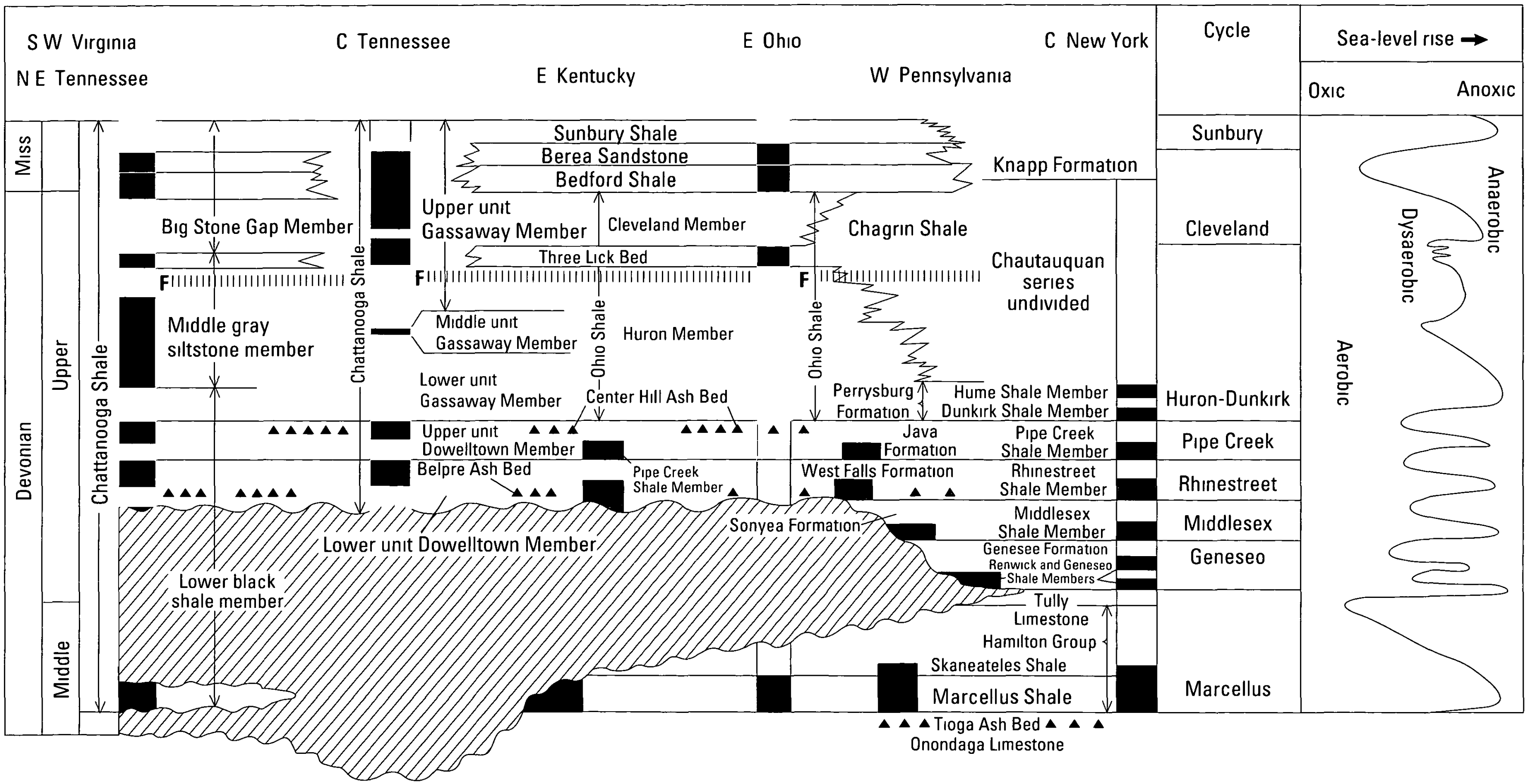

Figure 1. Correlation of Devonian black shale units in the Appalachian basin showing cycles and sea-level fluctuations Solid black pattern, black shale units, ||| F |||, *Foerstia* zone, ▲, ash bed (Modified from Roen, 1984)

of facies associated with the dark organic shale furnish additional clues for interpretation of the environments applicable to most of the Devonian shale in the Appalachian basin Where appropriate, evidence from the rocks will be used to substantiate the interpretations

Character of the Water Column

Organic mud accumulates and its color persists in the absence of oxygen Most well-oxygenated water in lakes, rivers, or oceans circulates through constant motion, stagnant, oxygen-deficient, or anoxic water remains motionless or circulates slowly beneath density layers in protected, closed, or silled basins Rhoads and Morse (1971) demonstrated how such a density layer affects biogenic activity Byers (1977) further related density stratification to the accumulation of shale rich in OM Density stratification has been proposed (Cluff, 1980, Cluff and others, 1981, Barrows and Cluff, 1984) to explain the accumulation of the OM-rich New Albany Shale in the Illinois basin (fig 2) In these models, the aerobic or oxygenated zone extends from the surface of the water to a minimum depth of about 150 feet (ft) The change in density occurs through an underlying zone, which is as much as 330 ft thick, this zone is known as a pycnocline In this zone, the oxygen concentration decreases to between 0 1 and 0 01 milliliter per liter (mL/L), and the environment is dysaerobic Where the dysaerobic zone intersects the sediment-water interface, bottom dwellers and infauna may survive, although some organic matter may be preserved In the anaerobic zone below the pycnocline, oxygen concentrations approach zero, although the water and the substrate can no longer support oxygen-dependent life, sulfur-fixing bacteria thrive Organic preservation is greatest in the anaerobic zone because of the absence of oxygen Locally, oxygen may be introduced into the anaerobic zone by turbidity currents

An alternative to the stratified-basin model of Rhoads and Morse (1971) is one based on an oxygen-minimum zone that was created by the rapid depletion of oxygen as the result of uptake in a nutrient-rich layer (Jenkyns, 1980) Because the upper limits of this model have the same character as the stratified basin, the oxygen-minimum zone corresponds to the anaerobic zone

One cause of stratification and stagnation of the water in a basin has been attributed to restriction by a sill (Heckel, 1977) Such a basin could be a repository for OM-rich muds during a eustatic rise or fall of sea level Anoxic events in Cretaceous oceans have been shown to be related to transgressions associated with interglacial episodes (Schlanger and Jenkyns, 1976) A similar transgressive sea during earlier interglacials has been related to black shale deposition in the Lower Ordovician, the Middle Silurian, and the Upper Devonian (Berry and Wilde, 1978) A

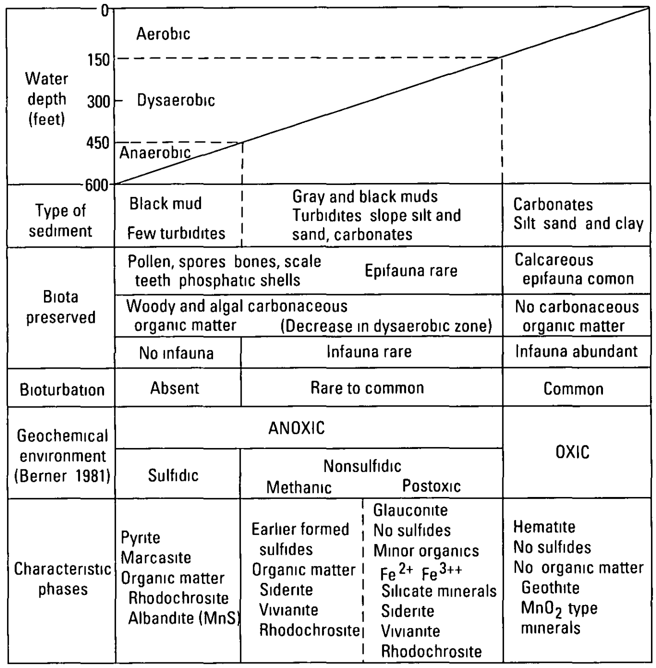

Figure 2. Idealized stratified basin The basic modifications are from Rhoads and Morse (1971), and additions of a geochemical classification of sediments are from Berner (1981)

transgressive sea also is associated with black shale deposition in the Upper Devonian and the Lower Carboniferous of Germany (Franke and others, 1978) A thorough analysis of the relation of transgressions to deposition in the Mesozoic and Cenozoic is presented by Haq and others (1987) The transgressive-regressive nature of the depositional sequence in combination with the stratified-water column, the restored lithologic sequence, and the resultant gamma-ray curve relates the depositional environment to the facies in a vertical sequence (fig 3)

Facies Relations

Because the sedimentation rate is related to current activity, available sediment, and preservation of sediment, the conclusion can be made that the sedimentation rate in the anaerobic zone is extremely low except for rare episodic turbidites, in the dysaerobic zone, the sedimentation rate is variable, and, in the aerobic zone, the sedimentation rate may be the greatest Current structures can be expected to be related to turbidites in the anaerobic zone, density and traction currents in the dysaerobic zone, and traction currents in the aerobic zone

Authigenic minerals, such as pyrite, marcasite, siderite, rhodochrosite, phosphates, and glauconite, have been identified in Devonian rocks For this reason, I have applied the classification of Berner (1981) to the model of Rhoads and Morse (1971) in figure 2 The model is applicable to

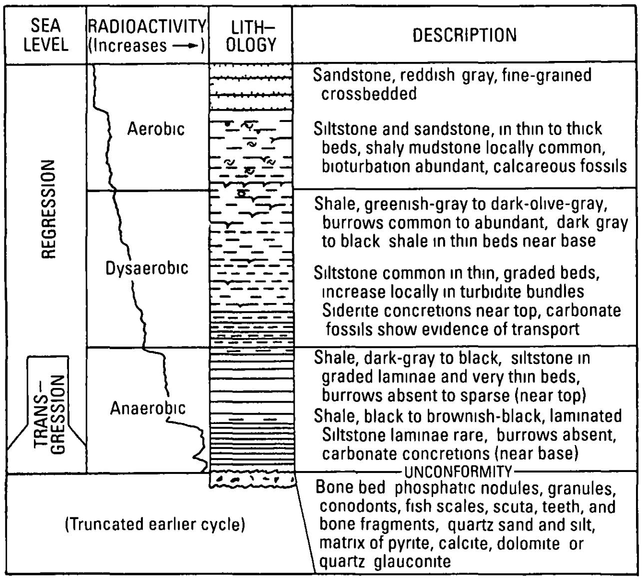

Figure 3. Idealized black shale cycle typefied by the Sunbury Shale and the Borden Formation in eastern Kentucky The gamma-ray log is diagrammatic The approximate thickness of the restored section is 600 ft

marine and nonmarine environments Associated marine fossils and rare salt-crystal impressions in the Devonian shale sequence considered here imply that most of the preserved rocks were deposited in marine environments

The sequential appearance of lithologies characteristic of each of these environments is considered to be a cycle Because the cycle begins with OM-rich black shale, it is here called the black shale cycle The inference from figure 2 and Rhoads and Morse (1971) is that the black shale represents the depositional environment in the deepest water Successive lithologies, then, represent a vertically shallowing, regressive sequence If the pycnocline were to remain stationary or to move uniformly in one direction during a depositional cycle, then facies boundaries in a vertical sequence of sediments would be clearly delineated, and the relative time of deposition of each facies, therefore, could be well understood However, the boundaries of the pycnocline are generally poorly defined in the rock sequence that exhibits a transitional zone because the pycnocline may rise or fall within the water column relative to sea level through changes in climate, tectonism, circulation of the surface-water layer, or other such factors Consequently, facies relations in the resulting sediments are transitional and, as a result, poorly defined

The black shale facies grades upward locally into a dark-gray shale in an ideal cycle Such a facies has been recognized in the upper part of the Big Stone Gap Member of the Chattanooga Shale at Big Stone Gap, Va , in rocks designated as equivalents of the middle and the upper parts of the Mississippian Sunbury Shale (Kepferle and others, 1981, pl 1), and in all the Upper Devonian cyclic formations in western and central New York (as outlined in Chapter B) The dark-gray shale facies is thought to have been deposited in the anaerobic zone but represents the initiation of an increase in the rate of sedimentation in the early part of the regressive cycle Deposition and preservation of organic matter proceed at the same rate as in the black shale facies, however, the proportion of silt and clay increases In other words, the carbonaceous matter is diluted by clastics

In a transition that is less than ideal, alternations of thin beds of black and gray shales may represent initial episodes of the terrigenous clastic deposition of the regressive phase of the cycle Continuation of the regression and the associated clastic deposition will bring the locus of deposition within the middle part of the dysaerobic zone There, gray and greenish-gray shale beds may alternate

The greenish-gray shale facies represents the distal part, or the initial deposition, of the aerobic zone Sedimentary structures are preserved only rarely, and bioturbation is pervasive The number and the thickness of turbidite siltstone beds increase proximally in the basin and vertically in the sequence, as do nodules and thin layers of siderite and dolomite

The siltstone facies in the basin commonly is attributed to turbidites, and individual beds may extend laterally into the more distal lower greenish-gray, gray, and black shale facies Because the turbidity currents are initiated somewhat higher on the sea floor than where the entrained sediments are ultimately deposited, they provide a mechanism for introducing oxygen-bearing water into either the dysaerobic or the anaerobic zone of the basin

Continual regression results in shallow-water deposition along a muddy shoreline, as suggested by Walker (1971) and Walker and Harms (1971) Promontories and river mouths provide foci for the introduction of sand and coarser detritus, including pebbles and cobbles At these places, a variety of sedimentary structures are found, fossils increase in abundance, and, according to Ellison (1965, p 11), hematite is a characteristic authigenic mineral

Superimposed on the influence of the geochemistry of the stratified-water column are the slope and the depth of the basin floor The amount of slope and the persistence of slope can affect the fetch and the velocity of density currents The direction and persistence of slope can be measured, in part, through such paleocurrent indicators as sole marks, crossbedding, and ripple marks, as well as oriented fossil shells and plant debris (Kepferle and others, 1978, Potter and others, 1979)

Paleocurrents

The direction of the clastic source and the slope of the basin floor can be determined, in part, through the analysis of paleocurrent indicators in the rocks (Potter and Pettijohn, 1963). Numerous studies in which the paleocurrents within localized stratigraphic units were analyzed have been summarized by Potter and others (1979, fig. 1, table 2). A significant contribution of these studies has been the additional paleocurrent determinations in the Brallier Formation of Pennsylvania, Maryland, West Virginia, and Tennessee (Lundegard and others, 1980); the Upper Devonian rocks of the northern outcrop area of Ohio, Pennsylvania, and western New York; and the oriented cores from six test wells drilled for the EGSP. These and later EGSP cores confirm a nearly uniform western orientation of the paleocurrents and indicate that the depositional strike of the sediments was nearly parallel to the isopach lines, that the source of the sediment lay to the east, and that turbidity currents transported most of the silt-sized clastics intercalated in the greenish-gray and black shale in the central and the western parts of the basin (fig. 4).

Variations in the western orientation of the paleocurrents are most common in areas of thicker, more numerous accumulations of siltstone. These areas may be associated with the depositional lobes postulated by Willard (1939, fig. 71), Pepper and others (1954), and Dennison (1971).

Corroborating the paleocurrent data is the general eastward thickening and coarsening of the sediment wedge (Oliver and others, 1967, figs. 8–10), the eastern encroachment of a kaolinite component in the clays (Hosterman and Whitlow, 1981b, figs. 4–10), a westward decrease in the clastic component of the OM-rich shale, and the decrease in the rate of sedimentation shown by sulfur isotopes (Maynard, 1980).

Depth and Slope

The absolute water depth and the angle of slope on the basin floor have been postulated through the distribution of depth-sensitive biofacies. The angle of slope on the basin floor during deposition of the Middlesex Shale Member of the Sonyea Formation has been calculated to be 1:400 (0°09′) by assuming a 330-ft thickness for the dysaerobic zone and by measuring a 25-mile (mi) width of the bioturbated nonfossiliferous biofacies characteristic of that zone (Byers, 1977, p. 11–14). The amount of slope on the distal edge of the Devonian and Mississippian clastic wedge in Kentucky has been postulated as being 1:210 to 1:44 (0°16′–1°18′) along the delta front across a width of 4 to 8 mi (Peterson and Kepferle, 1970, fig. 4*B*; Kepferle, 1977, p. 45). For the interval between the base of the *Foerstia* zone and the base of the Huron Member of the Ohio Shale along Lake Erie, a thickening rate of the sediments reaches only 5 feet per mile (ft/mi) west of Lake County, Ohio, and is over 8 ft/mi between Lake County and western Chautauqua County, N.Y. (0°03′–0°05′; fig. 5). These long-distance extrapolations are without regard to syndepositional compaction of sediment. Because the silt and sand

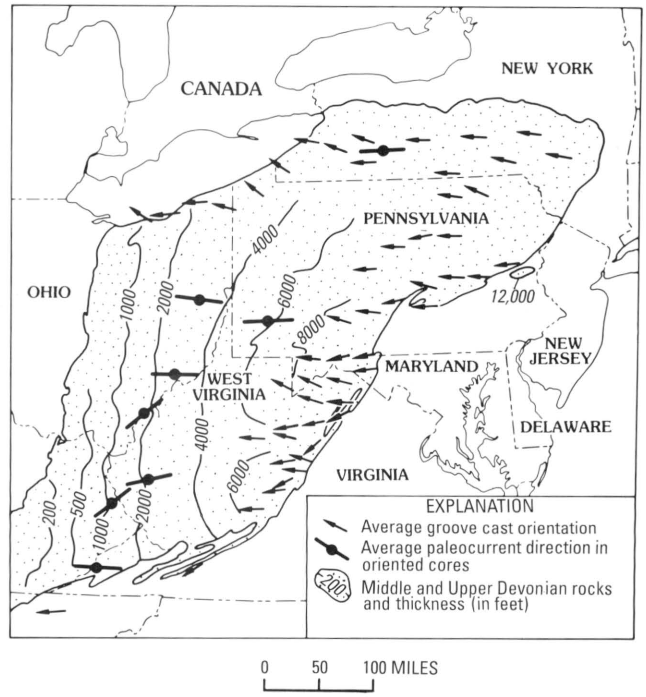

Figure 4. Basinwide paleocurrents and thicknesses of Middle and Upper Devonian strata. (Modified from Potter and others, 1979, fig. 1; de Witt and others, 1975.)

fraction increases eastward in the lower part of the Huron Member of the Ohio Shale, the effects of compaction offset those of subsidence. In fact, throughout the history of accumulation of these Devonian sediments, subsidence (or eustatic rise in sea level) that exceeded the regressive accumulation and westward migration of terrigenous clastics occurred only episodically.

Along such a slope, minor vertical fluctuations in the level of the pycnocline would produce large horizontal changes in the shoreward or basinward extent of the anaerobic environment. A rise in the pycnocline would expand the anaerobic environment and would drive the dysaerobic environment shoreward. A transgressive sea similar to that postulated for anoxic events in the Cretaceous Period best explains the broad, deep-basin extent of the black shale facies that is characteristic of the initial phase of successive cycles.

Such events are short-lived and presumably are followed immediately by a normal regressive sequence of sedimentation. Within the anaerobic zone, the onset of the regressive sequence is marked simply by an increase in the terrigenous clastics relative to the preserved organic matter; the clastics fall within the areas where gamma-ray and formation-density logs can be used to measure the percentage of OM in the sediments (fig. 6; Schmoker, 1979, fig. 3; 1981a, b, this volume). East of Schmoker's zone of geophysical log applicability, the sedimentation rate may have been too rapid for the uranium-related radioactivity to

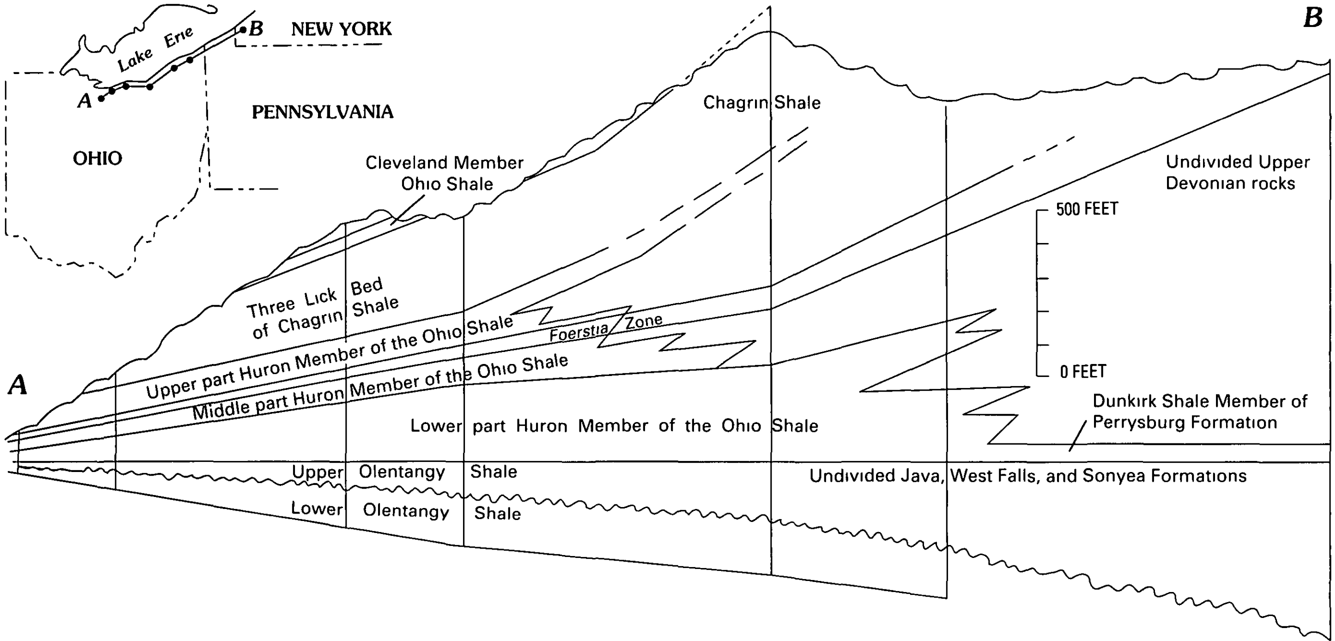

Figure 5. Relation of the *Foerstia* zone to the Upper Devonian rocks in outcrop and core along Lake Erie (Modified from Broadhead, 1979)

reach full equilibrium with the OM, which would effectively alter the gamma-ray response, or for the sediments to reach a compaction equilibrium, thereby altering the formation-density log response. West of the zone of geophysical log applicability, the basin sediments appear to be diminished in clastic components The organic content is much greater, and the relative abundance of marine and terrigenous varieties of OM is less well understood and may be more variable Also, this variability and the related preferential adsorption of uranium by terrigenous OM could have lowered the correlation between uranium and OM in the more distal western parts of the basin According to the depths ascribed to the anaerobic zone by Byers (1977, 1979), the area outlined in figure 6 probably lay beneath more than 500 ft of water during black shale accumulation Byers' value is twice the depth ascribed by Kepferle (1977), who based his calculations on the geometry of Lower Mississippian rocks

STRUCTURAL INFLUENCE ON SEDIMENTATION

Structural influence on sedimentation patterns for Middle and Upper Devonian rocks is documented for the Tully Limestone by Heckel (1973, p 129–139) and for Devonian rocks in Bradford County, Pa , by Woodrow (1968, p 34–38), both show that thickness and type of sediment are influenced by penecontemporaneous anticlines or down to the basin faults Irregularities in the sea bottom have influenced the thickness of accumulating black mud An extreme example is the paleocrater at Flynn Creek,

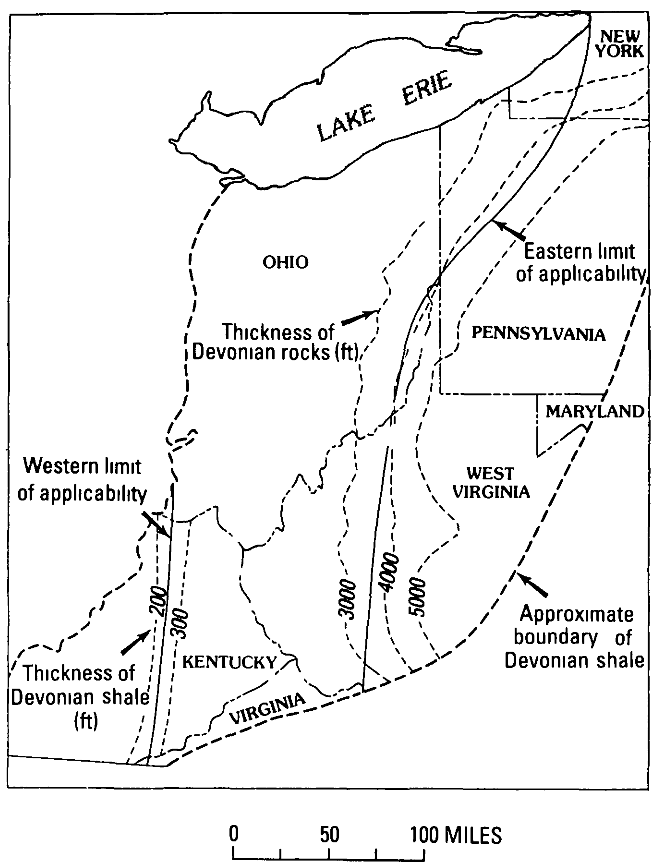

Figure 6. Limits of applicability of determination of organic content by means of significant correlation between gamma-ray intensity and formation density and their relation to section thickness (From Schmoker, 1981a, fig 16)

Tenn , in which more than 170 ft of Upper Devonian black shale was deposited while adjacent areas received little or no accumulation (Conant and Swanson, 1961, p 10, Huddle, 1963, p C55, Roddy, 1966, 1977) Further documentation of structural influence is discussed in Chapter K

Unconformities

Unconformities are a major manifestion of nondeposition on or erosion from positive areas of the basin floor Unconformities are most common around the margins of the present-day basin and are marked in the Devonian and Mississippian shale sequence by "bone beds" or zones of erosional detritus These beds may range in thickness from a single lamina less than 0 005 ft thick to a bed as much as 2 ft thick, a thickness of 0 1 ft is common Bone beds are accumulations of chemically resistant debris, such as a lag concentrate of fish bones and scales, scuta, teeth, phosphatic granules, conodonts, fragments of phosphatic brachiopod shells, chert grains, and rounded frosted grains of quartz silt and sand The detrital fraction commonly is surrounded by pyrite, calcite, or quartz as a secondary cement These zones, even within black shale, attest to the presence of gentle winnowing currents and (or) long breaks in sedimentation The thicker beds commonly can be traced over wider areas and presumably mark a longer hiatus

Extensive bone beds have been found at the bases of the Marcellus Shale, the Geneseo Shale Member of the Genesee Formation in the form of the Leicester Pyrite Bed, the Huron Member of the Ohio Shale, and the Sunbury Shale The time span represented by nondeposition and (or) subsequent winnowing of the sediment from these horizons appears to increase westward toward the western margin of the basin, where eventually, the hiatuses merge Examples are provided in a diagram by Heckel (1977, fig 14) and Baird and Brett (1986, fig 11) for the Leicester Pyrite

Details of local differential movement during the Middle Devonian are recorded in Kentucky in the distribution of the carbonate units On the western flank of the Applachian basin, the Boyle Formation (Dolomite) includes correlatives of the Jeffersonville and the Sellersburg Limestones, which crop out in the vicinity of Louisville The Jeffersonville, which is considerably older than the Tully Limestone, is truncated by erosion against the flank of a gentle northwest-dipping monocline Equivalent rocks in the basal Boyle of south-central Kentucky are preserved only in and near down-faulted areas and are absent along the eastern flank of the Cincinnati arch in northeastern Kentucky The upper part of the Boyle and the equivalent rocks show a similar, although less restricted, pattern of distribution, which indicates that during most of Hamilton time, the southwestern margin of the Appalachian basin was shoaling or nearly emergent Several models have been proposed to explain the occurrence of the various carbonate lithofacies in these rocks, all of which suggest shoaling, for example (Stephenson, 1979) Unconformities marked by bone beds locally abound within these carbonate units

Thickness

The thickness of the black shale sequence in Late Devonian is an indicator of subsidence during that time in the eastern North American craton Because the black shale facies is thin around the Nashville and the Jessamine domes and elsewhere along the Cincinnati arch, these features are considered to have been less negative than where the black shale facies is thicker, as in the Illinois basin to the west (470 ft) and the Michigan basin to the north (over 700 ft) (National Petroleum Council, 1979) In none of these areas was subsidence as continuous or as great as in the eastern area of the Appalachian basin, where as much as 9,000 ft of sediment accumulated during this same time, downwarping exceeded the sedimentation rate to such an extent that the mechanism has been termed a "clastic trap" (Heckel, 1973) Black shale is notably scarce within this trap The clastic trap mechanism was most active during deposition of the Tully Limestone and the Genesee Formation Westward from this trap, little coarse-grained clastic material was deposited (Oliver and others, 1967, p 1037) Later, where clastic influx exceeded the downwarping, coarser clastics spilled westward beyond the trap

Positive Elements

In the Appalachian region, positive elements were produced by the Acadian orogeny, which was a plate-collisional event The Acadian geanticline of Cumming (1967, p 1044) took form and was accompanied by granitic intrusion and deformation This area provided the bulk of the terrigenous clastics that were introduced marginally into the elongate cratonward basin The Kankakee arch appears to have restricted circulation between the Michigan and the Eastern Interior basins The Ozark uplift remained as a positive element throughout Devonian time (Collinson and others, 1967, p 936) The Wisconsin dome may have been uplifted in latest Devonian time (Collinson and others, 1967, p 936) Although the Cincinnati arch was also a positive element relative to the flanking basins, it was probably not emergent over a span of time sufficient to make it a major source of sediment (Much of the foregoing discussion is taken from the summary of the paleotectonics of the Mississippian by Craig and Varnes (1979, p 384–385))

Faults

Syndepositional faults in Late Devonian rocks have been identified in the outcrop in central Kentucky

(Kepferle, 1966, Peterson, 1966) Where erosion beveled Silurian rocks, normal faulting resulted in grabens in which Middle Devonian carbonate rocks are preserved In some of the grabens, thicker sequences of the more resistant Silurian dolomites are preserved, which indicates that movement began along the faults during the erosional beveling of the Silurian Over such erosional remnants, the Middle Devonian limestones are commonly absent, and the overlying black shale sequence is thinner than in surrounding nonfaulted areas of deposition, an example of this, from Estill County, Ky , is illustrated by Simmons (1967) The Mississippian Sunbury Shale was encountered in an exceptionally thick black shale section in a well in Morgan County, Ky , on the upthrown-block side of the northeast-trending Irvine-Paint Creek fault (Van Beuren, 1980, pl 2) This suggests that successive movements along faults were not always in the direction of the latest movement or surface expression The Irvine-Paint Creek fault coincides with a basement fault shown on the tectonic map of the United States (King, 1969) and also coincides with the northern edge of the Rome trough structural element in Kentucky (L D Harris, 1978, Webb, 1980, Chapter K)

DEPOSITIONAL CYCLES

The variations of the black shale cycle summarized in figures 2 and 3 will be discussed according to each individual cycle In each cycle, the black shale facies is assumed to have originated below the pycnocline, and the interbedded facies, whether black and gray, or black, gray, and green, or gray and green, is assumed to have originated within the dysaerobic zone of the pycnocline, greenish-gray shale and mudstone are assumed to have originated above the pycnocline in the aerobic zone Graded siltstone or sandstone beds that have sole marks are attributed to turbidites and may occur within any of the lithologies recognized above Thoroughly bioturbated silty mudrocks and reddish sandstones that are associated with fossiliferous shale also are assumed to have originated in the aerobic zone Each cycle will be discussed from the viewpoint of the site where its development is considered to be most complete within the basin Eastward, in a near-shore direction, correlative rocks within the cycle may be entirely aerobic throughout the span of the cycle Westward, beyond the clastic trap, the depositional basin is assumed to have been shallower, but the basin floor may have been totally beneath the anaerobic water layer, where sedimentation was extremely slow (see fig 7) The ideal vertical sequence should include all coeval facies, from the black shale in the west to the aerobic facies in the east, in a Waltherian reconstruction of the expected vertical sequence In some areas, the black shale facies could be missing through oxygenation, sediment influx, or destruction of the pycnocline, even though the facies is present in surrounding areas These subtle facies changes, which reflect possible subcycles within a major cycle, have been identified in many cases though the availability of excellent local exposures and closely spaced cores

Marcellus Cycle

The Marcellus cycle includes most of the rocks of the Hamilton Group in New York, Pennsylvania, Maryland, Virginia, and West Virginia Basal remnants appear in the eastern part of Ohio, the extreme eastern part of Kentucky, and northeastern Tennessee A widespread unconformity marks the base of the cycle nearly everywhere Locally, evidence for this unconformity is a pervasively bioturbated bone bed that contains glauconite and phosphorite, as in outcrop near Jasper, Va Elsewhere, the base appears to coincide with the Tioga Ash Bed (as in the cores of wells EGSP–OH7 and EGSP–NY4) or is separated from the Tioga by part of the Onondaga Limestone or its equivalents, as in central New York in Seneca County (Patchen and Dugolinsky, 1979, p 73) This unconformity was diagramed by Rickard (1984, fig 6) for the Lake Erie region

The Cherry Valley Limestone Member appears in the lower part of the Marcellus in New York as a dark, dense, deep-water carbonate Elsewhere, as in core EGSP–PA4, a carbonate-rich zone marked by carbonate nodules occurs in the lower part of the Marcellus Shale Other black shale facies in which carbonate concretions are conspicuous include the following overlying cycles the Geneseo, the Middlesex, the Rhinestreet, and the Huron-Dunkirk (the basal part of the Huron Member of the Ohio Shale in outcrop in Ohio and northernmost Kentucky) Dolomite is a prominent constituent in the lower part of the New Albany Shale in the Illinois basin and in equivalent rocks in the lower part of the Chattanooga Shale in central Kentucky Morris (1980, p 164–167) discussed postburial upward migration of carbonate ions from partial dissolution of aragonitic shells to explain similar concretions in the OM-rich Jurassic shales in England A carbonate-rich sequence that contains a basal black shale has been described for the underlying Needmore Shale at Keyser, W Va , and has been applied to the stratified-basin model by Newton (1979a, b)

Because the Marcellus cycle is the oldest of the Devonian and Mississippian black shale cycles within the prograding Catskill deltaic sequence, its axis lies nearest the clastic source to the east Correlative rocks in New York were summarized by Rickard (1964, 1975), who ascribed names first used by Caster (1934) to the facies above the Tioga Ash bed—limestone = "Onondaga," black shale = "Cleveland," argillaceous limestone and calcareous gray shale = "Moscow," gray shale and siltstone = "Big Bend," gray to purple silty shale, sandstone, and siltstone = "Smethport," and red and green shale, siltstone, and sand-

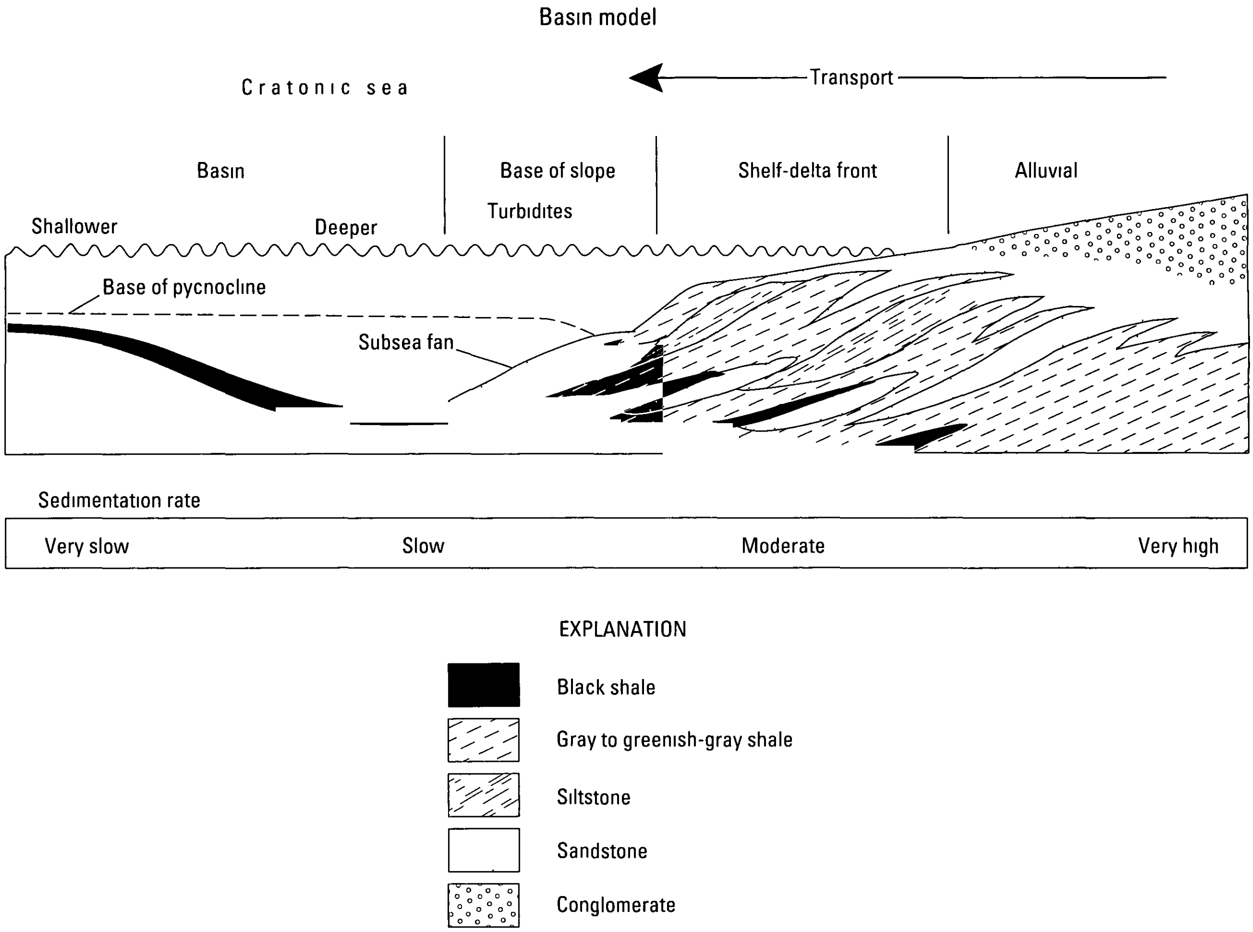

Figure 7. Stratified basin showing lateral facies relations Vertical exaggeration such that steepest slopes shown rarely exceed 1° at true scale (Modified from Potter and others, 1980a, fig 7)

stone = "Catskill " The cumulative thickness of these rocks is about 2,500 ft in eastern Pennsylvania Some of the "Moscow" facies is present across northern Ohio, and the entire sequence is absent or represented by scattered limestone of the "Onondaga" facies along the western outcrop of the Devonian rocks in southern Ohio, central Kentucky, and Tennessee

The Marcellus cycle is the most carbonate rich of any of the black shale cycles In addition, the organic-carbon content is lower than might otherwise be expected in sediment beneath or within the dysaerobic zone, the relation of color and organic carbon and the darkening effect of a carbonate component were discussed by Hosterman and Whitlow (1981a, b) Above the black shale facies, the low OM content and the episodic occurrence of thin detrital and possible deep-water limestone layers suggest a somewhat different environment during this cycle than for subsequent cycles The absence of the black shale facies immediately above the basal unconformity on the western side of the basin, as observed in cores and outcrops in northern Ohio (Broadhead and others, 1980), indicates that those areas may have remained above the anaerobic zone throughout the Marcellus cycle The alternate hypothesis that the Marcellus black shale facies may have been deposited and later removed is not supported by the presence of sedimentary structures, such as rip-up clasts Descriptions of the calcareous gray shale of this interval in central Ohio were taken from Tillman (1970)

The top of the Marcellus cycle is the base of the next younger black shale, the Geneseo Shale Member of the Genesee Formation, and its apparent lateral equivalent, the Burket Black Shale Member of the Harrell Shale The question of whether the Tully Limestone should appear as the top of the Marcellus cycle or in the base of the Geneseo cycle is discussed below The Tully Limestone has been investigated thoroughly by Heckel (1973), who concluded that, for the most part, it is transported carbonate detritus derived from the northeast Lithologies that are not continuous with the Tully and that are similar in all but fossil content are identified as Tully by drillers in the subsurface of New York, Pennsylvania, and Ohio The occurrences of the "drillers' Tully" attest to the cyclicity of the sedimentation during the later stages of the cycle These limestones are commonly older than the Tully but may occupy the same niche in the regressive sequence (the Tichenor Limestone Member of the Ludlowville Shale, for example) Sulfide beds mark lag deposits above and below the Tully (Heckel, 1972, p 266) The sulfide-rich bed above the Tully is the Leicester Marcasite Member of the Moscow Formation of Sutton (1951), which is progressively younger to the west (Baird and Brett, 1986) Conodonts from this bed have been identified as the same assemblage as those found in the North Evans Limestone of Rickard (1964) and were assigned a Middle Devonian age by Huddle and Repetski (1981, p B8–B10) Baird and Brett (1986) showed that their Leister Pyrite spans the Middle-Late Devonian boundary and that the North Evans Limestone has close affinities to the Genundewa Limestone Member of the Genesee Formation

The line of evidence that favors placing the top of the Marcellus cycle at the pyrite bed above the Tully Limestone is the reported occurrence of black shale below the Tully in the subsurface in Somerset and Westmoreland Counties in southern Pennsylvania (Harper and Piotrowski, 1979, fig 10), in exposures in Maryland and West Virginia (Dennison and Naegele, 1963, Hasson, 1966, fig 5), and locally below the Tully in central New York (Wallace de Witt, U S Geological Survey, written commun , 1987) This correlation, if substantiated, would mean that the transgression that initiated the expansion of the anoxic layer also resulted in a decrease in clastic deposition northward above the Tully Limestone and may have been responsible for the lag concentrate found in the sulfide bed west of the sheet of Tully Limestone The sulfide bed is not known to be present where the black shale facies underlies the limestones Thus defined, the parallelism of the Marcellus and the Geneseo cycles is enhanced

Geneseo Cycle

The interpretation of the Geneseo cycle is derived from a review of the excellent description of the Genesee Formation in western and central New York by de Witt and Colton (1978) In a vertical sequence, this second major cycle is made up of the lithostratigraphic units, which, in ascending order, are the Geneseo Shale, Penn Yan Shale, Sherburne Flagstone, Renwick Shale, Ithaca, and West River Shale Members Marker beds within the Ithaca include the "Starkey" black ("Stb") shale bed of de Witt and Colton (1978, p 13) (fig 8) and the Crosby Sandstone of Torrey and others (1932), which contains conodonts similar to those in the Genundewa Limestone Member The Genundewa lies between the Penn Yan and the overlying West River beyond the westernmost extent of the Ithaca A younger marker bed in the West River is the Bluff Point Siltstone Bed The stratigraphic cross section (fig 8) shows the restored relation among the various members of the Genesee Formation from west to east (replotted from de Witt and Colton, 1978, pls 2, 3)

Clearly, the section is dominated by turbidites in the east, beginning with the Sherburne Flagstone Member That the Geneseo Shale Member was mainly below the pycnocline is indicated by the absence of bioturbation The westernmost extent of the Geneseo is interpreted to mark the cratonward extent of the anaerobic zone during the initial transgressive phase of the cycle The Penn Yan Shale and West River Shale Member appear to be closely related to the dysaerobic zone Black shale deposition of the Renwick could have resulted from a rise in the pycnocline and in an expansion of the anaerobic zone without drastic changes in either sea level or tectonic stability That the eastern part of the basin subsided at a rate nearly commensurate with deposition is indicated by the occurrence of the "Starkey" black shale bed, which is locally above the lower part of the turbidites of the Ithaca Member

The carbonate nodules and layers, which are common in the shale members of the Genesee Formation, are an indication that the environment retained similarities to those that prevailed during the deposition of the Tully Limestone, as well as the underlying rocks of the Hamilton Group The thicker parts of the black Geneseo shale likely accumulated in the lower part of the basin floor immediately seaward from the thickest distal accumulation of siltstone and sandstone of the earlier Marcellus cycle Similarly, the western extent of the Sherbourne and the Ithaca turbidite sequences marks the locus along which the thickest successive black shale (the Middlesex Shale Member of the Sonyea Formation) might be expected to accumulate Similarities to the basin cross section (fig 7) can be seen in the scaled cross section (fig 8) in terms of a thick subsiding wedge of clastics from the east The Geneseo cycle, however, differs from the depicted model in that the western margin was within the dysaerobic zone during most of the regressive phase The top of the cycle is marked by the initial deposition of the Middlesex Shale Member of the Sonyea Formation—a transgressive black facies—of the next cycle (de Witt and Colton, 1959, fig 4)

Middlesex Cycle

The Middlesex Shale Member of the Sonyea Formation was the first of the Devonian shale units to be described relative to the stratified basin (Byers, 1977, 1979) In a vertical sequence, the third major cycle includes, in ascending order, the following members of the Sonyea Formation the Middlesex Shale Member, the Pulteney Shale Member, the Rock Stream Siltstone Member, and the Cashaqua Shale Member Of these, the Middlesex is a transgressive unit of the anaerobic zone, and the Pulteney, the Rock Stream, and

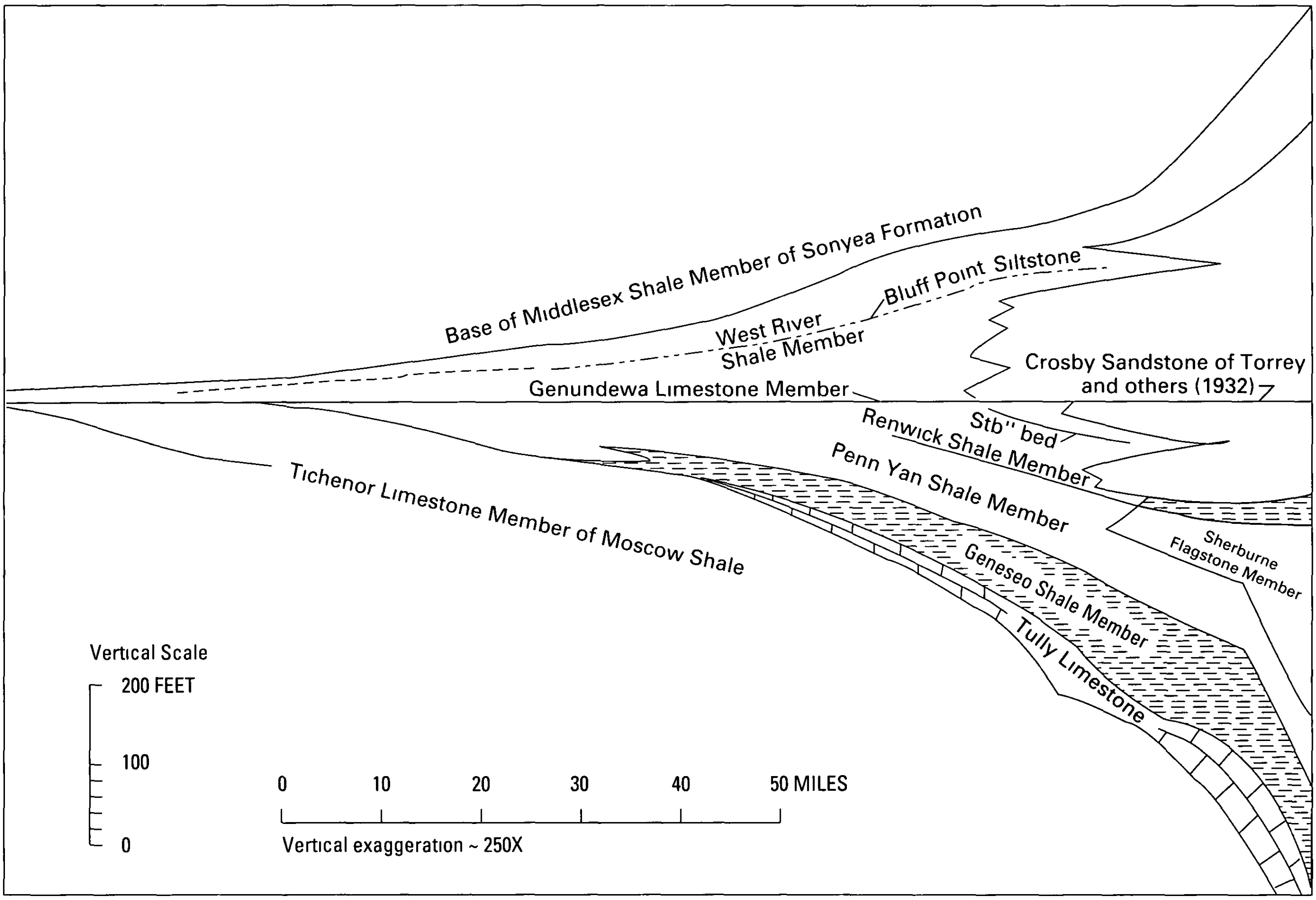

Figure 8. Genesee Formation along the outcrop belt from Lake Erie eastward to Ithaca, N Y (Modified from de Witt and Colton, 1978, fig 1, pls 2, 3)

much of the Cashaqua are regressive units The Pulteney was deposited in the anaerobic-dysaerobic zone into which the Rock Stream turbiditic sequence prograded from the east Colton and de Witt (1958, fig 8) outlined this relation very well The Cashaqua was deposited in the upper part of the dysaerobic zone The eastern separation of the Middlesex into the black shales of the Montour and the Sawmill Creek Members by the siltstone and the sandstone of the Triangle Member implies that much of the basin was stratified and anaerobic during the early regressive phase and that the turbidity currents may have been responsible for oxygen that was introduced into this otherwise anoxic environment This part of the sea has been described as a shallow-water shelf by several studies, including those of Sutton (1963), Sutton and others (1970), and Bowen and others (1974) Studies of the more nonmarine parts of the cycle include those of Burtner (1963), Fletcher (1963), Allen and Friend (1968), Buttner (1968), Fletcher and Woodrow (1970), and Ethridge (1977) This part of the cycle is not discussed here because these rocks, for the most part, do not overlie the initial black shale transgressive phase For this reason, the cycle is considered to have been truncated by that of the Rhinestreet, which is the transgressive black shale that marks the initiation of the next cycle

Eastward, the sea of the Middlesex cycle became shallower and better oxgenated, as evidenced by the increased faunal abundance and diversity Westward, beyond the limits of the recognizable Middlesex black shale, the dysaerobic zone prevailed, which impinged on the unconformity at the top of the Marcellus cycle in northwestern Pennsylvania In the absence of black shale, this unconformity is difficult to detect from either lithology or wire-line logs The rocks equivalent to the Sonyea Formation along the western outcrop of the Devonian of the Appalachian basin are missing at the unconformity

A 0 3- to 0 5-ft black shale underlies the Rhinestreet by about 4 ft and has been traced from Lake Erie to Keuka Lake (Wallace de Witt, U S Geological Survey, written commun , 1987) Such an occurrence attests to the local variations that may occur along with or before a major transgressive cycle, it also attests to the more than local persistence through time of the anaerobic zone in contact with the sediment-water interface and the general absence of currents that might disturb this persistence

Rhinestreet Cycle

The Rhinestreet Shale Member of the West Falls Formation is the black shale that marks the transgressive anoxic phase of the Rhinestreet cycle In western New York, where this fourth major cycle is best exposed, the West Falls Formation consists of, in ascending order, the Rhinestreet and the overlying Angola Shale Member Eastward, clastics were introduced as part of the regressive dysaerobic phase and are correlative in part to these two members Above the Rhinestreet, the clastics are the Gardeau Shale Member, the West Hill Member, and the Nunda Sandstone Member Farther east, equivalents of the basal part of the Gardeau Shale Member include the Hatch Shale Member and the Grimes Siltstone Member (Pepper and others, 1956, de Witt and Colton, 1959) There, the Grimes appears to be a turbiditic siltstone, which is intercalated with the less turbiditic Gardeau The Hatch, which is below the Grimes, is a clastic-rich regressive unit deposited mainly in the anaerobic zone Still farther east, time-equivalent rocks have been traced into shallower, better oxygenated environments

The Belpre Ash Bed (Roen, 1980b, Roen and Hosterman, 1982) has been identified in several cored drill holes along the central part of the Appalachian basin The ash bed is the equivalent of the Belpre Bentonite Bed of Collins (1979) The Belpre also has been found associated with the Rhinestreet on the outcrop in eastern Tennessee and western Virginia The bed substantiates volcanic activity during or shortly following the widespread transgression marked by the basal Rhinestreet The typical gamma-ray logs of the Rhinestreet interval, however, show fluctuations that imply nonradioactive zones that are not black shale These are probably gray shale or carbonaceous limestone nodules similar to the gray shale beds intercalated in the Rhinestreet Shale Member in western New York These fluctuations also may represent turbiditic clastic pulses into the anoxic zone or may represent vertical fluctuation of the pycnocline

The Rhinestreet cycle extends southward from Lake Erie for the entire length of the basin Its western extent appears to be greater than that of any of the preceding cycles except for the upper part of the Marcellus cycle Yet, it, too, fails to extend to the outcrop along the western margin of the basin, but laps out against the unconformity at the top of the Middle Devonian rocks in eastern Ohio (Schwietering, 1979) and Kentucky (Dillman and Ettensohn, 1980) As in the Middlesex cycle, the westward loss of the basal Rhinestreet Shale Member makes the contact between the West Falls Formation and the shales of the upper part of the Hamilton Group extremely difficult to pinpoint in logs and samples Even in outcrop in central Ohio, separating the lower part of the Olentangy Shale (Hamilton) from the overlying West Falls equivalent is difficult Continued western thinning is also difficult to document

Pipe Creek Cycle

The separation of the Pipe Creek cycle from that of the underlying Rhinestreet is made possible by an extremely widespread and persistent 1- to 3-ft bed of black shale that is easily identified on gamma-ray and compensated-formation-density logs (Roen, 1980a, de Witt and others, this volume)—the Pipe Creek Shale Member of the Java Formation Additional (at least two) thin black shale beds intercalated into gray shale beds make up the remainder of the member and are overlain by the Hanover Shale Member Greenish-gray shale characteristic of the Hanover crops out on the western margin of the basin as far south as Delaware, near Columbus, Ohio, where it makes up the upper Olentangy Shale as defined by Tillman (1970)

The areal extent and the ease of recognition add to the significance of the Pipe Creek cycle In addition, the basal black shale bed contains or is associated with a kaolinitic biotite-rich zone, which has been identified as another ash bed This ash bed has been correlated tentatively with the Center Hill Ash Bed in the upper unit of the Dowelltown Member of the Chattanooga Shale in Tennessee (Roen, 1980b) The low density of the lower bed of the Pipe Creek Shale Member suggests that the amount of clastic detritus was extraordinarily low throughout the basin, even for a black shale bed Volcanic activity indicated by the ash bed may have been accompanied by a tectonic disturbance that abruptly terminated the transgressive phase and accelerated the beginning of the regressive phase Although the Pipe Creek basal bed, as shown in core EGSP–KY4 from Johnson County, Ky , was identified tentatively as the thickest (1-ft) bed below the Ohio Shale, no ash bed has been found A series of thinner black shale beds above and below the basal Pipe Creek indicates interludes of restricted circulation An anoxic layer developed in depressions on the basin floor during these restrictive intervals Widespread correlation of these beds appears to be unlikely Introduction of clastics from the east continued during this regressive phase

Huron-Dunkirk Cycle

The Dunkirk Shale Member of the Perrysburg Formation is the transgressive black shale that marks the initiation of the Huron-Dunkirk cycle in New York In Ohio, the Dunkirk becomes the lower part of the Huron Member of the Ohio Shale This sixth major cycle is probably better known in the distal part than are the earlier cycles because most of the units crop out nearly continuously along the eroded western edge of the Appalachian basin from central Ohio into central Kentucky In Kentucky, the effects of the Cumberland saddle athwart the Cincinnati arch can be seen, and, there, the outcrop is continuous with the New Albany Shale on the eastern margin of the Illinois basin Because much of the outcrop along the Cincinnati arch is subparallel to the depositional strike, correlation of subdivisions of the Huron-Dunkirk cycle is easier than across northern Ohio, were sporadic exposures are difficult to correlate due to changes in thickness and lithology

Along the Cincinnati arch in south-central Kentucky and central Tennessee, the Huron-Dunkirk cycle is represented almost entirely by black shale Basinward, to the east, grayish-green carbonate shale is common near the cycle's base, and its gamma-ray profile resembles that of the Rhinestreet Shale Member of the West Falls Formation Evidence for winnowing currents in this part of the section are at least two fairly extensive "bone" beds in Kentucky (Kepferle and others, 1981) and cross-laminated silty layers Correlation of these beds has been facilitated by a series of more than 70 cores drilled under the auspices of the Kentucky Energy Cabinet (Barron and others, 1985) The onset of the persistent, dense, transgressive black shale above this lower winnowed zone is accompanied by pyrite-rimmed carbonate concretions similar to those described by Morris (1980) from anaerobic OM-rich Jurassic rocks of Great Britain

Manifestations of the eastern source of terrigenous clastics during the deposition of the Huron-Dunkirk cycle and the regressive nature of the sediments can be seen in the westward migration of the Chagrin Shale (a dysaerobic facies) in two distinct pulses The first pulse is recorded in rocks along the western outcrop belt simply by a dilution of OM in the anaerobic facies This pulse terminated the vertical extent of the Dunkirk Shale Member of the Perrysburg Formation in New York and coincides with the middle part of the Huron Member of the Ohio Shale in central Ohio, eastern Kentucky, and eastern Tennessee A widespread biostratigraphic marker, the *Foerstia* zone (Schopf and Schwietering, 1970), developed at this time The second major pulse of clastics brought the Chagrin facies well into north-central Ohio, western Pennsylvania, and West Virginia and was accompanied by the extension of the dysaerobic zone completely across the basin during its most extensive phase Three short dysaerobic episodes in Kentucky and Ohio outcrops are manifested by the Three Lick Bed (Provo and others, 1978), also termed the "Three Lick Tongue of the Chagrin" (Swinford, 1985) The Cincinnati arch remained beneath the pycnocline during this time

Cleveland Cycle

A rise in the pycnocline, which is marked in central Ohio, eastern Kentucky, and eastern Tennessee by the deposition of the Cleveland Member of the Ohio Shale, indicates the beginning of the seventh major cycle—the Cleveland The pattern of deposition of the Cleveland has been shown as lobes of thick black shale separated from each other by thinner areas (Lewis and Schwietering, 1971, fig 3) The thinner areas are thought to have been produced by depositional centers of terrigenous clastics introduced as a part of the continuation of the second pulse of Chagrin deposition mentioned above or by early introduction of clastics from the Bedford Shale and the Berea Sandstone in the final clastic pulse of the cycle (Pepper and others, 1954) OM-rich sandstone was reported in the lower part of the Cleveland Member (Broadhead and Potter, 1980) and beneath the Cleveland (Lewis and Schwietering, 1971) The Olmsted facies of Cushing and others (1931, p 35) in the lower part of the Cleveland along Lake Erie is regarded as the basinward continuation of the second clastic pulse of the Chagrin, the Three Lick Bed

The westward migration of clastics may have been restricted by the the Cincinnati arch in Kentucky because the Cleveland is immediately overlain by the Sunbury Shale in Estill and Powell Counties (Ettensohn and others, 1979) More recently, a thin dark-gray to black shale at the contact has been correlated with the greenish-gray Bedford Shale to the east (Kepferle and Pollock, 1983, Ettensohn and Elam, 1985)

Sunbury Cycle

The final transgressive-regressive cycle in the Appalachian basin is Mississippian in age The Sunbury cycle begins with the Sunbury Shale as the transgressive anaerobic facies—the lower member of the Sunbury Shale as described at Big Stone Gap by Kepferle and others (1981, pl 1) The middle and the upper parts of the Sunbury Shale of Kepferle and others (1981) are interpreted as being regressive anaerobic facies by Van Beuren (1980), Elam (1981), and Ettensohn (1985a, b) The upper part shows a gradation between the anaerobic and the dysaerobic facies Siderite concretions occur in the dysaerobic facies At Big Stone Gap, siltstone of the overlying Price Formation is interpreted as being a turbidite facies penetrating the dysaerobic zone The anaerobic layer of the stratified water column of the Sunbury cycle appears to have been more restricted areally than was the transgressive phase of the Huron-Dunkirk cycle, at least in its northeastern and southwestern extents Northwestward, the Sunbury extends into the Michigan basin To the southeast, the Big Stone Gap Shale extends eastward above the siltstone and the sandstone facies of the Brallier Formation in western Virginia (Kepferle and others, 1978)

The dysaerobic environment may have prevailed during much of the early deposition of the Price Formation in Virginia, the Grainger Formation in Tennessee, the Borden Formation in Kentucky, and the Cuyahoga Formation in Ohio—all of which are lithostratigraphic equivalents that contain some similar facies These facies range from deep-water anaerobic gray shale, to dysaerobic green and gray shale and siltstone of the basin floor, to slope-edge or delta-front dysaerobic-aerobic siltstones and mudstone, and, in the Black Hand Member of the Cuyahoga Formation of Ohio, to aerobic pebbly mudstones.

The final stage in the regressive Sunbury cycle is marked in the basin by a widespread hiatus (Whitehead, 1979) The terrigenous clastic surface in the dysaerobic to aerobic zone was heavily burrowed Glauconite and phosphatic concretions accumulated along a zone called the Floyds Knob Bed in Kentucky (Kepferle, 1971, 1977) These accumulations characterize a sediment depauperate basin in Illinois (Swann and others, 1965, Lineback, 1966)

BASIN ANALYSIS

The major cycles of transgression-regression occurred eight times in the Appalachian basin during the interval from Middle Devonian into Early Mississippian The stratified-basin model for the origin of black shales has contributed to the concept of the coincidence of the onset of black shale deposition accompanied by a eustatic rise in sea level Examples of cycles for younger rocks are shown by the curves of Vail and others (1977, 1980) for global and restricted areas A composite curve is presented here for the interval of the eight major transgressions mentioned above (fig 1) and reflects the cycles recognized by means of the basinwide stratigraphic network A sea-level curve based on basinward extent of reddish-brown shaly beds (interpreted to represent sea-level lowstands) was suggested for part of this interval in the Devonian by Dennison (1971, 1985) A comparison of the curves indicates that, basinward, sea-level changes are better indicated by the black shales, whereas, landward, lowstands are better shown in terrigenous rocks that are younger than mid-Late Devonian in age

Although the global relations and the significance of these curves are beyond the scope of this paper, a summary basin analysis interpretation is presented in table 1 Data are derived from various sources, several of which are included in this volume Figures 9 through 12 illustrate aspects of the basin summarized in table 1

Table 1. Basin analysis of Middle and Late Devonian and related rocks of the Appalachian basin
[m y , million years, ft, feet, mi^2, square mile, mi^3, cubic mile, OM, organic matter, CAI, conodont color alteration index]

Time span:

Middle Devonian (part) through Late Devonian into Early Mississippian (386–350 m y , Eifelian-Givetian, Frasnian, Fammenian, and Tournasian Stages) (Ziegler, 1978, p 338, Sohl and Wright, 1980, fig 1)

Boundaries:

Lower

Unconformable on basin margins, possibly unconformable near center

Upper

Conformable Biostratigraphic and lithostratigraphic definitions coincide in the west, diverge in the east Margins eroded everywhere except across Cumberland saddle in south-central Kentucky

Geometry·

Basin shape is elongate, asymmetrical, thickest fill along eastern faulted and folded margin Maximum thickness for time interval defined above—11,500 ft (Devonian), 3,000 ft (Mississippian, intervals A and B of Craig and others, 1979)

Area:

Occupies 160,000 mi^2 in parts of the following States—New York, Pennsylvania, Ohio, West Virginia, Maryland, Virginia, Kentucky Tennessee, Georgia, Alabama, and Mississippi

Volume:

Devonian OM-rich portion alone—12,600 mi^3

Sedimentology·

Lithic fill

Dominantly shale in the west, mudrock in the middle, siltstone and sandstone in the extreme east, minor carbonate rock in the basal part, phosphatic near the top, coarsens upward and westward through time (See fig 9)

Modal composition

Mainly litharenite to sublitharenite, some lithic subarkose to subarkose (fig 11)

Clay composition

Illite, some chlorite, and small amounts of mixed-layer clay in every sample, kaolinite present in about 25 percent of samples (Hosterman and Whitlow, 1981b), mainly in east or in volcanic ash beds

Organic constituents

Marine and terrestrial carbons are present Gas chromatography and mass spectrometry (Leventhal, 1981) and carbon isotopes (Maynard, 1981) serve to distinguish between the two and to indicate an eastern source for terrestrial carbon Total organic carbon can be determined from wire-line logs for a selected part of the basin (Schmoker, 1981a, b)

Dispersal patterns

An eastern source is indicated by paleocurrents (Potter and others, 1979), kaolinite distribution (Hosterman and Whitlow, 1981b), grain size (fig 9), and composition of clastic and organic-carbon constituents

Bathymetry:

The stratified water column in the anoxic basin indicates that the black shale was deposited at depths of greater than 500 ft By using a method proposed by Klein (1974), Lundegard and others (1980, p 55) indicated that the maximum water depth during deposition of the Brallier Formation in Virginia was less than 3,200 ft. This suggests that the maximum depth ranges from 500 to 3,200 ft for black shale deposition. By the beginning of the Mississippian Period, the shoreline of the epeiric sea probably coincided with the thickest accumulation of terrigenous clastic sediment of Devonian age. Toward the southwest, the basin is believed to have opened to a deeper ocean.

Structural style:

Predepositional

Thick accumulations of sediment during the Cambrian and in the Ordovician were accompanied by volcanism and apparently were derived from the east in earlier wedges of clastics similar to those that accumulated during the Middle and the Late Devonian in the Appalachian basin. Crustal negative areas during the Cambrian and the Ordovician lay somewhat to the east of the axis of the negative area of the basin of the Middle and the Late Devonian. The Rome trough and its northeastward extension were negative and locally downdropped during the Cambrian. The Grenville Front represents the western extent of late Precambrian continental-margin crumpling.

Syndepositional

A widespread unconformity at the base of the sequence indicates emergent or shallow-water conditions. During the initial Marcellus cycle, shelf carbonates are preserved in the less negative area long the Findlay arch in north-central Ohio and along the Cincinnati arch in south-central Kentucky, where thicker accumulations coincide with the Rome trough. Volcanism is an element of the early part of the cycle. The basin was consistently differentially negative to the east. Warping, rather than faulting, was the general style of deformation. Less negative areas of the basin floor are documented by a thin accumulation of sediment and locally by lag concentrations or "bone" beds. Successive cycles are accompanied by a westward migration of the depositional axis of the basin, volcanic activity in at least three of the cycles, and possibly, attendant seismic activity. Hinge lines, which bound areas of major thickening, are identified along the eastern margin of the Cincinnati arch, which extends from western Lewis County, Ky., southward to eastern Bell County, Ky., and help delimit the western extent of the Rhinestreet cycle and the overlying Pipe Creek cycle, as well as the thicker part of the Huron-Dunkirk cycle. It also appears to coincide with the thicker development of the Berea Sandstone in the upper part of the Cleveland subcycle. A parallelism with the Grenville Front, the Waverly arch of Woodward (1964), and this hinge line is noted. Faulting of pre-Upper Devonian age is inferred from well information shown on the cross section in Indiana County, Pa., by Harper and Piotrowski (1979), who also postulated positive movement on Laurel Hill and Negro Mountain anticlines as barriers to terrigenous clastic dilution of the Tully limestone in parts of central Pennsylvania. The potassium-argon method dates minerals that recrystallized in a crushed zone along the Tuscarora thrust in southern Pennsylvania at 340 m.y.; this points to Acadian movements on this fault (Clark and Stearn, 1968, p. 299).

Postdepositional

During the Mississippian, recurrent movement continued along some of the earlier identified warps and faults. Compressional effects were progressive from north to southwest, which caused uplift of the southward extension of the Appalachian positive element. The distribution of evaporites in Late Mississippian rocks of the Saltville, Va., area, the Eastern Interior basin, and the Michigan basin is attributed, in part, to tectonic control (de Witt and others, 1979). The compression culminated in the Ouachita orogeny during Middle Pennsylvanian time and eventually in the Alleghenian orogeny during Permian time, which resulted in thin-skinned deformation of the eastern part of the basin and which locally involved the OM-rich shale as a glide plane. Fractures resulting from this deformation are significant to the production and the migration of hydrocarbons in the Devonian shale.

Plate tectonics:

> "During the early Paleozoic the North American Continent was probably separated from other continents by oceans, on the east by a proto-Atlantic Ocean (the Iapetus Ocean of some authors). In the area of the present New England States in the Late Devonian, probably as a result of collisions of northeastern North America with northern Europe, an uplift was produced, 'Acadia' or 'Appalachia', the northern part of the Appalachian positive element. ... This collision, marked by the Late Devonian Acadian orogeny, also resulted in the destruction of the Caledonian geosyncline that, according to recent reconstructions, was continuous from the eastern United States, through the Maritime Provinces of Canada, and through the northern British Isles to Scandinavia and eastern Greenland" (Kay, 1969, p. 971).
>
> "The Appalachian geosyncline of both the Mississippian and Pennsylvanian Periods was apparently a southward- and westward-extending segment of the Hercynian geosyncline of central Europe, in spite of the interruption of this trough by the Appalachian positive element in New England.
>
> "During the Mississippian Period the destruction of the proto-Atlantic Ocean continued probably as a result of subduction of the oceanic plate beneath encroaching continental plates. The compressional effects were progressive from north to southwest in the United States, first causing the uplift of the southward extension of the Appalachian positive element during the Mississippian and then in the Early Pennsylvanian, the development of a highland from east to west through Texas.
>
> "This compression culminated in the Middle Pennsylvanian (Des Moines time) with the Ouachita geosyncline in Arkansas, Oklahoma, and west Texas, and eventually in the Appalachian Revolution [Alleghenian orogeny] during Permian time, which marked the termination of the Appalachian geosynclinal system.
>
> "All these compressional events were probably the result of the approach, collision, and adjustment of the African and South American plates with the North American plate and resulted in the destruction of the proto-Atlantic Ocean leaving these continental plates in close proximity at the end of the Paleozoic" (Craig and Varnes, 1979, p. 385).

Paleoclimate and paleogeography:

The distribution and the type of sediment and the relative abundance of marine and nonmarine fossil flora and fauna can be related to the inferred paleolatitude, the shape of the basin and the surrounding land mass, and the paleotectonic activity. Ettensohn and Barron (1981) reviewed several global reconstructions and concluded that the axis of the Appalachian basin was subparallel to the Equator at a latitude of 5° to 10° S. They also suggested that the climate was alternately humid and arid, depending on the height of

Table 1. Basin analysis of Middle and Late Devonian and related rocks of the Appalachian basin—Continued

[m y , million years, ft, feet, mi^2, square mile, mi^3, cubic mile, OM, organic matter CAI, conodont color alteration index]

the mountains to the east, the influence of these mountains on atmospheric circulation, and the presence of a rain shadow

Thermal history:

Conodont-color alteration has been used to assess the thermal alteration of Devonian rocks in the Appalachian basin (Epstein and others, 1977) and to relate the thermal history to the production potential for oil and gas The CAI increases with depth of burial and from local sources of plutonic heat Oil production can be expected from rocks near or less than the CAI–2 isograd Requirements for natural gas production are less restrictive (fig 11, A G Harris, 1978, Harris and others, 1978)

Illite crystallinity is another measure of thermal maturity The isograd map of crystallinity in the Devonian rocks of the Appalachian basin also shows an eastward-increasing pattern (fig 12), which is similar to that of the CAI

Economic potential·

The dark OM-rich shales of the Devonian-Mississippian sequence in the Appalachian basin are excellent source rocks for hydrocarbons Two south-trending thick belts of the OM-rich facies have the greatest potential where maturity and fracture density serve to stimulate migration to the bore hole Additional induced fracturing has been shown to enhance production Siltstone and very fine grained sandstone in turbidite bundles are primary targets where thermal maturity has driven lighter fractions from the underlying OM-rich source beds (Schwietering, 1980)

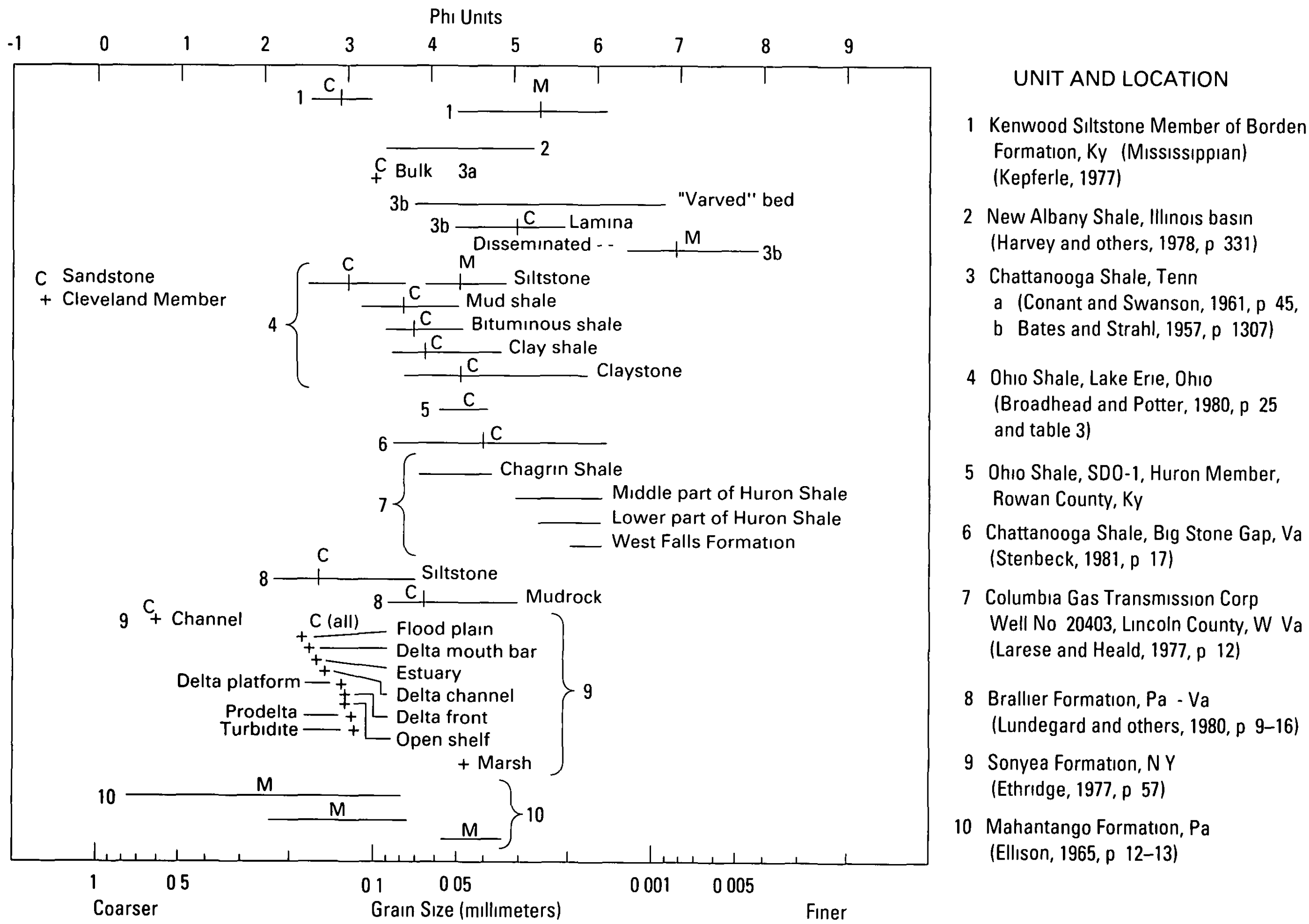

Figure 9. Grain size distribution in Devonian shale and associated rocks in the Eastern Interior United States Horizontal bar indicates grain size range, vertical bar indicates the average grain size, C indicates the coarsest grain size fraction, M indicates the median grain size fraction, plus sign indicates the average grain size for the indicated environmental interpretation

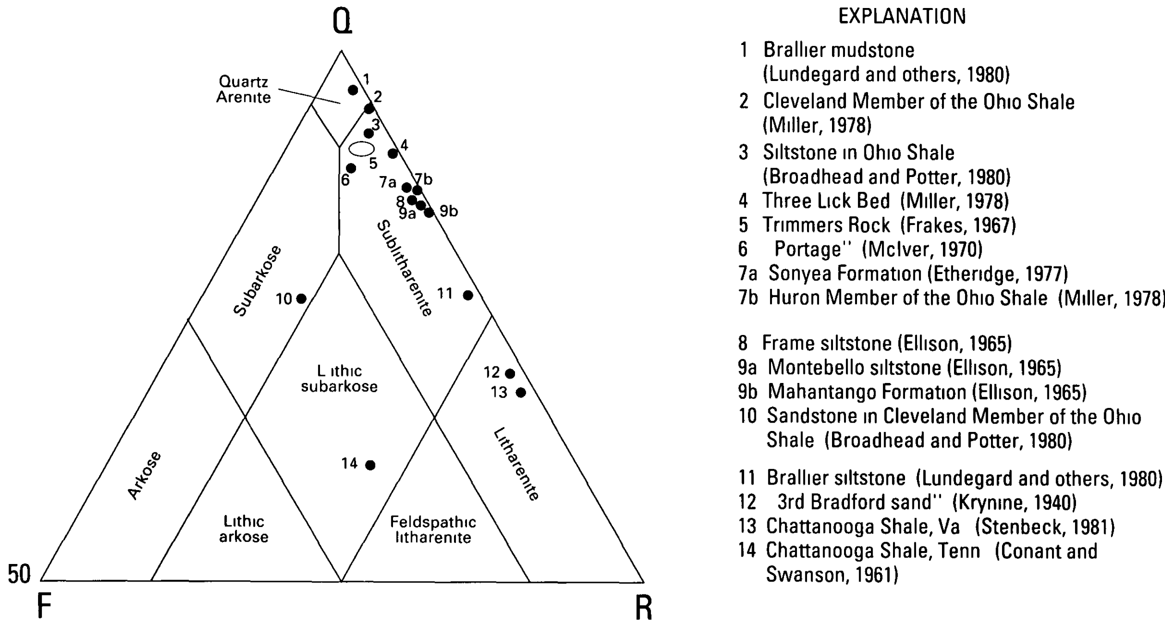

Figure 10. Modal analyses of framework grains in Devonian shale and related rocks in the Appalachian basin Q, quartz, R, rock fragments + chert + mica, F, feldspar Note that only the upper half of the triangular classification is used The classification is modified from McBride (1963)

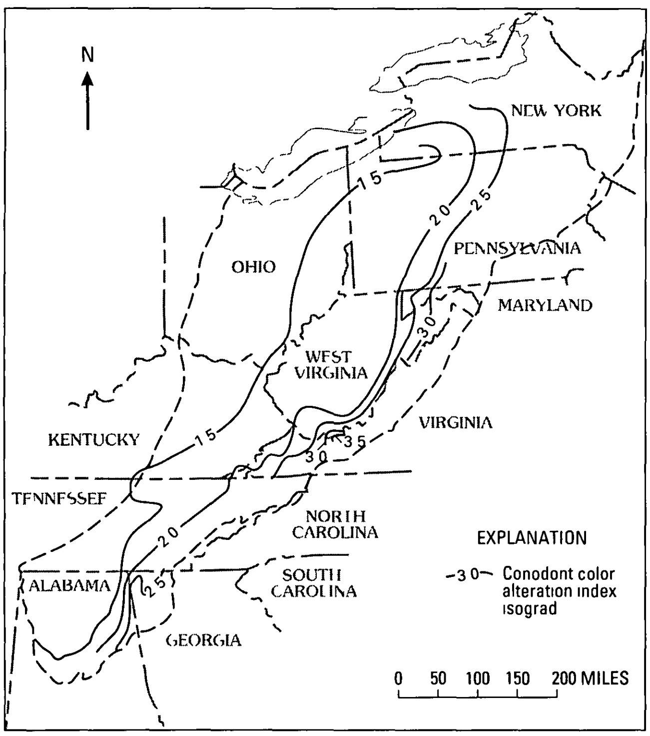

Figure 11. Conodont color alteration index isograds for the Upper Devonian through Mississippian rocks in the Appalachian basin (From Epstein and others, 1977, fig 17)

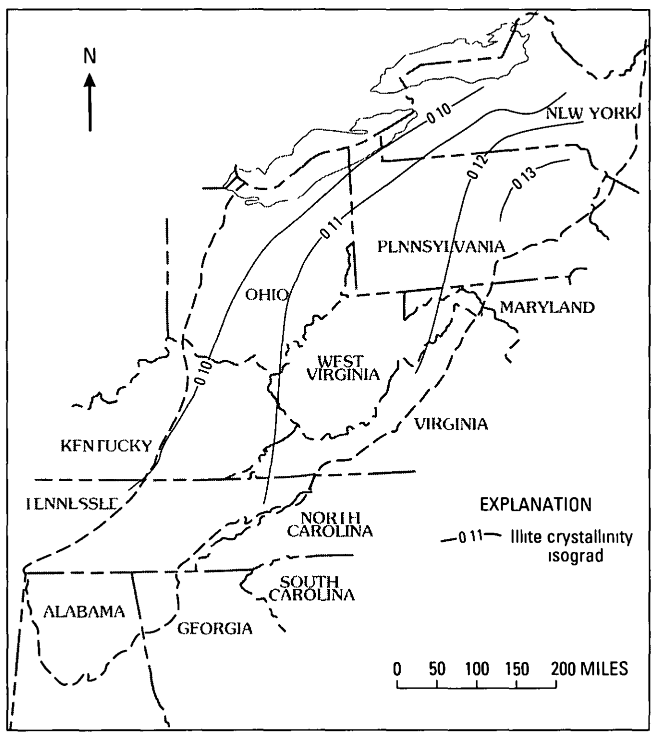

Figure 12. Illite crystallinity isograds of Devonian black shale in the Appalachian basin (From Hosterman and Whitlow, 1981b, fig 16)

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Chapter G

Illite Crystallinity as an Indicator of the Thermal Maturity of Devonian Black Shales in the Appalachian Basin

By JOHN W. HOSTERMAN

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PETROLEUM GEOLOGY OF THE DEVONIAN AND MISSISSIPPIAN BLACK SHALE OF EASTERN NORTH AMERICA

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FIGURES

TABLES

Illite Crystallinity as an Indicator of the Thermal Maturity of Devonian Black Shales in the Appalachian Basin

By John W Hosterman[1]

Abstract

The clay mineralogy of the Middle and Upper Devonian black shale units in the Appalachian basin was studied to identify criteria for predicting areas that might have gas or petroleum resources The clay minerals in the shale are chlorite, illite, and kaolinite and illite-smectite and illite-chlorite mixed-layer clays The nonclay minerals are quartz, pyrite, and calcite and minor amounts of dolomite, gypsum, marcasite, and barite Organic matter is abundant in the black shale Illite and chlorite were formed as a result of low-grade metamorphism (pregreenschist facies) from smectite through illite-smectite and illite-chlorite as intermediate steps During this study, I found that the symmetry of the 10-angstrom X-ray diffraction peak of illite varied depending upon the amount of illite-smectite mixed-layer clay associated with the illite Because the amount of illite-smectite mixed-layer clay can be correlated with the intensity of metamorphism, a good agreement exists among the illite crystallinity index and the conodont color alteration index It is possible, therefore, that the crystallinity index may be used in assessing the hydrocarbon potential of the black shale units

INTRODUCTION

The clay mineralogy of the Middle and Upper Devonian black shale units in the Appalachian basin was studied to identify criteria for predicting which areas might have gas or petroleum resources During this study, I found that the symmetry of the 10-angstom (Å) X-ray diffraction peak of illite from the black shale varied depending upon the amount of illite-smectite mixed-layer clay associated with the illite Because the amount of illite-smectite mixed-layer clay is temperature dependent and can be correlated with the intensity of metamorphism, the illite symmetry, or illite crystallinity index (ICI), may be used in assessing the hydrocarbon potential of the black shale units

In this chapter, I describe the methods that I used to measure the ICI, to identify the clay and nonclay minerals found in the black shale, to interpret the depositional history of the Devonian black shale units, and to describe the ash beds associated with the Devonian shales I also make a comparison between the ICI and the color alteration index (CAI) of conodonts (Epstein and others, 1977), which is a useful way to measure thermal maturity

METHODS

The mineral content of 2,200 samples from 84 drill holes in the Appalachian basin was analyzed The samples from drill cores were taken at 5-, 10-, 15-, or 20-foot (ft) intervals within each lithology The samples from drill cuttings were taken at 20- to 100-ft intervals depending upon the availability of material The number of samples per drill hole ranged from 3 to 77 and was controlled mainly by the length of the core or the cuttings and the sampling interval Most samples were taken from the dark-gray to black shale units, and a few were taken from the light-gray silty shale units No samples were taken from the Devonian limestone beds, except in places where the Tioga Ash Bed occurs in the top of the Onondaga Limestone Data on these drill-hole samples were discussed by Hosterman and Whitlow (1981)

About 25 grams (g) of each sample were ground in a tungsten-carbide ball mill for 15 to 20 minutes Alcohol was used to prevent overheating of the sample and possible damage to the structure of the clay minerals A 0 5-g portion of the ground material was pressed, along with 1 5 g of backing material, into a wafer 29 millimeters (mm) in diameter This wafer was used in an automatic X-ray diffractometer to determine the whole-rock mineralogy The remainder of the sample was dispersed in deionized water The less-than 2-micrometer clay fraction, which was obtained after settling for the time determined by Stoke's Law, was siphoned off and placed on a porous ceramic tile This sample on the porous tile was analyzed for the clay mineralogy

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[1] Deceased

The mineralogy was determined by an X-ray diffraction unit and copper (CuK) radiation The goniometer was run at a speed of 1° 2-theta per minute, and the count time interval was 1 second, these settings gave a digital count every 0 02° 2-theta The digital data were recorded to determine the whole-rock mineralogy by using the semiquantitative computer program described by Hosterman and Dulong (in press) The relative abundance of the clay minerals was determined by using the basal peak area method described by Schultz (1960) An electronic planimeter was used to measure the selected basal peak areas on the X-ray diffraction traces to obtain the proportions of individual clay minerals and to determine the area to peak height ratios used to calculate the symmetry (ICI) The relative amounts of clay minerals in each sample were calculated from the changes in the X-ray diffraction peak areas of the untreated clay, the clay saturated with ethylene glycol, and the clay heated to 350 °C The areas beneath the 10-Å (8 8° 2-theta), 7-Å (12 6° 2-theta), and 3 5-Å (25 4° 2-theta) peaks were measured Illite and mixed-layer clay proportions were calculated from the changes in area of the 10-Å peak The proportions of chlorite and kaolinite were calculated from a ratio obtained by measuring the areas of the double peak at about 3 5 Å and applying this ratio to the area of the 7-Å peak (Hosterman and Whitlow, 1983, p 5)

CLAY MINERALS IN DEVONIAN BLACK SHALES

The clay minerals of the Devonian-age shales in the Appalachian basin are illite, chlorite, and kaolinite and two types of mixed-layer clay (illite-smectite and illite-chlorite) (Hosterman and Whitlow, 1983) All shale samples analyzed contained considerable illite, some chlorite, and small amounts of mixed-layer clay Kaolinite is present in about 25 to 30 percent of the samples

Illite is the most abundant clay mineral in the Devonian black shale units—relative proportions range from 40 to 90 percent In this chapter, the term "illite" is applied to a clay-sized dioctahedral muscovite that has the approximate formula $(OH)_4K_2(Si_6Al_2)(MgFe)_6O_{20}$

Mixed-layer clay minerals result from the random interlayering of two or more clay minerals Two types of mixed-layer clay minerals are found in the Devonian black shale units The first type is the random interlayering of illite and the expandable clay mineral smectite and is called illite-smectite mixed-layer clay The second type is the random interlayering of illite and either a degraded chlorite or a vermiculite and is called illite-chlorite mixed-layer clay

Chlorite $(OH)_8(SiAl)_4(MgFe_3)(MgAl)_3O_{10}$ is present in almost all the Devonian shale samples that were analyzed On the basis of the relative intensities of the basal peaks in the X-ray diffraction traces, chlorite in the Devonian shales seems to range from varieties high in magnesium to those high in iron The relative chlorite concentration in Devonian shales ranges from about 0 to 30 percent, and the average is between 10 and 15 percent

Kaolinite $(OH)_8Si_4Al_4O_{10}$ is the least abundant clay mineral in the Devonian shale samples that were analyzed Kaolinite occurs in about 25 to 30 percent of the shale samples and reaches a maximum relative proportion of 20 percent in the clay fraction The presence of kaolinite in small amounts is extremely difficult to determine when chlorite is present A slight difference in the c-axis dimension of the two minerals is expressed as a doublet at 3 5 Å (25 4° 2-theta) for the second-order basal (002) peak of kaolinite and at 3 57 Å (24 9° 2-theta) for the fourth-order basal (004) peak of chlorite (Hosterman and Whitlow, 1983, p 3) This doublet was used to recognize the presence of kaolinite because neither heating nor acid treatment can remove one mineral without affecting the other

NONCLAY MINERALS IN DEVONIAN BLACK SHALES

Minerals other than clay minerals identified in the Devonian shale units include allogenic minerals that were either introduced during deposition of the clay or formed at the time of or shortly after deposition and that were from fossil material The allogenic minerals are quartz, K-feldspar, plagioclase, and biotite The authigenic minerals are calcite, dolomite, siderite, gypsum, pyrite, marcasite, and barite and reported traces of galena and chalcopyrite (Hosterman and Whitlow, 1983, p 5) Minerals derived from fossils are calcite, dolomite, and, chiefly, apatite Quartz is present in all analyzed shale samples, and pyrite is present in most of the samples, especially those high in organic carbon Calcite is most abundant in the Middle Devonian units, which are found predominantly in Pennsylvania and New York All the other allogenic and authigenic nonclay minerals throughout the Appalachian basin occur in amounts of less than 1 percent and are not listed in table 1

STRATIGRAPHY OF DEVONIAN UNITS

The mineralogy was determined for 2,200 (1,895 black shale and 305 limestone, siltstone, and ash bed) samples from 84 drill holes throughout the Appalachian basin of New York, Pennsylvania, Ohio, West Virginia, Virginia, Kentucky, Tennessee, and Alabama The following Upper and Middle Devonian shale units, which are grouped in stratigraphic order according to their correlation (fig 1), are represented by the analyzed samples

Table 1. Average color and mineralogy of 11 Middle and Upper Devonian shale units in the Appalachian basin

[—, not present, tr, present in trace amounts]

Unit	Number of drill holes	Number of samples	Total footage sampled	Average Munsell color	Average lithology	Average mineral content (in percent)				Clay mineral content (in percent)				
												Mixed-layer clay		
						Quartz silt	Clay	Pyrite	Calcite	Chlorite	Illite	Illite-smectite	Illite-chlorite	Kaolinite
Cleveland Member of the Ohio Shale and equivalent units	20	73	574	10 YR 4 1/ 2	Silty shale	30	65	5	—	10	60	30	tr	tr
Chagrin Shale and equivalent units	10	131	2,984	N 6 1	Shale	25	75	tr		15	55	25	tr	5
Huron Member of the Ohio Shale														
Upper unit	12	66	764	10 YR 5 2/ 5	-----do-----	25	70	5	—	10	55	30	tr	5
Middle unit	18	178	4,602	N 5 5	-----do-----	25	75	tr	—	10	60	25	tr	5
Lower unit and equivalent units	38	358	5,254	10 YR 4 9/ 5	-----do-----	25	70	5	—	15	60	20	tr	5
Java Formation and equivalent units	26	77	1,264	N 6 0	-----do-----	25	70	5	tr	20	55	25	tr	tr
Rhinestreet Shale Member of the West Falls Formation and equivalent units	37	189	6,292	10 YR 5 3/ 5	-----do-----	25	75	tr	tr	20	60	20	tr	tr
Middlesex Shale Member of the Sonyea Formation	17	26	1,180	10 YR 4 4/ 5	-----do-----	25	65	5	5	25	55	20	tr	—
Genesee Formation and equivalent units	29	64	2,290	10 YR 4 5/ 5	Slightly limy shale	20	60	5	15	25	60	15	tr	—
Mahantango Formation of the Hamilton Group and equivalent units	50	444	14,527	N 5 2	Limy shale	20	60	tr	20	25	60	15	tr	—
Marcellus Shale of the Hamilton Group and equivalent units	48	189	4,952	N 3 4	-----do-----	20	50	5	25	15	70	15	tr	—

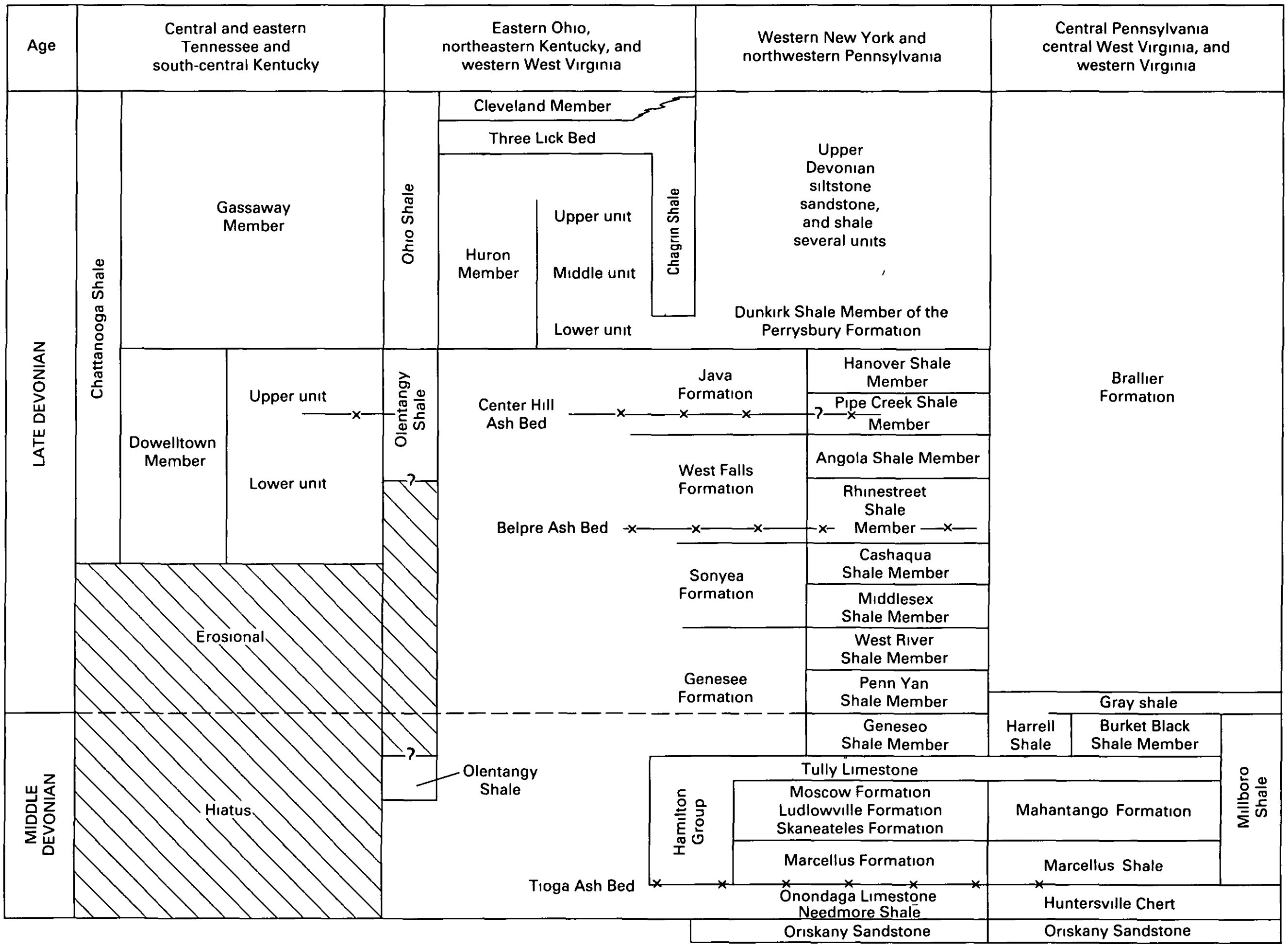

Figure 1. Generalized correlation of Middle and Upper Devonian shale units studied for clay mineralogy (Modified from Oliver and others, 1969)

Cleveland Member of the Ohio Shale
Cleveland Bed of the Gassaway Member of the Chattanooga Shale
Chagrin Shale
Three Lick Bed of the Ohio Shale

Upper unit of the Huron Member of the Ohio Shale

Middle unit of the Huron Member of the Ohio Shale

Lower unit of the Huron Member of the Ohio Shale
Dunkirk Shale Member of the Perrysburg Formation
Huron Bed of the Gassaway Member of the Chattanooga Shale

Hanover Shale Member of the Java Formation
Pipe Creek Shale Member of the Java Formation
Upper unit of the Dowelltown Member of the Chattanooga Shale

Rhinestreet Shale Member of the West Falls Formation
Lower unit of the Dowelltown Member of the Chattanooga Shale

Middlesex Shale Member of the Sonyea Formation

Penn Yan Shale Member of the Genesee Formation
Geneseo Shale Member of the Genesee Formation
Burket Black Shale Member of the Harrell Shale

Mahantango Formation of the Hamilton Group
Millboro Shale (excluding the "Marcellus Member")

Marcellus Shale of the Hamilton Group
"Marcellus Member" of the Millboro Shale

The regional subsurface correlations listed above are based, in part, on gamma-ray log interpretations by Roen (1980, 1984) These units contain the beds of black shale that have been proven to be the best known sources of natural gas in the Appalachian basin (Bagnall and Ryan, 1976, Patchen, 1977) Table 1 gives the average mineral content, the clay mineralogy, the average color, the dominant lithology, and the number of samples analyzed for each of the shale unit groups listed above

Depositional History of Black Shales

It is impossible to determine accurately the original suite of allogenic minerals because all the shale units have been subjected to diagenesis and to some low-grade metamorphism Probably the only unaltered original major detrital minerals are quartz and kaolinite Quartz, which occurs in the silt- and clay-sized fraction, is ubiquitous and does not reveal a depositional pattern by size distribution or quantity variations The occurrence of kaolinite in minor amounts, however, does indicate a depositional pattern for 7 of the 11 shale unit groups Kaolinite is usually coarser grained than the other clay minerals, consequently, when transported by water, it does not remain in suspension for long and is deposited close to the source area Kaolinite does not occur in samples from the four older shale units, such as the Marcellus Shale of the Hamilton Group and equivalent units, the Mahantango Formation of the Hamilton and equivalent units, the Genesee Formation and equivalent units, and the Middlesex Shale Member of the Sonyea Formation The Rhinestreet Shale Member of the West Falls Formation and equivalent units contain two small areas of kaolinite—one in northern Pennsylvania and adjacent New York and the other in West Virginia Kaolinite is much more widespread in the younger units, such as the Java Formation and equivalent units, all three units of the Huron Member of the Ohio Shale, and the Chagrin Shale and equivalent units The kaolinite occurrence in the Cleveland Member of the Ohio Shale and equivalent units is restricted to a small area in eastern Kentucky and eastern Tennessee (Hosterman and Whitlow, 1983)

The areal distribution of kaolinite in the eastern and the northeastern parts of the seven youngest shale units (table 1) indicates that the source area for kaolinite and the other detrital material was probably to the east and the northeast Because the four oldest units (table 1) contain no kaolinite, the location of the source area for these units is not known It also may have been east or northeast of the basin of deposition for the older units The distance between the source area and the basin of deposition during Devonian time is also unknown However, the restriction of kaolinite to the younger units may indicate that the basin of deposition had its largest areal extent in the Middle Devonian during Marcellus time and a smaller areal extent during Java, early Huron, and Dunkirk time Therefore, the distance to the source area was probably greatest during the deposition of the Marcellus Shale and least during the deposition of the Java Formation, the lower unit of the Huron, and the Dunkirk The decreasing size of the basin of accumulation and the decreasing distance between the center of the basin and the source area increased the depositional energy that contributed kaolinite to the younger black shale units

Mineralogy of Ash Beds

Three ash beds are recognized in the Middle and Upper Devonian rocks (fig 1) of the Appalachian basin In descending order, they are the Center Hill, the Belpre, and the Tioga These metamorphosed bentonite beds have been referred to as "bentonite," "metabentonite," and "K-bentonite" by many authors Roen and Hosterman (1982) suggested that these terms not be used because the physical, chemical, and mineralogical properties of these beds do not conform to the accepted definition of bentonite (Grim and Guven, 1978)

The Center Hill Ash Bed occurs predominantly in the western part of the Appalachian basin from northwestern Pennsylvania to Tennessee, but it crops out only in Tennessee The bed is in the Pipe Creek Shale Member of the Java Formation and in the upper unit of the Dowelltown Member of the Chattanooga Shale

The Belpre Ash Bed is in the basal part of the Rhinestreet Shale Member of the West Falls Formation Its areal distribution, which is similar to that of the Center Hill Ash Bed, is in the western part of the Appalachian basin from northwestern Pennsylvania to Tennessee

The Tioga Ash Bed probably is distributed more widely than the other ash beds It occurs in the eastern and central parts of the Appalachian basin from northern New York to southern West Virginia and from eastern Pennsylvania to central Ohio It may be correlative with ash beds in the Illinois and Michigan basins Droste and Vitaliano (1973), Droste and Shaver (1975), and Dennison and Textoris (1977) believed that the Tioga Ash Bed can be recognized in the Illinois basin Baltrusaitis (1974, 1975) stated that his Kawkawlin Bentonite in the Michigan basin can be correlated with the Tioga Ash Bed The Tioga Ash Bed is near the contact between the Onondaga Limestone and the Marcellus Shale of the Hamilton Group Although it occurs in a few places in the Marcellus Shale, it is generally found in the Onondaga Limestone or the equivalent Needmore Shale

Because they are usually very thin and are easily altered by weathering, the ash beds are very difficult to recognize, even though their lithology is different from that of the enclosing rocks The beds range in thickness from 1 to 75 mm but average from about 15 to 20 mm In fresh, unweathered drill-core samples, the ash beds are identified easily by conspicuous dark-brown biotite flakes In weathered outcrops, the biotite flakes in the ash beds are recognized by their light-bronze color, but the scattered biotite flakes are very difficult to see In the ash beds, biotite occurs in flakes from 1 to 2 mm in diameter and ranges in abundance from a trace amount to as much as 45 percent Flakes of biotite also are found scattered in the adjacent enclosing black shale, particularly in the northern part of the basin It is doubtful that the biotite flakes are authigenic because the grade of metamorphism is not high enough It is also doubtful that the biotite flakes were derived from a metamorphic terrane because biotite cannot withstand the weathering and the erosion without some alteration Therefore, the biotite flakes are probable allogenic and were derived from volcanic ash Because of the ash beds and the possibility that the scattered biotite flakes obviously not associated with the ash beds are volcanic, I suggest that the Devonian black shales contain considerably more volcanic material than is presently known

The mineralogy of the ash beds, although somewhat different from that of the enclosing rocks, shows mixing with the components of the enclosing rocks The Center Hill and the Belpre Ash Beds contain disordered (Md) illite, kaolinite, and illite-smectite mixed-layer clay and a small amount of quartz Because the enclosing shales of the Center Hill and the Belpre do not contain kaolinite, it is probably an alteration product of the original volcanic ash The composition of the Tioga Ash Bed varies depending upon the lithology of the enclosing rocks In a shale sequence, the Tioga is composed of (Md) illite, illite-smectite mixed-layer clay, smectite, and kaolinite and a trace of quartz In limestone, the Tioga is composed of (Md) illite and illite-smectite mixed-layer clay and contains no smectite or kaolinite (Roen and Hosterman, 1982, table 1, Hosterman and Whitlow, 1983, table 2)

Variation in the mineralogy of the ash beds has been explained partly by Hoffman and Hower (1979) in their study of clay-mineral assemblages in low-grade metamorphic rocks The reaction that converts a bentonite bed to a metamorphosed bentonite bed is different from the reaction that occurs in a shale where the necessary components of K^+ and Al^{+3} are readily available directly from the shale The following reactions are possible

$$\text{Smectite} + \text{No } K^+ = \text{Kaolinite} + \text{Quartz}$$
$$\text{Smectite} + \text{Some } K^+ = \text{Illite-smectite} + \text{Kaolinite} + \text{Quartz}$$
$$\text{Smectite} + \text{Much } K^+ = \text{Illite-smectite} + \text{Quartz}$$

The second reaction applies to the ash beds in the shale The third reaction might apply to the Tioga Ash Bed that occurs in limestone except that this reaction does not account for the lack of quartz

DIAGENESIS AND METAMORPHISM

Pelitic sediments that became Devonian shales consisted of the clay minerals illite, smectite, chlorite, and kaolinite, as well as quartz, varying amounts of feldspars, and organic matter The nonminerals in this assemblage are relatively stable through diagenesis and low-grade metamorphism At low temperatures, only the most reactive mineral phases begin to transform toward reequilibration Eberl and Hower (1976) showed that smectite is one of the most reactive minerals in pelitic rocks Hower and others (1976) demonstrated that at temperatures of about 50 to 95 °C, smectite begins a transition to illite-smectite mixed-layer clay The mineralogic criteria for identifying increasing grades of metamorphism of shales are the conversion of smectite to illite through an intermediate step of illite-smectite mixed-layer clay, the presence of chlorite, and the absence of K-feldspar K-feldspar is absent because the conversion of disordered (Md) illite to ordered (2M) illite needs additional potassium derived from the K-feldspar

The clay minerals—(2M) illite, chlorite, and mixed-layer clay—in the black shale are the result of low-temperature metamorphism These minerals are the precursors to greenschist minerals in prograde metamorphism, therefore, the term "pregreenschist facies" is applicable as used by Hower (Hoffman and Hower, 1979) The (2M) illite was derived from (Md) illite and smectite, and the chlorite was derived from smectite The illite-smectite mixed-layer clay is an intermediate step from smectite to (2M) illite, and the illite-chlorite mixed-layer clay is probably an intermediate step in the formation of chlorite Authigenic quartz results when the minerals mentioned above are reformed in a reaction stated by Hower and others (1976) as

$$\text{Smectite} + K+ + Al+3 = \text{Illite} + \text{Chlorite} + \text{Quartz}$$

Potassium and aluminum are available from K-feldspar, mica, or free ions

Distinctive distribution patterns are recognized for the clay minerals that formed as a result of low-temperature metamorphism of the analyzed Devonian black shales The chlorite content increases generally from about 10 percent in the younger units to about 25 percent in the older units (table 1) Conversely, the illite-smectite mixed-layer clay mineral content generally decreases from about 30 percent in the youngest units to about 15 percent in the oldest units The amount of illite remains more or less constant in all the black shale units

The symmetry of the 10-Å (001) X-ray diffraction peak for illite at 8 8° 2-theta varies depending upon the number of illite-smectite mixed-clay layers associated with the illite This symmetry can be calculated from the area of the peak and its height by the formula

$$ICI = A / h$$

where A is the area and h is the height of the 10-Å (001) illite peak on the X-ray diffraction trace The symmetry of the peak is an approximate measure of the number of illite-smectite layers associated with the illite A sample that has a high percentage of illite-smectite mixed-layer clay will produce an asymmetrical peak (ICI =<0 10), whereas a sample containing a low percentage of illite-smectite will produce a symmetrical peak (ICI =>0 14) close to that of pure (2M) illite Because the illite crystallinity index varies from sample to sample, the highest index found in a stratigraphic interval from the same drill hole was used for that location (fig 2)

The ICI is lower in shale that contains calcite than it is in shale lacking calcite, if both shales were subjected to the same metamorphic intensity This pattern is similar to the color-value variation of organic carbon in black shales with and without calcite (Hosterman and Whitlow, 1981) In an area of south-central Virginia, a black shale sample without calcite had an ICI of 0 14 and a CAI of 4 0; a few feet away in the same stratigraphic interval, a black shale sample containing calcite had an ICI of 0 11 and a CAI of 3 5 (A.P Schultz, U S Geological Survey, oral commun , 1987) Calcite seems to be an important factor in controlling the color and the illite crystallinity of black shales that have the same diagenetic and metamorphic history For the Devonian black shales in the Appalachian basin, the ICI ranged from about 0 10 to 0 14 (fig 2)

As mentioned above, the illite-smectite mixed-layer clay indicates an intermediate step in low-grade metamorphism The ICI reflects the amount of illite-smectite layers associated with the illite and provides an approximate measure of the grade or intensity (temperature) of metamorphism Although the variation in the ICI is generally moderate, it increases with depth in almost every drill core sampled and regionally toward the east and the southeast (fig 2) This regional increase in the ICI corresponds very closely to the regional increase in metamorphic grade, the regional thickening of the Devonian sequence, and the isograd pattern of the CAI of Epstein and others (1977) An ICI of 0 10 closely matches a CAI of 1 5 to 2, which has a temperature range of 50 to 140 °C, an ICI of 0 12 closely matches a CAI of 2 5, and an ICI of 0 14 is probably closely equivalent to a CAI of 4, which has a temperature range of 190 to 300 °C

Damberger (1974) compiled data showing the rank of surface coals and the coalification pattern for Pennsylvanian age coals of the Appalachian basin The fixed carbon of the coal increases from 60 percent carbon in eastern Ohio to 96 percent carbon in eastern Pennsylvania The ICI isograds are parallel to the northeast-trending isoranks (lines of equal rank) Claypool and others (1978) published data on four

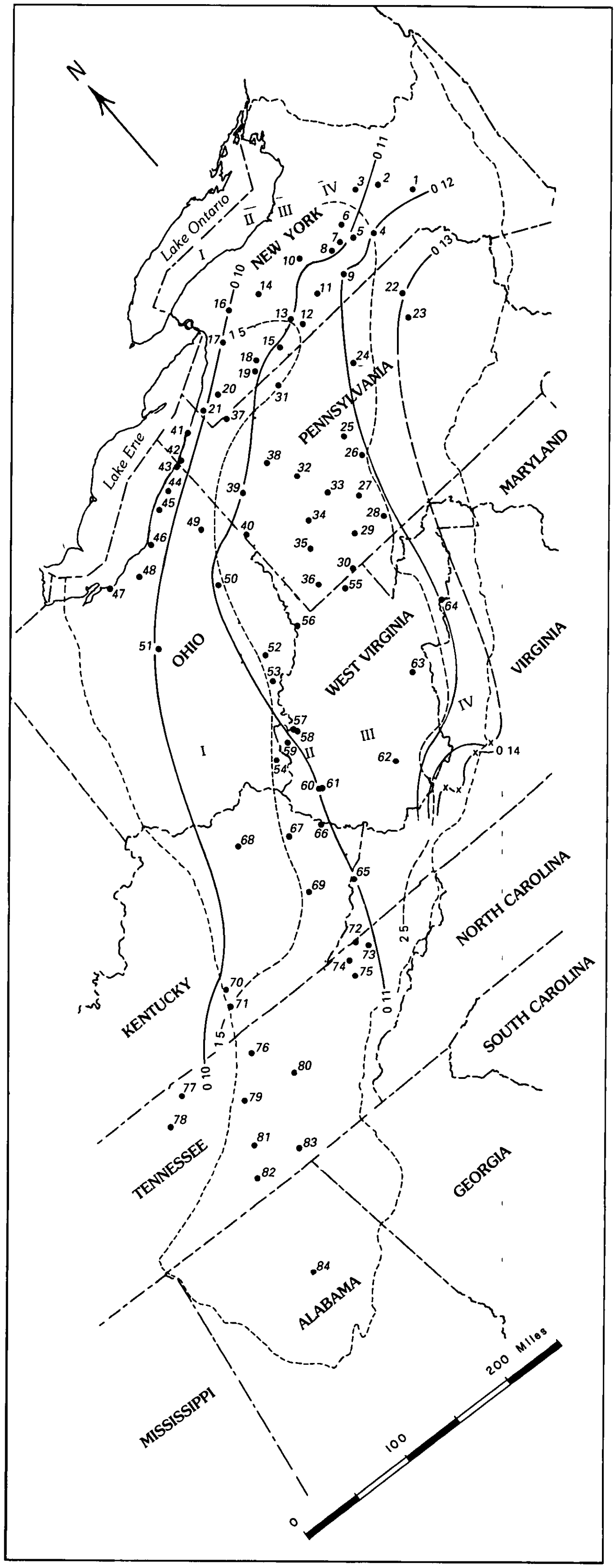

Figure 2. Illite crystallinity index (ICI) isograds (solid lines), conodont color alteration index (CAI) isograds (dashed lines), and boundaries (dotted lines) of thermal regions (roman numerals) (see table 2) of 11 Middle and Upper Devonian shale units in the Appalachian basin Solid circles indicate samples from drill holes, and crosses indicate surface samples See Hosterman and Whitlow (1981) for drill-hole-sample data

Table 2. Correlation chart comparing illite crystallinity with conodont color alteration

ICI	Thermal		
	CAI[1]	Regions[2]	Coalification[3]
0 10	1 5–2 0	I	High volatile bituminous
11	2 0–2 5	II–III	Medium volatile bituminous
12	2 5–3 0	IV	Do
13	3 0–3 5	IV	Low volatile bituminous
14	4 0	IV	Semianthracite

[1] From Epstein and others (1977)
[2] From Claypool and others (1978) See figure 2
[3] From Heroux and others (1979)

regions of different degrees of thermal conversion of organic matter to gas Region I, which has a 5-percent degree of conversion, occurs in central and eastern Ohio (fig 2), whereas Region IV, which has an 80-percent degree of conversion, occurs to the east and the southeast in central Pennsylvania, eastern West Virginia, and southwestern Virginia The northeasterly trends of these regions parallel the ICI isograds, illite in Region I has an ICI of 0 10 or less, and illite in Region IV has an ICI of greater than 0 12

CONCLUSIONS

The ICI, which is based on the 10-Å X-ray diffraction peak of the illite plus illite-smectite mixed-layer clay, appears to be a tool for measuring the thermal maturity of Devonian black shales Along with the CAI of Epstein and others (1977), the ICI also reflects other regional trends that are the result of regional low-grade (pregreenschist) metamorphism (table 2)

The ICI may be used to predict the thermal maturity or metamorphic grade from the X-ray diffraction traces that are used to determine the mineralogy In evaluating the thermal maturity of source beds for a regional analysis of hydrocarbon potential of selected strata, the ICI may be used most effectively in conjunction with the conodont CAI The ICI seems to be more accurate for shale samples that do not contain calcite, and the conodont CAI seems to be more accurate for limestone samples because conodonts are easier to extract from limestone than from shale

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Chapter H

Petrography and Reservoir Geology of Upper Devonian Shales, Northern Ohio

By RONALD F. BROADHEAD

U.S. GEOLOGICAL SURVEY BULLETIN 1909
PETROLEUM GEOLOGY OF THE DEVONIAN AND MISSISSIPPIAN BLACK SHALE OF EASTERN NORTH AMERICA

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Petrography and Reservoir Geology of Upper Devonian Shales, Northern Ohio

By Ronald F. Broadhead

Abstract

The Upper Devonian of northern Ohio consists predominantly of shales that have produced marginal quantities of gas for more than 100 years This shale sequence was deposited in the northwestern part of the Appalachian basin It thins depositionally westward from 2,000 feet in northeastern Ohio to less than 500 feet in north-central Ohio

Stratigraphy reflects an east-to-west facies change In the east, the Chagrin Shale consists of organic-poor gray shales and minor siltstones, it overlies the lower part of the Huron Member of the Ohio Shale, which consists predominantly of organic-rich black shales Chagrin shales have abundant laminations of quartz silt and were deposited by distal turbidity currents that traveled west down the turbidite slope of the Catskill delta Chagrin siltstones are thinly bedded distal turbidites Shales of the lower Huron Member were deposited in distal deeper parts of the Appalachian basin

In the west, the Cleveland Member of the Ohio Shale overlies the Three Lick Bed of the Ohio Shale, which overlies the Huron Member of the Ohio Shale These three units consist of laminated organic-rich black shales and laminated to unlaminated organic-poor gray shales Shales in the Three Lick Bed are siltier and contain thicker silt laminations than shales in the Huron and the Cleveland Members The Three Lick Bed contains minor thin siltstone beds. The laminated organic-poor shales and the siltstones are turbidite deposits in the distal deeper parts of the Appalachian basin

Gas shows and production are concentrated in the Chagrin Shale and the Three Lick Bed The abundant thick silt laminations and siltstones in those stratigraphic units probably act as permeable conduits and reservoirs Gas shows are least abundant in units that have the highest concentrations of organic carbon—the Huron and the Cleveland Members of the Ohio Shale

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INTRODUCTION

The Upper Devonian shales of northern Ohio have produced marginal quantities of gas for more than 100 years (fig 1) The gas in these shales is associated with silt-rich lithologies (Broadhead and others, 1982) The petrography of Upper Devonian shales in northern Ohio was studied to determine their composition and the distribution of shale types present in the various stratigraphic units Petrographic analyses were related to depositional environments and gas production

Acknowledgments

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STRATIGRAPHY

The Upper Devonian shale sequence in northern Ohio has been divided into three formations (fig 2, Broadhead and others, 1980, 1982)—the Ohio, the Chagrin, and the Olentangy Shales The upper part of the Olentangy Shale is Late Devonian in age, and the lower part is Medial Devonian in age The Ohio Shale has been divided into three members, in ascending order—the Huron Member, the Three Lick Bed, and the Cleveland Member The Huron Member, in turn, has been divided informally into lower, middle, and upper parts

Lithostratigraphic units within the Upper Devonian shale sequence are defined by recognizable differences in the content of three basic rock types—brownish- to olive-black shale, gray or greenish-gray shale, and siltstone In

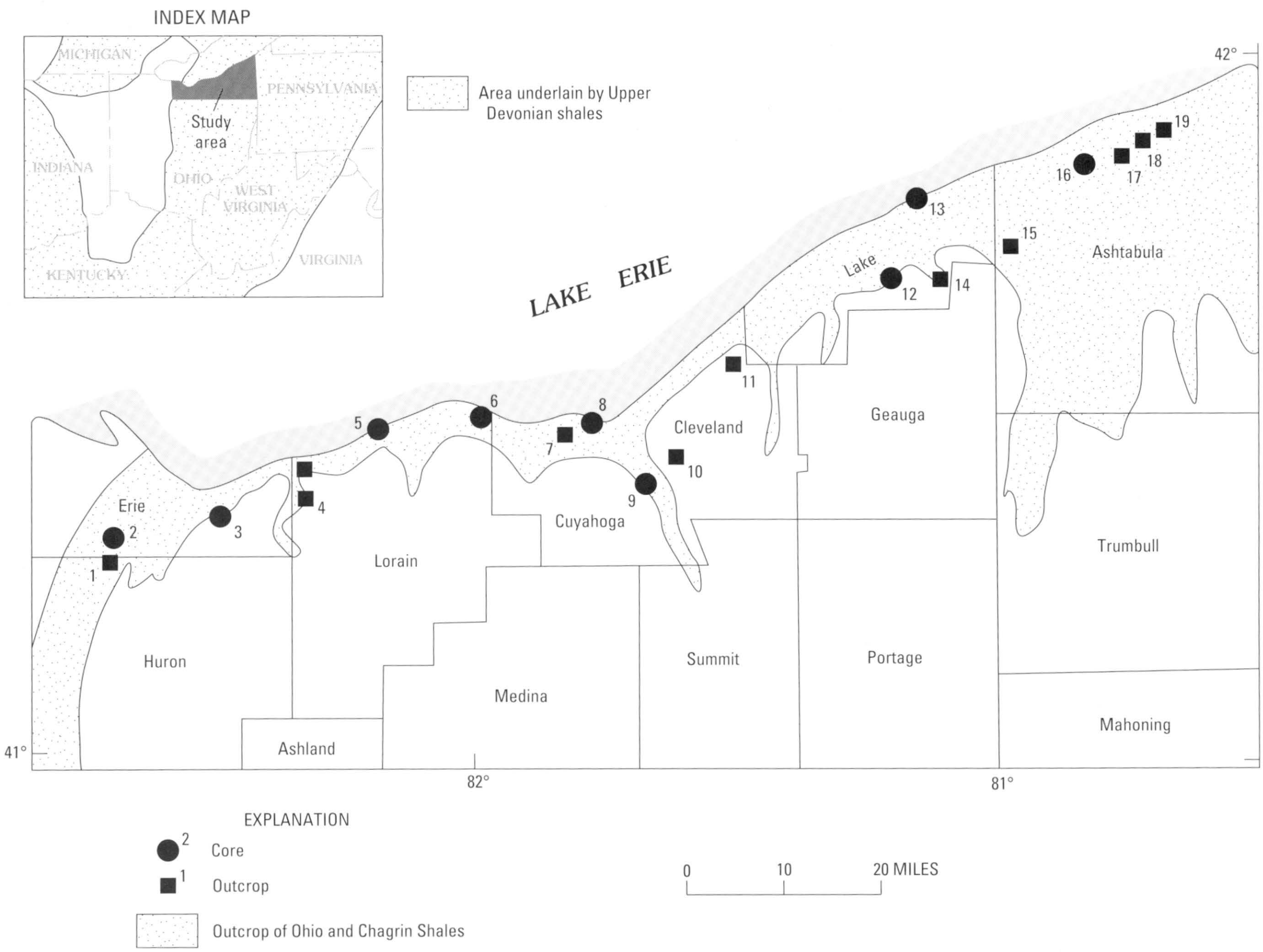


Figure 1. Location of the study area in northern Ohio. (From Broadhead and others (1982); see Broadhead and others (1980) for identification and descriptions of numbered outcrop and core holes.)

northern Ohio, the Upper Devonian shale sequence thins depositionally westward from a maximum of 2,000 feet (ft) at the Pennsylvania-Ohio border (fig. 3) to less than 500 ft near Sandusky, Ohio. West of Sandusky, the Upper Devonian shales have been truncated by Holocene and preglacial erosion on the Findlay arch. Westward thinning is accompanied by a facies change from gray shale and siltstone in the east to black shale in the west. In the east, the Chagrin Shale includes 65 to 90 percent gray shale, 5 to 30 percent siltstone, and only 5 to 10 percent black shale. In the west, the Ohio Shale includes 40 to 95 percent black shale, 5 to 60 percent gray shale, and 0 to 20 percent siltstone. The Ohio Shale consists of three units that have relatively large percentages of black shale (the lower and the upper parts of the Huron and the Cleveland Members) intercalated with two units that have relatively small percentages of black shale (the middle part of the Huron Member and the Three Lick Bed).

PETROFACIES

The Upper Devonian shales of northern Ohio consist of a wide variety of petrographic types, or petrofacies, most of which are shales. Definitions of shale petrofacies based on a modified classification of Potter and others (1980) are shown in figure 4. A few minor nonshale petrofacies are also present (table 1). Petrofacies of the Upper Devonian shales of northern Ohio were described in the style of Folk (1960) to establish the petrographic variability within and among stratigraphic units (Broadhead and Potter, 1980).

Shale Petrofacies

The following major shale petrofacies dominate the Upper Devonian shales of northern Ohio: claystone, clayshale, mudshale, siltstone, and bituminous shale (fig. 5).

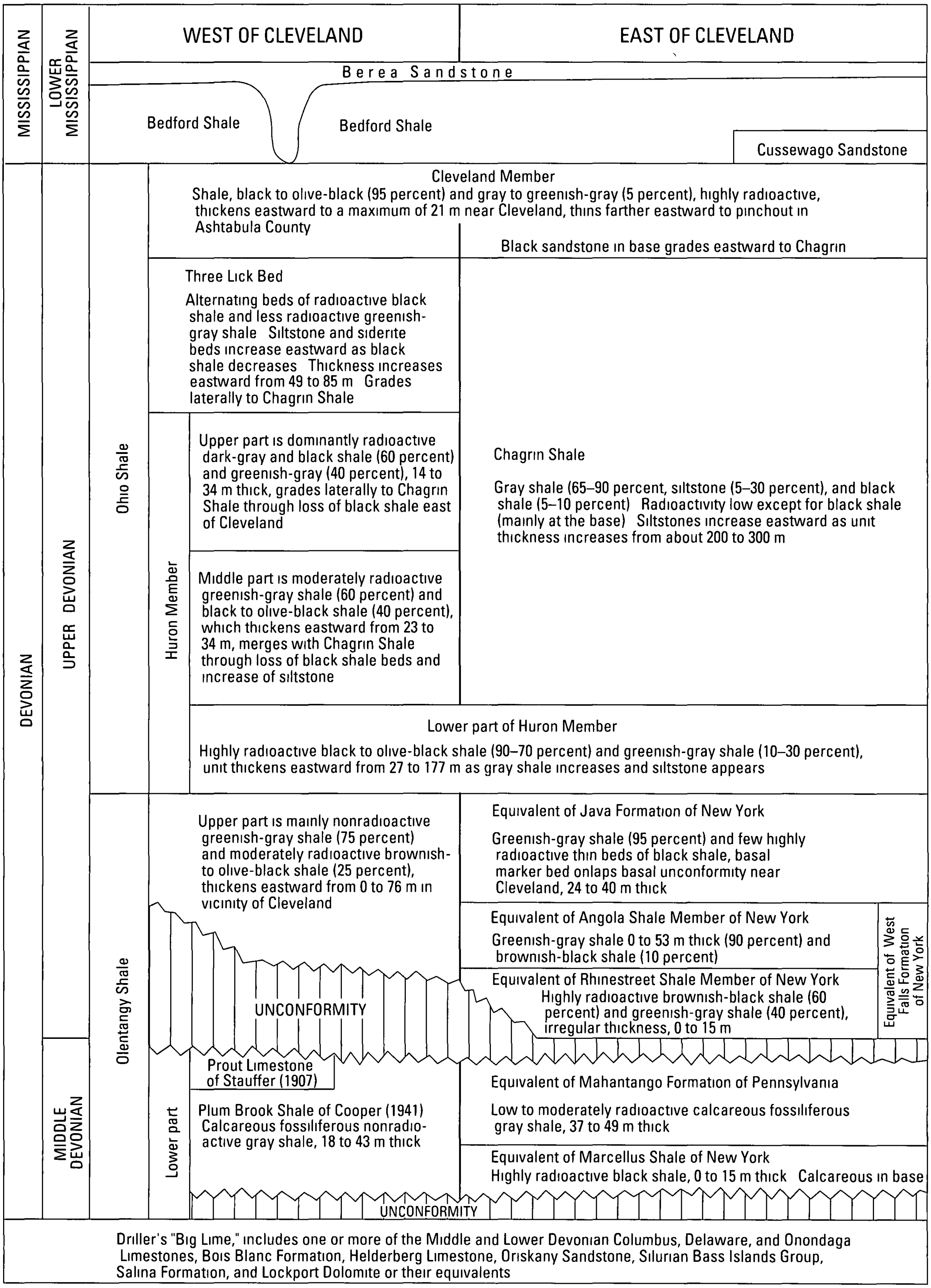


Figure 2. Stratigraphy and lithology of the Upper Devonian shale in northern Ohio (From Broadhead and others, 1982)

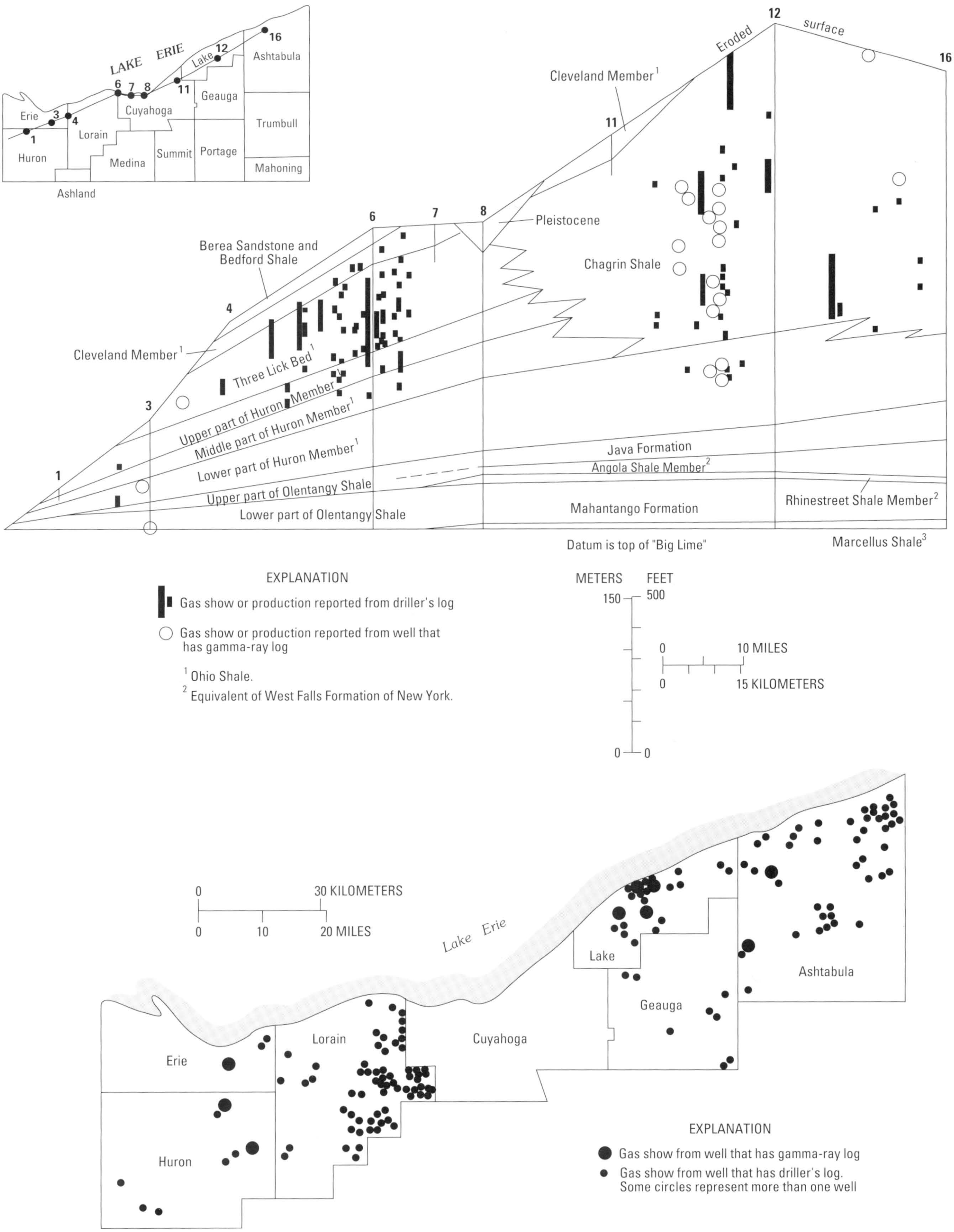


Figure 3. Locations of the holes from which gas shows, production, or both have been reported from the Upper Devonian shale sequence in northern Ohio. The data are from Ohio Geological Survey files. No records of early drilling are available for Cuyahoga County. (From Broadhead and others, 1982.)

PERCENTAGE OF CLAY PLUS MICA

	100–65	65–32	32–0
Unlaminated	Claystone	Mudstone	Unlaminated siltstone
Laminated	Clayshale	Mudshale	Laminated siltstone
Greater than or equal to 15 percent organic material	Bituminous shale		
Greater than or equal to 25 percent carbonate	Marlstone		Unlaminated siltstone
			Unlaminated siltstone
Greater than or equal to 15 percent pyrite	Pyritic shale		

Figure 4. Definition of the shale petrofacies. (From Broadhead and Potter, 1980.)

Marlstones and pyritic shales are present in relatively minor amounts. Mudstones, which are unlaminated shales that include subequal amounts of clay and silt, were not found in the Upper Devonian of northern Ohio.

Petrographic study revealed that 13 components comprise the shale petrofacies (table 2). Quartz, clay, and organic material are the major components (table 3). Only quartz, clay, mica, organic material, pyrite, and carbonate are present in significant amounts. Detrital shale components are quartz, feldspar, clay, mica, organic material, *Tasmanites*, heavy minerals, bone fragments, and conodonts. Because the clays and the micas may have undergone authigenesis, they may have mineralogies that are different from their depositional mineralogies. The organic materials are algal and woody plant remains and have been chemically altered since deposition. The other shale components (pyrite, calcite, dolomite, siderite, chert) are authigenic.

Composition of a shale is an important variable when considering the depositional environment. Bituminous shales are generally dark gray to black, and mudshales, mudstones, clayshales, and claystones are generally lighter

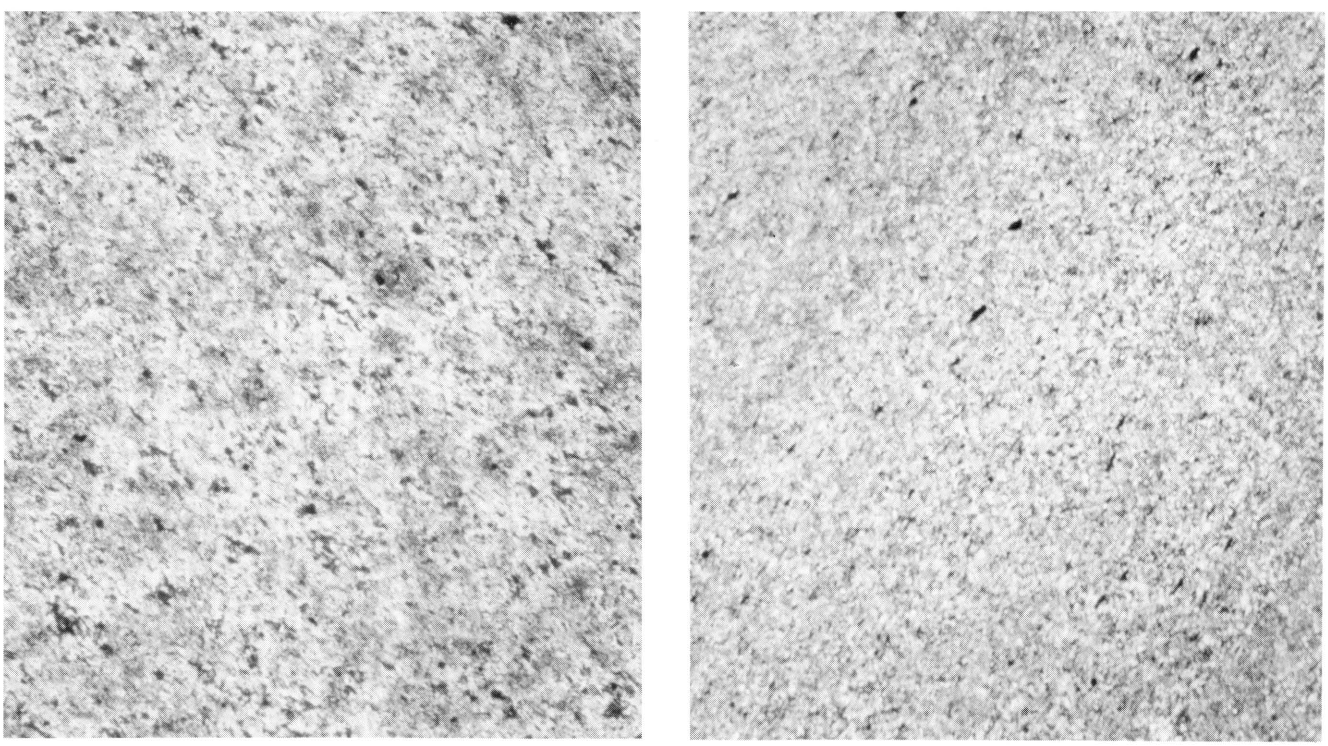
Table 1. Brief descriptions of minor nonshale petrofacies in the Upper Devonian shales of northern Ohio

Sandstone:

Very fine grained, very poorly sorted, angular, texturally immature feldspathic graywackes. Present in Cleveland Member of Ohio Shale in eastern Cuyahoga County.

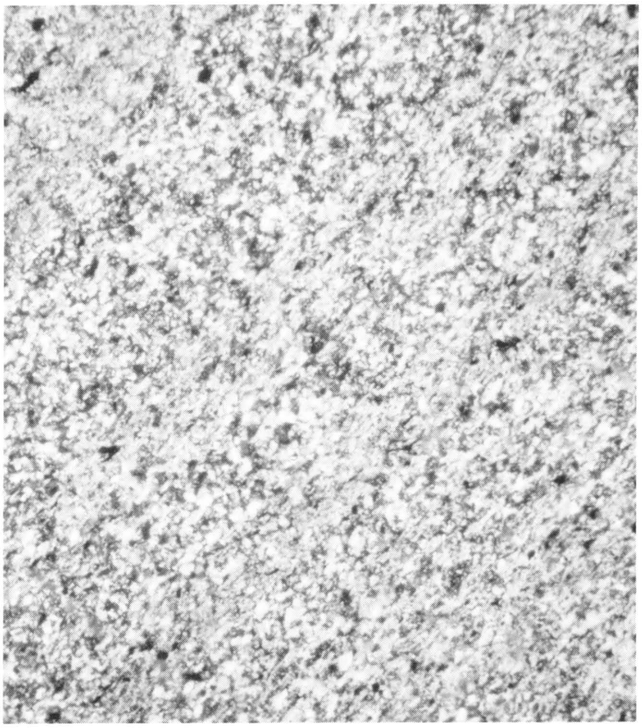
Limestone:

Microcrystalline lime mudstone. Present as very thin lenticular beds in the Chagrin Shale of Ashtabula County.



A 0 .05 MM *B* 0 .05 MM

Figure 5. Thin section photomicrographs. *A*, Claystone. *B*, Clayshale that has laminations of silt-sized quartz. *C*, Mudshale that has laminations of silt-sized quartz. *D*, Siltstone. *E*, Bituminous shale that has quartz and organic laminations. *F*, Fine-grained sandstone that includes abundant organic detritus.



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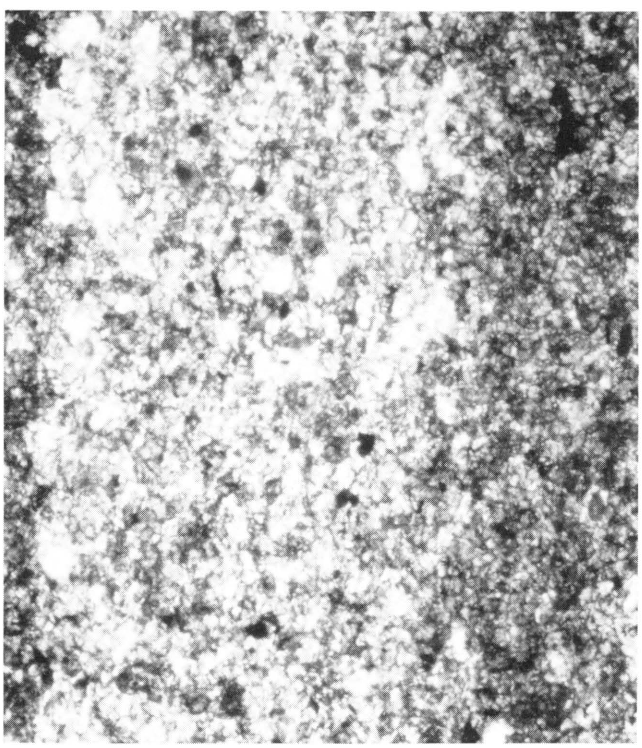

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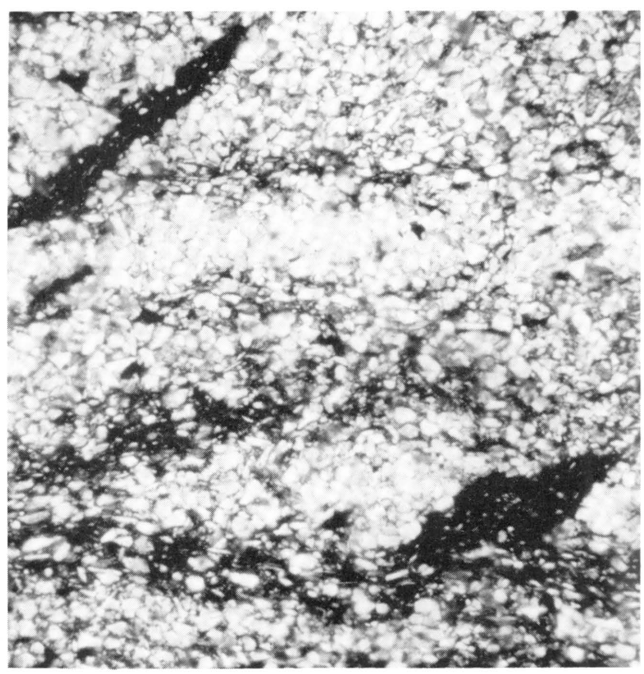

F

0 .05 MM

Figure 5. Continued.

Table 2. Summary of shale components
[mm, millimeter]

Quartz:

Subangular to very angular, equant to elongate, silt- to very fine sand-sized grains, most quartz monocrystalline

Feldspar·

Angular, silt-sized orthoclase and twinned plagioclase, fresh or slightly altered to clays

Clay:

Smaller than 0 01 mm, aggregates of illite and chlorite that have aggregate polarization, aggregates elongate parallel to bedding and (or) lamination, clays bent around quartz, feldspar, pyrite, *Tasmanites*, and opaque organics

Mica:

Larger than 0 01 mm, elongate chlorites, muscovite, and rare biotite, long axes of micas subparallel to bedding and (or) lamination, most grain outlines sharp, micas bend around quartz, feldspar, pyrite, *Tasmanites*, and opaque organics

Organic Material:

(1) Translucent, amorphous, orange to brown, irregular strands typically 0 02 mm long, bent around quartz, feldspar, clay, mica, pyrite, and *Tasmanites*

(2) Opaque, amorphous, black material in equant to elongate fragments typically 0 05 mm long, many fragments partially pyritized

Tasmanites

Yellow to orange hollow spheres made of amorphous, translucent organic material, sporelike, sphere wall typically 0 02 mm thick, most individuals crushed and elongate parallel to bedding and (or) lamination, some not crushed and infilled with pyrite and (or) chert before compaction, typically 0 2 mm in diameter, regarded by Sommer (1956, p 180) as a fossil algae, probably pelagic (Wall, 1962, p 360)

Pyrite:

Euhedral to anhedral disseminated crystals, infillings of *Tasmanites*, and irregular patches in quartz laminae, disseminated crystals typically 0 01 mm in diameter, patches of quartz laminae typically 0 04 mm in diameter

Carbonate:

Anhedral to euhedral calcite, siderite, dolomite, occurs as isolated crystals in shale and as cement in quartz laminae and in siltstones and siltshales, crystals typically 0 02 to 0 05 mm in diameter, replaces quartz, locally extensive

Other:

Detrital, rounded, fine silt-sized zircon and tourmaline, authigenic chert, bone fragments, and conodonts

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shades of gray or greenish gray in the Upper Devonian of northern Ohio Bituminous shales contain large quantities of unoxidized organic remains and, therefore, represent deposition in either an anaerobic or a dysaerobic environment Siltstones and mudshales contain abundant silt-sized quartz grains, which generally are concentrated into quartz laminations The presence of the quartz laminations may indicate deposition from suspension or traction currents

Composition of a shale is also an important factor when considering reservoir quality Organic-poor greenish-gray shale has more microporosity than organic-rich black shale (Thomas and Frost, 1980) In addition, shale porosity will decrease with burial depth and will vary inversely with the amount of carbonate material in the shale The carbonate acts as a cement, especially in quartz laminations, which decreases porosity and permeability

Lamination is an important variable in shale petrology The presence or the absence of lamination is fundamental to shale description and classification (fig 4, Potter and others, 1980) Other aspects of lamination that should be carefully described are the types of laminations present within the shale (table 4), thickness of laminations, nature of contacts with the surrounding rock, lateral continuity, cementation, porosity, and vertical grain size distribution within a single quartz lamination (table 4)

Lamination is important when evaluating the reservoir quality of a gassy shale A laminated shale can be expected to have greater permeability than one that is unlaminated Therefore, a laminated shale can be expected to produce more gas than an unlaminated one, given comparable maturation levels and kerogen content The type of lamination is also important when evaluating reservoir quality Quartz laminations generally will be more permeable than clay laminations and organic laminations because of the larger size of constituent grains Therefore, relative reservoir quality should increase as the abundance of quartz laminations increases Reservoir permeability also should increase as the lateral continuity of individual laminations increases Thus, any study of a gas reservoir in shale should give high priority to the nature and the distribution of the laminations

Lamination is an important variable when interpreting the depositional environment of a shale Good lamination may be developed when bottom conditions are unfavorable to burrowing or crawling organisms (Hallam, 1967, Byers, 1977, Ekdale, 1985), therefore, as a first degree of approximation, lamination or its absence can be linked to the degree of oxygenation of bottom waters Additionally, the kind of lamination and its associated microsedimentary structures should be directly relatable to depositional processes, which vary with different muddy environments (McCave, 1972, Reineck, 1974, Kuehl and others, 1988), but information is still scant for most shales Quartz laminations may be ungraded, coarse-tail graded, or distribution graded (Middleton, 1967) Graded quartz laminations may indicate deposition from suspension currents, whereas ungraded laminations may more commonly represent deposition from traction

Petrography of Stratigraphic Units

The volume percentage of each petrofacies was calculated for each stratigraphic unit in the Ohio and the

Table 3. Summary of major petrofacies
[tr, trace]

Petrofacies	Average modal composition (percent)[1]								Lamination[2] types	Mean quartz lamination thickness (mm), standard deviation
	Quartz + feldspar	Clay	Mica	Organics	*Tasmanites*	Pyrite	Carbonate	Other		
Claystone	10 4	79 2	2 5	3 3	tr	2 2	2 1	tr	None	
Clayshale	13 8	71 3	2 5	5 0	tr	4 8	2 5	tr	Quartz[2] Organic[2]	0 11, 0 06
Mudshale	31 2	50 2	3 5	7 2	1 0	5 0	1 5	tr	Quartz[2] Organic[2]	0 32, 0 30
Bituminous shale	13 0	50 3	2 5	24 3	1 4	5 8	2 2	tr	Quartz[2] Organic[2] Clay[3]	0 096, 0 07
Siltstone	68 5	6 1	3 9	tr	0	T	19 1	1 0	Quartz[2]	

[1] Calculated from 200 point counts on 71 thin sections
[2] Present in more than 50 percent of samples
[3] Present in less then 50 percent of samples

Table 4. Types of laminations found in the Upper Devonian shales of northern Ohio

Clay laminations:

More than 95 percent clay minerals, oriented in plane of lamination, aggregate polarization Sharp contacts with surrounding shale Rare to common

Organic laminations:

Quartz + clay + organics, more organics than surrounding shale Most contacts with surrounding shale sharp, some gradational Common to abundant

Quartz laminations:

More than 75 percent silt-sized quartz grains, most grain-to-grain contacts long and point Carbonate cements some laminations, locally replaces quartz extensively Quartz laminations are subdivided according to type of grain size grading

Ungraded

No grain size variation perpendicular to lamination

Coarse-tail graded

Quartz content and grain size decreases vertically within the lamination with an accompanying increase in clays, grading mostly normal, some reverse

Distribution graded

Quartz size decreases upward within the lamination

Chagrin Shales of northern Ohio (table 5) Consideration was given to samples that were unevenly distributed throughout the section and to different drill holes that penetrated the different thicknesses of section

The Chagrin Shale consists predominantly of claystone, clayshale, and mudshale (table 5) It has no bituminous shales, marlstones, or sandstones Although siltstones are evident in surface exposures of the Chagrin (Hoover, 1960, Broadhead and others, 1982), they comprise only 5 percent of the Chagrin Perhaps most of what has been described in outcrop as siltstones are actually mudshales The absence of bituminous shales indicates the water column and the sediment were reasonably well oxygenated during deposition of the Chagrin Therefore, it is likely that Chagrin muds contained a reasonable abundance of infauna that exhibited a tendency to bioturbate the Chagrin sediments, at least for several centimeters immediately below the sediment-water interface An abundance of laminated shales (clayshales and mudshales) indicates that deposition must have been rapid enough that the infauna could bioturbate only relatively small volumes of sediment Broadhead and others (1982) concluded that laminated shales in the Chagrin were deposited rapidly by distal turbidity currents that traveled west down the turbidite slope of the Catskill delta The petrographic data support that conclusion

The lower part of the Huron Member consists predominantly of bituminous shale, although some claystones, clayshales, and marlstones are also present (table 5) It has the largest percentage of bituminous shale of any stratigraphic unit of the Ohio and the Chagrin Shales in northern Ohio The bituminous shales of the lower Huron were deposited in an anoxic environment The lower Huron was deposited in the distal, deeper parts of the Appalachian basin below the pycnocline (fig 6) Coeval Chagrin siltstones and nonbituminous shales were deposited upslope and to the east in oxygenated waters above the pycnocline (the boundary between anoxic water below and oxic water above) The prevalence of silt laminations and bituminous laminations in bituminous shales results from deposition in an anoxic setting and a corresponding paucity of organisms that could bioturbate and homogenize newly deposited mud

The origin of the organic-poor claystones, clayshales, and marlstones interbedded with the bituminous shales is not clear The intercalation of bituminous and nonbituminous shales occurs at scales of centimeters, meters, or even

Table 5. Volume percentage of each petrofacies in each stratigraphic unit
[Based on analyses of 136 thin sections]

Stratigraphic unit	Number of samples	Claystone	Clayshale	Mudshale	Bituminous shale	Siltstone	Marlstone	Sandstone
Cleveland Member[1]	6	14	0	0	47	19	0	19
Three Lick Bed[1]	21	38	35	11	0	12	5	0
Huron Member[1]								
Upper part	11	44	26	0	30	0	0	0
Middle part	10	18	11	0	51	0	20	0
Lower part	22	11	9	0	74	0	7	0
Chagrin Shale	22	23	55	18	0	5	0	0

[1] Ohio Shale

tens of meters The intercalation has at least two possible origins The laminated nonbituminous shales may represent far-distal turbidity currents that traveled along the bottom into and under bottom waters (fig 7) Some of those nonbituminous shales generally are associated with thin beds of siltstone and generally contain graded silt laminations and an appreciable content of dispersed silt-sized quartz Many of the siltstone beds contain base-truncated Bouma sequences

Other greenish-gray thin nonbituminous shales are bioturbated (unlaminated) and are not associated in an obvious way with turbidity current deposits The occurrence of such thin bioturbated beds is less clear but appears to be related to vertical migration of a pycnocline along a very gently dipping basin floor (fig 7) as has been inferred by Cluff (1980, p 777–778) for thin greenish-gray shale beds in the Upper Devonian of the Illinois basin Why migration of the pycnocline may have occurred is unknown, but climatic changes or intrusion of oceanic currents may have been responsible Such beds should contain less silt than those deposited by turbidity currents because turbidites consist of resedimented material that was deposited originally much farther east and closer to the Catskill delta The absence of mudstones in the Upper Devonian supports the hypothesis of a nonturbidite origin for the burrowed shales The beds will be extensively bioturbated because the migrating pycnocline results in oxic bottom waters and colonization of the sediment substrate by burrowing organisms Demaison and Moore (1980, p 1184–1185) illustrated the details of the oxic and the anoxic environments

Large-scale (meters and tens of meters) interbedding of bituminous and nonbituminous shale may represent long-term migration of the pycnocline or it may be caused by several other possible phenomena First, the large-scale interbedding may represent major westward progradation of the Catskill delta and associated subsea fans in the Appalachian basin Periods of rapid progradation would result in the basin floor and slope aggrading above a stable pycnocline and in oxic bottom conditions If deposition subsequently slowed, then isostatic subsidence resulting from added weight of the subsea fans would cause depression of the basin floor beneath the pycnocline, anoxic bottom conditions would return, and organic-rich bituminous shales would be deposited Large-scale interbedding of bituminous and nonbituminous shales also could be the result of major climatic changes or major changes in basinal circulation (Heckel, 1977, p 1054)

The middle part of the Huron Member consists predominantly of bituminous shale, marlstone, and claystone, some clayshale is also present The abundant bituminous shales are representative of the dominantly anoxic condition below the pycnocline in which the middle Huron was deposited The clayshales may have been deposited by far-distal turbidity currents The largest percentage of nonbituminous shales are, by far, the unlaminated varieties—claystones and marlstones—that occur mostly in thin beds They probably represent frequent vertical migrations of the pycnocline Why this should have occurred is not clear, but the thin interbedding with bituminous shales indicates a strong cyclic mechanism The origin of the calcite in the marlstones is poorly understood because it is not present as calcareous shells or tests However, the calcite may have been deposited originally as organic remains and then may have been remobilized The almost exclusive occurrence of marlstones in the middle Huron suggests depositional, rather than diagenetic, controls

The upper part of the Huron Member consists of claystone, clayshale, and bituminous shale Although outcrops and cores indicate a greater percentage of dark shales in the upper Huron than in the middle Huron, the former has only 30 percent bituminous shales, and the latter has 50 percent bituminous shales This indicates a generally upward decrease in the truly organic-rich bituminous shales and, therefore, represents a general waning of anoxic depositional conditions The increase in the percentage of claystones also represents an increase in oxic conditions The upward increase in percentage of clayshales reflects the increased influence of turbidity currents caused by westward progradation of the Catskill delta and its associated subsea fans

The Three Lick Bed of the Ohio Shale includes primarily claystone and clayshale but, unlike the underlying Huron Member, also contains significant amounts of mudshale and laminated to unlaminated siltstones The Three

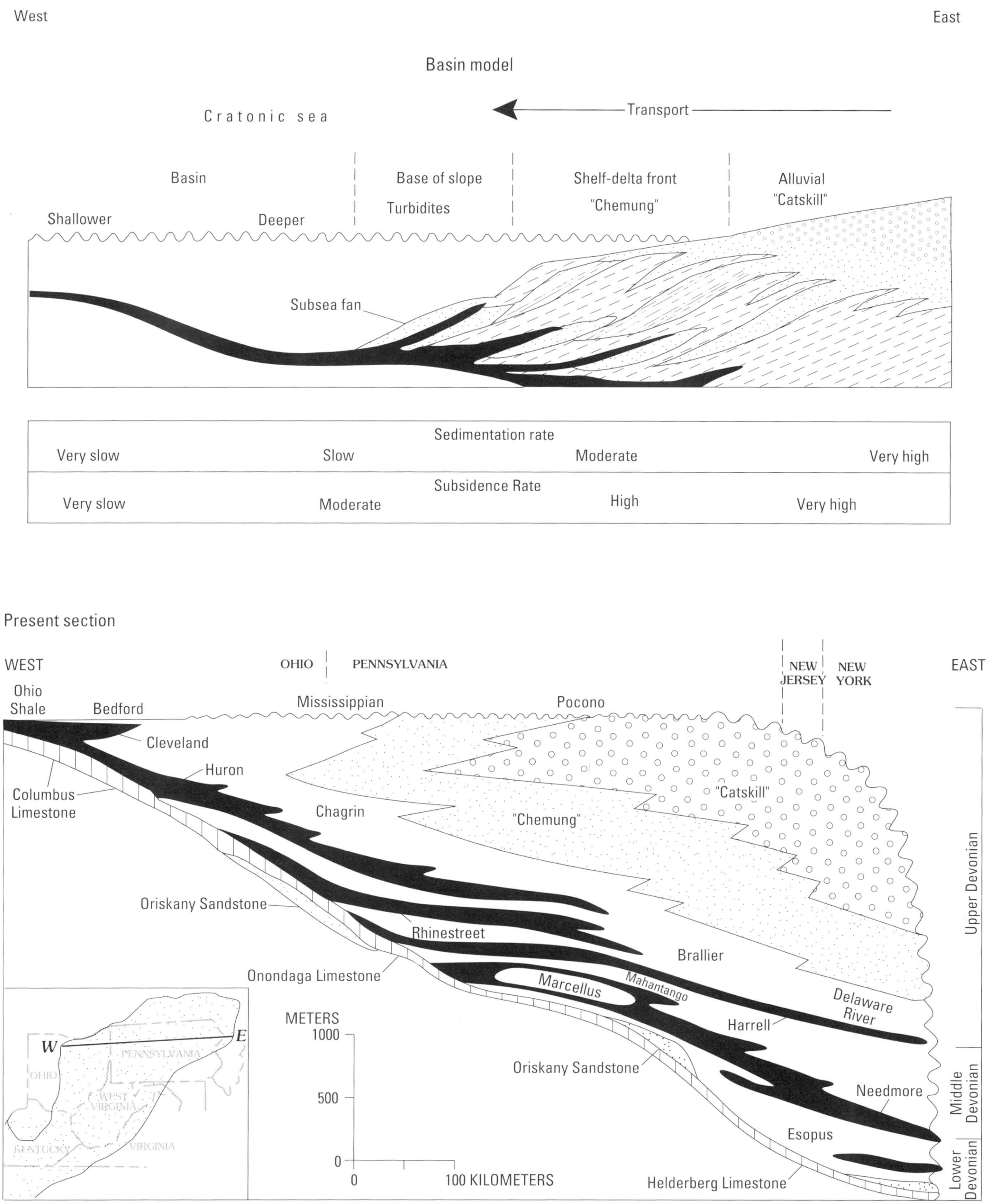

Figure 6. The relation of lateral facies variations to depositional environments, sedimentation rate, and subsidence rate in the Appalachian basin. Northern Ohio was the locus of the deep cratonic basin. Sediment was derived from the east. (From Broadhead and others, 1982.)

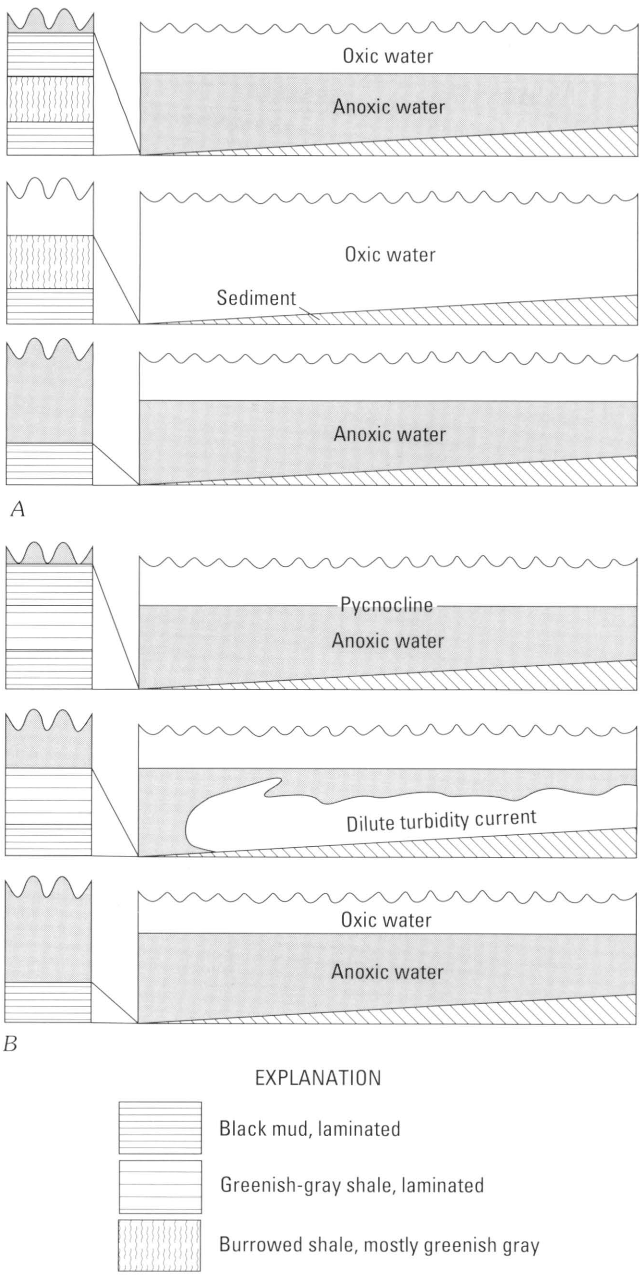

Figure 7. Two possible origins of interbedded greenish-gray and black shales. No vertical scale is implied. (From Broadhead and others, 1982.)

Lick Bed is comprised entirely of siltstone and mudshale in Cuyahoga County. To the west, in Lorain and Erie Counties, claystone and clayshale are dominant, and mudshale and siltstone are minor constituents. The Three Lick Bed contains no bituminous shales. The general petrographic composition of this unit indicates a general cessation of anoxic depositional conditions. The east-to-west variation in petrofacies represents the dominance of siltier, more proximal turbidities in the east and finer grained distal turbidites (clayshales) and fine-grained hemipelagic oxic sediments (claystones) in the west. That lateral variation represents the presence of the middle to the lower parts of a subsea fan of the Catskill delta. The absence of anoxic depositional conditions may have resulted from aggradation of the sea floor above the basinwide pycnocline. That aggradation resulted from progradation of the subsea fan into north-central Ohio. The presence of the Three Lick Bed, therefore, represents a distinct change in depositional conditions from basin-floor sedimentation to distal-fan and base-of-slope sedimentation. It appears that the Three Lick Bed was deposited at a bathymetric level permanently above the highest levels of the basinwide pycnocline.

The Cleveland Member of the Ohio Shale overlies the Three Lick Bed and the Chagrin Shale with a sharp, distinct contact. The Cleveland Member consists mostly of bituminous shale and accessory claystone, siltstone, and fine-grained sandstone. The siltstones and sandstones are present only east of the city of Cleveland where the Cleveland Member overlies the Chagrin Shale. The abundant bituminous shales represent a return to anoxic sedimentation. The siltstones are laterally continuous thin turbidite beds. Paleocurrent measurements indicate that they were derived from the Catskill delta to the east (Potter and others, 1979). The sandstones are bituminous and were deposited in submarine channels. Their presence is known only from cores; the author knows of no outcrops of Cleveland sandstones. The sudden return to deposition of bituminous shales in Cleveland time indicates either a major regional subsidence of the basin floor or a drastic regional rise in the basinwide pycnocline. An absence of all but the mildest tectonic structures in north-central and northeastern Ohio strongly supports the latter thesis. The turbidite siltstones and sandstones represent continued westward progradation of subsea fans associated with the Catskill delta.

GEOCHEMISTRY

Organic carbon, whole-rock hydrogen, and whole-rock nitrogen were analyzed to infer the source of gas in the Upper Devonian and to establish geochemical facies in the Upper Devonian. Thirty-two shale samples were analyzed for organic carbon, whole-rock hydrogen (organic hydrogen + mineral hydrogen + hydrogen in irreducible water), and whole-rock nitrogen (table 6) by using a Perkin-Elmer 240 Elemental Analyzer. Samples were ground and treated with hydrochloric acid to remove mineral carbon. The insoluble residues were placed inside a capsule in the elemental analyzer and combusted. The resulting gases were analyzed for weight percent carbon, hydrogen, and nitrogen; those values were corrected for weight loss during acid treatment. Weight percent carbon is equivalent to percent organic carbon because mineral carbon was removed by acid solution.

Average percentages of organic carbon, whole-rock hydrogen, and whole-rock nitrogen were calculated for each

Table 6. Mean values and 90-percent confidence intervals of organic carbon, whole-rock hydrogen, and whole-rock nitrogen for the Ohio and the Chagrin Shales in northern Ohio and source-rock evaluation

Stratigraphic unit	Organic carbon (weight percent)	Hydrogen (weight percent)	Nitrogen (weight percent)	Organic carbon in bituminous shale (weight percent)	Source-rock evaluation[1]	Number of samples
Cleveland Member[2]	4 60 ± 1 09	0 76 ± 0 14	0 18 ± 0 06	4 06 ± 1 09	Excellent	4
Three Lick Bed[2]	1 39 ± 1 23	0 67 ± 0 07	0 10 ± 0 02	[3]0	Good	6
Huron Member[2]						
Upper part	3 88 ± 1 35	0 74 ± 0 14	0 14 ± 0 05	6 01 ± 3 44	Excellent	6
Middle part	2 67 ± 3 16	0 64 ± 0 25	0 12 ± 0 08	4 94 ± 4 77	do	4
Lower part	4 65 ± 1 78	0 76 ± 0 16	0 13 ± 0 07	7 17 ± 1 46	do	9
Chagrin Shale	0 51 ± 0 40	0 52 ± 0 23	0 09 ± 0 05	[3]0	Poor	3

[1] Rated by percent organic carbon (see Thomas, 1979)
[2] Ohio Shale
[3] Unit does not contain bituminous shales

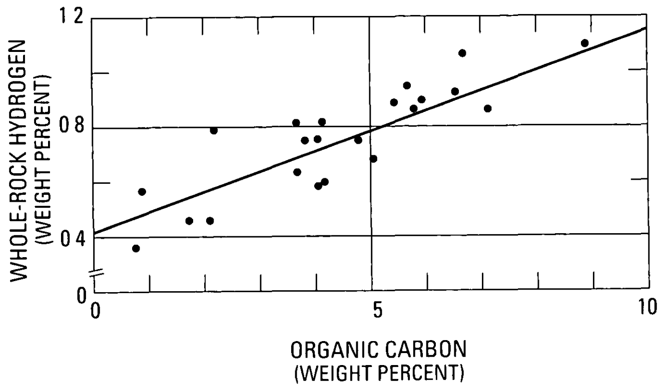

Figure 8. Linear regression of whole-rock hydrogen and total organic carbon

stratigraphic unit as was the average percentage of organic carbon in the bituminous shales of each stratigraphic unit (table 6) The source-rock character of stratigraphic units was rated on the basis of organic-carbon content (Barker, 1979, Thomas, 1979) of each unit as a whole and of the average organic-carbon content of bituminous shales within each unit (table 6) Although this rating system does not account for thermal maturity or kerogen type, it can be used to compare shaly units deposited in generally similar environments that have been buried to similar maximum burial depths, which is the case for all Upper Devonian shales of northern Ohio The Chagrin Shale contains no bituminous shales, average organic-carbon content is lean, only 0 51 weight percent, which would give it a poor source potential, according to criteria established by Barker (1979) and Thomas (1979) The Three Lick Bed contains no bituminous shales, but average organic-carbon content of the Three Lick shales is 1 39 weight percent, which gives the Three Lick Bed a good source-rock rating according to Barker (1979) and Thomas (1979) The Cleveland and the Huron contain abundant bituminous shales that are rich in organic carbon, consequently, they have excellent source-rock ratings

One method used to estimate the thermal maturity of kerogen is to calculate the atomic hydrogen to carbon ratio (H C) of the kerogen This could not be done directly for the Upper Devonian of northern Ohio because no apparatus was available to measure organic hydrogen Only whole-rock hydrogen could be measured However, an average H C could be calculated for all the Upper Devonian shales of northern Ohio To plot whole-rock hydrogen versus organic carbon, a simple linear regression was performed (fig 8) The intercept at zero organic carbon is 0 42 weight percent, which is the average amount of inorganic hydrogen present in the shales The slope of the line is 0 079, which is the average weight ratio of organic hydrogen to organic carbon It converts to an atomic H C of 0 94

The average H C of 0 94 is typical of Upper Devonian shales in Ohio (Potter and others, 1980) The H C decreases eastward to approximately 0 4 in central West Virginia because of increasing thermal maturity that was caused, at least in part, by greater depths of burial (Potter and others, 1980) The greater depths of burial were responsible for higher paleotemperatures in West Virginia than in Ohio Vitrinite reflectance (R_o) of the Upper Devonian shale sequence also increases eastward from Ohio into West Virginia (Potter and others, 1980) R_o values in the Upper Devonian of northern Ohio are typically less than 0 5 Those R_o values place the Upper Devonian of northern Ohio in a thermally immature facies of dry gas and heavy oil generation, according to the hydrocarbon metamorphic facies established by Raynaud and Robert (1976)

PETROLEUM GEOLOGY

Records of 93 wells that have reported gas production and (or) shows of gas (fig 3) were examined to delineate gassy zones and to determine which geologic factors control gas occurrence in the Ohio and the Chagrin Shales of northern Ohio The well data were obtained from files of the Ohio Geological Survey, no records of early drilling were available for Cuyahoga County Wells used in the study are

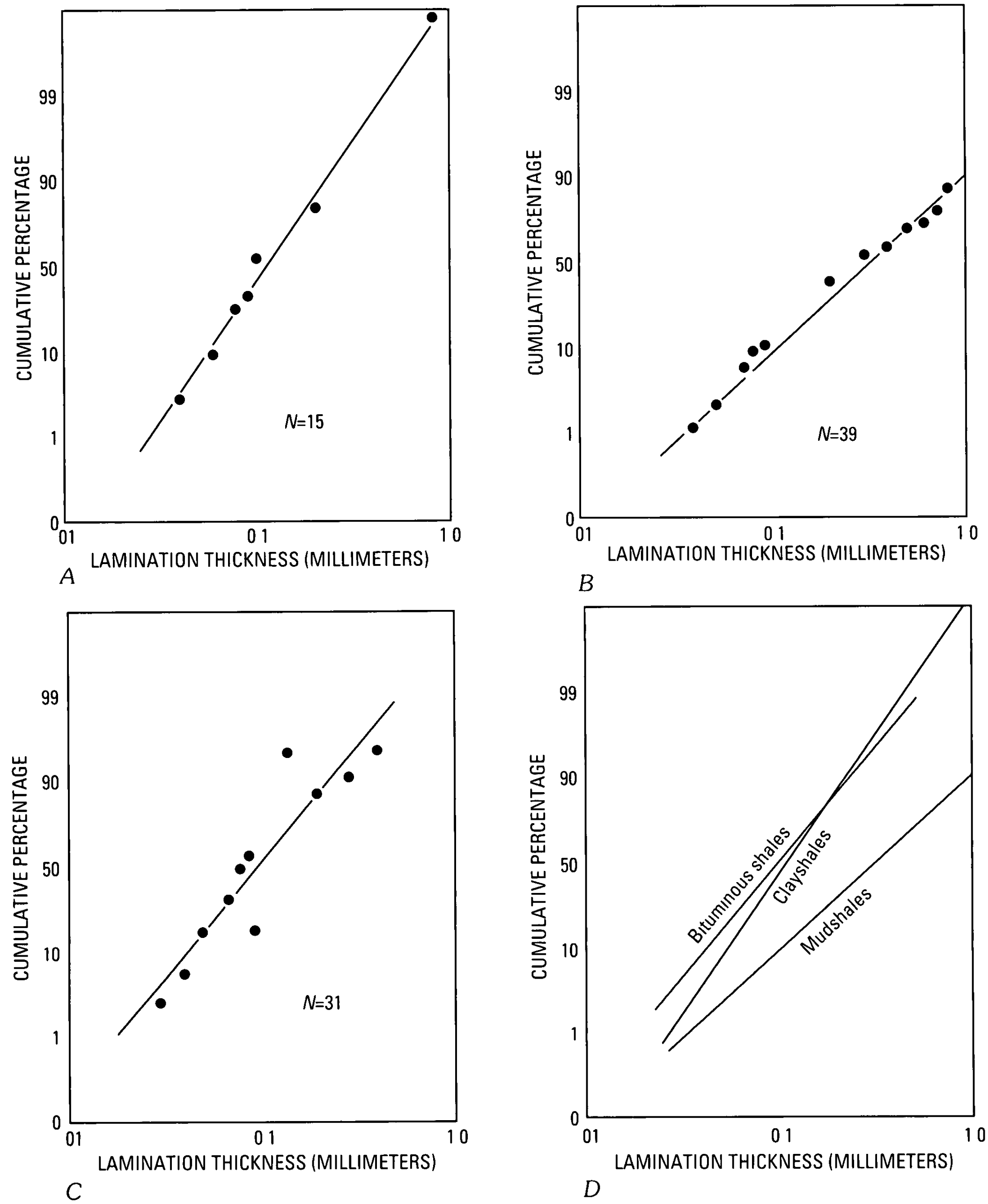

Figure 9. Cumulative probability curves of quartz lamination thickness *A*, Clayshales *B*, Mudshales *C*, Bituminous shales *D*, Curves superimposed for comparison

located less than 5 miles from the line of the east-west cross section All the drill holes used penetrate the entire section of the Ohio and the Chagrin Shales All but two were drilled to the "Big Lime", those two wells reached total depth in the Olentangy Shale By selecting wells that penetrate the entire study area, the possibility of preferentially recording shallower gassy zones, which would introduce a stratigraphic bias into the data, is precluded Data concerning the depths of most gas shows came from scout cards and drillers' logs The presence of some gas shows was interpreted from cooling anomalies recorded by open-hole temperature logs When available, gamma-ray bore-hole logs were used to determine the stratigraphic position of gas shows The gas shows were projected along depositional strike into the cross section

Gas shows are most abundant in the Chagrin Shale and the Three Lick Bed of the Ohio Shale (fig 3), probably because those units contain the most siltstone and mudshale Gas shows are least abundant in the Huron and the Cleveland Members of the Ohio Shale, despite observations and analyses that indicate those units have the highest percentages of bituminous shales, the highest concentrations of organic carbon, and the best source-rock ratings (table 6) Because gas shows are not related to present depth of burial, they appear to be independent of any differential thermal maturity in northern Ohio

The abundant thick silty quartz laminations in the siltstones and mudshales probably act as permeable conduits and reservoirs for gas Although clayshales and bituminous shales contain abundant quartz laminations, the quartz laminations found in those petrofacies are generally much thinner than the quartz laminations found in mudshales (fig 9) and, of course, siltstones (where the entire siltstone bed behaves essentially as a single lamination) Quartz laminations in clayshales have about the same average thickness (approximately 0 1 mm) as quartz laminations in bituminous shales The lognormal distributions of lamination thickness are approximately the same for those two shale types Only about 10 percent of the laminations exceed a thickness of 0 2 mm, in mudshales, however, average quartz lamination thickness is about 0 3 mm, and approximately 60 percent of all quartz laminations are thicker than 0 2 mm

The source of the gas in the Chagrin Shale and the Three lick Bed has not been determined directly from isotopic or other geochemical analyses However, possible sources of the gas may be deduced from the analyses of total organic carbon (table 6) As previously mentioned, the Chagrin Shale contains 0 51 percent organic carbon, which is close to the value of 0 5 percent given by Barker (1979) as the minimum concentration of organic carbon needed for a unit to function as a source rock The Chagrin, therefore, could act only as a lean source of indigenous gas The Three Lick Bed has a good source rock rating and is probably the source of gas indigenous to that unit It is possible that gas in the Chagrin Shale migrated from other Upper Devonian source rocks, such as organic-rich bituminous shales in the Cleveland and the Huron Members

Insofar as gas shows are controlled by stratigraphy and petrofacies, they are related to primary sedimentation and are broadly mappable Within the greenish-gray shale and siltstone facies, individual shows are as yet unexplained It is uncertain to what extent the gas shows in northern Ohio are dependent upon matrix or fracture porosity Nevertheless, gas is associated with the silty facies deposited on the medial and the distal parts of the submarine fans of the Catskill delta Those facies should be prospective for gas south of the study area covered by this chapter

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Chapter I

Source Rocks and Hydrocarbon Generation in the New Albany Shale (Devonian-Mississippian) of the Illinois Basin—A Review

By ROBERT M. CLUFF

U.S. GEOLOGICAL SURVEY BULLETIN 1909
PETROLEUM GEOLOGY OF THE DEVONIAN AND MISSISSIPPIAN BLACK SHALE OF EASTERN NORTH AMERICA

CONTENTS

FIGURES

Source Rocks and Hydrocarbon Generation in the New Albany Shale (Devonian-Mississippian) of the Illinois Basin—A Review

By Robert M. Cluff[1]

Abstract

For many years, the New Albany Shale (Devonian-Mississippian) has been suspected of being one of the major petroleum source beds in the Illinois basin because of its high organic content and its stratigraphic position beneath most of the major producing horizons in the basin. Recent studies of the New Albany and equivalent units in the Appalachian basin concluded that these shales were deposited in deep-water stratified anoxic basins conducive to the preservation of abundant hydrogen-prone organic matter. Anoxic organic-rich sediments were deposited in the deepest basinal portions of the paleo-Illinois basin, as well as in several shelfward-extending transgressive tongues. Variations in the stratigraphic and areal distribution of black shale have been attributed to changes in position of the oxygen minimum zone. These same studies documented a close relation between the type of organic matter and the depositional environment of the shales, which allows source-bed quality to be predicted largely by subsurface facies analysis. The laminated anoxic black to brownish-black shales contain high amounts (2.5–9 weight percent total organic carbon) of sapropelic Type II kerogen. The predominant organic components of this facies are "amorphous" organic matter, alginite (mainly *Tasmanites*), and minor amounts of vitrinite, semifusinite, and inertinite. The bioturbated dysaerobic gray to greenish-gray shales contain only modest amounts of humic Type III to Type IV organic matter (0–2 percent total organic carbon). The laminated black shale facies is an excellent liquid hydrocarbon source, whereas it is unlikely that the bioturbated gray shale facies generated significant quantities of any hydrocarbons.

Vitrinite reflectance and liptinite fluorescence studies of the New Albany Shale have defined a regionally consistent pattern of increasing maturation southward toward an area of greatest paleoburial depths (and possibly higher heat flow) in extreme southeastern Illinois and adjacent western Kentucky. In this area, the present-day maturation of the shales lies within the uppermost oil generation window and probably is within the wet gas generation zone in at least one very localized anomalous area. Across most of the Illinois basin, which includes the major producing regions of Illinois, Indiana, and western Kentucky, the present-day maturity of the New Albany is within the principal oil-generation zone.

The observed thermal maturity of the New Albany is consistent with the oily, generally undersaturated condition of most Illinois basin petroleum reservoirs and the distribution of significant gas fields in extreme southern Illinois and parts of western Kentucky. The geographic distribution of the most favorable oil-prone organic facies coincides with the area of maximum thermal maturity in the New Albany. A recent Lopatin modeling study of the Illinois basin not only reinforced the observed maturation patterns for the New Albany but also defined the timing of principal oil generation as the period between 300 million and 150 million years before present. Peak oil generation was achieved only in a restricted area of southeastern Illinois and western Kentucky between 200 million and 250 million years before present. Most of the major anticlinal structures in the basin are known to have developed before or early within this period; detailed paleostructural analysis indicates that the major migration directions out of the New Albany and toward these structures would have been along essentially modern structural dip. Thus, not only is the New Albany organic rich and mature in the right areas to explain charging of the known oil and gas reservoirs, but also the timing of generation and migration is correct. The very rapid decrease in oil field sizes and the small number of producing areas found beyond the limit of mature oil-prone New Albany Shale strongly imply that this stratigraphic unit was the source for most of the oil and gas fields in the basin. Essentially all Mississippian and Pennsylvanian oil fields, which account for more than 90 percent of the basin's reserves, probably are charged with New Albany oil and possible minor dilution by hydrocarbons from younger source beds. Most of, if not all, the Devonian and the Silurian pools also are associated with the nearby New Albany source rocks that most likely charged these stratigraphically deeper reservoirs. Only fields in the Ordovician "Trenton" Limestone follow a

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pattern that is inconsistent with a New Albany source and contain geochemically distinct crudes

INTRODUCTION

Oil has been commercially produced from the Illinois basin for nearly 100 years The Illinois State Geological Survey estimates more than 3 2 billion barrels (bbl) of oil has been produced in Illinois alone, primarily from Devonian and younger strata, together with more than 38 billion cubic feet of natural gas Total cumulative oil production in the Indiana portion of the basin exceeds 0 5 billion bbl, and a similar amount probably has been produced in western Kentucky Depending on the potential for enhanced oil recovery in several giant fields, more than 5 billion bbl ultimately could be produced from the Illinois basin, which would rank it as one of the major petroleum provinces in North America

Most of the oil production has come from lenticular sandstone reservoirs in the Chesterian (Upper Mississippian) and the Pennsylvanian sections (fig 1) Significant oil reserves also are found in carbonate reservoirs of Valmeyeran (Middle Mississippian), Devonian, and Silurian ages, a few relatively smaller fields produce from Champlainian (Middle Ordovician) "Trenton" Limestone reservoirs A single well in western Kentucky reportedly produces from older Black River-age carbonates Although more than 70 tests have been drilled to the St Peter Sandstone and stratigraphically deeper objectives, neither production nor even significant shows of hydrocarbons have been found in the sub-Black River Cambrian-Ordovician section As is the situation in many petroleum provinces, the largest petroleum accumulations and the majority of the reserves in the basin are associated with a few large anticlinal structures Literally thousands of small structural/stratigraphic and stratigraphic oil and gas fields also have been discovered and account for the remaining reserves and production

Despite the long history of petroleum exploration and production in the Illinois basin, few attempts were made to identify or characterize the major source beds for oil and gas before the mid-1970's Several stratigraphic intervals containing dark-colored or apparently organic-rich fine-grained rocks have been suspected or proposed as probable source strata by geologists working in the area These include Pennsylvanian coals and associated black marine shales, which have total organic carbon (TOC) values as high as 30 percent, Upper Mississippian prodelta dark-gray shales, which have organic-carbon values ranging between 1 and 1 5 percent, mid-Mississippian fine-grained limestones, which include probable tidal flat, lagoonal, and deep-water basinal deposits, black Lower Mississippian through Middle Devonian marine shales of the New Albany Shale, Lower and Middle Devonian fine-grained limestones, dark Upper Ordovician shales of the Maquoketa Group, which have organic-carbon contents ranging from 1 25 to greater than 4

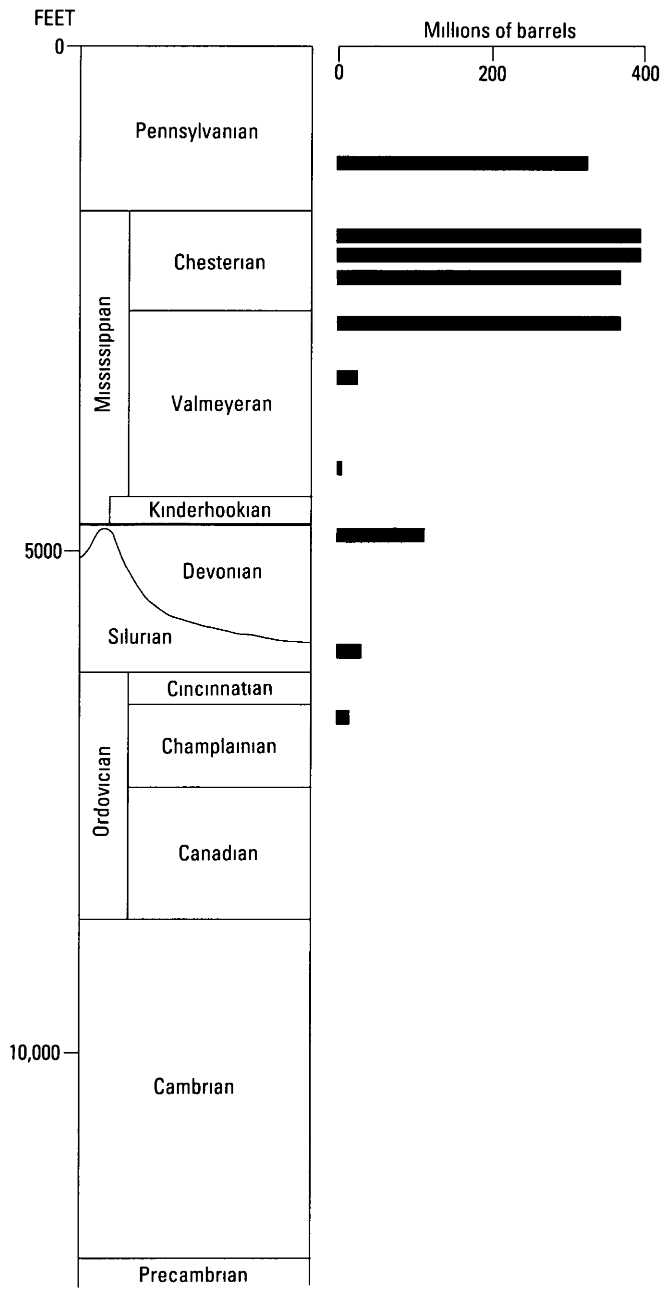

Figure 1. Stratigraphic distribution of oil production for the Illinois basin to 1958 (From Swann and Bell, 1958)

percent, Middle Ordovician shaly carbonates, which, at least on the extreme northern flank of the basin, contain abundant algal organic matter and are locally known as "oil rock" because they contain sufficient hydrocarbons to burn, Cambrian and Ordovician carbonates of the Knox Megagroup, and Cambrian shale and shaley carbonates of the Eau Claire Formation

Of these units, the New Albany Shale is the thickest, most widespread, and most continuous organic-rich interval in the Illinois basin Because of its stratigraphic proximity to oil reservoirs in the immediately underlying Middle

Devonian through Silurian carbonates, geologists have long inferred that the New Albany was a significant source rock across much of the basin. Black New Albany shales underlie almost the entire oil-producing area of the Illinois basin; however, they are separated from the major reservoir intervals by several hundred to over 1,000 feet (ft) of dense, apparently impervious limestone or siltstone containing few significant oil or gas accumulations. Any relation between source beds in the New Albany and the oil fields in the Mississippian and the Pennsylvanian has been difficult to prove because of the lack of data on the New Albany itself and on oil-source-rock correlation and incomplete knowledge of migration mechanisms and pathways that could allow vertical migration through hundreds of feet of what are now largely impermeable strata.

This paper is a review and summary of research on the New Albany Shale by the author and many of his colleagues—especially Mary H. Barrows, Mark L. Reinbold, and Jerry A. Lineback—at the Illinois State Geological Survey between 1976 and 1981. The research included a broad spectrum of topics on the geology and geochemistry of the New Albany. The main thrust of the research effort was to determine and define those factors most likely to control unconventional gas accumulations in shale reservoirs. One of the primary benefits was to increase the data base and the understanding of a major petroleum source rock in this basin. A summary of the research projects undertaken at the Illinois Survey was published by Bergstrom and others (1980); numerous detailed reports on specific aspects of the work are cited therein. Results of a parallel project at the Indiana Geological Survey on the New Albany in Indiana were published by Hasenmueller and Woodard (1981), and a brief report on the stratigraphy of the New Albany in western Kentucky was published by Schwalb and Norris (1980); the Illinois Survey acted as coordinator of these three research projects.

A complete treatment of petroleum source rocks in the Illinois basin also would assess other potential source intervals, as cited above, and would include geochemical data to correlate crude oils with their most probable sources. These aspects are beyond the scope of this chapter. Similarly, I will not attempt to address the many questions concerning oil migration that must be solved to link the New Albany to oil accumulations in the basin. As will be discussed in this chapter, the evidence for oil generation from the New Albany is very strong. No other unit can be shown to contain sufficient organic material of an appropriate type within the correct maturation window and have each of these characteristics in the proper geographic area to charge the major reservoirs in the basin.

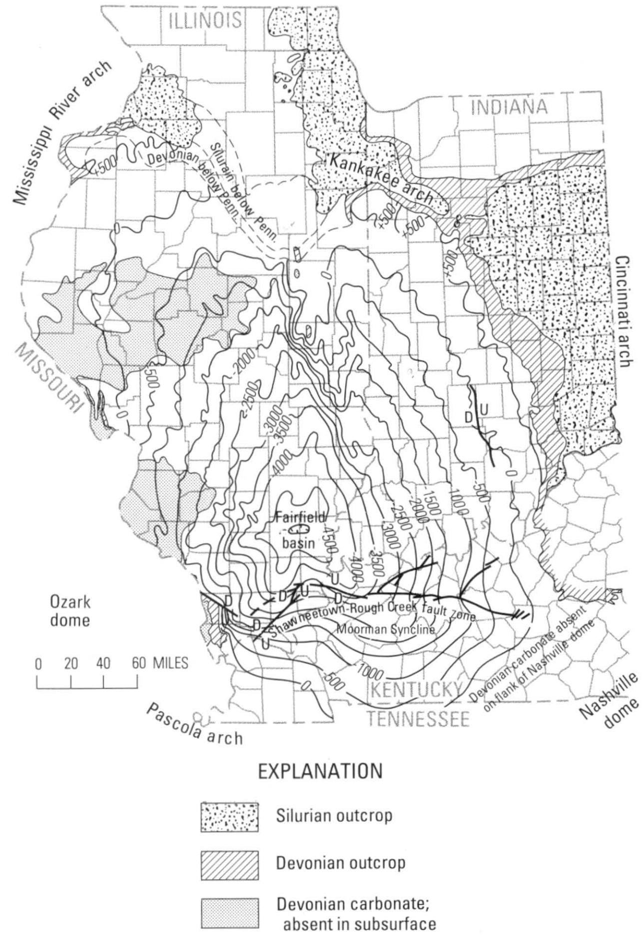

Figure 2. Structure of the base of the New Albany Shale.

GENERAL GEOLOGIC HISTORY

The Illinois basin is a broad, relatively shallow, intracratonic basin covering an area of about 60,000 square miles in southern Illinois, southwestern Indiana, and western Kentucky (fig. 2). The sedimentary fill reaches a maximum thickness of about 14,000 ft near the center of the Fairfield basin area in southern Illinois and probably exceeds 20,000 ft in portions of the Moorman syncline of western Kentucky. Subsidence of the southern portions of the proto-Illinois basin probably began in the Late Precambrian and continued intermittently throughout the Paleozoic. The central portion of the modern Illinois basin began to subside somewhat later, most likely in the Middle or the Late Cambrian. During most of the Paleozoic, major bounding arches defined the western, northern, and eastern flanks of the basin, and various lines of evidence indicate that the basin was open to the south. The resulting sedimentary fill consists almost entirely of Paleozoic rocks ranging in age from Middle Cambrian through Pennsylvanian (fig. 1). A thin veneer of Pleistocene glacial sediments covers much of the northern part of the basin, and, in the extreme southern part of the basin, the Paleozoic rocks are overlapped by Late Cretaceous and Tertiary rocks of the Mississippi embayment.

The above exceptions notwithstanding, the lack of a post-Pennsylvanian sedimentary record makes it very difficult to establish the structural and burial history of the basin from the Late Pennsylvanian to the present Sedimentation is believed to have continued into the Permian without interruption, and a few erosional remnants of presumably Permian strata have been preserved in fault grabens in western Kentucky (Kehn and others, 1982) Although Permian and perhaps even post-Permian sediments probably once covered much of the southern part of the Illinois basin, they have since been removed by Mesozoic and Cenozoic erosion By using computer models, Cluff and Byrnes (1991) estimated that the greatest depth of burial of basin sediments occurred during the Permian or the Triassic and that significant erosion did not begin until sometime during the Jurassic or the Cretaceous

STRATIGRAPHY OF THE NEW ALBANY SHALE

The stratigraphy of the New Albany Shale has been discussed in detail in publications by Cluff and others (1981) and Hasenmueller and Woodard (1981) A succinct summary of the stratigraphic nomenclature and the correlation of the many formations or members within the shale across the Illinois basin is presented in Chapter C As discussed in that chapter, the New Albany has been assigned group status in Illinois, whereas it is considered to be a formation in Indiana and Kentucky, where the total unit is generally thinner The subunits within the New Albany, either formations or members, were named for exposures on opposite flanks of the basin without knowledge of their continuity through the subsurface of the basin The resulting nomenclature varies by State and is, unfortunately, very complex The major subdivisions of the New Albany were defined by variations in shale color, organic content, or degree of bioturbation or, most commonly, by all three These factors were controlled by local conditions in the marine depositional environment, and, as a consequence, all the major subunits of the shale, whether formations or members, grade laterally into one or more of the other units Throughout this chapter, I will use a simplified version of the Illinois terminology and generally will ignore the changes in nomenclature and unit status at the State lines The reader is referred to Hasenmueller (this volume) for a complete rigorous treatment of the stratigraphy of the New Albany

PALEOENVIRONMENT

Evidence for deposition of the organic-rich shales in the New Albany in a deep-water stratified anoxic basin is very strong The first line of evidence comes from observation of the sedimentary structures and overall fabric of the mudrocks Several facies have been described (Cluff, 1980) and can be broadly lumped into two categories—organic-rich laminated black shales and organic-poor bioturbated greenish-gray mudstones The former are commonly pyritic, lack biogenic sedimentary structures and benthic body fossils, are typically thinly and evenly laminated but may be thickly or irregularly laminated in places, and have TOC contents considerably in excess of 1 weight percent In contrast, greenish-gray mudstones are extensively to totally bioturbated and less pyritic and contain a sparse fauna of calcareous benthic organisms in places and less than 1 percent TOC, however, their clay mineralogy is essentially identical to that of the black shales

The second line of evidence comes from detailed correlation of internal marker beds that demonstrate an interfingering relation between a large area of basin-centered black shales and the surrounding region, which is dominated by greenish-gray mudstones Throughout a large area of the central and southern portions of the Illinois basin, including southern Illinois, southwestern Indiana, and much of western Kentucky, the black shales occur where the New Albany is thickest This essentially continuous body of thick black shale thins into, grades laterally into, and interfingers with greenish-gray mudstones toward the north and west This relation also can be documented but is much less pronounced on cross sections extending from the central area of the basin northward and eastward into Indiana When combined with detailed thickness maps of individual black and gray shale units, these stratigraphic correlations appear to show a paleobasin that was centered in southern Illinois and western Kentucky and was filled with black shale The basinal black shales interfinger with contemporaneous greenish-gray mudstones, which appear to occupy basin-flanking positions The distribution of these major lithologies superimposed on a total thickness map of the New Albany Shale is shown in figure 3

The final line of evidence comes from studies of the stratigraphic units above and below the New Albany The area of maximum New Albany thickness and maximum black shale development coincides almost exactly with the position of the Silurian through Lower Devonian deep basin Evidence for this includes detailed correlation of the thick Middle Silurian shelf carbonate section into thin basinal fine-grained carbonates and shales and thickness maps that clearly show the maximum accumulation of pre-Middle Devonian sediments in southern Illinois This pre-New Albany basin was filled entirely with sediments during the Late Silurian and Early Devonian, which are predominantly deep-water cherty lime mudstones and carbonate turbidites The post-New Albany basin was filled by over 1,000 ft of deep-water deltaic clastics, deep-water cherty lime mudstones, and deep-ramp crinoidal grainstones during the early part of the Mississippian (Kinderhookian-Osageian) (Lineback, 1966, 1969) Again, the position of thick lower Mississippian deposits coincides

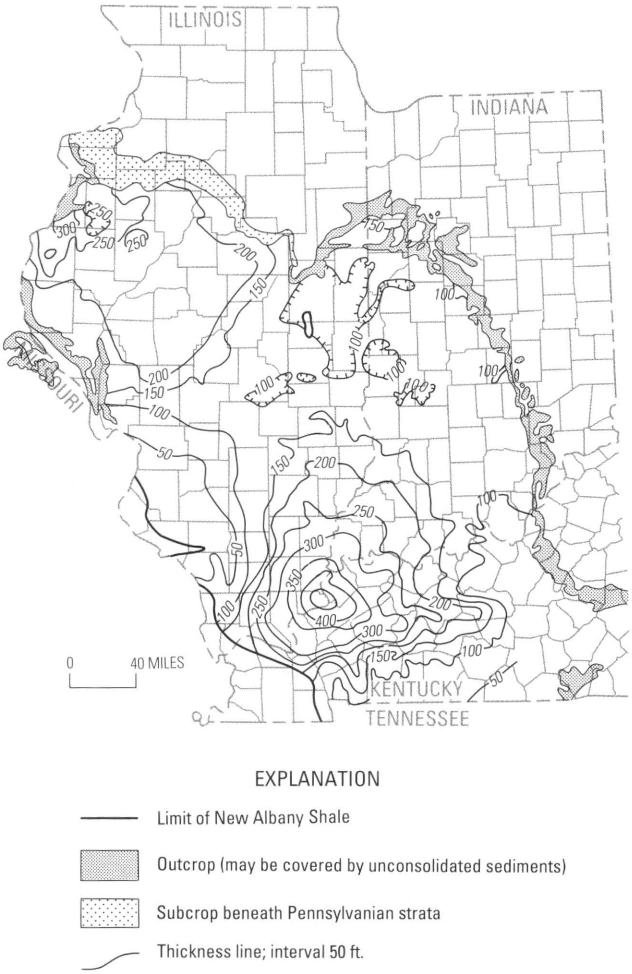

Figure 3. Thickness of the New Albany Shale and major lithotopes superimposed.

with the position of the thick black shale lithotope of the New Albany.

Taken in combination, the evidence indicates that the black shales were deposited in anoxic environments that were unable to support benthic organisms, whereas the greenish-gray mudstones were deposited in moderately oxygenated (or "dysaerobic") environments that were able to support a soft-bodied infauna. Only a few isolated localities around the western edge of the basin have preserved outcrops of rocks that were deposited in fully oxygenated conditions that allowed the development of an abundant shelly benthic fauna. The black shales were deposited mostly in the deep central area of the basin, whereas the greenish-gray mudstones were deposited mostly around the shallower flanks of the basin. This indicates oxygen stratification in the water column and severe oxygen depletion in the deeper waters. Comparison to modern anoxic basins, such as the Black Sea, indicates that normal winds, waves, and currents are capable of oxygenating surficial water and mixing the oxygenated water to a depth of several hundred feet, which suggests that portions of the Illinois basin had to be several hundreds to over 1,000 ft deep to maintain anaerobic conditions for millions of years. The regional interfingering of the black and greenish-gray shale lithotopes, the occurrence of some green shale beds in the deepest areas of the basin, and the extension of a few thin tongues of black shale far out onto the margins of the basin indicate that the oxygen boundaries fluctuated upward and downward in the water column over time. If, for example, the position of the interface between anaerobic and dysaerobic water moved up by only a few tens of feet, then it could move laterally many tens of miles because the bottom slope was extremely low. Such fluctuations probably formed the regionally persistent thin marker beds of gray or black shale that are critical to correlation and are the basis for the major stratigraphic subdivisions of the New Albany.

HYDROCARBON SOURCE POTENTIAL OF THE NEW ALBANY SHALE

Most petroleum geologists and geochemists agree that source rocks for oil or gas must meet the following three basic criteria:

- Some minimum amount of organic matter must be present for the rock to generate and expel from its own pore system any significant amounts of hydrocarbons.
- The type of organic matter deposited in the source rock strongly influences the composition and amount of petroleum generated and the level of thermal maturity required to generate petroleum.
- The organic matter must have been heated to a high enough temperature for a long enough period of time to break chemical bonds in the organic molecules of the sedimentary organic matter and thereby to form petroleum molecules.

This last process, of course, is termed "maturation." Each of these major criteria is addressed in the following sections as they apply to the New Albany Shale.

Organic-Matter Content

Studies by Stevenson and Dickerson (1969), Lineback (1970), Frost (1980), and Frost and others (1985) indicate that sufficient organic matter has been preserved within at least some intervals of the New Albany Shale to qualify it as a potential source rock for hydrocarbons throughout its present geographic extent. The exact minimum cutoff value for what constitutes a potential source is controversial, but most estimates range from 1 from 1.5 percent TOC for fine-grained siliciclastics.

Frost and others (1985) reported TOC analyses for 392 core and drill-cutting samples of New Albany Shale from across the entire basin. Of the total, 331 samples (or

84 5 percent) had organic-carbon contents greater than 1 percent, 41 samples (or 10 5 percent) had values between 0 5 and 1 percent, and only 20 samples (or 5 percent) had less than 0 5 percent organic carbon The lowest organic-carbon values were found in the greenish-gray Hannibal and Saverton Shales (average, 1 3±1 2 percent, range, 0 15–6 14 percent), especially in the northern and northwestern areas of the basin In this same area of the basin, the Grassy Creek and Sweetland Creek Shales, although dark in color, have TOC values that generally are below 3 percent, which is low for these units In all other parts of the basin, the Grassy Creek, Sweetland Creek, and Selmier Shales have high to very high organic-carbon contents, which range from 1 6 to over 15 percent (average, 6 5±2 2 percent) and exceeding 10 percent in eight samples The lowermost black shale unit, the Blocher Shale, has high organic-carbon values in the range of 3 to 9 percent (average, 5 3±1 5 percent) Hasenmueller and Woodard (1981, p 45–52) reported values for the New Albany in Indiana that indicate that TOC values are comparable to or higher than those obtained for the shales in Illinois and western Kentucky

High organic content of the shale generally correlates directly with dark shale color (the most organic-rich shales are brownish black to very dark gray), high natural gamma-ray intensities recorded by wireline logs, and high in-situ gas contents measured by degassing of core samples (Cluff and Dickerson, 1982, Lineback, 1980) The New Albany is, therefore, an exceedingly organic-rich unit on average and contains at least some beds that have TOC values of greater than 1 5 percent throughout its entire extent From the standpoint of organic content alone, the New Albany must be considered a potential source across the entire Illinois basin

Types of Organic Matter

The types of insoluble organic matter (or kerogen) preserved in a source rock substantially control the amount and composition of hydrocarbons that can be generated from that rock (Tissot and Welte, 1978, Hunt, 1979) Barrows and others (1979) and Barrows and Cluff (1984) reported on detailed petrographic studies of organic matter in the New Albany Acid-insoluble (HCl and HF treatment) residues of shale samples were examined to determine the relation among the types of organic matter, the abundance of various organic constituents, and shale facies

Because the bioturbated greenish-gray mudstones contain minor amounts of organic matter, the acid-maceration treatment of 20 to 30 grams of shale does not yield sufficient material to characterize the types of organic matter present Only vitrinite and inertinite, the humic group macerals, are observed in the kerogen concentrates of these shales The predominance of humic material in the greenish-gray mudstones corresponds to the Type III kerogen of Tissot and Welte (1978), which also is called Type IV kerogen when the atomic hydrogen to carbon ratio is very low This kerogen assemblage probably results from the destruction of most of the primary depositional sedimentary organic matter by detritus-feeding invertebrates and by bacterial degradation in a moderately oxygenated (dysaerobic) environment Only those organic components that are primarily the refractory humic type and resistant to breakdown by the digestive systems of the infauna and to bacterial destruction were preserved in the sediment

The laminated black shales, which were deposited beneath anoxic waters, are very rich in amorphous organic matter This material is lower in reflectance than associated vitrinites and commonly has a weak, dark-brown fluorescence under ultraviolet excitation Amorphous organic matter, commonly termed "sapropel," accounts for 90 to 95 percent of the total organic matter, and recognizable structured organic matter (including liptinites, vitrinites, and inertinites) accounts for only 5 to 10 percent of the kerogen concentrates The amorphous organic matter in the laminated black shale facies was probably derived from marine algae *Tasmanites*, an alginite, is the most commonly recognized maceral and is identified easily in thin sections, core samples, and drill cuttings because of its large size, distinctive disk shape, and orange to brown color Vitrinite, semifusinite, and various inertinite macerals are present in these shales but make up a very small percentage of the total kerogen This mixed assemblage of predominantly marine and some nonmarine organic-matter constituents is typical of Type II kerogen (Tissot and Welte, 1978) Apparently, this kerogen assemblage is locally derived, well-preserved marine planktonic organic material that has minor land-derived organic contributions

Thermal Maturation of Organic Matter

In recent years, it has been recognized that oil is generated within a relatively narrow maturation range (the "oil window") and that natural gas is formed over a much broader range (Tissot and Welte, 1978) For Type II kerogen, which is typical of the New Albany Shale, the range of vitrinite reflectance (R_o) corresponding to the oil generation window is between 0 5 and 1 3 percent Peak oil generation and expulsion occur at maturation levels that correspond to over 0 7 percent R_o The maturation level referred to as the immature stage corresponds to of less than 0 5 percent R_o

Vitrinite reflectance analyses for the New Albany Shale were reported by Barrows and Cluff (1984) Their map (fig 4), which was constructed from the analysis of over 230 shale samples, shows several distinct patterns that can be related to basin tectonics and paleoburial In three areas of the New Albany, values were significantly greater

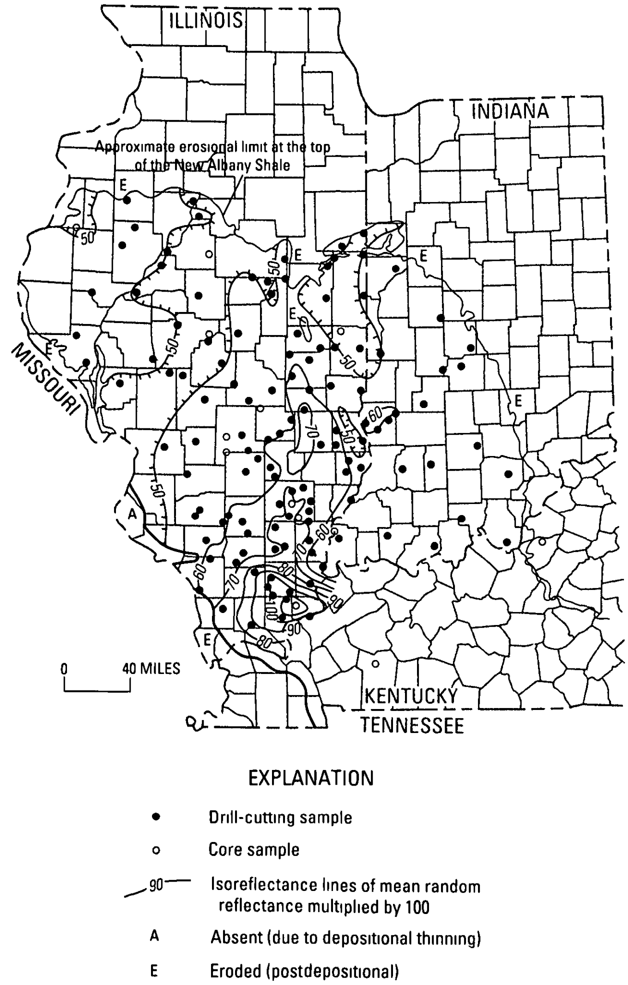

Figure 4. Vitrinite reflectance in the New Albany Shale (From Barrows and Cluff, 1984)

than 0 6 percent R_o The northernmost of these is centered in Cumberland and Jasper Counties, Ill , between the Clay City anticlinal belt to the west and the La Salle anticlinal belt to the east The New Albany in this southward-plunging syncline has been covered by an additional 1,000 to 2,000 ft of section relative to areas immediately to the east and west This area of the shale has been subjected to slightly elevated burial temperatures compared to adjacent locations

The second area of increased reflectance is shown by a narrow finger of the 0 7-percent R_o contour that extends northward out of extreme southern Illinois toward Wayne and Hamilton Counties, Ill (fig 4) This area is the present-day area of maximum burial of the New Albany Shale (fig 2) and, like the area discussed above, has been subjected to slightly elevated burial temperatures

The highest reflectance in the New Albany Shale is in extreme southern Illinois and parts of western Kentucky south of the Rough Creek lineament The maximum observed reflectance (approximately 1 2 percent R_o) was found in the immediate vicinity of Hicks Dome, a cryptoexplosive feature in Hardin County, Ill Although the New Albany is not buried to great depths in this area, southern Illinois is characterized by extensive faulting, mineralization, and scattered small igneous intrusions Damberger (1971, 1974) suggested that a deep-seated igneous pluton may have been emplaced beneath extreme southern Illinois sometime after the Pennsylvanian, thus resulting in significantly increased heat flow and consequent maturation of organic matter in the overlying sedimentary strata

An alternate explanation for the apparently high degree of maturity in the southern part of the basin comes from stratigraphic evidence, which indicates that nearly all the Devonian, Mississippian, and Pennsylvanian stratigraphic units thicken progressively southward to their present-day erosional limits It seems very likely that these units originally continued to thicken southward toward the Mississippi embayment and that much of their thickness has been removed by subsequent uplift and truncation This suggests that the area of greatest paleoburial depth might have been significantly south of the present-day structural center of the basin (fig 2) Cluff and Byrnes (1991) reconstructed the approximate thickness of the eroded section by using an iterative approach between Lopatin model predictions and actual observed maturation patterns in the New Albany (Barrows and Cluff, 1984) and the Pennsylvanian Herrin (No 6) coal seam (Damberger, 1971) Their modeling indicates that at least 3,000 ft of erosion is required to match the observed maturity of the Herrin coal at its southernmost extent in Illinois and that from 4,000 to over 9,000 ft of erosion is required to predict correctly the maturity of the New Albany in some locations (fig 5) Their analysis also indicated that a major heating event or pluton emplacement is not necessary to account for the maturation patterns, but if such an event did occur, then it would substantially reduce the required overburden

Various studies have shown that the fluorescence of liptinites also may be used as a guide to the rank of coals and to the maturity of organic matter dispersed in sedimentary rocks (van Gijzel, 1967, Ottenjahn and others, 1975, Robert, 1979), as well as an aid in maceral identification (Cook and Kantsler, 1980) Tissot and Welte (1978) indicated that, as maturation increases, fluorescence intensity decreases, and fluorescence colors move from the yellow toward the red Fluorescence generally disappears at vitrinite reflectance values greater than about 1 0 percent Although fluorescence studies are not as precise as vitrinite reflectance studies, the patterns observed in figure 6 support the patterns of increasing vitrinite reflectance shown in figure 4 The fluorescence intensity is also useful for discriminating between reflectance patterns that result from increasing thermal maturity and those that arise from other phenomena, for example, the slight increase in vitrinite reflectance values along the northern erosional edge of the New Albany in east-central Illinois is probably a result of

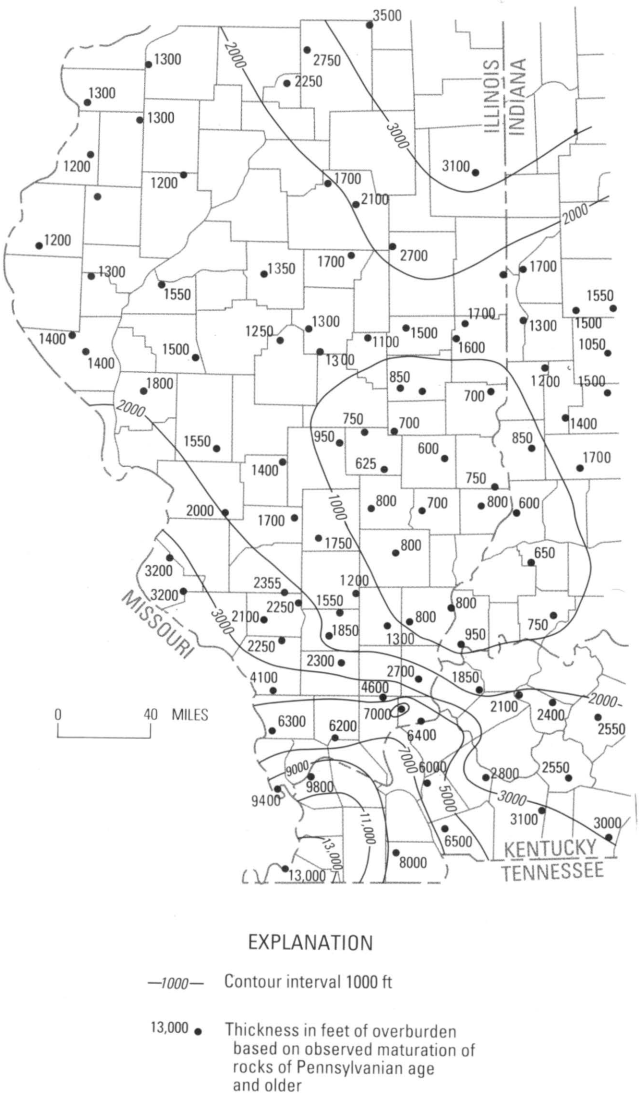

Figure 5. Total estimated thickness of post-Pennsylvanian strata eroded from the Illinois basin. (From Cluff and Byrnes, 1991.)

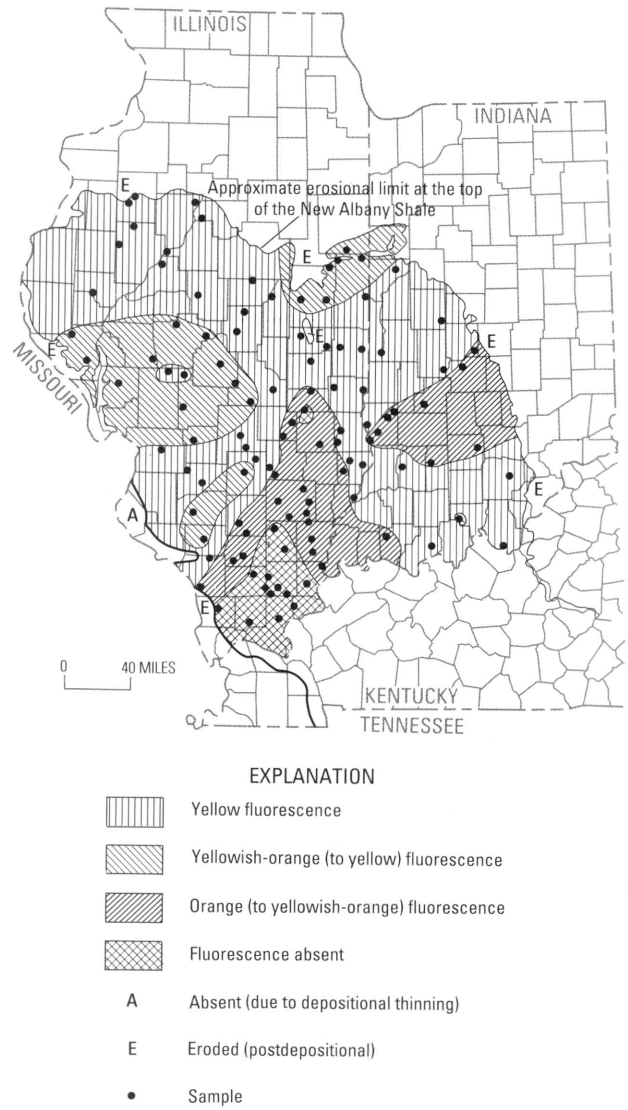

Figure 6. Liptinite fluorescence. (From Barrows and Cluff, 1984.)

early Pennsylvanian oxidation of organic matter. The fluorescence map does not show any anomaly in this region.

Two other sets of observations that bear on the problem of defining areas of hydrocarbon generation are worth noting. Studies of polished blocks of shale under reflected light allow direct observation of the distribution of organic constituents and their alteration that often cannot be made by using acid residues. Barrows (1980) observed that, in areas of low maturity, the amorphous organic matter completely surrounds and is intertwined with the inorganic matrix in the form of a continuous, well-connected network. In some areas, and particularly where vitrinite reflectance of the shale exceeds 0.9 percent, the continuous network of amorphous material is replaced entirely by a lighter gray nonfluorescent mass of angular organic fragments (fig. 7). In areas where vitrinite reflectance is between 0.7 and 0.9 percent, the amorphous organic network and the angular fragments commonly are observed within the same sample. This change in the nature of the amorphous organic matter from a continuous network to a mass of disrupted small fragments is interpreted to reflect chemical and physical alterations of the sapropel that result from hydrocarbon generation. In these same areas, dark- to medium-gray uniform organic material, which is generally of lower reflectance than vitrinite within the same sample, was observed as fillings in fusinite pores (fig. 8). No fluorescence of the filling materials was observed. The pore fillings and some associated similar-appearing angular particles are believed to be solid hydrocarbons, which also are referred to as "exsudatinite" (Stach and others, 1982), "pyrobitumen" (Alpern, 1970), or "bitumen" (Robert, 1973). This material is a residue produced during maturation and is a strong indication of liquid hydrocarbon expulsion.

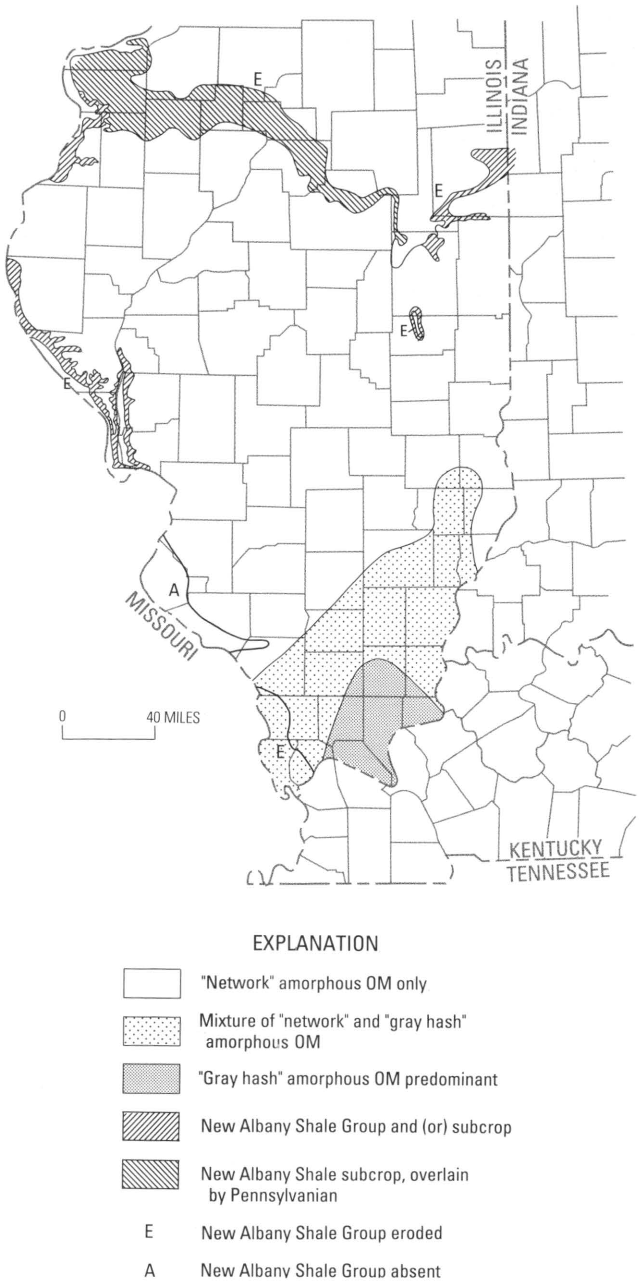

Figure 7. Amorphous organic-matter (OM) alteration. (From Barrows, 1981.)

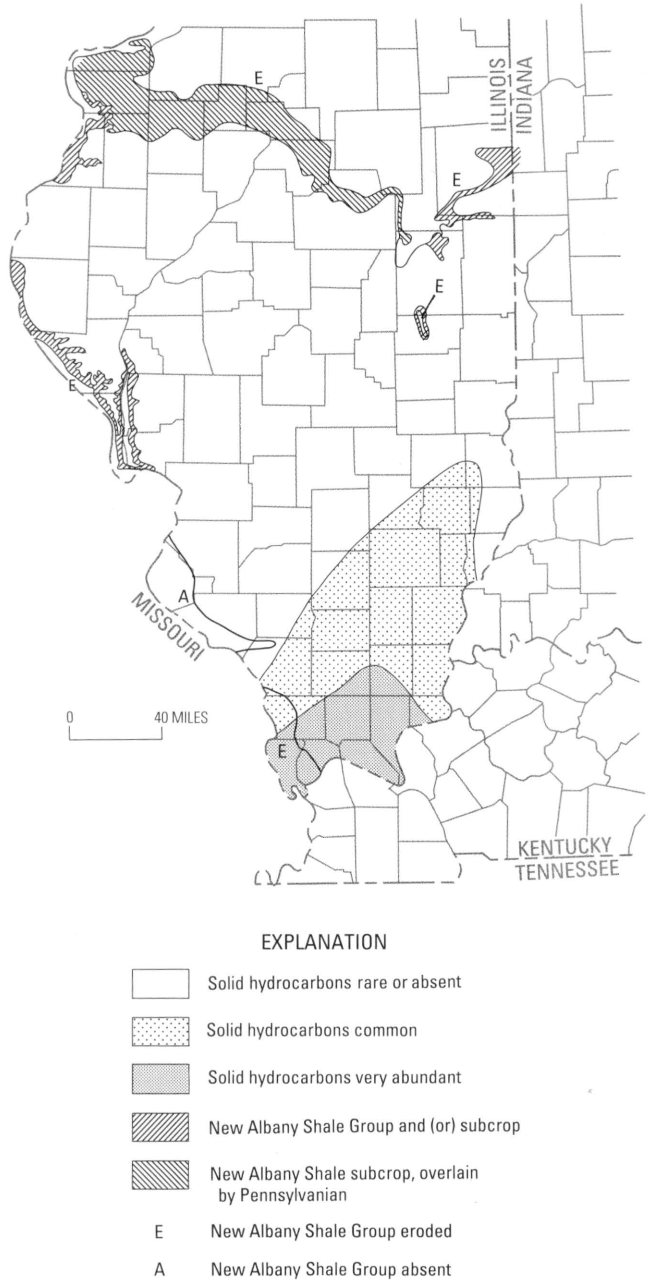

Figure 8. Distribution of solid hydrocarbon pore fillings. (From Barrows, 1981.)

Shale Pyrolysis

Dickerson and Chou (1980) reported the results of controlled stepwise pyrolysis-gas chromatography analyses for several selected samples of New Albany Shale from Illinois and western Kentucky. In general, they found that heating the shale up to 350 °C released the highly volatile C_1 to C_8 hydrocarbons and medium volatile C_9 to C_{12} hydrocarbons that are trapped in the shale matrix. Samples from a core in Wayne County, Ill., which is near the center of the Fairfield basin (fig. 2) and is in an area where vitrinite reflectance values exceed 0.7 percent (fig. 4), yielded C_9 to C_{12} hydrocarbons in greater proportion than C_1 to C_8 hydrocarbons. Samples from cores in lower maturity areas yielded the C_1 to C_8 hydrocarbons in greater proportions. Further heating of the shale samples to 550 °C and above resulted in the evolution of large amounts of C_1 to C_8 gases, as well as moderate amounts of heavier hydrocarbons. The hydrocarbons derived at these high pyrolysis temperatures were formed by the breakdown of the nonvolatile organic matter in the shale. Gas yields varied linearly with organic-carbon content, up to a maximum of about 30 standard cubic feet of gas per cubic foot of shale. Oil yields of New Albany Shale samples from Indiana are directly proportional to organic content, and gas yields vary widely and do not correlate well with TOC (Hasenmueller and Woodard, 1981). The results of these pyrolysis analyses show that considerable amounts of volatile hydrocarbons, presumably formed by natural maturation and generation, are trapped in the shale matrix; the proportion of heavier hydrocarbons (C_{9+}) increases as thermal maturity increases. The New Albany Shale has considerable generative potential remaining over most of the basin.

Oil-Source-Rock Correlation

Unfortunately, only a few chemical analyses of Illinois basin crude oils have been published, and the question of crude oil-source-rock correlation has not been studied in depth. Rees and others (1943) showed that most Mississippian and Pennsylvanian oils in Illinois are very similar. Their analyses of the gravity, sulfur content, and fractional distillation products of Illinois crudes fall within a narrow range that is generally typical of crudes derived from Type II kerogen (fig. 9). Some Pennsylvanian-age crudes vary from this mean trend and may represent bacterially degraded crudes or, perhaps, a different source rock altogether. The close grouping of crude compositions shown in figure 9 is strong evidence for a common source or, at least, for sources that have very similar organic-matter types. If multiple source beds that have different kerogen types had played significant roles in the formation of petroleum accumulations in the basin, then such a low variation in composition would be very difficult to explain.

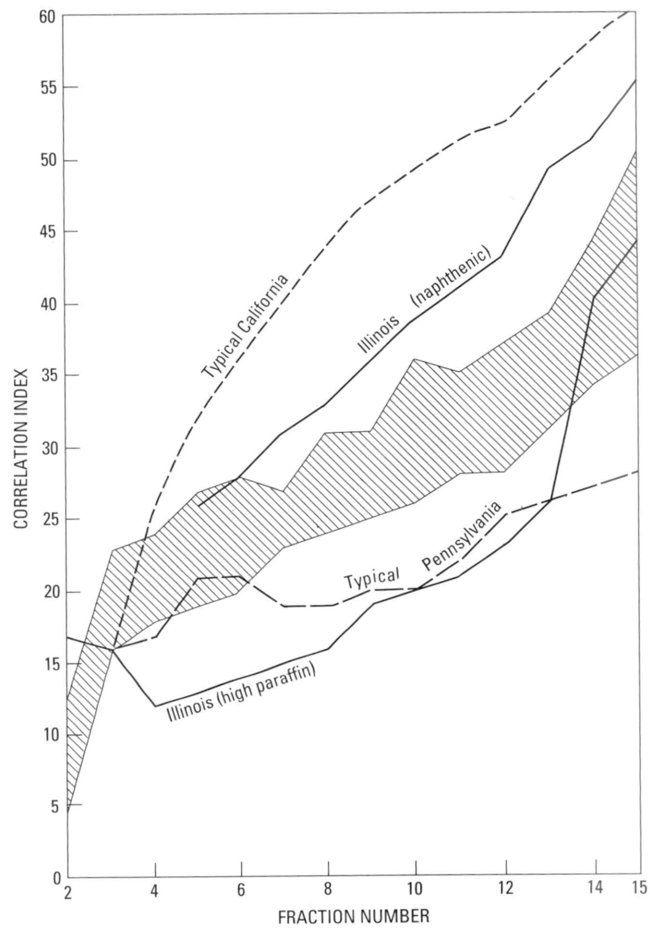

Figure 9. Crude oil fractional distillation curves for Illinois crudes. Hachured area includes 70 percent of a representative suite of crude oils from Illinois. (From Rees and others, 1943.)

AREAS OF HYDROCARBON GENERATION IN THE NEW ALBANY SHALE

The previously described patterns of major depositional environments, shale facies, organic-matter types, and maturation levels in the New Albany can be combined to give a fairly complete picture of where and in what relative proportions hydrocarbons have been generated. The following evidence suggests that extreme southern Illinois and parts of western Kentucky were areas of intense oil generation (fig. 10):

- Predominance of black shales that have organic-carbon contents of over 2 weight percent and that have an aggregate thickness of 100 to 350 ft.
- Predominance of oil-prone Type II kerogen in the black shale facies.
- Thermal maturity within the oil generation window for Type II kerogen as shown by vitrinite reflectance values of greater than 0.6 percent and alginite fluorescence within the orange or higher range.
- Presence of solid hydrocarbons as pore and fissure fillings within the shale matrix and extensive alteration of amorphous kerogen from a continuous network to a fragmented particulate appearance.

Within the region of intense oil generation shown in figure 10 is a small area where vitrinite reflectance values exceed 1.1 percent, which is the approximate "floor" of oil generation. At these levels of maturity, wet gas and condensate are the major hydrocarbons formed by the breakdown of kerogen (Harwood, 1977). The wet gas area appears to be restricted to parts of extreme southeastern Illinois. Although data are scarce for western Kentucky, it is possible that similarly high levels of maturity occur in the deeper parts of the Moorman syncline in western Kentucky. Many of the significant gas fields in the Illinois basin have been found in the eastern part of the Moorman syncline, which suggests gas generation to the west and subsequent migration into shallower traps updip. Virtually all known

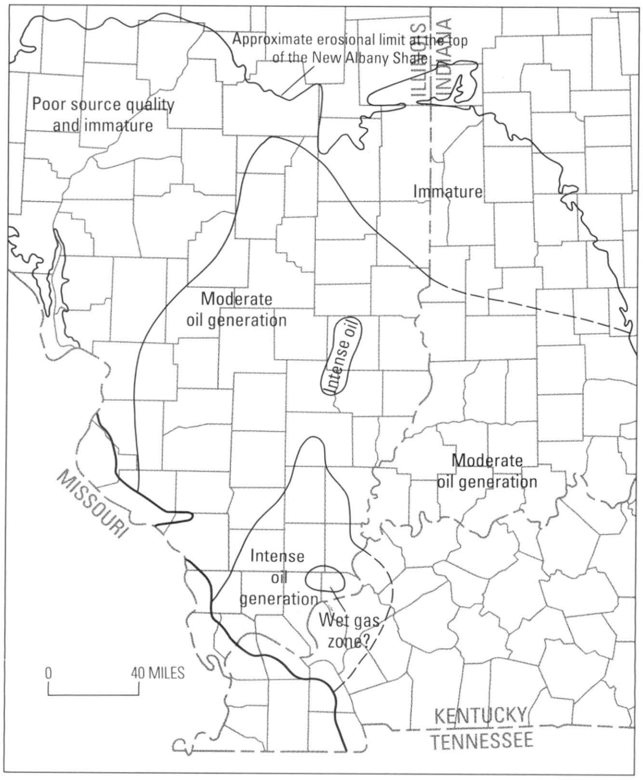

Figure 10. Areas of hydrocarbon generation in the New Albany Shale. (From Barrows and Cluff, 1984.)

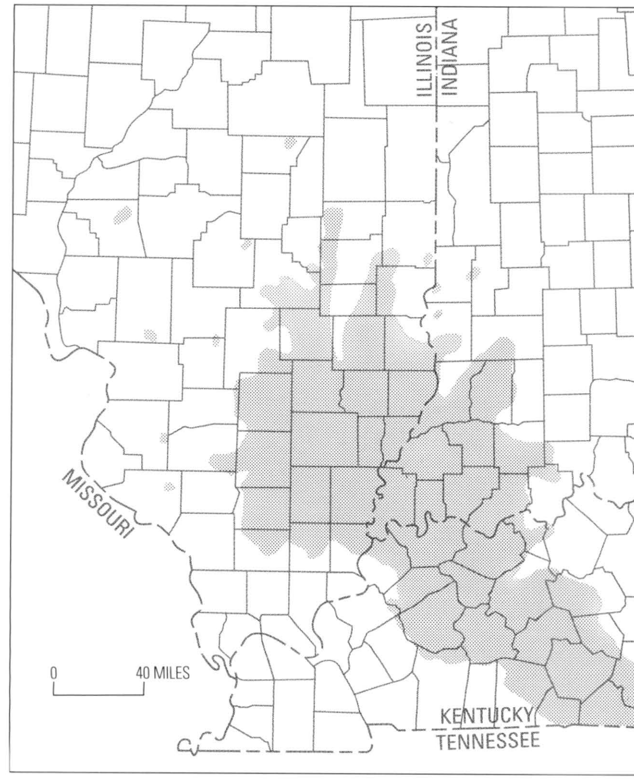

Figure 11. Areas of petroleum production (shaded) from reservoirs of Valmeyeran age.

remaining gas in the basin occurs as solution gas within oil reservoirs and a few gas-capped oil fields. Meents (1981) published analyses of natural gas from various sources in Illinois, including 412 gas and 166 oil wells. His compilation showed that most of the gas in southern Illinois is moderately wet, which is consistent with its cogeneration with liquid petroleum.

Surrounding the region of intense oil generation is a broad area that encompasses much of southwestern and central Illinois, southwestern Indiana, and western Kentucky, where oil generation may have been less intense but is still very significant (fig. 10). Although the New Albany is generally thinner in this region and contains a smaller proportion of organic-rich shales, it still contains at least some beds of good source quality. Although reflectance and fluorescence analysis indicate lower levels of maturity (0.5–0.6 percent R_o; yellow to yellowish-orange fluorescence), the values are still within at least the initial stages of oil generation (fig. 4). Gas analyses from wells in this region (Meents, 1981) indicate largely dry gas that has only traces of ethane and heavier hydrocarbons.

It is probable that no significant hydrocarbon generation occurred in the New Albany Shale across most of western Illinois or along the northern fringes of the New Albany in Illinois and Indiana. In these areas, stratigraphic studies show that only a very small part of the shale section contains appreciable organic matter, and, even in those beds, it is in low concentrations. Reflectance and fluorescence studies indicate that the organic matter has not yet reached the point of oil generation, probably because of insufficient burial.

IMPORTANCE OF NEW ALBANY OIL IN THE ILLINOIS BASIN

Maps showing the location and approximate areal extent of oil production from Valmeyeran, Chesterian, Pennsylvanian, Devonian, Silurian, and "Trenton" reservoirs in the Illinois basin are presented in figures 11 to 16. Comparison of these maps with the map showing likely areas of oil and gas generation from the New Albany Shale (fig. 10) is quite revealing.

Most of the basin's Valmeyeran oil (fig. 11) occurs within or near the area of intense oil generation in the New Albany Shale shown in figure 10. Most of the remaining accumulations in the basin occur in Chesterian (fig. 12) and Pennsylvanian (fig. 13) strata, primarily in areas immediately surrounding the area of intense generation and almost entirely within the area of at least moderate generation. All the significant oil fields in the Illinois basin (fields larger than 5 million bbl) lie within 30 miles of the area of oil

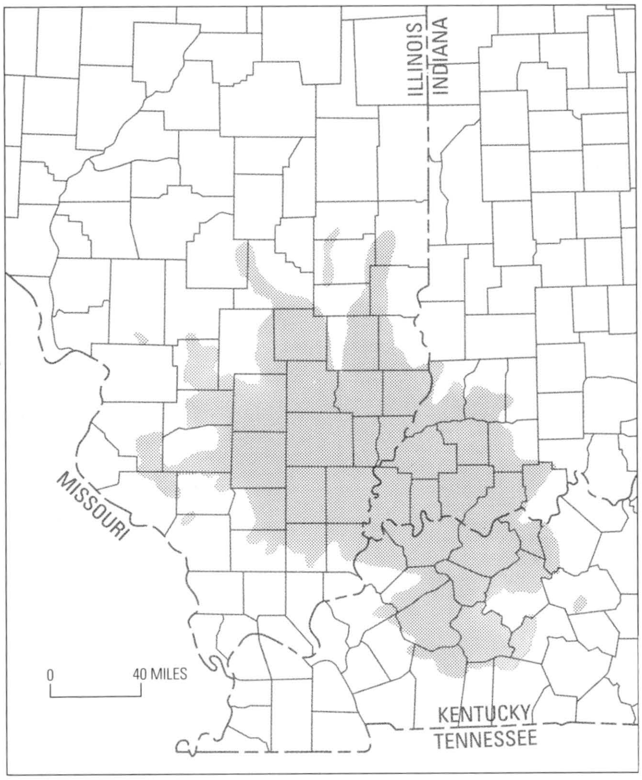

Figure 12. Areas of petroleum production (shaded) from reservoirs of Chesterian age.

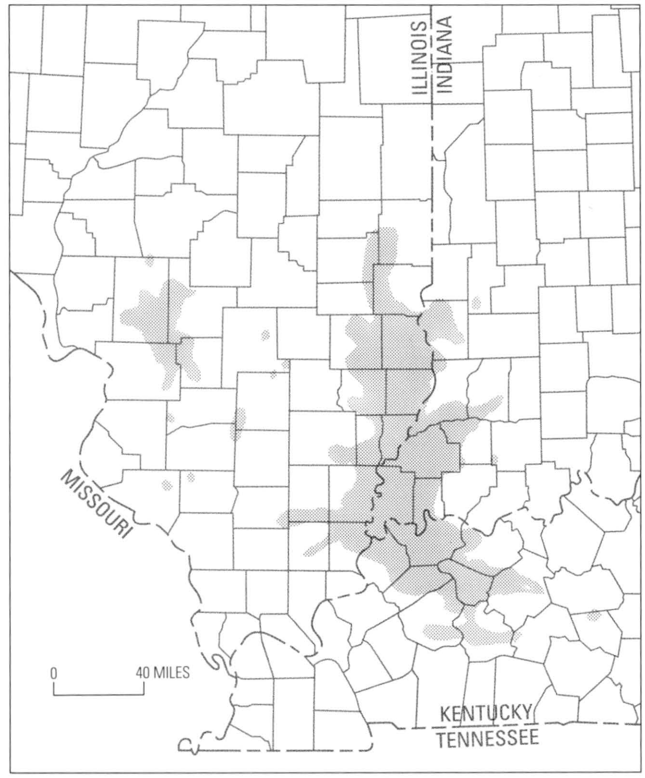

Figure 13. Areas of petroleum production (shaded) from reservoirs of Pennsylvanian age.

generation. This indicates that, if the New Albany were the primary source for oil in these traps, then over 90 percent of the basin's known oil reserves could be accounted for by oil that was locally generated and subsequently migrated vertically upward and no more than a few tens of miles laterally.

Five of the largest oil fields in the basin—Louden, Salem, New Harmony Consolidated, Lawrence County, and Main Consolidated—lie very near, but significantly outside, the area of most intense generation. Two very large fields—Clay City Consolidated and Dale Consolidated—lie within or adjacent to the area of intense generation. Two important generalizations that are especially pertinent to petroleum exploration in frontier provinces come from this observation—at the time of generation and migration, these large structures apparently gathered the hydrocarbons generated from a very broad area surrounding them, and, although the maturity levels in the immediate vicinity of these structures are below the peak oil generation window, these giant (over 100 million bbl of oil) accumulations were formed because the gathering area was large, the quality of the source rock was very good, and the thickness of the source rock was considerable. Thus, the volume of hydrocarbons available for collection was quite large, even though the source rock was not generating and expelling oil at its maximum rate.

After comparing the known producing areas and the areas of probable generation in the New Albany Shale, it appears that the bulk of the Mississippian and the Pennsylvanian oils in the Illinois basin were derived from the New Albany; some minor dilution by thin source beds possibly occurred within the various younger carbonates and shales. Although the relative contribution of younger source beds to the reserves of the basin cannot be assessed quantitatively at present, all the younger strata are at lower maturity levels than that of the New Albany, and none approach it in total bulk volume of potential source material, either in terms of organic richness or thickness of organic-bearing section. Most of the Upper Mississippian and Pennsylvanian strata were deposited in deltaic and shallow oxygenated marine environments. The organic matter in these sediments is probably degraded Type III or Type IV kerogen and, therefore, would not be a likely source for liquid petroleum.

Devonian and Silurian oil production (figs. 14, 15) occurs mostly toward the fringes of the basin, away from the areas of most oil generation in the New Albany Shale.

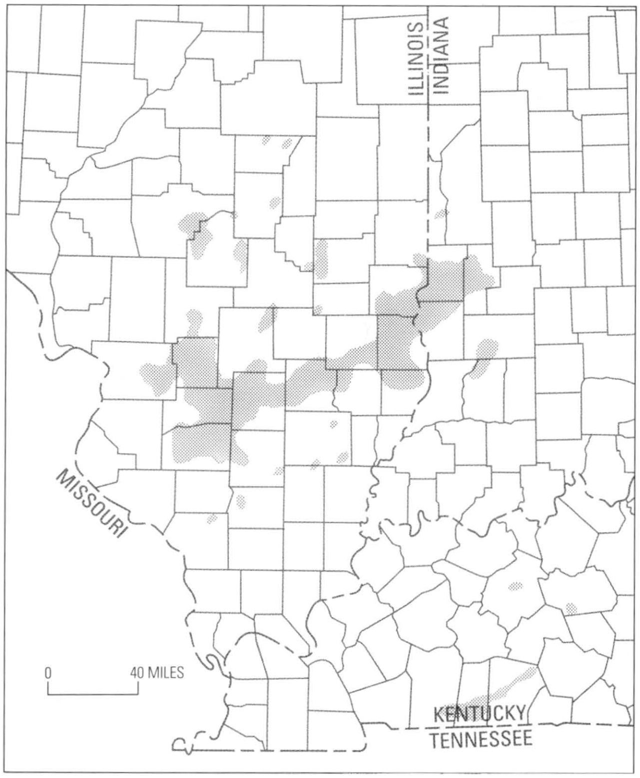

Figure 14. Areas of petroleum production (shaded) from reservoirs of Devonian age.

Figure 15. Areas of petroleum production (shaded) from reservoirs of Silurian age.

Although these fields occur in units that are stratigraphically below the New Albany, they are found to be structurally higher than mature New Albany source rocks. The deepest production yet established in the Illinois basin (5,400 ft) is from the Devonian Dutch Creek Sandstone Member at the Mill Shoals Field in White County, Ill. Mature New Albany Shale is found to be structurally deeper in the synclines on either side of this field. The distribution of Devonian and Silurian fields is controlled primarily by the occurrence of reservoir-quality porosity, which has been found toward the margins of the basin in association with several significant unconformities. These basin margin reservoirs could have been charged with New Albany oil that migrated relatively long distances (tens of miles) from structurally deeper mature areas.

Alternatively, the Devonian and Silurian reservoirs may have been locally charged from the overlying New Albany Shale or organic-bearing carbonate beds within the Devonian-Silurian succession itself or from the deeper Maquoketa Shale Group (Ordovician). I have found no evidence to support the hypothesis of effective source strata within the Devonian-Silurian carbonate section, and the Maquoketa Shale is not significantly more mature than the New Albany. This raises the question of how much oil might have been generated at the marginally mature to immature levels (about 0.5 percent R_o) found in these areas. Considering the very high organic content of the New Albany, it appears likely that, even with only a very small percentage conversion of kerogen to oil, oil fields up to a few million barrels in size might be charged in regions that would be thought of as immature.

The distribution of known "Trenton" pools is also worth noting. Like most of the Devonian-Silurian pools, they are confined to the margins of the basin where dolomitization has created reservoir-quality porosity in what is regionally a thick sequence of dense limestones (fig. 16). Thus, they pose a similar set of problems and potential answers. Oil from "Trenton" pools differs from that of other oil fields in the Illinois basin, however, in that it is highly paraffinic (Rees and others, 1943), much like Ordovician oil in other basins of the world. This geochemical evidence suggests an entirely different source rock for the "Trenton" accumulations, possibly the organic-rich shales in the immediately overlying Maquoketa.

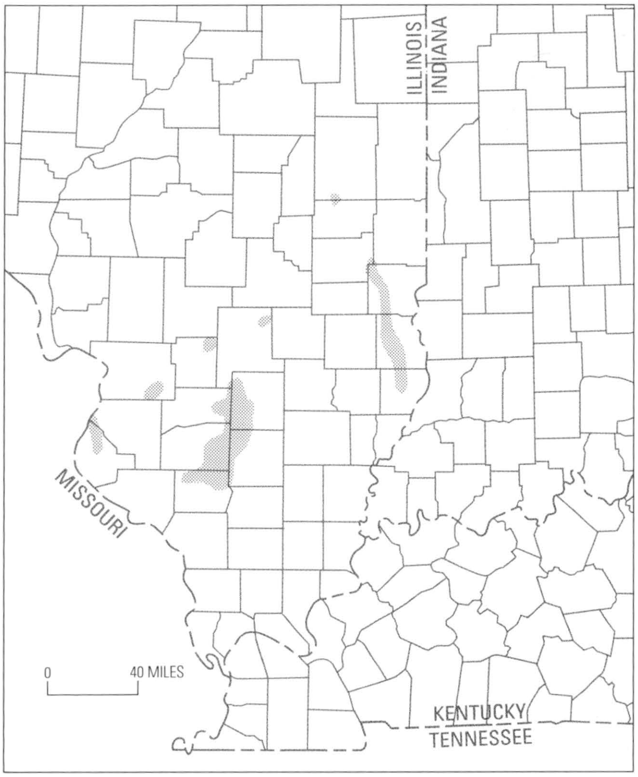

Figure 16. Areas of petroleum production (shaded) from reservoirs in the "Trenton."

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Chapter J

Use of Formation-Density Logs to Determine Organic-Carbon Content in Devonian Shales of the Western Appalachian Basin and an Additional Example Based on the Bakken Formation of the Williston Basin

By JAMES W. SCHMOKER

U.S. GEOLOGICAL SURVEY BULLETIN 1909
PETROLEUM GEOLOGY OF THE DEVONIAN AND MISSISSIPPIAN BLACK SHALE OF EASTERN NORTH AMERICA

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FIGURES

Use of Formation-Density Logs to Determine Organic-Carbon Content in Devonian Shales of the Western Appalachian Basin and an Additional Example Based on the Bakken Formation of the Williston Basin

By James W. Schmoker

Abstract

Organic-rich black shales of Middle and Late Devonian-Early Mississippian age are present in a number of basins of the North American craton and have economic importance as hydrocarbon source rocks and as unconventional reservoir rocks Organic-carbon content is an important characteristic for assessing the source-rock and hydrocarbon potential of these shales Patterns of organic-matter distribution also convey information on sedimentary processes, depositional environments, and volume of expelled hydrocarbons

Examples drawn from the Devonian shale of the western part of the Appalachian basin and the upper and lower shale members of the Bakken Formation of the Williston basin demonstrate that the organic-carbon content of black shales can be calculated accurately from formation-density logs The fundamental requirement of the density-log method is that changes in formation density result principally from changes in organic-matter content The density-log method offers the advantage of continuous large-volume sampling of the shale section and is based on wire-line logs, which are common and readily available sources of data Test calculations show good agreement between organic-carbon content calculated from density logs and that measured by laboratory analyses

Total organic carbon (weight percent) is calculated from formation-density logs by using the following equation

$$\mathrm{TOC}=(A/\rho)-B$$

where TOC is total organic carbon, ρ is formation density (grams per cubic centimeter), and A and B are constants for a particular black shale facies and geographic area In practice, A and B show little variation among different black shales

The thickness of organic-rich shale facies (defined here as having total organic carbon greater than 0 6 percent) in the western part of the Appalachian basin ranges from less than 300 feet in east-central Kentucky to more than 1,000 feet locally on the Kentucky-West Virginia border The average organic-carbon content of these facies increases systematically from about 1 5 percent in the eastern part of the mapped area to 5 percent in east-central Kentucky By comparison, the organic-carbon content of both Bakken shales exceeds 0 6 percent everywhere and averages 12 1 percent in the upper member and 11 5 percent in the lower member A regional depletion of organic carbon in the Bakken shales, which correlates with increasing levels of thermal maturity, reflects the conversion of organic matter to oil and subsequent expulsion of the oil from the formation

Facies thickness and organic-carbon content may have much different patterns of distribution The mass of organic carbon per unit surface area (proportional to the product of thickness and total organic carbon) shows the total amount of organic carbon in the shale and is mapped here for both examples The mass of organic carbon per unit surface area for the two Bakken shale members combined is roughly one-fourth that of the organic-rich Devonian shale facies of the western Appalachian basin

INTRODUCTION

The Devonian shale sequence in the western half of the Appalachian basin contains several hundred trillion cubic feet of natural gas (Charpentier and others, 1982), but these low-porosity and low-permeability shales are not reservoir rocks in the normal sense of the word Gas production depends upon permeable pathways, such as

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open fracture systems and, perhaps, siltstone laminae, to conduct gas from the matrix to the well bore.

All else being equal, recharge of the permeable system in response to the disequilibrium induced by a well is proportional to the volume of movable gas in the matrix. Laboratory analyses by contractors of the U.S. Department of Energy (Streib, 1981) and computerized well-log analyses (Hashmy and others, 1982) show that the volume of gas in the Devonian shale matrix generally increases as organic-matter content increases. Organic-matter content, which commonly is expressed as weight percent organic carbon, is, therefore, one indicator of the productive potential of the shale.

The significance of organic matter in gas production is supported by the common practice of dividing the Appalachian Devonian shales into "black" and "gray" facies in the western part of the basin. The darker zones, which have higher organic-carbon content, are ordinarily more productive than the organic-carbon-poor gray zones (see, for example, Bagnall and Ryan, 1976; Patchen, 1977). The National Petroleum Council Committee on Unconventional Gas Sources (1980, p. 30), found a statistical correlation between the initial gas production rate and the thickness of the black shale section on a county-by-county basis.

Organic matter within the Appalachian Devonian shales is the probable source of the natural gas produced from these rocks. The shales act as source rock and reservoir, the characterization of which requires quantitative knowledge of amounts and areal distributions of organic carbon.

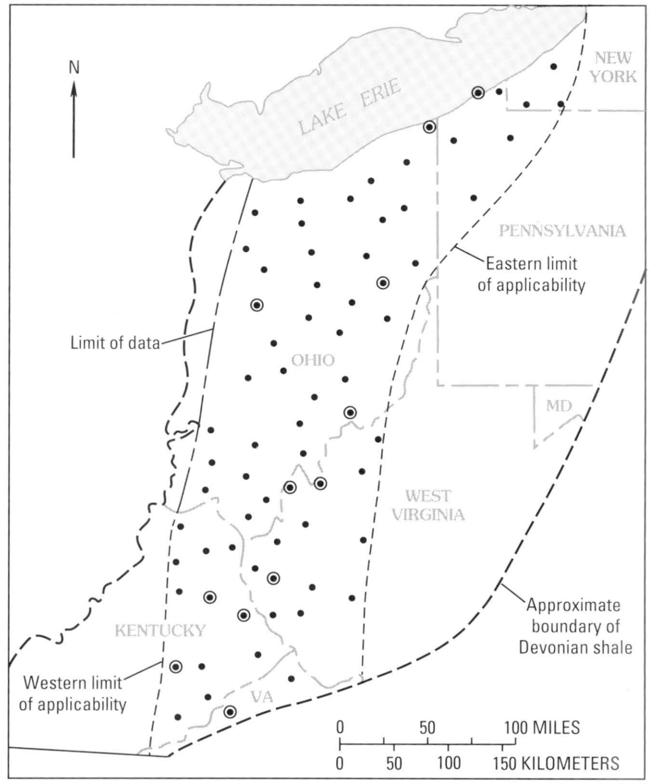

Figure 1. Study area in the western Appalachian basin showing the well locations (solid circles) used to calculate organic-carbon content from density logs (eq. 9). The circled locations indicate the wells used for comparisons with laboratory analyses. The limits of applicability define the region of inverse correlation between density and gamma-ray intensity (see "Region of Study" section). (Modified from Schmoker, 1981.)

Advantages of Wire-Line Data for Determining Organic-Carbon Content

Organic-carbon content of the Devonian shales can vary sharply in vertical distances of less than 3 feet (ft) (Leventhal and Shaw, 1980), and discrete laboratory measurements may not adequately average properties of these vertically heterogeneous rocks. Continuously recorded wire-line logs reduce the statistical uncertainties of limited and, possibly, nonrandom analyses.

Wire-line logs are also more common and more readily available than core samples. Formation-density logs form a large accessible data pool in most hydrocarbon provinces.

Although direct economic comparisons are not available, the determination of organic-carbon content is probably considerably less expensive and less time consuming from wire-line data than from laboratory analysis of core samples.

Scope of Work

This chapter, written in 1986, summarizes studies by the author on the organic-carbon content of Devonian shales in the western half of the Appalachian basin (fig. 1). Organic-carbon values are calculated from formation-density logs by using a mathematical model derived from physical properties of the shales. The model is evaluated against laboratory determinations of organic carbon. To demonstrate the relevance of the concept to other shales that have similar physical properties, an application of this model to the Bakken Formation of the Williston basin is also described.

Waples (1984) perceived the emphasis in source-rock evaluation to be shifting from traditional analysis-based methods to model-based approaches in which measured data serve to test and calibrate conceptual representations. Such model-based approaches provide a strong framework for projecting between sparse data points and extrapolating beyond available data (Waples, 1984). Uses of wire-line data for source-rock evaluation, such as is described here and by Hashmy and others (1982) and Meyer and Nederlof

(1984), are examples of such model-based approaches to geochemistry

Acknowledgments

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COMPUTATION OF ORGANIC-CARBON CONTENT FROM DENSITY LOGS

Derivation of Generalized Model

Development of a generalized equation for calculating organic-carbon content from formation-density logs follows the approach of Schmoker and Hester (1983) The model is applicable to shales that have physical properties that reasonably satisfy the assumptions used in its derivation

Organic-rich black shales are treated as a four-component system comprised of rock matrix, interstitial pores, pyrite, and organic matter and are represented by the subscripts *m*, *i*, *p*, and *o*, respectively High-density minerals, other than pyrite, are assumed to constitute a fixed but unknown percentage of the rock matrix The formation density (ρ) is then a function of the densities (ρ_o, ρ_p, ρ_i, ρ_m) and the fractional volumes (ϕ_o, ϕ_p, ϕ_i, ϕ_m) of these four components ($\phi_m = 1 - \phi_o - \phi_p - \phi_i$)

$$\rho = \phi_o\rho_o + \phi_p\rho_p + \phi_i\rho_i + (1 - \phi_o - \phi_p - \phi_i)\,\rho_m \quad (1)$$

Reduction of the number of unknowns in equation 1 begins with the assumption that the porosity of the shale does not vary sufficiently to alter significantly formation density Porosity is assumed to be low so that density differences between pore-fluid types can be neglected Pore space, therefore, is considered to be a fixed property of the rock matrix, and ρ_m is redefined to represent the volume-weighted average of grain and pore-fluid density (ρ_{mi}) This reasoning simplifies equation 1 to

$$\rho = \phi_o\rho_o + \phi_p\rho_p + (1 - \phi_o - \phi_p)\rho_{mi} \quad (2)$$

Pyrite is a common constituent of black shales and has a relatively high density of 5 0 grams per cubic centimeter (g/cm^3) Measurements of pyrite content in the Appalachian Devonian shales suggest that an increase of pyrite as organic matter increases can be approximated by the following empirically derived linear equation (Schmoker, 1979)

$$\phi_p = 0\ 135\phi_o + 0\ 0078 \quad (3)$$

Equation 3 is assumed here to be the general case, which seems reasonable in view of the similar properties of many black shales but which is a possible source of error

By substituting for ϕ_p using equation 3, setting ρ_p equal to 5 0 g/cm^3, and rearranging terms, equation 2 becomes

$$\phi_o = (\rho - 0\ 992\rho_{mi} - 0\ 039)/(\rho_o - 1\ 135\rho_{mi} + 0\ 675) \quad (4)$$

Weight percent total organic carbon (TOC) is the most common measure of organic richness and is related to the fractional volume of organic matter (ϕ_o) by the equation

$$\mathrm{TOC} = \phi_o(100\rho_o)/(R\rho) \quad (5)$$

where R is the ratio of weight percent organic matter to weight percent TOC By substituting for ϕ_o using equation 4, equation 5 becomes

$$\mathrm{TOC} = [(100\rho_o)(\rho - 0\ 992\rho_{mi} - 0\ 039)]/[(R\rho)(\rho_o - 1\ 135\rho_{mi} + 0\ 675)] \quad (6)$$

Equation 6 represents a generalized model for calculating organic-carbon content from density logs in formations typified by organic-rich Devonian shales of the western part of the Appalachian basin In practice, the rather formidable appearance of equation 6 can be simplified

$$\mathrm{TOC} = (A/\rho) - B \quad (7)$$

ρ_o and R are not true constants but vary with changes in organic-matter type and level of thermal maturity, ρ_{mi} similarly varies with changes in matrix composition However, as demonstrated by test calculations (see section "Test Calculations"), the first-order assumption used here of fixed values for these parameters throughout the study area is adequate in a practical sense Ideally, with sufficient geochemical and compositional information, A and B (eq 7) could be adjusted for individual facies and particular geographic areas

In the great majority of instances, specific measurements of ρ_o, ρ_{mi}, and R are not available Furthermore, such measurements are difficult and time consuming to obtain in the laboratory, and to do so negates the simplicity that is one of the major advantages of the density-log method described here Evidence that the porosity of black shales may increase as organic-matter content increases (Hashmy and others, 1982) further complicates the picture, the value for ρ_o of about 1 0 g/cm^3 suggested by Smith and Young (1964) may reflect organic matter and porosity associated with the organic matter Kinghorn and Rahman (1983) found that the specific gravity of kerogen, as determined by centrifuging kerogen concentrates in heavy liquids, may be at least 1 3 g/cm^3 Nevertheless, comparisons of computed values of organic-carbon content to laboratory measurements for Appalachian Devonian shales, the two shale members of the Bakken Formation (Williston basin), and the Woodford Shale of the Anadarko basin indicate that the constants A and B of equation 7 vary within narrow ranges Although A and B are evaluated here in terms of ρ_o, ρ_{mi}, and R, it may prove more realistic in future work to regard A and B as empirically determined constants incorporating the complex effects of shale and organic-matter properties and interactions

Specific Model for Appalachian Devonian Shales

The specialized equation used by Schmoker (1979, 1980) to compute organic-matter content of Devonian shales of the western Appalachian basin follows from equation 4 by setting ρ_o equal to 1 0 g/cm^3 (a density that may represent organic matter and additional porosity associated with it) and ρ_{mi} equal to 2 69 g/cm^3 and by defining ρ_B as the formation density if no organic matter is present (that is, ρ is equal to ρ_B if ϕ_o is equal to 0)

$$\phi_o = (\rho_B - \rho)/1\ 378 \qquad (8)$$

To calculate organic richness as weight percent TOC, rather than fractional volume of organic matter (ϕ_o), equations 5 and 8 are combined to eliminate ϕ_o If ρ_o is equal to 1 0 g/cm^3 and assuming R is equal to 1 3 as a regionally representative value for the organic matter in the Devonian shales, then

$$\mathrm{TOC} = 55\ 822[(\rho_B/\rho) - 1] \qquad (9)$$

Equation 9 is the specialized equation used by Schmoker (1979, 1980) modified to express organic richness as weight percent organic carbon and is written in a form analogous to that of the generalized model (eq 7) At each well location, ρ_B is determined from the density log by examining the most dense intervals of the gray shale zones, which are assumed to contain relatively insignificant amounts of productive organic matter Such an empirical determination of ρ_B corrects the density log for calibration bias Log values of ρ_B in the Appalachian Devonian shales typically range between 2 67 and 2 72 g/cm^3

Test Calculations

The laboratory measurements of TOC of core samples from 74 intervals in 12 widely spaced wells (fig 1) provide a representative data set for comparison to organic-carbon values calculated from density logs by using equation 9 The laboratory data are taken from Schmoker (1979) and Monsanto Research Corporation (1978, 1979) Comparison intervals average about 80 ft in thickness and were selected on the basis of lithologic boundaries within the shales and availability of laboratory analyses

Agreement between interval organic-carbon contents calculated from density logs (eq 9) and that measured in the laboratory is good (fig 2) Significant systematic deviations from the line of ideal correlation are not apparent, and no log-determined organic-carbon values are patently "wrong " Because identical sample sets are not compared and experimental errors are also present in laboratory data, differences between laboratory and density-log results

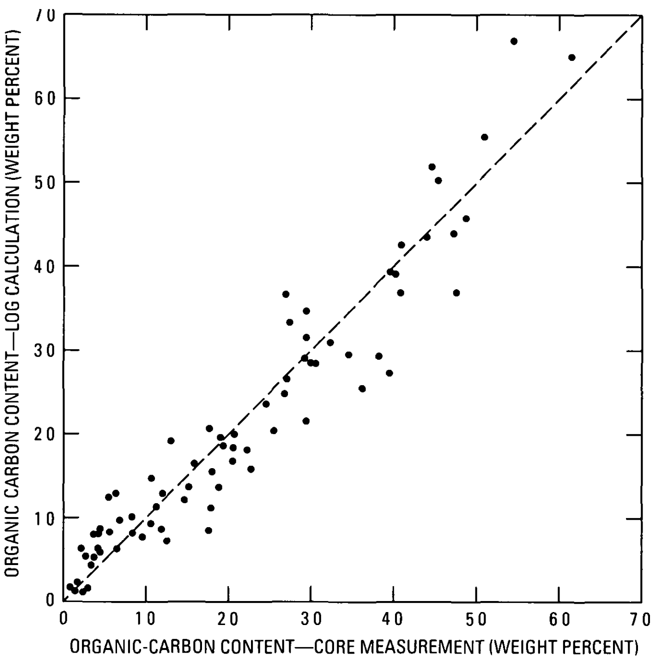

Figure 2. Comparison of the organic-carbon contents of selected intervals of Appalachian Devonian shales calculated from density logs (eq 9) and measured from core samples Ideal agreement is shown by the dashed line

should not be attributed solely to inaccuracies in the density-log method

The distribution of differences between interval organic-carbon content measured in core samples and that calculated from density logs has a mean of 0 03 percent and a standard deviation of 0 48 percent and resembles a normal distribution (fig 3) Considered together, the data of figures 2 and 3 show that assumptions used in the derivation of the computational model are reasonable, that the values used for A and B (eq 7) represent the shale and organic-matter system, and that the density-log method is sufficiently accurate and reliable for most geologic applications in which detailed vertical resolution is not a requirement

DISTRIBUTION OF ORGANIC CARBON

Region of Study

The fundamental requirement of the density-log method is that changes in formation density result principally from changes in organic-matter content For the case of the Appalachian Devonian shales, data from the gamma-ray log provide an independent check of this requirement

The gamma-ray log records the intensity of natural gamma radiation emitted by potassium-40 and elements in the uranium and thorium decay series Devonian shale facies rich in organic matter have high gamma-ray intensities because uranium is associated with the organic matter,

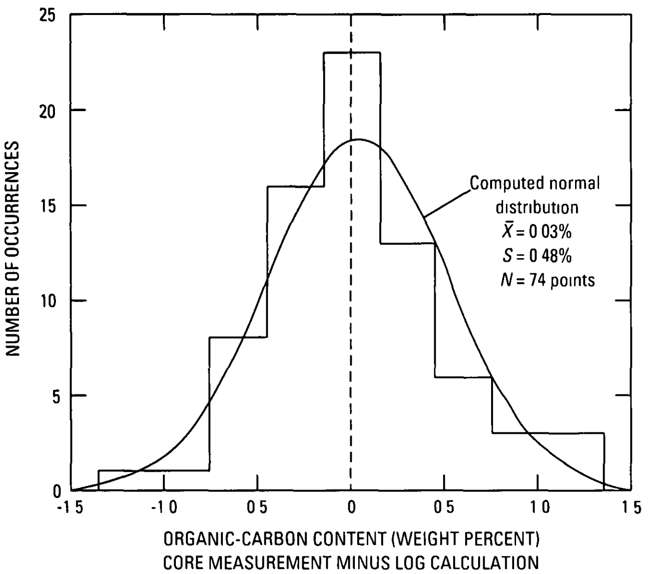

Figure 3. Distribution of differences between the organic-carbon contents of selected intervals of Appalachian Devonian shales measured from the core samples and calculated from the density logs (eq 9)

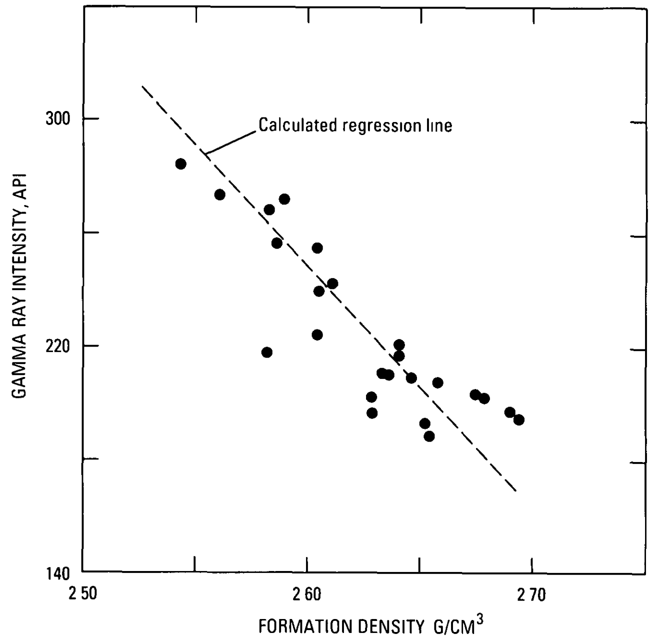

Figure 4. Wire-line data from Jackson County, W Va , smoothed by averaging 20-ft intervals, showing inverse correlation between formation density and gamma-ray intensity that is typical of Devonian shales in most of the western Appalachian basin. The linear correlation coefficient is −0 86, and the standard deviation of density about the regression line is 0 021 g/cm^3 API, American Petroleum Institute (Modified from Schmoker, 1979)

whereas concentrations of thorium and potassium-40 are relatively constant at a given location (McKelvey and Nelson, 1950, Swanson, 1956, Conant and Swanson, 1961, Leventhal and Goldhaber, 1978) Consequently, an inverse correlation between density and gamma-ray intensity in a given well indicates that density variations are indeed caused primarily by variations in organic-matter content

The region of applicability (fig 1) marks an area of about 50,000 square miles in the western part of the Appalachian basin where, in a given well, formation density and gamma-ray intensity, which are smoothed by averaging log intervals of 20 to 40 ft, show a significant inverse correlation (fig 4) Such a correlation increases confidence in the density-log method and is used here to define the region of study In the general case, however, uranium concentration can also vary in response to factors unrelated to organic-matter content, and the inverse correlation typified by figure 4 is not a requisite condition for application of the density-log method

Organic-Rich Facies

Traditionally, color has been the criterion for separating the Devonian shale sequence into "black" (organic-rich) and "gray" (organic-poor) facies The quantitative data of Hosterman and Whitlow (1981) confirm a correlation between color and organic-matter content However, because "black" usually is determined subjectively, the internal consistency and correspondence between studies are difficult to establish (Charpentier and Schmoker, 1982) Definitions of organic-rich and organic-poor facies also have been based on gamma-ray intensity "Black" facies have higher gamma-ray intensities because uranium and organic matter are associated (see preceding section) However, the organic-matter content that corresponds to a given gamma-ray level varies within the basin (Schmoker, 1981), and facies definitions based on gamma-ray criteria are, therefore, not absolute

Schmoker (1980) considered Devonian shale facies that have an organic-matter content of greater than 2 percent by volume (TOC equals 0 6 percent in the context of this chapter) to be organic rich, that quantitative and regionally invariant definition is accepted here The boundary value of 0 6 percent organic carbon is somewhat arbitrary but corresponds closely to a commonly accepted level for hydrocarbon source rocks of 0 5 percent organic carbon (Tissot and Welte, 1978, p 430) On the basis of analyses of the methane content of Devonian shale core that was sealed immediately upon recovery, the 0 6-percent boundary corresponds also to a transition point below which the movable-gas content of the shales decreases sharply (Schmoker, 1980)

The density-log method is applied here to facies of the Appalachian Devonian shales that have an organic-carbon content of greater than 0 6 percent Data from the various organic-rich intervals of a given well are aggregated without stratigraphic differentiation

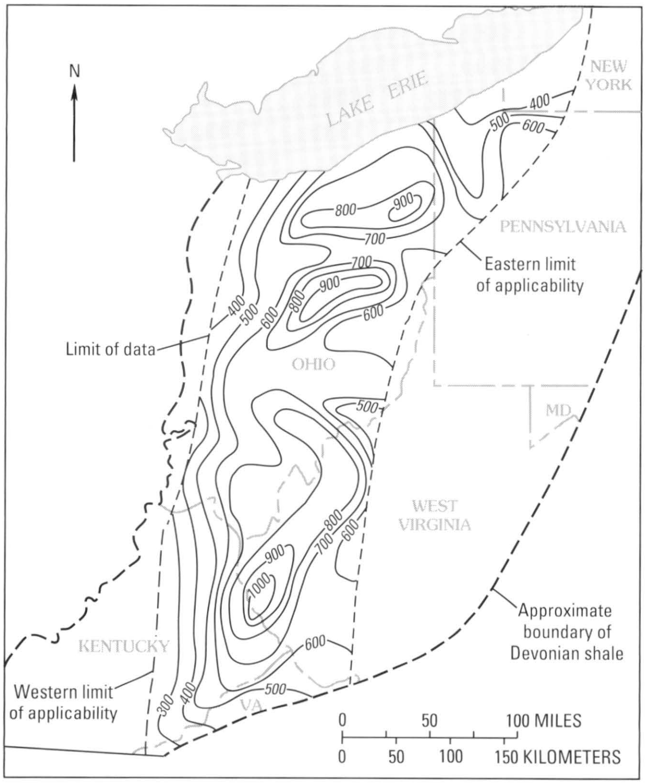

Figure 5. Thickness, in feet, of the organic-rich Devonian shale facies (total organic carbon is greater than 0.6 percent as determined from density logs (eq. 9)). Data are from the well locations shown in figure 1. Contour interval is 100 ft. (Modified from Schmoker, 1980.)

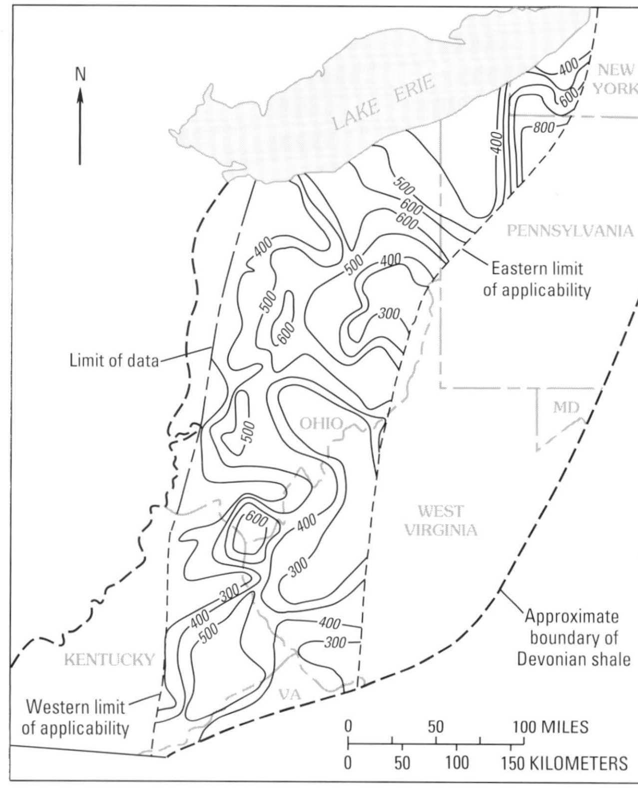

Figure 6. Thickness, in feet, of the "black" Devonian shale facies based on the color of well cuttings (Wallace and de Witt, 1975). Contour interval is 100 ft.

Thickness of Organic-Rich Facies

The thickness of organic-rich Devonian shale facies in the western Appalachian basin ranges from less than 300 ft in east-central Kentucky to more than 1,000 ft locally on the Kentucky-West Virginia border (fig. 5). Several maxima occur along the north-south trend that is the dominant regional feature of the map. Three east-trending lobes appear to continue beyond the mapped area (fig. 5).

The isopach map of "black" Devonian shale facies compiled by Wallace and de Witt (1975) on the basis of the color (subjectively determined) of well cuttings shown in figure 6 shows general trends similar to those of figure 5. Wallace and de Witt's boundary between "black" and "gray" facies is probably about 1.2 percent organic carbon (Charpentier and Schmoker, 1982). Differences between figures 5 and 6 reflect the inclusion in figure 5 of shales that have organic-carbon contents of between 0.6 and about 1.2 percent and are considered here to be effective source rocks where thermally mature and to contain significant reserves of natural gas. In the study area, the volume of shale that has an organic-carbon content of greater than 0.6 percent, as determined by planimetry from figure 5, is approximately 700×10^{12} cubic feet (ft^3).

Organic-Carbon Content

The average organic-carbon content of the organic-rich Devonian shale facies, which is calculated from formation-density logs by using equation 9, increases systematically from about 1.5 percent in the eastern part of the mapped area to 5 percent in east-central Kentucky (fig. 7). The organic-rich facies become steadily "blacker" to the west, whereas their thickness, which has a regional maximum trending roughly through the center of the study area (fig. 5), follows a much different pattern. Facies thickness alone does not adequately characterize the organic-rich shales.

A histogram of the average organic-carbon content of 40-ft intervals in the organic-rich facies of the study area is shown in figure 8. About one-third of the intervals have an organic-carbon content of between 0.6 and 1.2 percent. Maximum richness is about 9 percent. The frequency of occurrence decreases roughly exponentially as organic-carbon content increases.

The distribution of figure 8 includes data from many wells and combines subtrends within the study area (for example, Schmoker, 1980, fig. 7). This histogram (fig. 8) and its exponential approximation are, therefore, broad-scale statistical characterizations and not quantitative

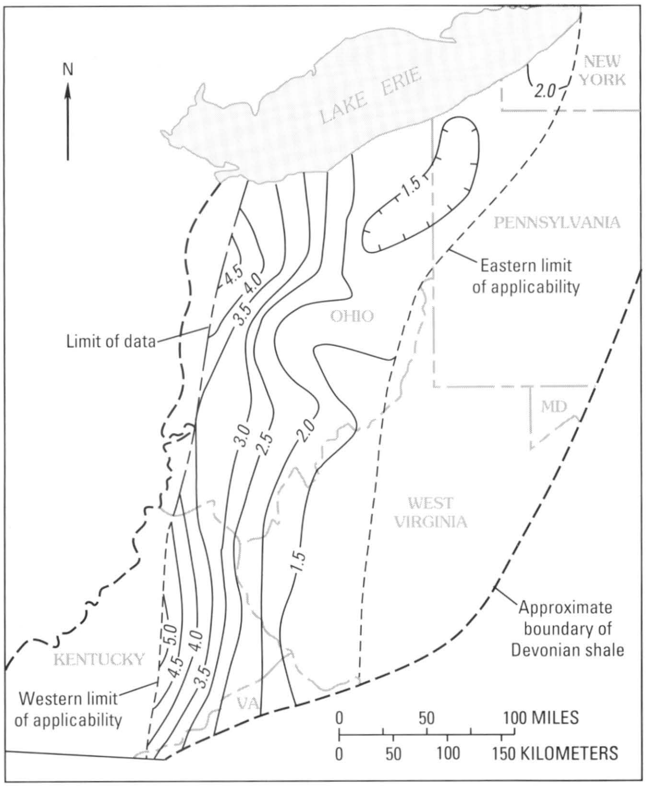

Figure 7. Average organic-carbon content (weight percent) of organic-rich Devonian shale facies (total organic carbon is greater than 0.6 percent). The organic-carbon content is determined from formation-density logs (eq. 9). Data are from the well locations shown in figure 1. Contour interval is 0.5 percent. (Modified from Schmoker, 1980.)

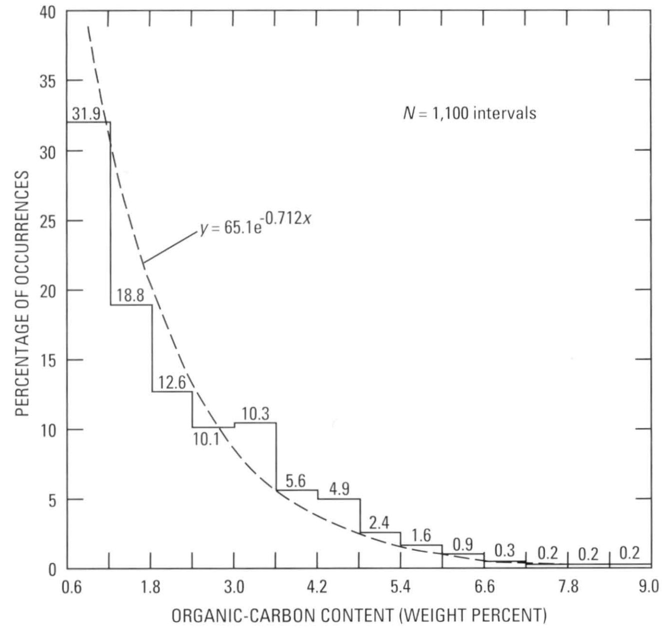

Figure 8. Average organic-carbon content of 40-ft intervals of the organic-rich Devonian shale facies (total organic carbon is greater than 0.6). The organic-carbon content is determined from formation-density logs (eq. 9). Data are from the well locations shown in figure 1.

predictors of the organic-carbon distribution at a given location.

Mass of Organic Carbon

The organic-carbon content (figs. 7, 8) is independent of facies thickness (fig. 5) and, therefore, is not a measure of the total amount of organic material in the organic-rich Devonian shale facies. For this reason, the mass of organic carbon per unit area of ground surface (in kilograms per square centimeter), which is defined as the product of organic-carbon content (weight percent per 100), formation density (kilograms per cubic centimeter), and facies thickness (centimeters), is introduced (fig. 9). Figure 9 shows the amount of organic carbon (kilograms per square centimeter) in the blanket of organic material that would remain if all inorganic minerals were removed.

The mass of organic carbon per unit area ranges between about 0.4 and 2.0 kilograms per square centimeter (kg/cm^2) in the study area (fig. 9). A north-trending maximum extends from eastern Kentucky to Lake Erie and has three areas of local increase. The total mass of organic carbon in the organic-rich Devonian shale facies of the mapped area, which is estimated by planimetering the isopleths of figure 9, is about 1.2×10^{15} kilograms (kg), which corresponds to a volume of organic material of about 52×10^{12} ft^3. Under favorable conditions, enormous volumes of hydrocarbons could have been generated within these facies.

Vitrinite reflectance (R_o) data indicate that thermal maturity increases generally to the east-southeast in the region of study (fig. 9). A value of 1.5 percent R_o, which is attained in western West Virginia, implies maturity beyond peak oil generation, whereas the 0.6-percent contour is often assumed to approximate the onset of oil generation (for example, Tissot and Welte, 1978, p. 451). Significantly, a substantial fraction of the organic matter in the study area is probably thermally immature (fig. 9) and, thus, did not generate appreciable volumes of thermogenic hydrocarbons.

Decreasing vitrinite reflectance (fig. 9) correlates roughly with increasing organic-carbon content (fig. 7). However, the regional increase in organic-carbon content continues west of the 0.6-percent reflectance contour into the area that is thermally immature. Variations in organic-carbon content, thus, are influenced by original depositional patterns, as well as by a probable depletion of organic matter basinward as a result of the generation and subsequent expulsion of hydrocarbons.

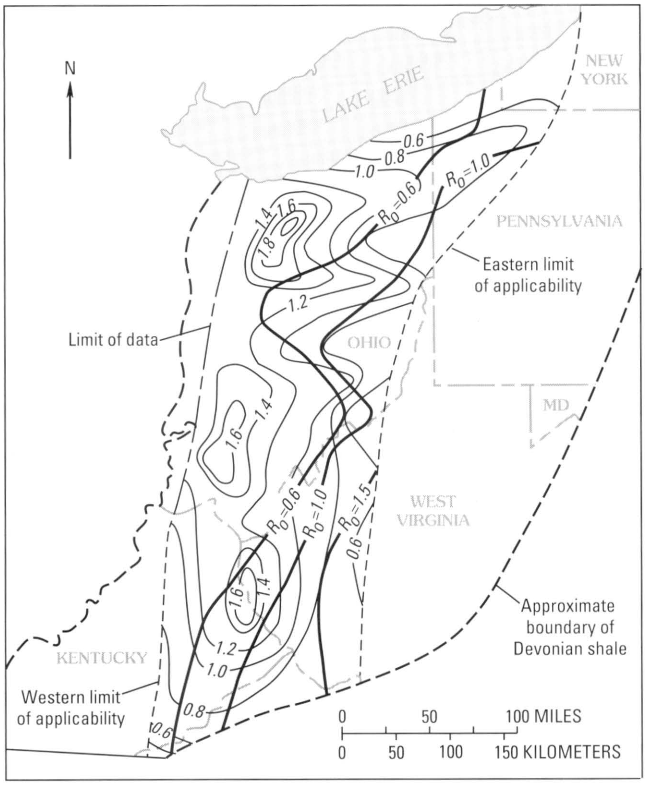

Figure 9. Mass of organic carbon per square centimeter of surface area, in kilograms per square centimeter, in the organic-rich Devonian shale facies (total organic carbon is greater than 0.6 percent). Data are from the well locations shown in figure 1. The contour interval is 0.2 kg/cm^2. (Modified from Schmoker, 1980.) The heavy lines contour the average vitrinite reflectance of the Devonian shale section at 0.6, 1.0, and 1.5 percent R_o. This illustration is based on data from 13 wells compiled by Streib (1981).

APPLICATION TO OTHER AREAS

Organic-rich black shales of Middle and Late Devonian and Early Mississippian age are present in a number of basins of the North American craton. In addition to the Devonian shales of the Appalachian basin, examples include the Antrim Shale of the Michigan basin, the New Albany Shale of the Illinois basin, the Bakken Formation of the Williston basin, and the Woodford Shale of the Anadarko basin. Such formations have significant economic importance as source rocks.

The various black shales have physical characteristics that satisfy the basic assumptions of equations 1 through 7, and the model applied here to Devonian shales of the western part of the Appalachian basin is therefore applicable to black shales of other basins as well. The following example based on the Bakken Formation illustrates a second application.

Geologic Setting of the Bakken Formation

The Williston basin is oil prone, and geochemical characterizations show that the Bakken Formation is a source of oil in the basin (Dow, 1974; Williams, 1974; Thode, 1981). The Bakken Formation can be divided into upper and lower black shale members separated by a calcareous siltstone containing essentially no organic matter (Kume, 1963). These three members are recognizable on gamma-ray and formation-density logs and maintain their general character throughout the basin.

Source-rock and oil-reservoir properties of the Bakken Formation have been described by Meissner (1978), Schmoker and Hester (1983), Wilson (1983), Price and others (1984), Webster (1984), and Hester and Schmoker (1985).

Distribution of Organic Carbon in the Bakken Formation

Because of the log settings normally used in the Williston basin, gamma-ray intensity is generally off scale in the Bakken shale members and so cannot be correlated against formation density in the manner illustrated in figure 4. Also, because no shale intervals occur in which organic-matter content approaches zero, the specialization of equations 8 and 9 is inappropriate. Rather, the organic-carbon content of the upper and the lower Bakken shale members is calculated from density logs by using the basic model of equation 7 (Schmoker and Hester, 1983),

$$\mathrm{TOC} = (154.497/\rho) - 57.261 \qquad (10)$$

Test data from 39 wells in North Dakota show good overall agreement between organic-carbon contents calculated from density logs (eq. 10) and those measured in the laboratory (Schmoker and Hester, 1983). Values for A and B (eq. 7), which are slightly different than those assumed for Appalachian Devonian shales, optimize agreement with laboratory analyses.

Throughout most of the area mapped (figs. 10, 11), average organic-carbon content of the upper and lower Bakken shale members is very high, averaging 12.1 percent in the upper member and 11.5 percent in the lower member. Locally, organic-carbon content decreases toward the southeastern and the extreme southwestern map edges of the upper member (fig. 10) and the northeastern map edge of the lower member (fig. 11). Organic matter in these edge zones may not have been as well preserved during deposition, thus resulting in a lower organic-carbon content and a more refractory kerogen that has poorer oil-generation potential (Schmoker and Hester, 1983; Price and others, 1984).

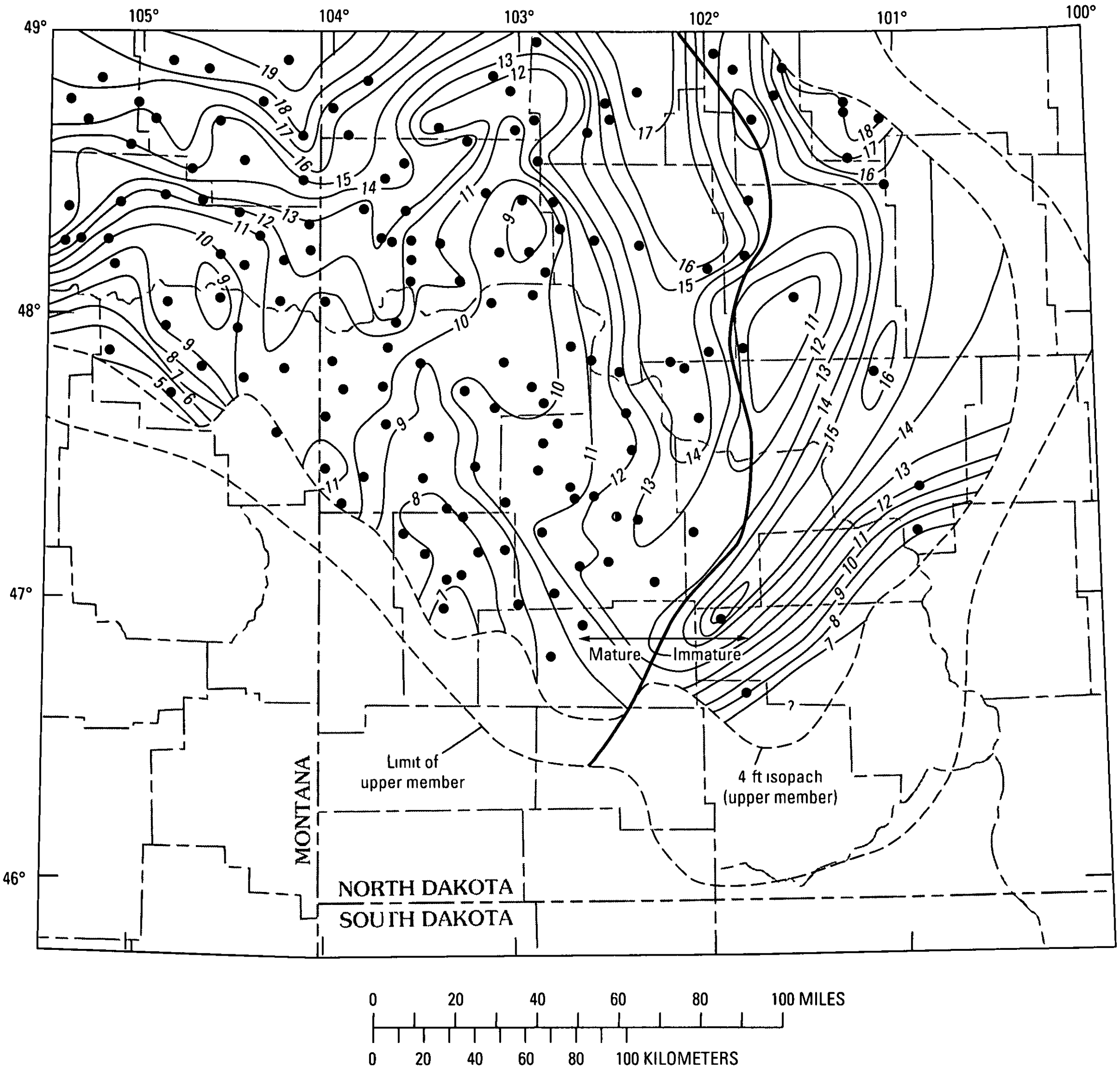

Figure 10. Average organic-carbon content (weight percent) of the upper member of the Bakken Formation. The organic-carbon content is determined from formation-density logs (eq. 10) at the locations shown by solid circles. The boundary between thermally mature and immature regions is modified from Meissner (1978). The 4-ft isopach marks the minimum thickness for representative density-log response. The contour interval is 1.0 percent. (Modified from Schmoker and Hester, 1983.)

Although the Bakken shales are exceptionally rich in organic matter (figs. 10, 11), they are relatively thin. Maximum thickness of the upper member is about 20 ft and of the lower member is about 45 ft. The mass of organic carbon per unit area of ground surface (figs. 12, 13, measured in grams per square centimeter rather than kilograms per square centimeter as in fig. 9) can be as high as 150 g/cm^2 in the upper member and 350 g/cm^2 in the lower member. Regional trends are relatively simple and primarily reflect changes in member thickness. Organic carbon per unit area for the upper and the lower Bakken shale members combined (figs. 12, 13) is roughly one-fourth that of the organic-rich Devonian shale facies (fig. 9).

Organic Carbon and Thermal Maturity

Considered regionally, organic-carbon content of both shale members in the thermally mature portion of the study area tends to increase outward from the central basin in a horseshoe-type pattern that opens to the southwest (figs. 10, 11). This trend resembles the pattern of present-day Bakken isotherms but does not correlate well with structure and thickness patterns, which partially reflect depositional parameters (Hester and Schmoker, 1985). The observed regional trend in organic-carbon content is likely the result of the conversion of organic matter to oil (subsequently expelled from the formation), in a process

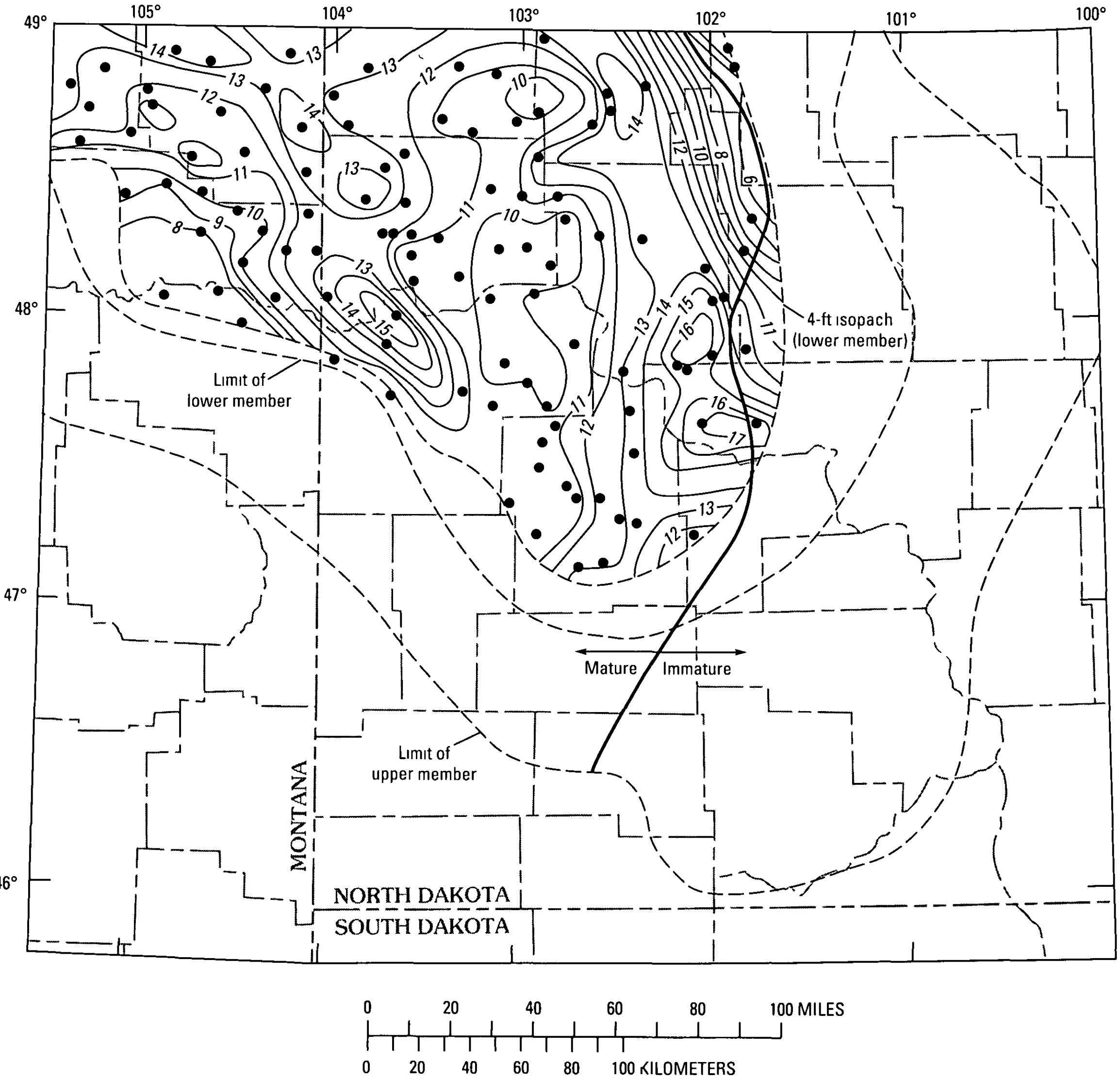

Figure 11. Average organic-carbon content (weight percent) of the lower member of the Bakken Formation The organic-carbon content is determined from formation-density logs (eq 10) at the locations shown by solid circles The boundary between thermally mature and immature regions is modified from Meissner (1978) The 4-ft isopach marks the minimum thickness for representative density-log response The contour interval is 1 0 percent (Modified from Schmoker and Hester, 1983)

that has proceeded longer and at greater rates in the more thermally mature area of the basin

This interpretation is reinforced by the data in figure 14 As vitrinite reflectance increases beyond a threshold value, the organic-carbon content progressively decreases from the average representative of immature shales The inflection point in the data of the figure indicates that significant expulsion of oil from the formation begins at about 0 55 percent R_o The onset of oil generation would be at slightly lower maturity and lower than the value assumed for Appalachian Devonian shales (0 6 percent R_o, fig 9) Scatter in the organic-carbon data of figure 14 reflects local depositional variations upon which regional effects of thermal maturation are superposed Roughly estimated, however, the organic-carbon content drops from a background level of 13 7 percent to about 8 percent at 1 05 percent R_o Formation-density logs thus provide independent evidence for the significance of the Bakken Formation as a source of hydrocarbons

The total mass of organic carbon in the upper and lower members of the Bakken Formation in the mapped area, which was estimated from figures 12 and 13 by planimetry, is about 68×10^{12} kg and 58×10^{12} kg, respectively, of which 47×10^{12} kg and 55×10^{12} kg are within the thermally mature region defined by Meissner (1978) If it is assumed that an average of 170 milligrams of hydrocarbons per gram of TOC has migrated out of the thermally mature Bakken shales (Jones, 1981, table 1), which is equivalent

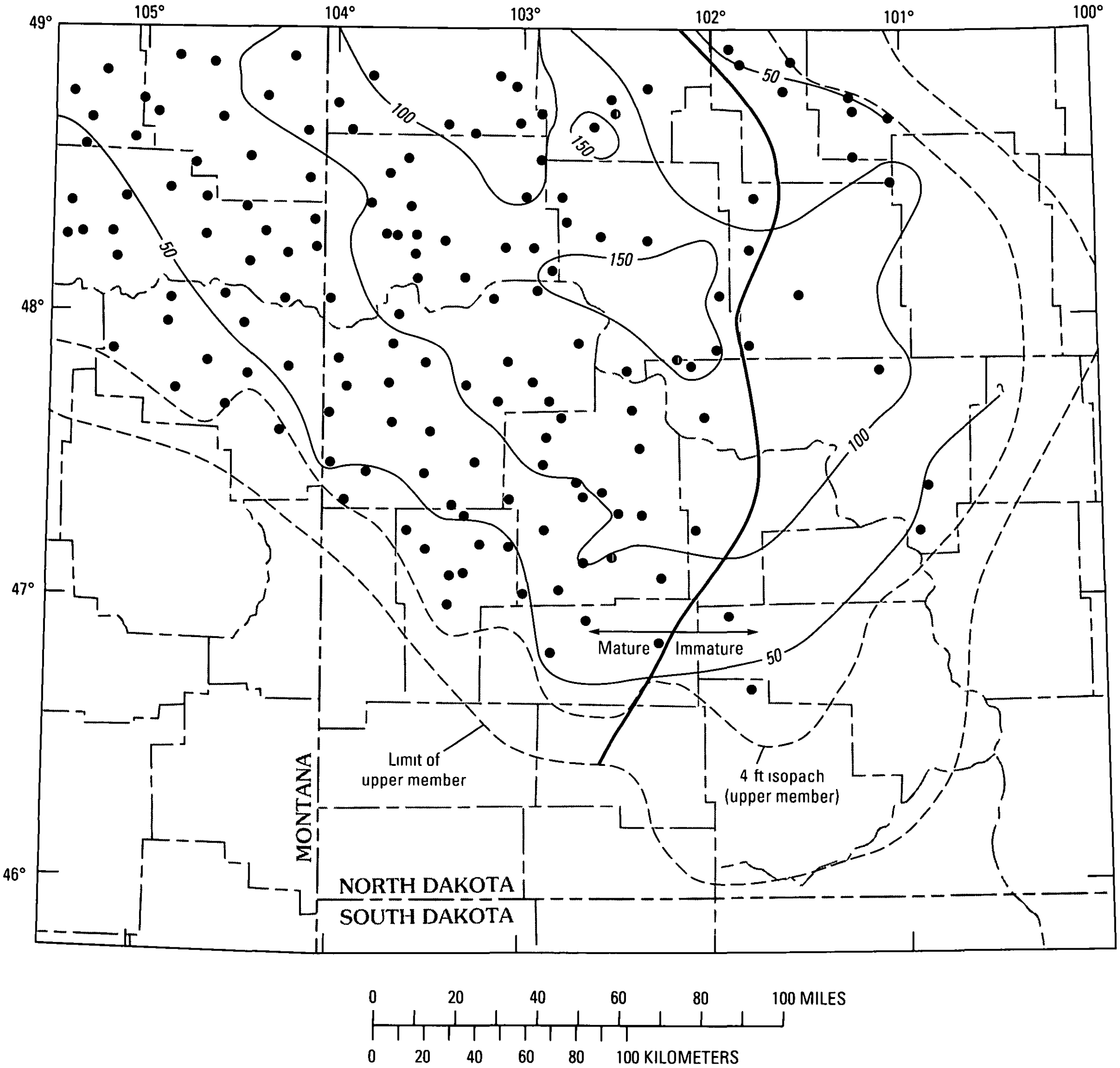

Figure 12. Mass of organic carbon per square centimeter of surface area, in grams per square centimeter, in the upper member of the Bakken Formation Solid circles show well locations The boundary between thermally mature and immature regions is modified from Meissner (1978) The 4-ft isopach marks the minimum thickness for representative density-log response The contour interval is 50 g/cm^2 (Modified from Schmoker and Hester, 1983)

to an average decrease in organic-carbon content from 13 7 to 12 1 percent (fig 14), then a mass of hydrocarbons equal to more than 130 billion bbl of 43° (American Petroleum Institute gravity) oil has been expelled from the U S portion of the Bakken shale members (Schmoker and Hester, 1983)

SUMMARY

Quantitative determinations of organic-carbon distribution in black shales convey significant information on source-rock potential, hydrocarbon resources, depositional environments, sedimentary processes, and burial diagenesis The method described here for determining the organic-carbon content from wire-line data offers technical advantages that include economy, applicability to large geographic areas, continuous sampling of vertically heterogeneous shale sections, a large sample volume (several cubic feet), and the ready availability of density logs In addition, the reliability and the accuracy of results appear to be about equal to those of core analyses

As a cautionary note, however, shales to which this method is applied must have physical and geochemical

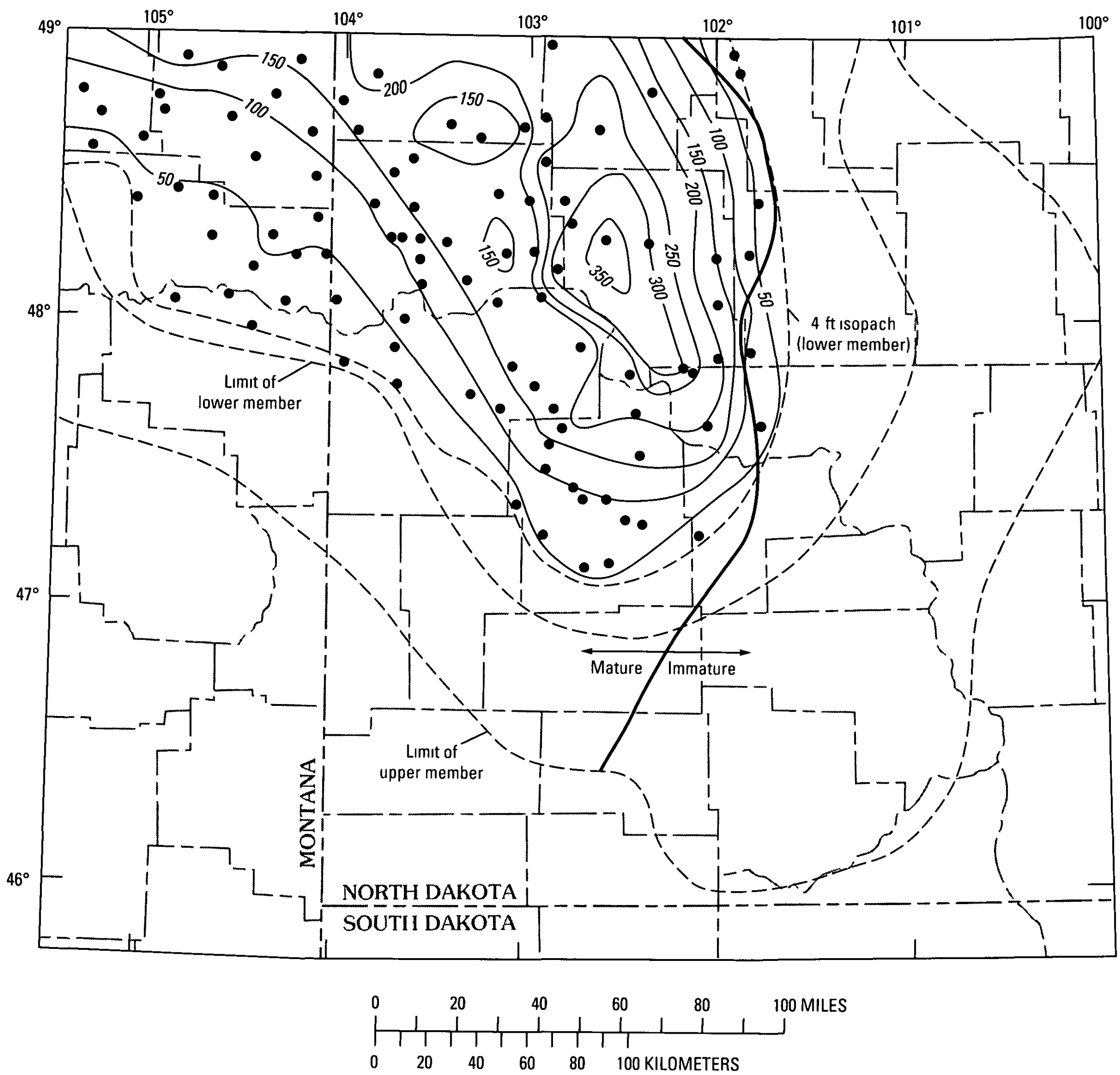

Figure 13. Mass of organic carbon per square centimeter of surface area, in grams per square centimeter, in the lower member of the Bakken Formation Solid circles show well locations The boundary between the thermally mature and immature regions is modified from Meissner (1978) The 4-ft isopach marks the minimum thickness for representative density-log response The contour interval is 50 g/cm^2 (Modified from Schmoker and Hester, 1983)

characteristics that reasonably satisfy assumptions used in the derivation of the general model, that is, the shales must have properties quite similar to those of the organic-rich Devonian shale facies of the western Appalachian basin Organic-rich shales meeting this requirement are present in a number of cratonic basins, and the approach reported here appears to have rather broad utility

A considerable conceptual difference exists between a set of measurements and a predictive model This chapter describes a model-based approach to evaluation of organic-carbon content, in which traditional laboratory analyses are used to calibrate and test the model representation The approach provides a framework for the projection and extension of measured data

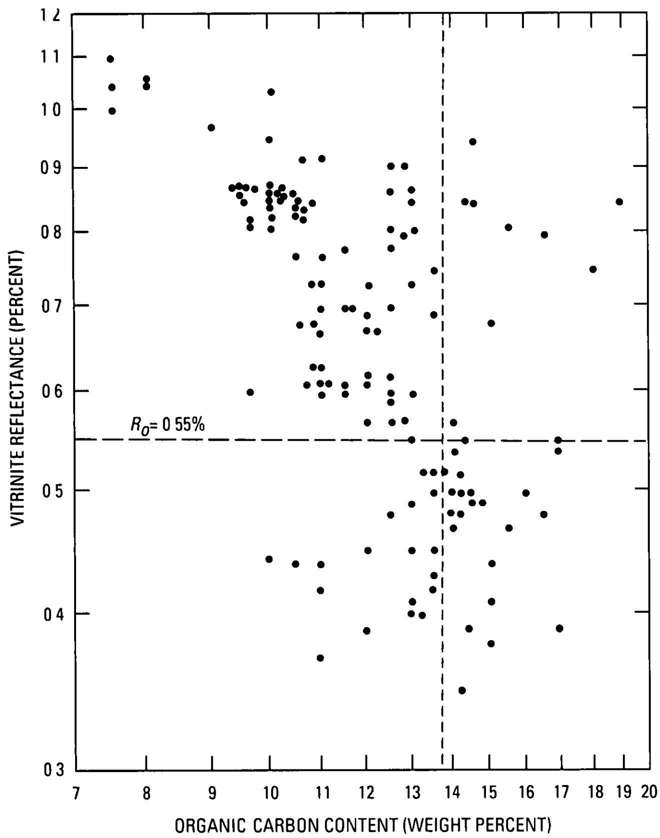

Figure 14. Vitrinite reflectance from Dembicki and Pirkle (1985) versus organic-carbon content as determined from formation-density logs of the upper and lower members of the Bakken Formation The vertical dashed line shows the average organic-carbon content of immature (less than 0 55 percent R_o) shales The organic-carbon content of mature shales tends to decrease as reflectance increases in response to the conversion of organic matter to hydrocarbons and to subsequent expulsion of these hydrocarbons from the formation

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Chapter K

Structural Parameters That Affect Devonian Shale Gas Production in West Virginia and Eastern Kentucky

By ROBERT C. SHUMAKER

U.S. GEOLOGICAL SURVEY BULLETIN 1909
PETROLEUM GEOLOGY OF THE DEVONIAN AND MISSISSIPPIAN BLACK SHALE OF EASTERN NORTH AMERICA

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FIGURES

Structural Parameters That Affect Devonian Shale Gas Production in West Virginia and Eastern Kentucky

By Robert C. Shumaker[1]

Abstract

Study of empirical relations between geologic structure and gas production from Devonian shale gas fields of western West Virginia and eastern Kentucky indicates that the highest production follows the flanks of very low folds above basement faults of Cambrian age The Cottageville Field in West Virginia is adjacent to a sharp bend in a basement fault zone The Midway-Extra Field, also in West Virginia, is near the intersection of two postulated basement faults Seismic data across both fields show that these basement faults do not extend above seismic reflections correlated with Ordovician sediments, which are several thousand feet below the Devonian shale reservoir

Oriented cores taken through the shale in the Cottageville Field demonstrate that high flows of gas come from partially mineralized open-fractures These small vertical joints form a pattern that is unique to the lower Huron organic shale, which is the primary reservoir Analyses of additional oriented cores, samples, and final open-flow data from the Devonian shale across West Virginia, eastern Kentucky, and southeastern Ohio indicate that the reservoir's unique fracture pattern formed by differential shortening and tectonic transport, probably during times of overpressure in the lower Huron and other organic shales of the Devonian shale sequence The blanketlike commercial production, which is so characteristic of the shale in southwestern West Virginia and eastern Kentucky, lies near the disappearance of shear fractures found in the distal portion of shale decollement zones This relation suggests that a zone of optimum permeability occurs where great density of vertical tension fractures caused the permeability and where sealing shear fractures have decreased to a minimum This permeability can be greatly enhanced to form high-production trends above the basement structure

Commercial shale gas production in the Appalachian basin reaches its peak in eastern Kentucky, particularly in Martin and Floyd Counties The Martin County production is synclinal, like that of the two fields in West Virginia Wells that have high gas flow follow the southern margin of the Rome trough along the Lovely monocline, which connects the two centers of high flow The Floyd County production lies within the Floyd County basement low in a foreland area detached primarily in the lower Huron organic shale reservoir Slickenside striations and vertical joint trends from oriented cores outside of the field center suggest that more diverse stress fields were present in eastern Kentucky than in West Virginia The area of high gas flow extends eastward from Floyd County toward the northern end of the Pine Mountain thrust, where strike-slip cross faults have been mapped in the subsurface Although not enough geologic and geophysical data are available to understand completely the geologic setting of eastern Kentucky, the empirical relations of production to structure appear to be similar to those established at the Midway-Extra and Cottageville Fields

INTRODUCTION

The Devonian shale has been an important reservoir within the Appalachian basin (fig 1) for over 100 years (yr) and has produced in excess of 2 trillion cubic feet of high-quality natural gas during that time (Tetra Tech, Inc , 1980) The reservoir is unique in that open-fractures and, occasionally, thin silt stringers form the permeability, whereas the shale matrix forms the source and the seal for the entrapped gas

Although the highest production is centered within the southern part of the Appalachian basin (fig 1), small areas of commercial production have been established elsewhere along the western flank of the basin, for instance, minor quantities of shale gas have been produced for many years along the shores of Lake Erie in eastern Ohio and western New York (fig 1) Through the years, production has been extended into the deeper parts of the basin, particularly during times of gas shortage and price escalation, such as that experienced in the United States during

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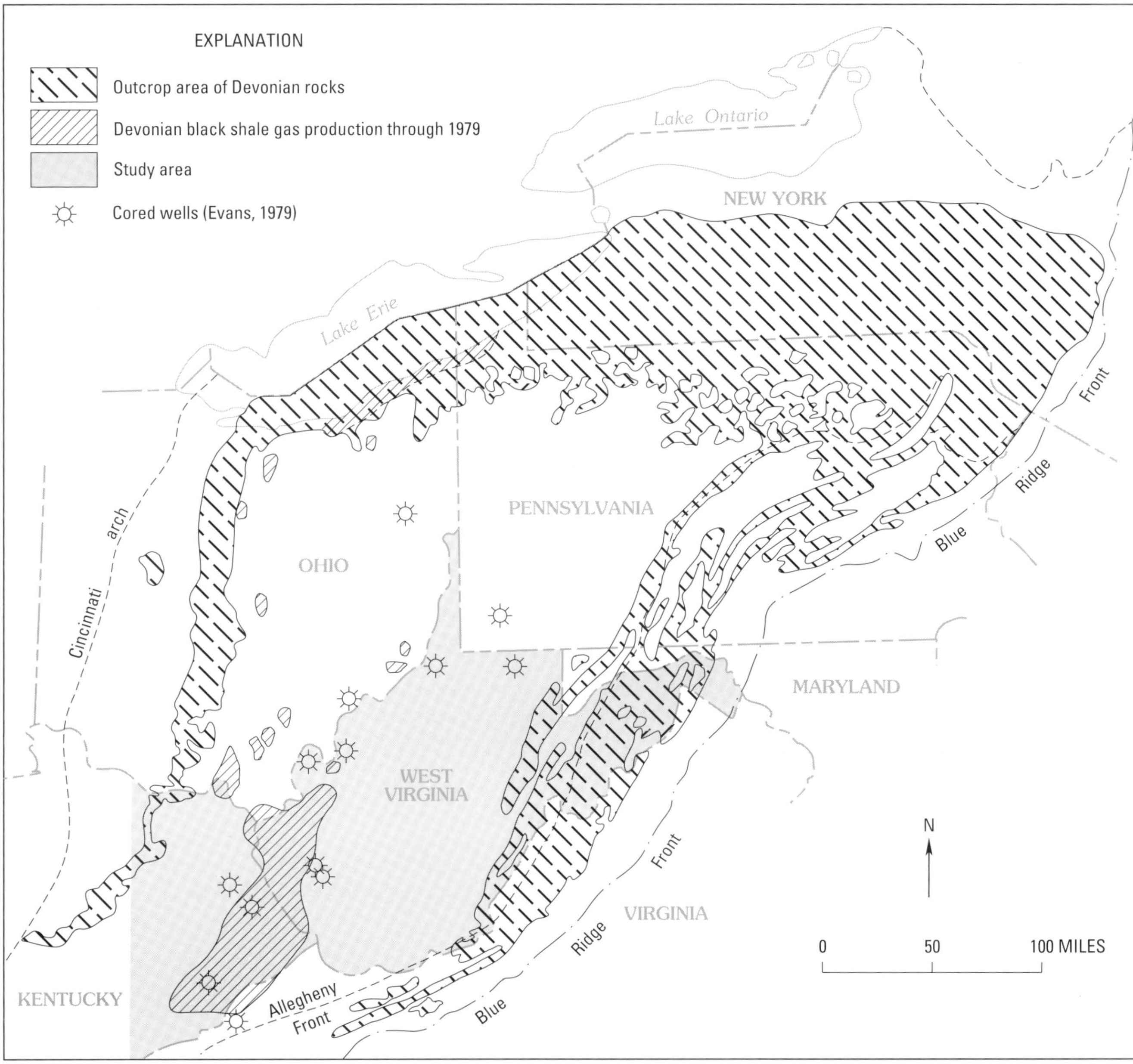


Figure 1. Location of the study area.

the late 1970's and the early 1980's. Small quantities of oil are being recovered in the deeper and thermally more mature parts of the basin in northwestern West Virginia (Patchen and others, 1983).

During this past decade, the Devonian shale of the Appalachian basin and its equivalents in the continental interior have been the subject of geologic research because of the shale's vast extent outside the area of commercial production. These studies have focused, for the most part, on an evaluation of its resource potential, the development of new techniques to expand the area of commercial production, and the development of technology to extract more gas from the productive shale. This chapter presents the results of studies to determine the influence of geologic structure on commercial shale gas production of the historic producing area in the southern part of the Appalachian basin.

Stratigraphic Setting

The stratigraphy of the reservoir within eastern Kentucky and southwestern West Virginia (fig. 2) consists of interbedded gray silty shale and darker organic-rich shale. The highly organic-rich lower part of the Huron Member of the Ohio Shale and, to a lesser degree, the Rhinestreet Member of the West Falls Formation and the Cleveland

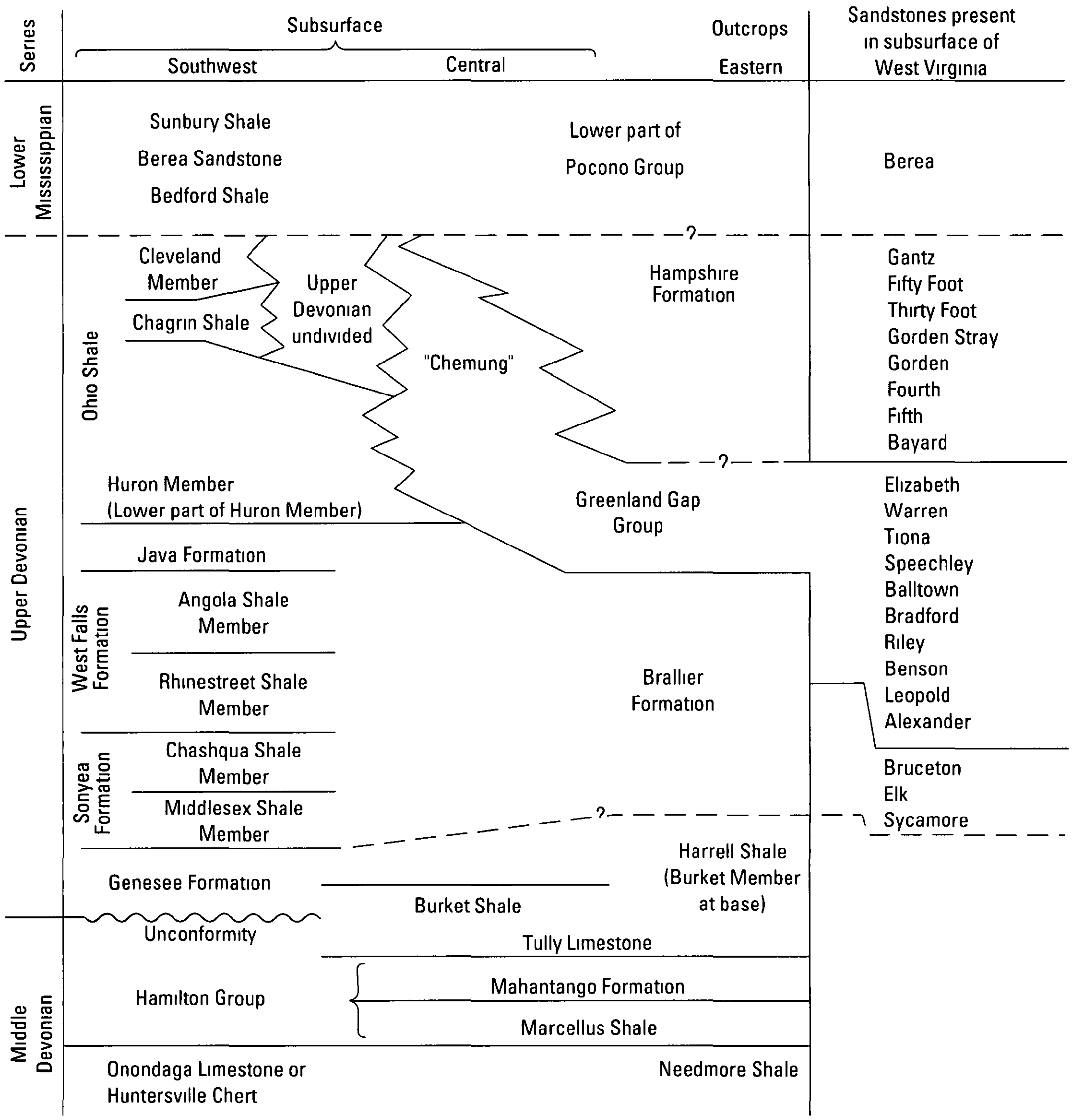


Figure 2 Middle and Upper Devonian formations in West Virginia (Modified from Schwietering, 1980)

Member of the Ohio Shale are the primary producing intervals (Ray, 1968, Negus-deWys, 1979, Nuckols, 1980) in this area Gas operators have routinely completed shale wells in what they term the "brown shale" zones, which are in the Cleveland and the lower part of the Huron Member of the Ohio Shale (fig 3) of eastern Kentucky However, commercial production can, and often does, come from open-fractures at any stratigraphic level throughout the entire sequence Of course, production can come from coarser clastics, but these reservoirs are generally absent in the area under discussion and, therefore, are excluded from this study

The shale sequence of eastern Kentucky, southern Ohio, and southwestern West Virginia grades northeastward into the producing sands, silts, and shales of central West Virginia (fig 2) Gas shows encountered when drilling through the Upper Devonian formations, along with temperature and sibilation (noise) log surveys run through these units after drilling, indicate that silts and sands produce gas in central West Virginia and Pennsylvania Because the facies change is gradual, the boundary is transitional from the southwestern area that produces gas primarily from the shale to the northeastern area that produces gas from the coarser silts and sands Identification of specific producing lithologies in the transition area is obscured by the interbedded character of the lithologies, the general practice of completing wells across a wide stratigraphic interval, and the habit of comingling production This study is concerned only with the area of shale production that is in the southwestern part of the basin

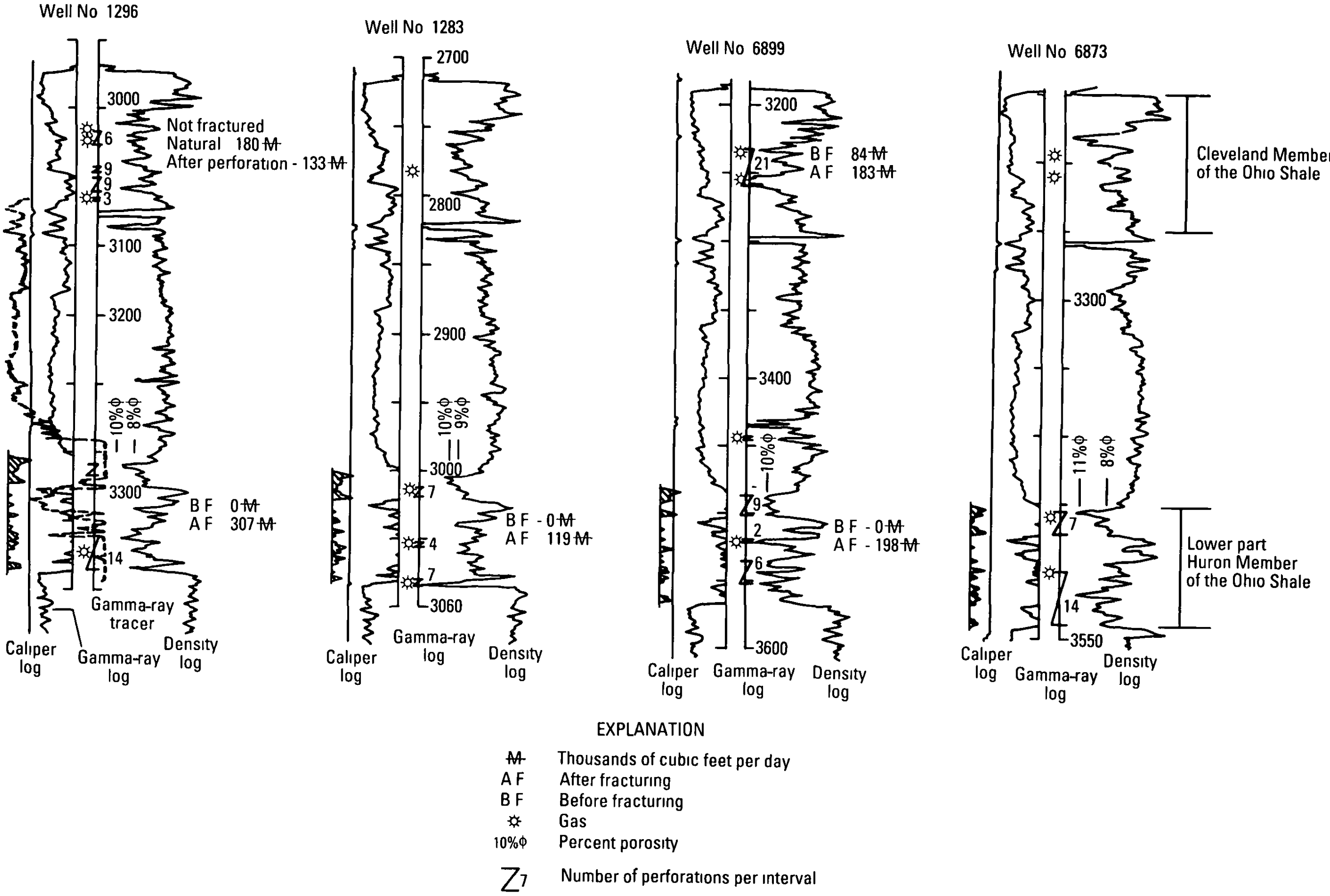


Figure 3. Fractured Devonian shale wells, Perry County, Ky (Modified from Ray, 1968)

Production Techniques

Nearly all wells drilled into or through the organic portions of the shale in eastern Kentucky and southwestern West Virginia produce gas after stimulation The production declines rapidly at first, but then it stabilizes and can be maintained at low levels, often for several decades This longevity has been related to the slow diffusion of gas from the organic shale matrix into the fracture permeability (Negus-deWys and Shumaker, 1978) Very few shale wells are classified as dry holes in the area of historical production Those wells that have high final open-flows usually stabilize at higher annual production rates than those that have initial low-flows

The lack of predictable trends of fracture permeability and the small size of most lease blocks have caused exploration to proceed primarily on the basis of a strategy of leasing and drilling adjacent to better producing wells or as plug-backs from deeper exploration failures Geology has been of little importance in exploration, and the rate of drilling is primarily influenced by temporal economics, the availability of gas pipe lines, and the specific reserve and (or) demand needs of local gas utility companies

The marginal profitability of most shale wells and general pervasive production in the southern part of the Appalachian basin have made industry reluctant to adopt the more expensive and advanced drilling, logging, and completion practices Before the 1960's, most shale wells were drilled by cable tool rigs and completed open-hole after explosive shooting In those wells, drillers' descriptions form the basis for identification of lithologic contacts (Lee, 1980) It has only been during the last two or three decades that wells have been drilled by using rotary air-drilled rigs Because of the poor quality of samples from these rigs, geophysical logs have become essential for identification and correlation of the Devonian shale units During drilling, gas shows to be stimulated are usually detected by sibilation logs or by temperature surveys run using a gamma-ray-density logging program Now, drill holes are routinely cased and fractured by using gas or foam that carries a sand proppant However, wells that flow gas naturally in excess of 200 or 300 thousand cubic feet of gas per day (mcf/d) on initial test are commonly completed without stimulation Even though the modern stimulation techniques commonly increase initial gas flows severalfold, natural fractures are still considered to be essential for large gas flows (Holditch and Associates, 1984)

Acknowledgments

The author wishes to acknowledge the efforts of fellow faculty and graduate students at West Virginia University who compiled much of the data on which this chapter is based Many conclusions reached by these principal investigators in their own, more specific studies are incorporated in this chapter However, certain interpretations presented here diverge from those made by these workers Much of the divergence is based on new data that were not available when those studies were made In a few cases, interpretations differed substantively

Scientists involved in specific phases of this investigation include Janet Dixon of ARCO, Kevin Lee of Marathon Oil, Brian Long of the West Virginia Department of Natural Resources, Jane Negus-deWys of Exxon, E B Nuckols, William Schaefer, Kathryn Stewart, Eberhard Werner, Julie Lim, and Paul Sutter, James Templin of the Columbia Gas Transmission Corporation, Russell Wheeler of the U S Geological Survey, and Henry Rauch and Thomas Wilson of West Virginia University

Gratitude is also expressed to the gas industry, which supplied a vast amount of proprietary data for our use The Kentucky-West Virginia Gas Company (Ernest Jenkins and Robert Hagar) provided the opportunity for us to collect subsurface data to construct isopotential, structure, and isopach maps for eastern Kentucky The Consolidated Gas Supply Company, the Columbia Gas Transmission Corporation, and the Cities Service Corporation supplied much of the information for the Cottageville Field study, and the Union Oil and Gas Company provided most of the raw data for the Midway-Extra Field study

The Columbia Gas Transmission Corporation kindly gave their permission to inspect the seismic data in the Midway-Extra Field area Joe Lemon and Richard Beardsley of Columbia Gas aided by obtaining permission to publish one of the lines and assisted the author in a preliminary interpretation of seismic records Tom Wilson was very helpful in interpreting seismic data and discussing his research for the Gas Research Institute on Devonian shale William Dunne was particularly helpful in editing the original manuscript to improve its technical and scientific quality

A special word of thanks goes to the U S Department of Energy (DOE) and the Gas Research Institute for funding this study and to the technical project directors of these organizations The author also wishes to thank William Overbey, Arlen Hunt, Claude Dean, and Charles Komar of the DOE's Morgantown Energy Technology Center and Richard McBane, Timothy Kurtz, and Richard Scheper of the Gas Research Institute Debbie Benson and Alison Hanham are thanked for their invaluable assistance in the preparation of this manuscript

PURPOSE

The purpose of this study was to determine if relations exist between geologic structure and commercial gas production from the Devonian shale The approach was to collect, compile, and analyze data on the structural geology of eastern Kentucky and West Virginia for comparison with shale primarily shown by gas production map patterns of final open-flow At regional and local scales, gas flows were compared with lineaments, surface and subsurface structures, surface and subsurface fractures, seismic velocity anomalies in the Midway-Extra Gas Field, and groundwater geochemistry in two gas field areas Summary results of seismic investigations have been reported by Williams and others (1982) and Wilson and Swimm (1985) Results of ground-water chemistry and lineament analyses have been reported by Wheeler (1980), Rauch and others (1984), and Rauch (1985)

METHODOLOGY

During 1978 and 1979, structural and production data were collected from gas company files for evaluation of two small gas fields, the Cottageville and the Midway-Extra, in West Virginia and of nearly 5,000 wells in the Big Sandy Field in eastern Kentucky All data on surface and subsurface fractures (fig 4) in the producing area as of 1979 were compiled because open-fractures are considered to be the main source of commercial permeability in the reservoir Data on surface joint orientations and spacing in eastern Kentucky (fig 5) were collected by Long (1979) Subsurface fractures from oriented Devonian shale cores (fig 5) were described by Evans (1979)

Although existing subsurface structure maps of the study area were useful, they generally are contoured at intervals too broad to identify low-amplitude folds and faults of small displacement that could cause fractures that might affect shale production Consequently, detailed contour maps had to be constructed for the study area, data for eastern Kentucky were obtained by Lee (1980), Jackson County, W Va , by Negus-deWys and Shumaker (1978), Kutner (1979), and Nuckols (1980), and Putnam County, W Va , by Kutner (1979) and Schaefer (1979) Computer-generated structure maps of eastern Kentucky were produced by using data from Lee (1980)

Detailed long-term production records (Nuckols, 1980) were available only for the Cottageville Field in Jackson County Final open-flow data were available from cooperating companies for nearly 5,000 shale wells in the Big Sandy Field in eastern Kentucky (Negus-deWys, 1979) and all the wells in the Midway-Extra Field (Schaefer,

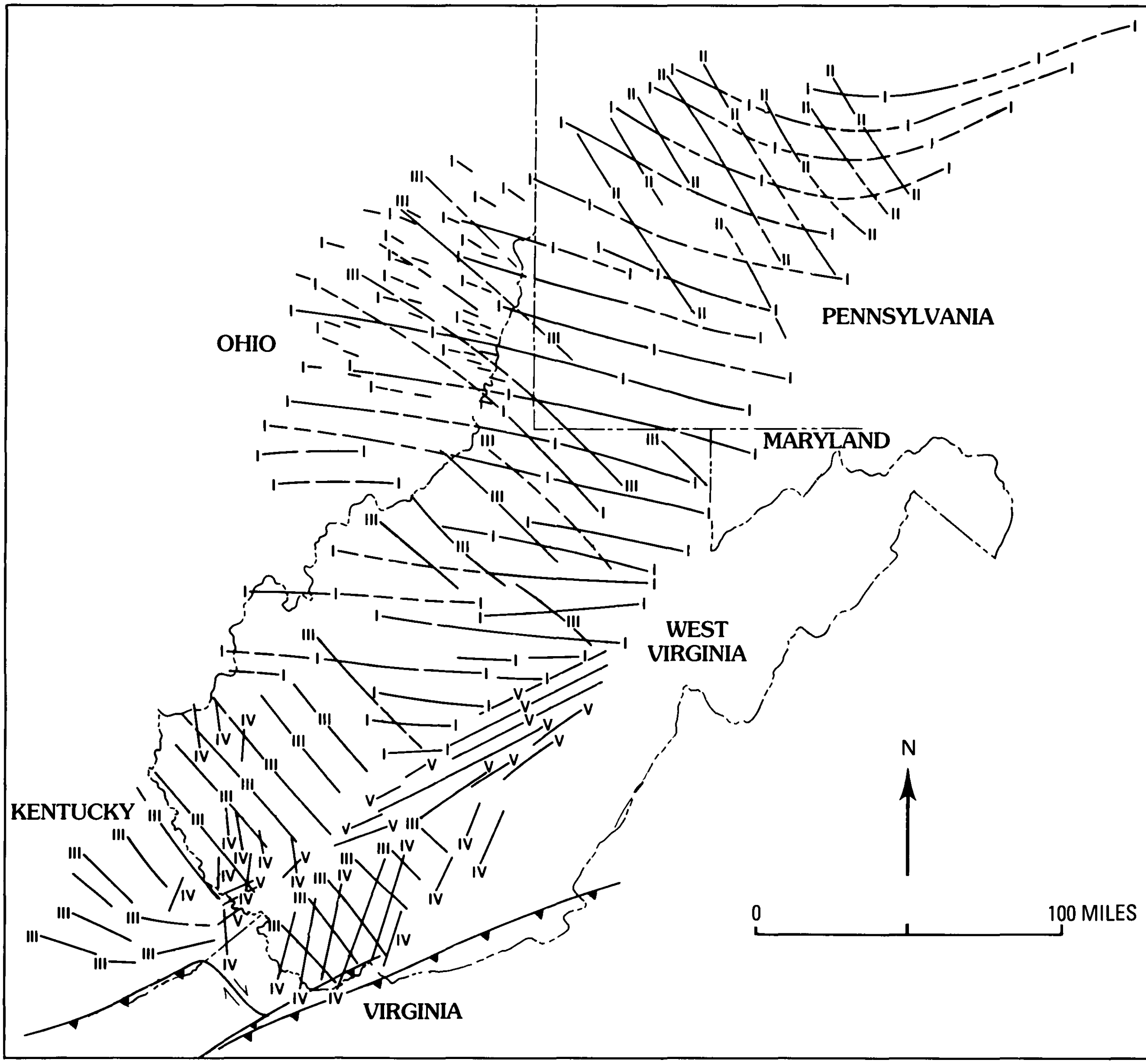


Figure 4. Regional face cleat and shale joint trends The roman numerals indicate similar sets (From Nickelsen and Hough, 1967, Long, 1979, Kulander and Dean, 1980)

1979) No effort was made to differentiate between wells stimulated by shooting and those that were fractured Because the majority of the wells in the data base were drilled before the 1960's, well completions can be considered to be open-hole and to have been shot with explosives

A drawback to the analysis of gas production is the use of final open-flow data for most of the area studied Final open-flow estimates give only an indication of the potential productivity of a well Most drillers and company personnel know from experience that a relation exists between the two Such a relation was established for the Cottageville Field by Negus-deWys and Shumaker (1978) and Nuckols (1980), they reported that wells having large final or initial open-flows usually produced more than those having small flows Recent analyses across the study area (Holditch and Associates, 1984, Moody and others, 1986, Baranoski and others, 1987, Patchen and Hohn, this volume) support and have refined this general relation between production and final open-flows of gas from the shale

The quality of other data used in this analysis has limitations, and cautionary statements should alert the reader to potential inaccuracies in the results of this study, particularly in the Kentucky area where the data were collected from drillers' records in company files Even though most companies report data accurately to one another, not all do Fortunately, the eastern Kentucky data

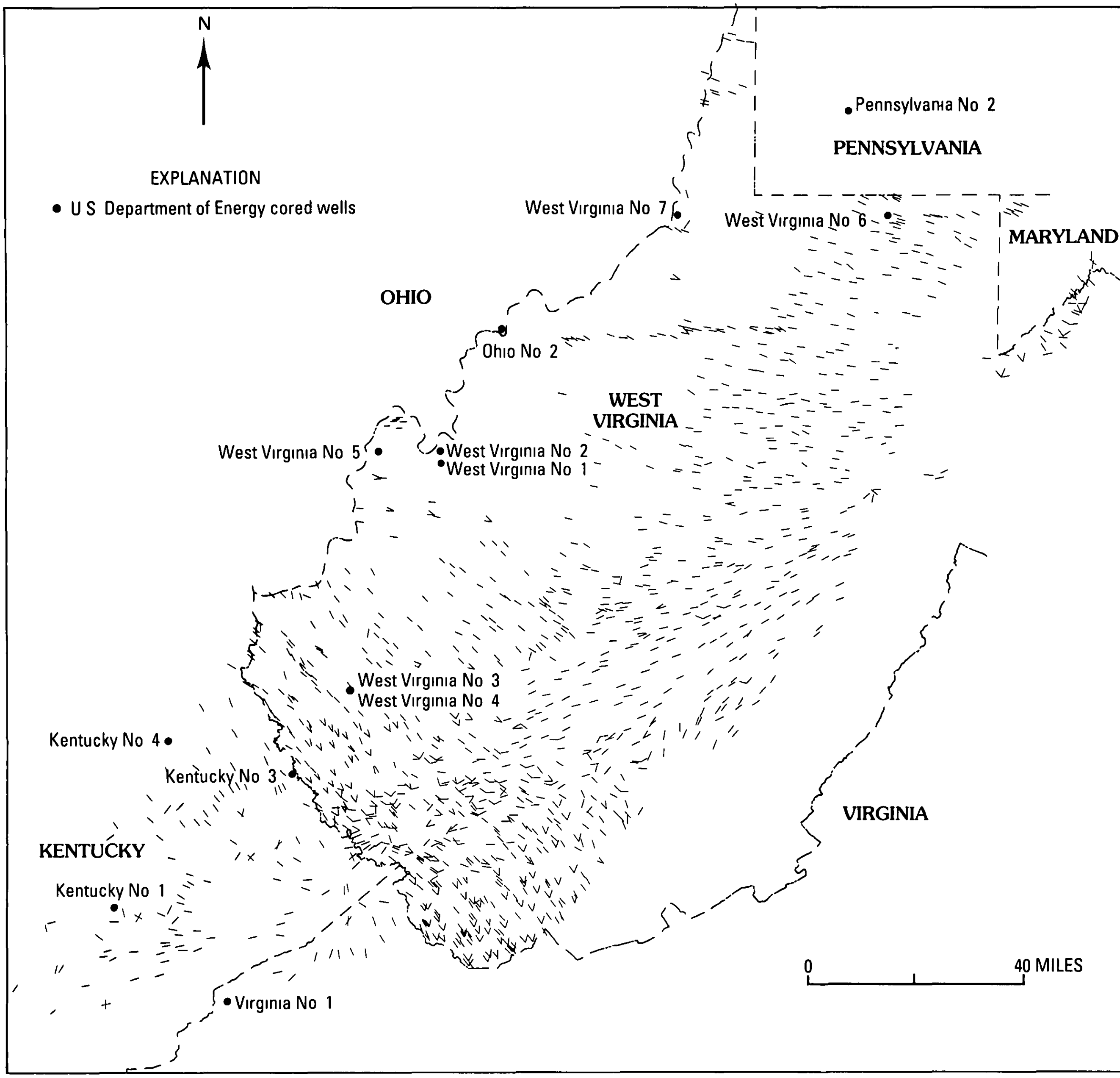


Figure 5. Location of cored wells (Evans, 1979) and coal face cleat trends (pattern) from the surface coals (Long, 1979)

were collected from company files with the aid of gas company personnel who were often familiar with the quality of the data

In eastern Kentucky, the large quantity of drillers' subsurface geologic data (from the Big Sandy Field (Lee, 1980)) overwhelms any shortcomings in the quality of a particular data point value, the values for the top or the bottom of the Devonian shale were as reported by the driller A point was considered to be anomalous and was eliminated only if it had a significantly different value when compared with the values of surrounding data points Because of the overall simplicity of structure in the area, spotting anomalous values was not difficult Generally, values recorded for adjacent wells were surprisingly consistent for easily recognizable lithologic changes, such as the base of the drillers' Mississippian "Big Lime" (Greenbrier Limestone), the Berea Sandstone, and the "Big White Slate" (base of the lower part of the Huron Member or Ohio Shale) In spite of the quantity of data, the reliance on drillers' tops limits detailed map accuracy in eastern Kentucky However, in the Midway-Extra (Schaefer, 1979) and the Cottageville (Nuckols, 1980) Field areas, reported tops were checked against samples and geophysical logs wherever possible

Objections to the validity of any isopotential map that is based primarily on drillers' estimates also must be addressed A wide difference in gas flow was selected for the contour interval on the eastern Kentucky isopotential map to minimize small errors that drillers might make in estimating or measuring gas flows during final open-flow tests It was thought, for instance, that an experienced driller could readily tell or measure the difference between a well flowing at 250 mcf/d and one flowing at 500 mcf/d The areal clustering of high and low values and the general continuity of trends shown on the resulting isopotential maps suggest that the gas-flow variations seen are real The positive correlation between geologic features and final open-flow values, which are discussed in the section "Results." also attests to the overall validity of the isopotential map, as well as the structural maps discussed above

The reliability of fracture data from the oriented cores is limited by two factors First, inexperienced geologists, who were unfamiliar with the methods of identifying coring-induced fractures (Kulander and others, 1977), logged all fractures in the Kentucky No 1 and West Virginia No 1 wells (fig 5) as natural fractures (joints) Trends of natural and coring-induced fractures from these two wells remain undifferentiated because a major part of these cores were destroyed by intense sampling before they could be relogged Fortunately, Larese and Heald (1977) mapped the mineralized fractures in the producing zone of the West Virginia No 1 well For other wells, these two types of fractures were differentiated (Evans, 1979) Second, the lack of oriented-core data from the highly productive center of shale gas production in eastern Kentucky (fig 1) limits our knowledge of subsurface fractures in this most productive area However, oriented cores at the periphery of the field document subsurface fractures in the less-productive adjacent shale that may be indicative of fracturing in the more productive center

TECTONIC HISTORY

The stated purpose of this study is to evaluate the influence of geologic structure on commercial shale gas production by focusing on initial production as indicated by final open-flow values This analysis presumes that major and abrupt variations in gas flow from a tight reservoir, such as the Devonian shale, reflect the extent and the permeability of the fracture network in the reservoir Therefore, this study of the fractures that cause the permeability attempts to determine if they relate to geologic structure and were formed because of local and (or) regional tectonism and if a particular structural style is associated with production Such determinations are essential for an accurate appraisal of new areas or the extension of production beyond the confines of existing production, for instance, if a particular style of basement structure is the sole cause for the fracture permeability, then detached structures are eliminated from consideration, or if a detached deformation created the permeability, then orogenic forelands become prospective areas for development

It is often presumed that fractures in sediments of an orogenic foreland are formed by detached deformation related to orogeny However, a large body of literature shows that surface joints and fracture patterns in the Appalachians have been variously related to orogenic deformation, basement deformation, stress release and unloading, and, most commonly, a combination or series of geologic events (Nickelsen and Hough, 1967, Kulander and Dean, 1980, Engelder, 1985, W M Dunne, personal commun , 1986) Occasionally, fracturing and fracture trends have been related to sedimentary slumping or compaction (Kulander and others, 1977) Obviously, open-fractures caused by different mechanisms can be important to gas production Even though the study area lies in plateau rocks that appear to be relatively undeformed at the surface, our analysis of the region shows that the subsurface structure, particularly at the basement level, is complex Therefore, a review of the structural history of the area is essential to understand how the various tectonic events and regional structures may have affected the formation of the fracture permeability of the shale

Precambrian Structure

The Grenville orogeny (1 billion yr) formed the metamorphic and igneous basement rocks under the study area (King and Zietz, 1978) Wells on the western side of the study area have penetrated the basement in sufficient numbers to allow broad definition of the shape of its surface Total magnetic intensity maps also help define the shape of its upper surface and the lithology of the basement because little igneous activity has occurred within the basin since Precambrian time to complicate the magnetic patterns produced by basement rocks

One magnetic linear feature, the northeast-trending New York-Alabama lineament shown in figure 6, has been interpreted as being a major shear zone of Grenville age (King and Zietz, 1978) The linearity of the magnetic trend is interrupted in the study area (Johnson and others, 1980), but its trend along the Warfield anticline can be extended from West Virginia across the study area along the trace of the D'Invillers anticline (fig 7) In southern West Virginia, the lineament follows a major subsurface basement fault (Lee, 1980), which also is the eastern margin of the Rome trough (fig 8) (Woodward, 1961, Donaldson and Shumaker, 1981) that formed during the Cambrian as part of a more extensive system of grabens (Shumaker, 1975a, 1986a)

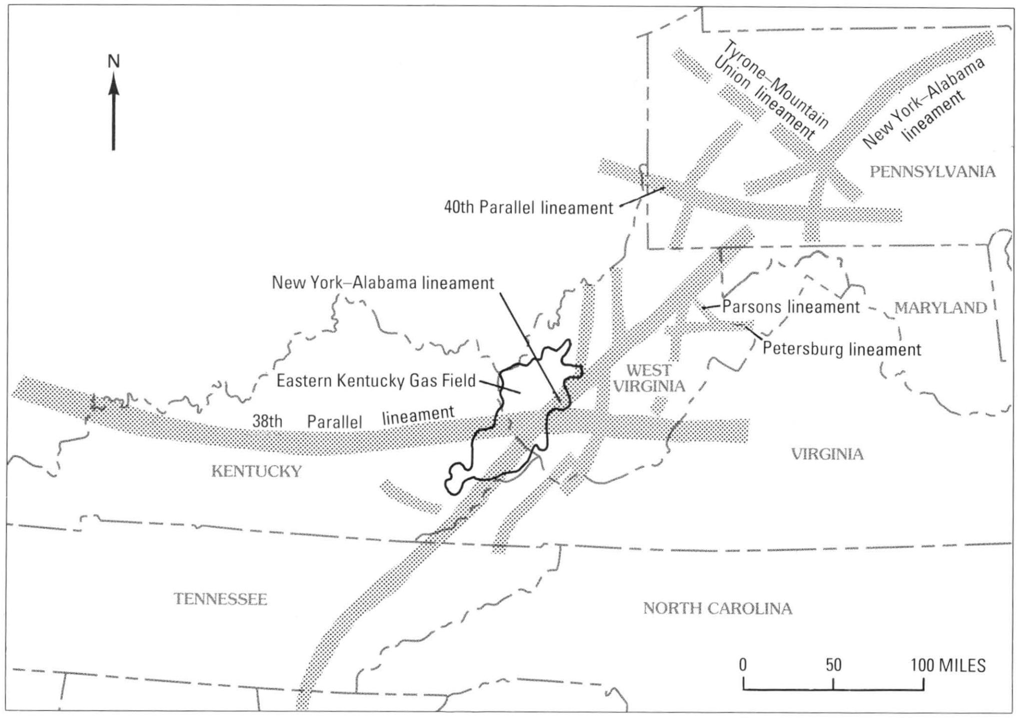


Figure 6. Central Appalachian regional lineaments.

Cambrian Graben Formation

During Early and Middle Cambrian time, a series of grabens, which were called the Eastern Interior graben system by Shumaker (1986a) or the Eastern Interior aulacogen by Harris (1978), developed across the craton from Pennsylvania to Arkansas (fig. 8). This Cambrian graben system reactivated preexisting basement structures in several places along its length (Beardsley and Cable, 1983). In the study area, reactivation occurred near the Kentucky-West Virginia border at the intersection of the New York-Alabama lineament (fig. 6) and the east-west-trending Rome trough (fig. 8). At this intersection, the east-west-trending Rome trough turns northward to either follow or form part of the New York-Alabama lineament. The Eastern Kentucky fault system, which is the surface expression of the northern boundary of the Rome trough in eastern Kentucky, is also a part of another regional structural feature called the 38th Parallel lineament (Heyl, 1972) that extends from the Central United States into the folded Appalachians (fig. 6). Mineralization and igneous activity of Mesozoic and Cenozoic ages along segments of the lineament (Heyl, 1972) suggest recurrent structural activity of basement faults in this structural zone.

The minor displacement that occurred along many basement faults during the Paleozoic (Donaldson and Shumaker, 1981) affected sedimentation patterns and thicknesses for such units as the Devonian shale. These vertical displacements, which may have included more lateral strike-slip than vertical movement, probably created local fracture zones and modified certain of the later-formed regional joint patterns (Kulander and Dean, 1980). Changes in regional coal cleat trends (fig. 5) found along certain of these basement structures, such as the Warfield anticline (fig. 7), attest to the importance of basement structure to the orientation of surface fracture trends.

Alleghenian Orogeny

The Permian Alleghenian orogeny was the most significant deformation to affect Paleozoic sediments of the Appalachian foreland. Thin-skinned structures of this deformation, which are detached in several different horizons, are visible in the surface rocks along the eastern side of the shale-producing area (fig. 7), and it is the only pervasive deformation found within the sedimentary cover that has been documented across the entire width of the foreland area. Therefore, it is almost universally invoked to explain some or all of the fractures and the folds of the foreland.

The trends and distribution of detached structures were affected by the thickness and distribution of the various decollement horizons (Rodgers, 1963). The Devonian shale contains several stratigraphic units (primarily organic shale members) that are lithologically equivalent to and contiguous with shales carrying major decollement horizons immediately to the east of the producing area (Rich, 1934; Shumaker, 1975b; Wilson and others, 1980).

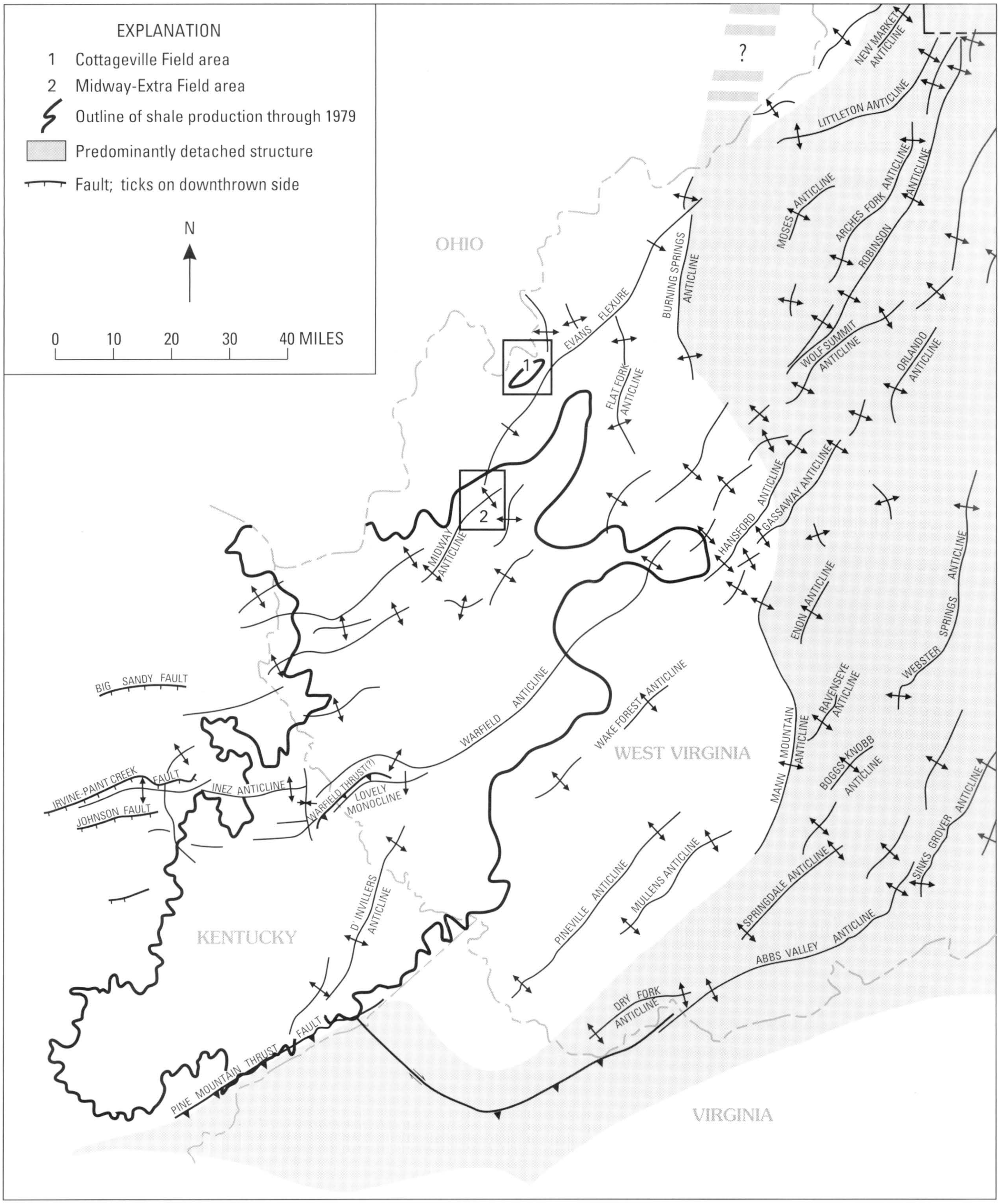


Figure 7. Study area.

The Alleghenian orogeny postdates the youngest sedimentary rocks within the study area, so it has not affected sedimentation, as have movements of the basement. Recognition of growth during sedimentation has been useful in determining the origin of certain structures. Judiciously used, it can be important in identifying basement structure that can determine the location and trend of detached structures in the plateau (Shumaker, 1986b).

The effects of the Alleghenian deformation that extend beyond the limit of recognized detached folding form a subtle mechanical fabric (Cliffs Minerals, Inc., 1982) in the Devonian shale that is parallel to the outer folds

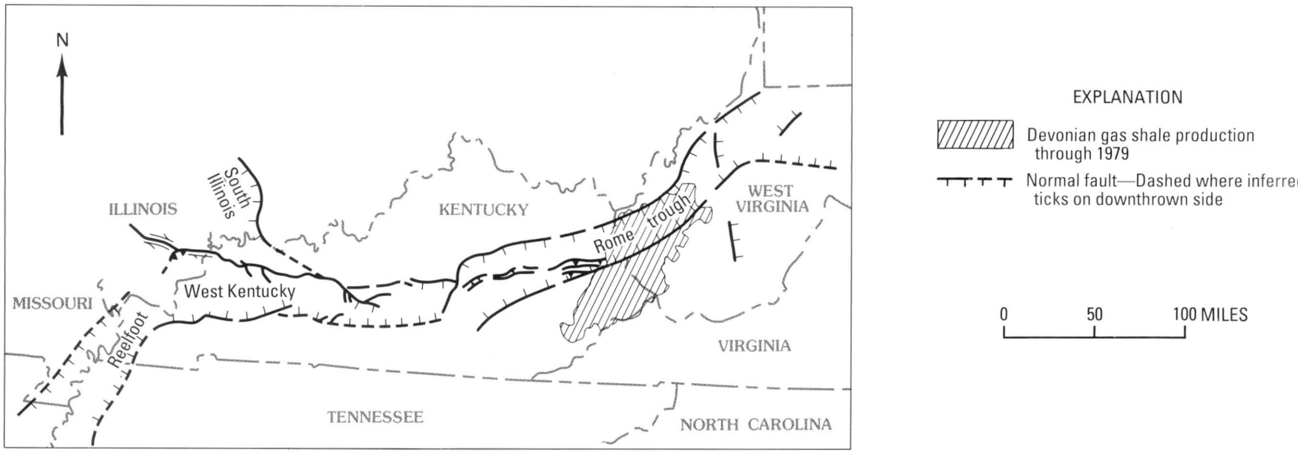


Figure 8. Eastern Interior graben system.

of the Appalachian foreland (figs. 7, 9) and that extends far beyond the usually recognized limits of detached folding. The shale's fabric may be important in localizing joints caused by release and removal of overburden (Engelder, 1985). This fabric and the present in-situ stress are also important factors to consider when predicting the direction taken by induced fractures (Cliffs Minerals, Inc., 1982) that are formed during stimulation of the shale. Of course, stress related to Alleghenian deformation has been recognized for some time as being important to the formation of fractures in foreland sediments (Nickelsen and Hough, 1967).

Not all the deformation ascribed to the Alleghenian orogeny is detached. Surface faults mapped in Carboniferous sediments, such as those at the western edge of the study area (fig. 7), generally are thought to have been formed during the Alleghenian. The absence of post-Alleghenian rocks that overlap these faults precludes dating the age of their movement with any degree of certainty. Although most of the structures are the surface expression of basement faults formed at an earlier time, their surface expression does not necessarily indicate a major deformation, only the reactivation of earlier formed faults.

Post-Paleozoic Deformation

The extent of Mesozoic and Cenozoic deformation within the study area is uncertain. Mineralization and igneous activity along the 38th Parallel lineament were noted in the section "Cambrian Graben Formation," and Evans (1979) showed that certain natural fractures within oriented cores from the shale parallel the present in-situ maximum stress. Also, uplift and erosion of the Appalachian Plateaus may have formed unloading fractures that are parallel to the present in-situ maximum stress direction (Engelder, 1985). The occurrence of historical earthquakes in the producing area (Hinze and others, 1977) attests to the continued seismic activity within the region, but the effects of these stresses and rock motions on the formation of fractures remain largely unknown. Study of alluvial terraces directly northwest of the shale production along the Kentucky River fault system (Van Arsdale, 1986) has shown that the recent terrace material is slightly offset above certain of these faults. It is clear that post-Paleozoic tectonic events have affected the area, but their effects on shale gas production remain largely unassessed.

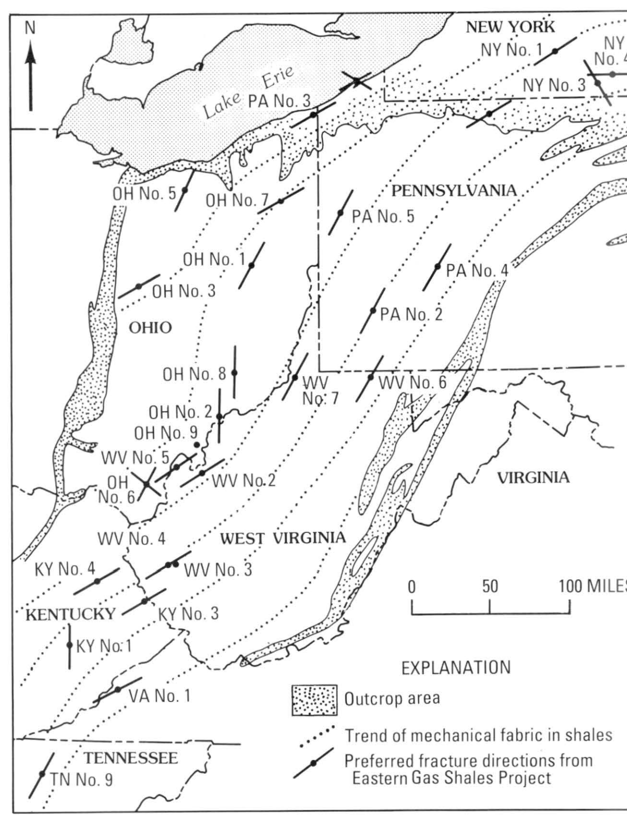


Figure 9. Directional properties of the Devonian gas shales. (From Cliffs Minerals, Inc., 1982.)

RESULTS

Results of this study are discussed under two headings—"Locally Enhanced Production" and "Regional Production." This division emphasizes two important distributions of shale gas flow—the local areas or trends of much higher flow in and outside of the producing area and the regional area of enhanced flow in the Appalachian foreland, where nearly all shale wells have commercial gas flows. Isolated wells of high final flows and groups of wells that have slightly greater flows than others occur throughout the producing area. The cause for such small variations in flow is not addressed here.

Locally Enhanced Production

Two areas of locally enhanced production in West Virginia, the Midway-Extra Field and the Cottageville Field (fig. 7), at the northern margin of regional production were studied in detail.

Midway-Extra Field

The investigation of the Midway-Extra Field by Schaefer (1979) established a direct relation between final open-flow values from the lower part of the Huron Member of the Ohio Shale (fig. 10) and geologic structure (fig. 11). He showed that after explosive stimulation, final open-flows (fig. 10) were greatest along the northwestern limb of the low-relief Midway anticline (fig. 11), near the flex line of the adjacent syncline (fig. 11), and, to a lesser extent, along the southeastern limb of the syncline.

Isopachs of the lower part of the Huron Member (fig. 12), which is the primary reservoir, show thickening into the adjacent synclines that suggests growth of the Midway structure during sedimentation. On the basis of this proposed growth, Schaefer (1979) concluded that the fold had been formed by basement deformation. The data obtained from a seismic line (fig. 13) shot across the northern end of the field (fig. 11) confirm the presence of a basement fault zone that steps down to the east over a distance of several miles in the field area. This fault zone developed during the Cambrian as part of the Rome trough and has had slight post-Cambrian movement. Seismic reflections from post-Cambrian sedimentary rocks show a very low relief monocline above the fault zone that lies directly east of the trend of highest gas flows in the field. The shape of the surface fold is simple and fairly symmetrical when compared with structures seen on the seismic line. Unfortunately, the line does not pass directly over the highest part of the surface fold, and reflections correlated with Devonian rocks are of insufficient quality to determine if the surface anticline (fig. 11) is detached or if it relates to basement structure. The cause for the disparity in gas flows between the two limbs of the Midway anticline is unknown. However, the disparity demonstrates that no rigid relation exists between fracture intensity and near-surface structure or underlying basement faulting.

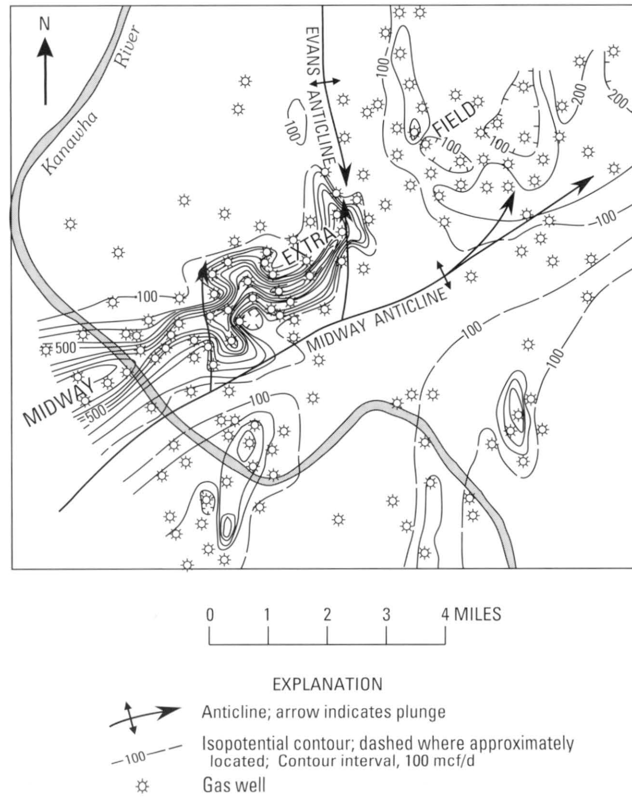
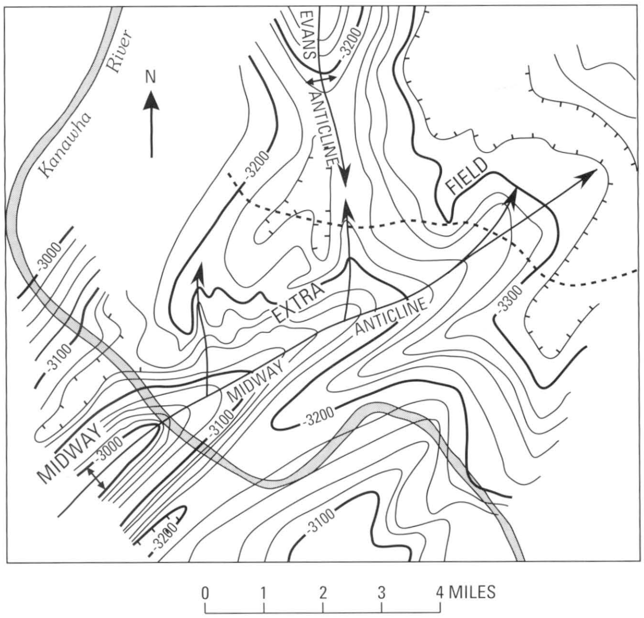


Figure 10. Final open-flows from the Devonian shale in the Midway-Extra Field, W. Va. (From Schaefer, 1979.)

Limited geologic evidence from the Midway-Extra Field and the regional geology provide possible reasons for the asymmetric nature of the production. Subsurface structure along the northern flank of the structure shows several small north-trending anticlinal noses (fig. 11) that parallel a broader low-amplitude anticline at the northern end of the Midway anticline. The north-trending, low-amplitude anticline is the southern terminus of the Evans flexure (fig. 7), which was mapped by Kutner (1979) and Perkey (1981). The highest gas flows in the field (fig. 10) occur on the synclinal margin of the Midway anticline near its plunging northern end and close to its intersection with the Evans flexure. Isopotential lines generally parallel the Midway structure; this indicates that the major fracture permeability relates to that fold. However, several north-south cross trends in the shape of isopotential lines suggest a north-south intersection and subsidiary permeability related to the Evans flexure trend. It is likely that increased gas flows found at this northern end of the Midway structure relate to increased permeability caused by the intersecting fractures that are related to both structures. The increased permeability reflected in isopotential flows (fig. 10) also may be caused by the interaction of detached Alleghenian deforma-



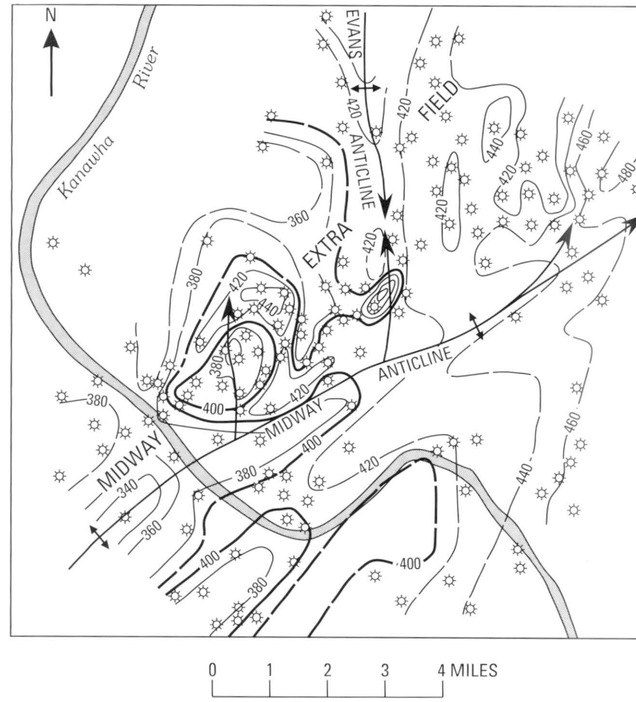
EXPLANATION

Anticline; arrow indicates plunge

-3000 Structure contours on base of Huron Member, Ohio Shale; interval 20 ft; hachures indicate depressions

------- Approximate location of seismic line of figure 13

Figure 11. Subsurface structure of the Midway-Extra Field, W. Va. (From Schaefer, 1979.)



EXPLANATION

Anticline; arrow indicates plunge

-400 Isopachs; dashed where approximately located; contour interval, 20 ft

Gas well

Figure 12. Lower part of the Huron Member of the Midway-Extra Field, W. Va. (From Schaefer, 1979.)

tion and preexisting basement structure that took the form of a slight increase in structural dip or small faults on the northern flank of the fold.

Evidence favoring the importance of detachment in forming the fracture permeability in the Midway-Extra area comes from regional analysis of the fractures found in the reservoir (Evans, 1979), local analysis of well cuttings, and the stratigraphically restricted nature of the production. Analyses of gas shows and production from the Cottageville and the Midway-Extra Fields (Schaefer, 1979; Nuckols, 1980) indicate that gas comes primarily from the lower part of the Huron, which was a regional decollement zone in the adjacent foreland during the Alleghenian deformation (Shumaker, 1975b; Wilson and others, 1980). In 8 of the 10 wells that penetrate the reservoir at the Midway-Extra Field, Templin (1979) noted that free spar (fracture filling) and slickensided shale occurred in cuttings from the lower part of the Huron. Stewart (1979) obtained comparable results in a similar study of samples from producing wells in the Cottageville Field. The occurrence of mineralized fracture and slickensided shale in the lower part of the Huron are compatible with decollement and mineralization in the Midway-Extra and the Cottageville Field areas.

Cottageville Field

If one combines the knowledge gained from the Midway-Extra and Cottageville Fields (Shumaker and others, 1982), then greater insight is obtained into the specific causes for areas of locally enhanced production. At first glance, the Cottageville and Midway-Extra Fields appear to be structurally dissimilar—the Devonian shale production at the Cottageville Field is contained in a southeast-dipping homocline (Negus-deWys and Shumaker, 1978), and the production trends (figs. 14, 15) (Negus-deWys and Shumaker, 1978; Nuckols, 1980) are sublinear and have been related to basement faulting (Martin and Nuckols, 1976).

Interpretation of seismic data from the Cottageville (Sundheimer, 1978) demonstrates the presence of a geologic structure in the basement (fig. 16) and the near-basement sediments and a small basement fault under the trend of some of the most productive wells along the southeastern margin of the field (compare figs. 15, 16). Reprocessing, model studies, and reinterpretation of seismic data by Wilson and Swimm (1985) indicate the following:

- The basement fault of Sundheimer (1978) is either a zone of faulting or a number of faults that assume a much more complex fault pattern and a structural setting similar to that seen in the basement under the Midway-Extra Field (fig. 13).

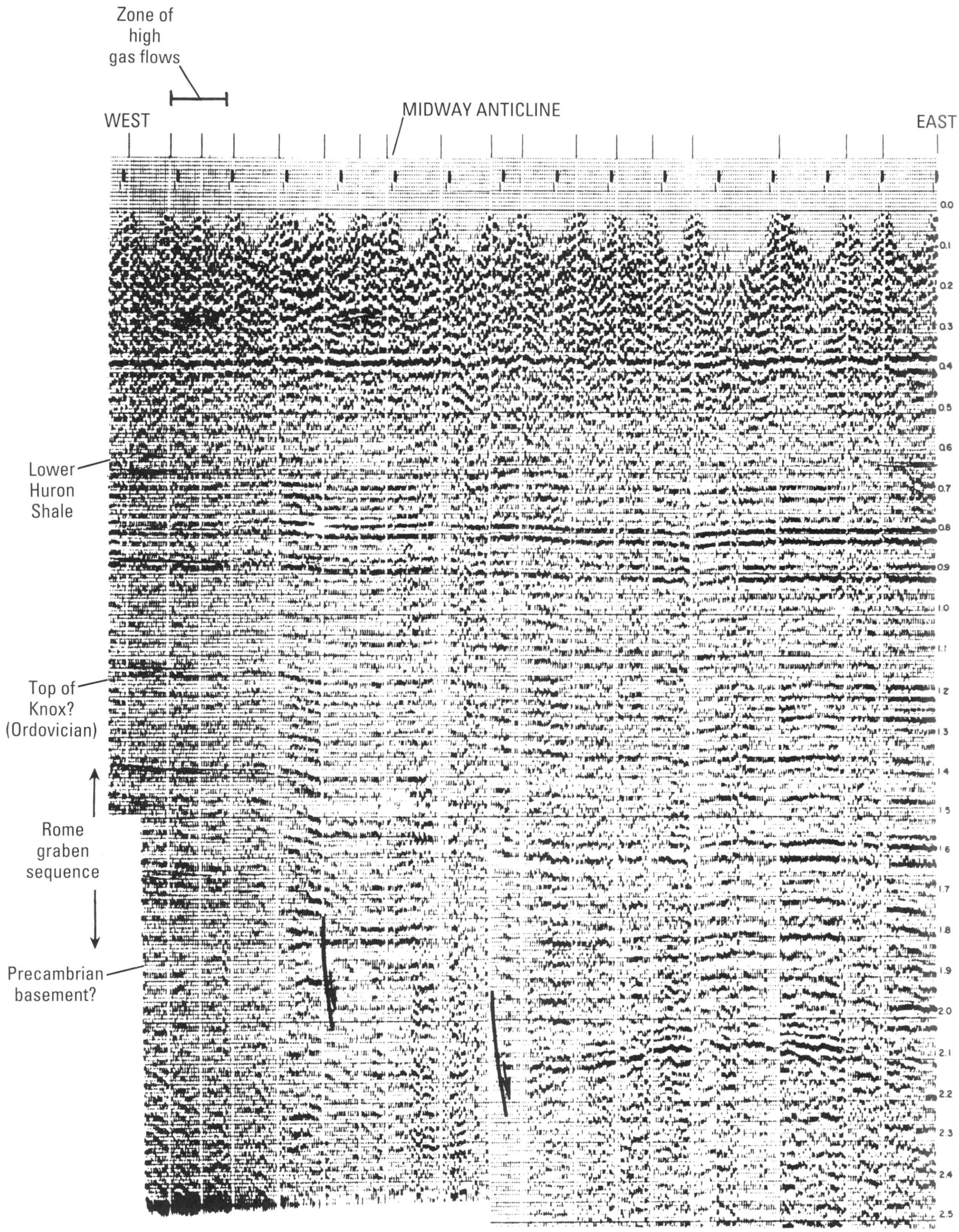


Figure 13. Seismic line of the Midway-Extra Field area, West Virginia. See figure 11 for location of the seismic line.

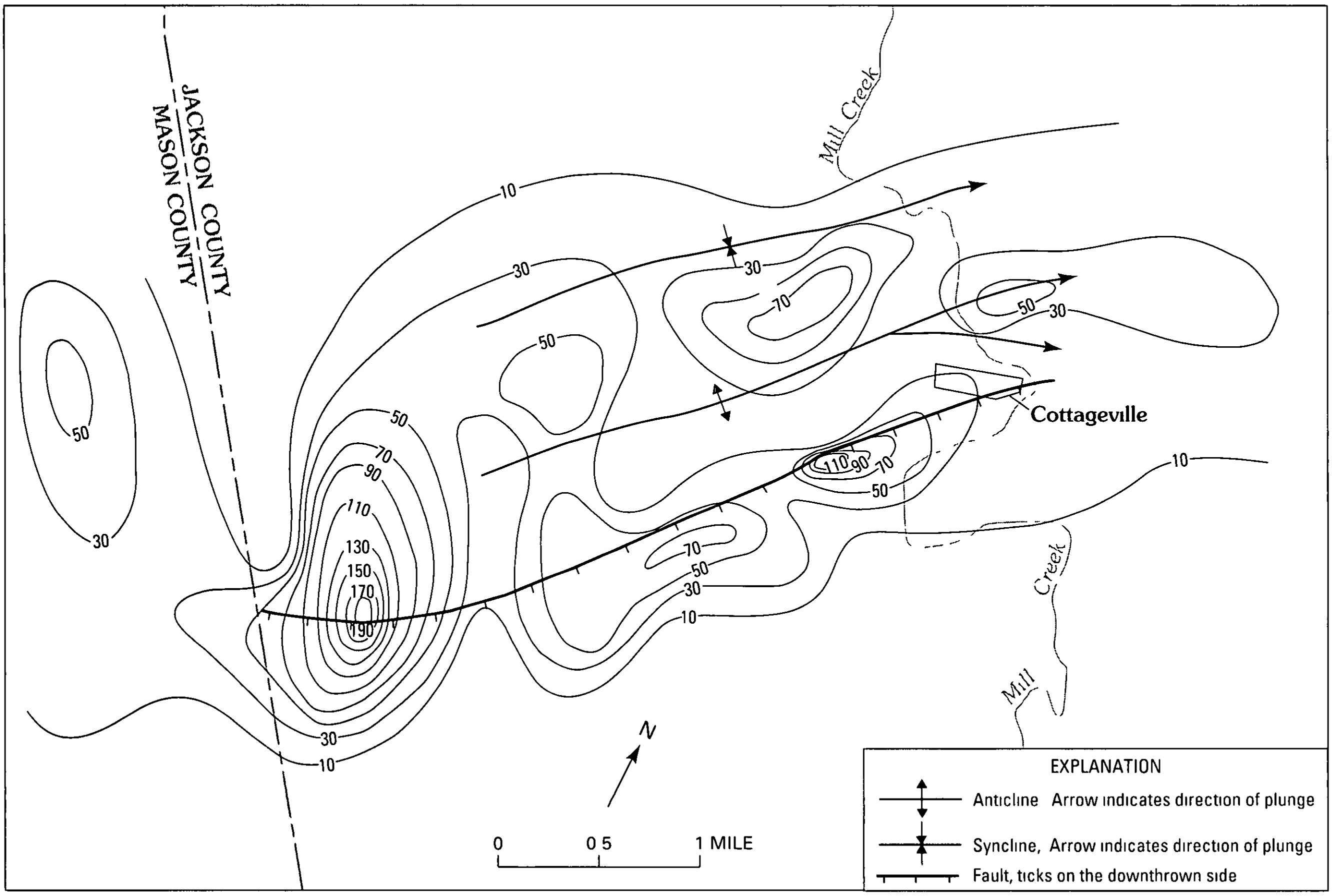


Figure 14. Highest annual production (first- or second-year production) of the Cottageville Field, W Va (From Negus-deWys and Shumaker, 1978) Contour interval 20 mmcf/yr

- The higher level of production may not occur uniquely in the shale directly above faults mapped by the offset of the seismic reflections from the basement and the overlying Lower and Middle Cambrian rocks

Shumaker and others (1982) interpreted the basement fault zone at Cottageville as being a southward extension of a much larger basement fault that underlies the Evans flexure (figs 7, 17) Like the Midway-Extra Field, higher-than-normal production at the Cottageville Field occurs either near a bend in a basement fault zone or at the intersection of basement structures

On the basis of the relation between gas flow and structure at the Midway-Extra Field (figs 10, 11), the position of the fault, the fold crestal trace, and the trace of the flanking northern syncline can be compared with the production trends at the Cottageville Field (figs 14–16) The best production lies on the flanks of the fold, not at the crest Production data at the Cottageville Field are more complete and of better quality than those at the Midway-Extra Field, and, by all gas flow (Nuckols, 1980) and production standards (Negus-deWys and Shumaker, 1978), it is clear that better wells occur off-structure The maps of Negus-deWys and Shumaker (1978) show that the best production does not follow the thicker lower Huron shale (Nuckols, 1980), as it did at the Midway-Extra Field (figs 10, 12) Even though the best wells generally occur near what Sundheimer (1980) mapped as a basement fault, there is scatter, and not every high-producing well can be explained by one or even two fault zones

For the Cottageville Field, precise data on the nature of the mineralized fracture permeability come from oriented cores taken through much of the Ohio Shale section (Evans, 1979) in the West Virginia Nos 1 and 2 wells (figs 5, 17) The West Virginia No 1 well lies within the highly productive trend along the southern side of the field It flowed gas on initial test at a rate of over 1,000 mcf/d despite being drilled years after the major pressure decline of the reservoir (Nuckols, 1980) The West Virginia No 1 well was not stimulated because of its high flow, and it was quickly put into production The West Virginia No 2 well subsequently was drilled at the northern margin of the field (fig 17) Because it failed to flow gas on initial (natural) test and flowed only at the rate of 180 mcf/d from the lower Huron shale after stimulation, it was considered to be an economic failure

The contrast in flow from these two wells, which are only 3 miles apart and which produced from the same stratigraphic interval in the lower Huron, is striking The

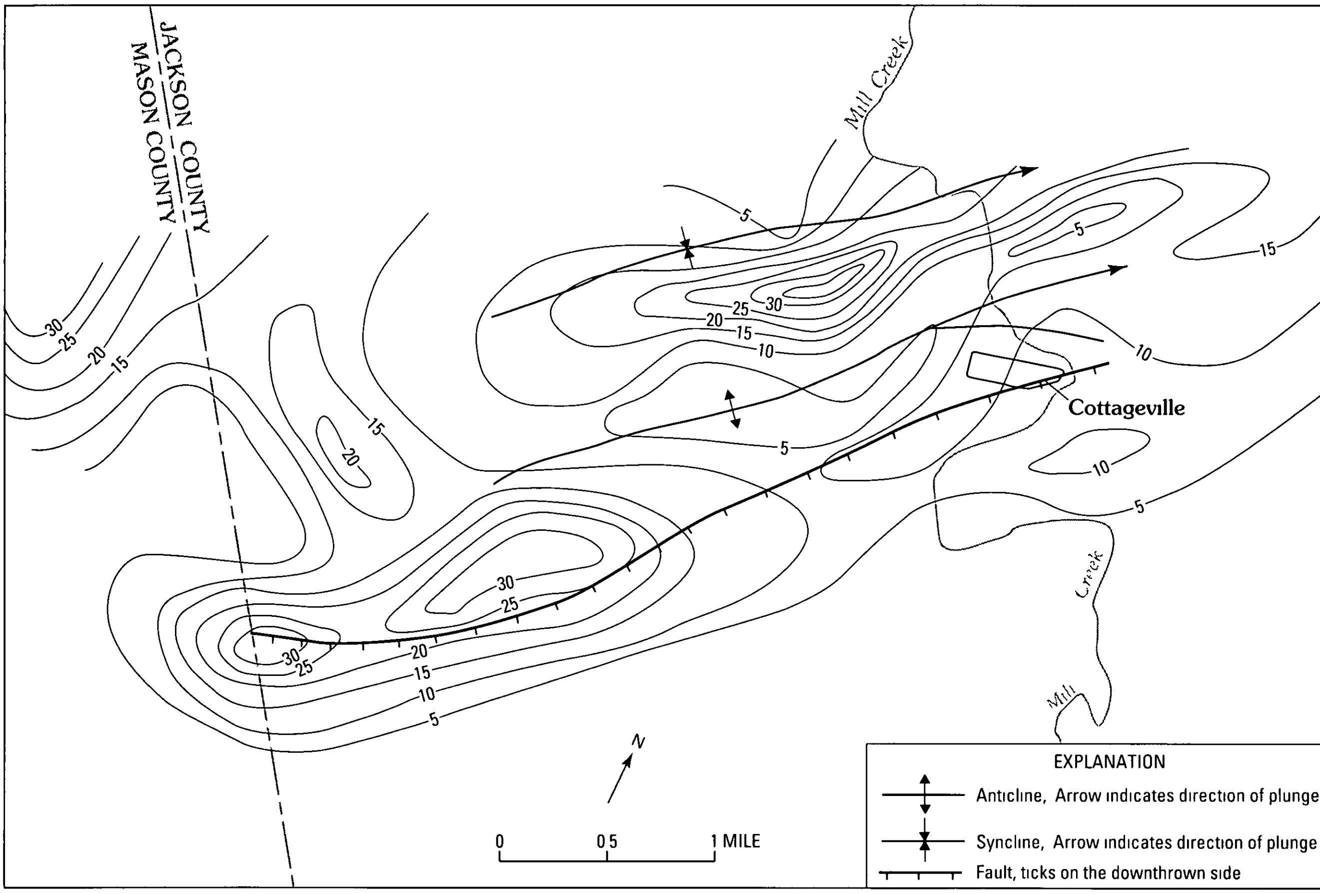


Figure 15. Mean annual production of the Cottageville Field, W Va (From Negus-de Wys and Shumaker, 1978) Contour interval 5 mmcf/yr

abrupt lateral change in production between wells is similar to abrupt changes in flows found elsewhere, such as that just described in the Midway-Extra Field Gamma-ray-density log responses through the lower Huron reservoir in the West Virginia Nos 1 and 2 wells (fig 18) are nearly identical as are the orientations of small joints above the producing interval In both wells, the joint patterns became more diverse at the reservoir interval (fig 18), and in the West Virginia No 1 core, small vertical fractures were more common and were propped open by spar (Larese and Heald, 1977) The major difference in the lower Huron reservoir between the two wells was the absence of mineral-propped vertical fractures in the unproductive West Virginia No 2 core and their presence in the West Virginia No 1

Correlation of the unique joint pattern in the productive interval between the two wells indicates that the pattern is laterally extensive and that it imparts a lateral, nonvertical permeability to the shale The permeability occurs only in the organic-rich lower Huron, however, no evidence has been found of vertical permeability along high-angle faults or through-going master joints in the shale cores from either well Likewise, no abnormal dips were reported in the shale (Byrer and others, 1976) to suggest that a local flexure caused local joint patterns in the reservoir These data suggest that the fracture permeability does not develop upward through the stratigraphic section from a basement structure even though much of the production occurs over basement faults The lateral continuity of a complexly fractured interval is compatible with detachment

Further evidence for detachment comes from an inferred change in paleostress direction across the reservoir (the lower Huron) The change in stress direction is based on a change in the trend of induced fractures found below the lower Huron in cores taken at the Cottageville Field and elsewhere in the study area (Shumaker, 1975b, Evans, 1979) Small joints in sediments above the lower Huron at the Cottageville Field had a nearly uniform northeasterly trend (Evans, 1979) that paralleled a very weak mechanical fabric (fig 9) in the shale and the coring-induced joint trend noted by Evans (1979) Induced joints below the lower Huron shale (Evans, 1979) in the Java Shale of the West Virginia No 1 well trend slightly west of north, nearly at right angles to those found in the shale above the reservoir Slight differences in the orientation of induced fractures have been noted across the lower Huron shale in other oriented cores of the study area (Shumaker, 1975b, Evans, 1979) This orientation change, which suggests that either a

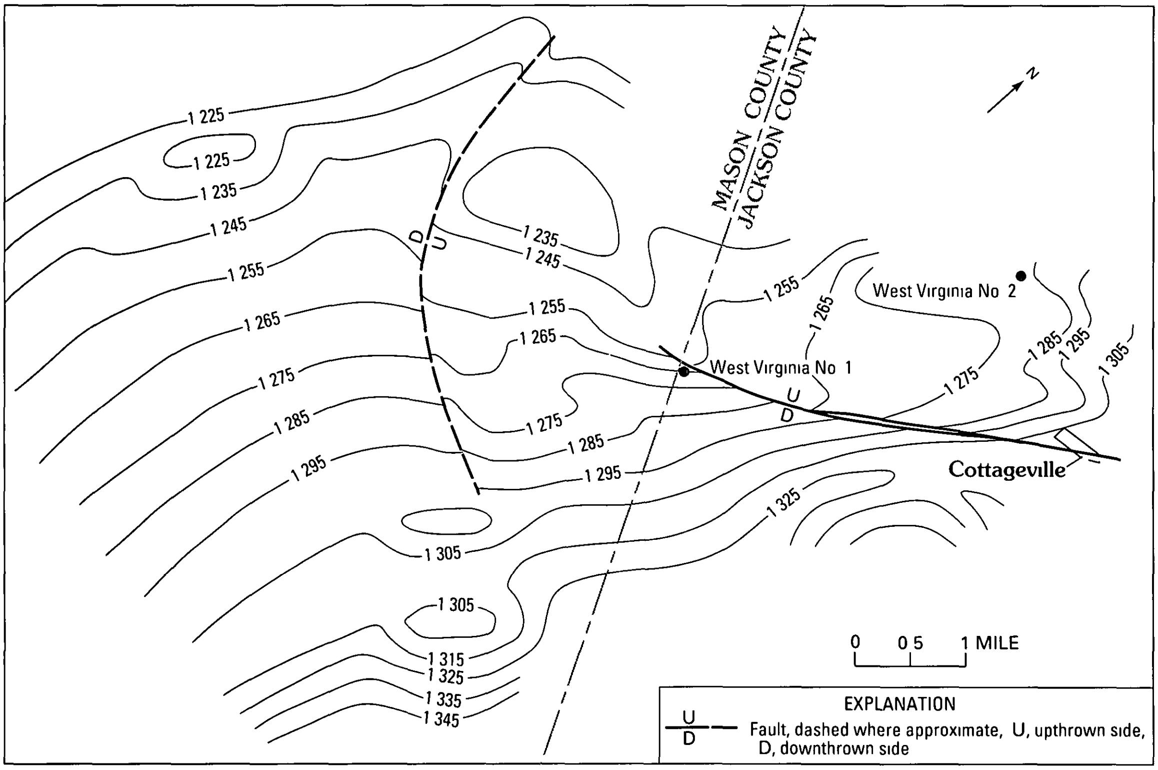


Figure 16. Top of the basement in the Cottageville Field area, West Virginia (From Sundheimer, 1980) Contour interval 0 010 s

different stress field or a transition in stress field occurs across the lower Huron shale, is a characteristic that is compatible with detachment

Additional direct evidence in favor of differential horizontal movement was in the form of low-angle horizontal slickensides in both of the cores taken at the Cottageville Field Slickensides and horizontal mineralized fractures were present, but their orientations were not mapped in the West Virginia No 1 well (Byrer and others, 1976) The West Virginia No 2 well contained only three slickensided surfaces, but all were near or in the reservoir horizon (Evans, 1979) Slickensided shale was noted in samples of the lower Huron from most wells in the Cottageville (Stewart, 1979) and Midway-Extra (Templin, 1979) Fields, which suggests that differential movement within the lower Huron was more widespread than indicated by the data from the West Virginia No 2 core In other cores taken in the region just east of the Midway-Extra Field in Lincoln County (West Virginia Nos 3 and 4 of figs 5, 19, 20), the presence of low-angle shear surfaces and slickenside stria, which are oriented parallel to the implied maximum Alleghenian stress, confirms that differential tectonic transport occurred across the lower parts of the Huron Member of this region Such transport also is suggested by analysis of adjacent structures, such as the Burning Springs anticline (fig 7), where several thousand feet of lateral transport was transferred from rock above a detachment surface in the Silurian salt to rock in and above the Devonian shale (Calvert, 1987) The direction of transport (fig 20) of rocks above the shale detachment is roughly perpendicular to the mechanical fabric (fig 9) found in the shale, this adds credence to the interpretation that Alleghenian stress extended well beyond the folded margin

Discussion

The detailed analyses of two shale gas fields indicate that similar geologic conditions exist in both areas of enhanced production Intensely fractured and mineral-propped vertical joints form fracture porosity in a rock unit that is an areally extensive decollement zone of the adjacent fold belt Seismic records confirm that the enhanced production occurs near or above low-relief basement structures that formed before the detached deformation The similar characteristics of fractures found in the same reservoir of both fields suggest that the fracture permeability formed during Alleghenian detached deformation when the lower

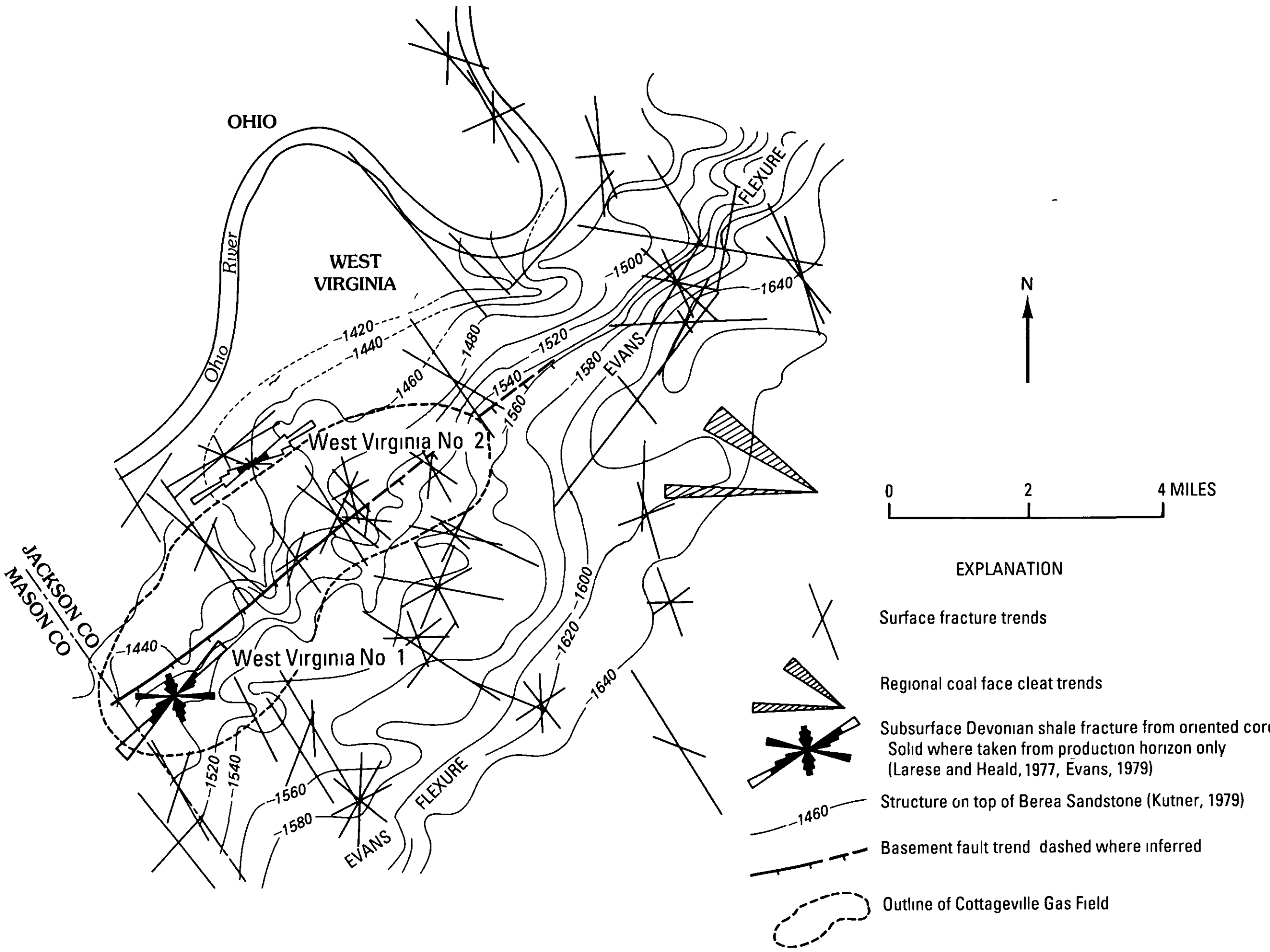


Figure 17. Subsurface structure and surface joints of the Cottageville Field area, West Virginia (From Shumaker and others, 1982) Contour interval 20 ft

Huron shale was overpressured The abnormally complex fracture pattern of the reservoir indicates that either the stress field was more complex above the low-relief basement structure or several episodes of fracturing occurred when the stress trajectories varied

Irrespective of the cause or causes of localized zones of fracture permeability, studies of the Midway-Extra (Schaefer, 1979) and Cottageville (Shumaker, 1980, 1986a) Fields demonstrate the importance of local geologic structure to the formation of increased fracture permeability, which accounts for two local trends of high production from the shale The trapping mechanism for these two fields is the absence of updip fracture permeability in the shale reservoir Therefore, the likelihood of drilling commercial wells can be increased within the area of regional shale gas production by locating wells on the flanks of or in the syncline adjacent to low-amplitude anticlines and monoclines Wells drilled at intersecting basement trends in these lows are most favorable for successful development

Regional Production

The magnitude of regional production, which is the number of commercial shale wells per unit area, increases southwestward from the Cottageville and Midway-Extra Fields along the trend of the New York-Alabama lineament and the Rome trough into eastern Kentucky (figs 6, 8, respectively) As the trend of regional production crosses the 38th Parallel lineament (fig 6) near the Kentucky-West Virginia border, production increases From there, the trend of production extends southward into central eastern Kentucky, diverging from the east-west trend of the Rome trough (fig 8) but remaining roughly symmetrical to the trend of the 38th Parallel lineament Although the shale reservoir becomes thinner and less silty and its organic content changes very little into eastern Kentucky, the increase in regional production is not easily explained by a change in the stratigraphy or geochemistry of the shale itself

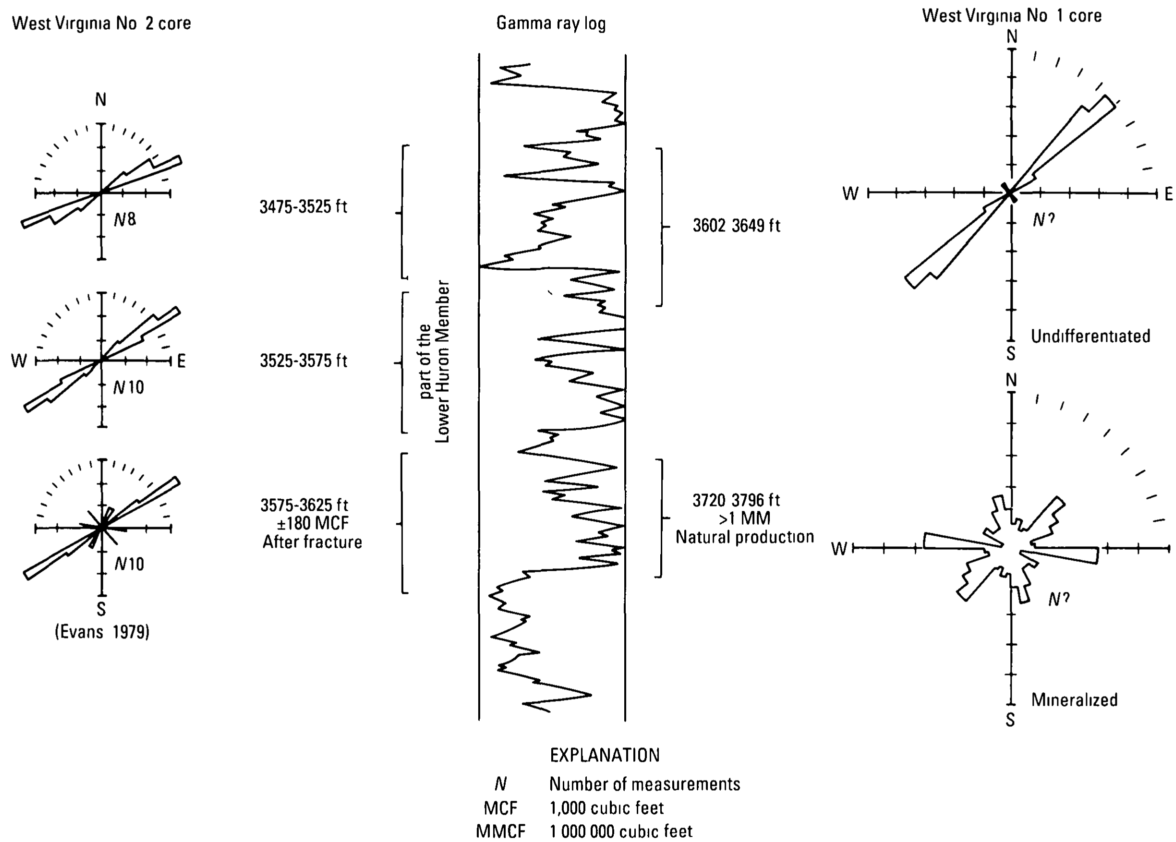


Figure 18. Devonian shale fracture and production data from West Virginia Nos 1 and 2 wells API, American Petroleum Institute (Modified from Larese and Heald, 1977, Evans, 1979)

Gas flow and structural data for the nearly 5,000 wells that are distributed over a large area in eastern Kentucky permitted a more comprehensive look at the regional production Even though gas flow, structure, and isopach maps were constructed for almost the entire area of commercial production, only the two areas where gas flows were abnormally high, which are shown in figure 21, were studied in detail

Reservoir Permeability

In the commercially productive area of eastern Kentucky (fig 1), nearly 90 percent of the wells (Negus-deWys, 1979) drilled before 1976 were commercial Such widespread commercial production implies widespread fracture permeability, that is, a fracture pattern and attendant permeability that are regional in extent Favoring such interconnecting permeability is the large area of pressure decline (fig 22) (Hunter and Young, 1953) and the historic development of the field itself (fig 23) Maps of final open-flow for the earliest periods of development (fig 23*A*, *B*) show two centers of high gas flow—in the Floyd-Knott Counties area and in Martin County These two areas have maintained their position as the productive centers of the field (Negus-deWys, 1979) Subsequent time intervals (fig 23*C*, *D*) show that progressively fewer large flowing wells were drilled in these two areas and that wells ouside these two areas generally have not had large flows of gas even when reservoir pressures were virgin (fig 22) The shapes of the 200-pound pressure lines for successive time intervals shown in figure 22 are also of interest in regard to the distribution of permeability The shapes are not perfectly circular, but they are elongate in a northeast-southwest direction In northern Floyd County, the lines swing eastward toward Martin County, and, in western Floyd County, the lines are close together The steep gradient to the west suggests the presence of an abrupt decrease in fracture permeability The eastward swing in northern Floyd County suggests a change in the trend of open-fractures toward Martin County

The Reservoir

The vertical or stratigraphic distribution of fracture permeability in eastern Kentucky is similar to that described previously at the Cottageville and Midway-Extra Fields In West Virginia and eastern Kentucky, the primary reservoir is the lower part of the Huron Member of the Ohio Shale It and, to a lesser extent, the Cleveland Member are the usual targets for stimulation in eastern Kentucky (fig 3) Recent

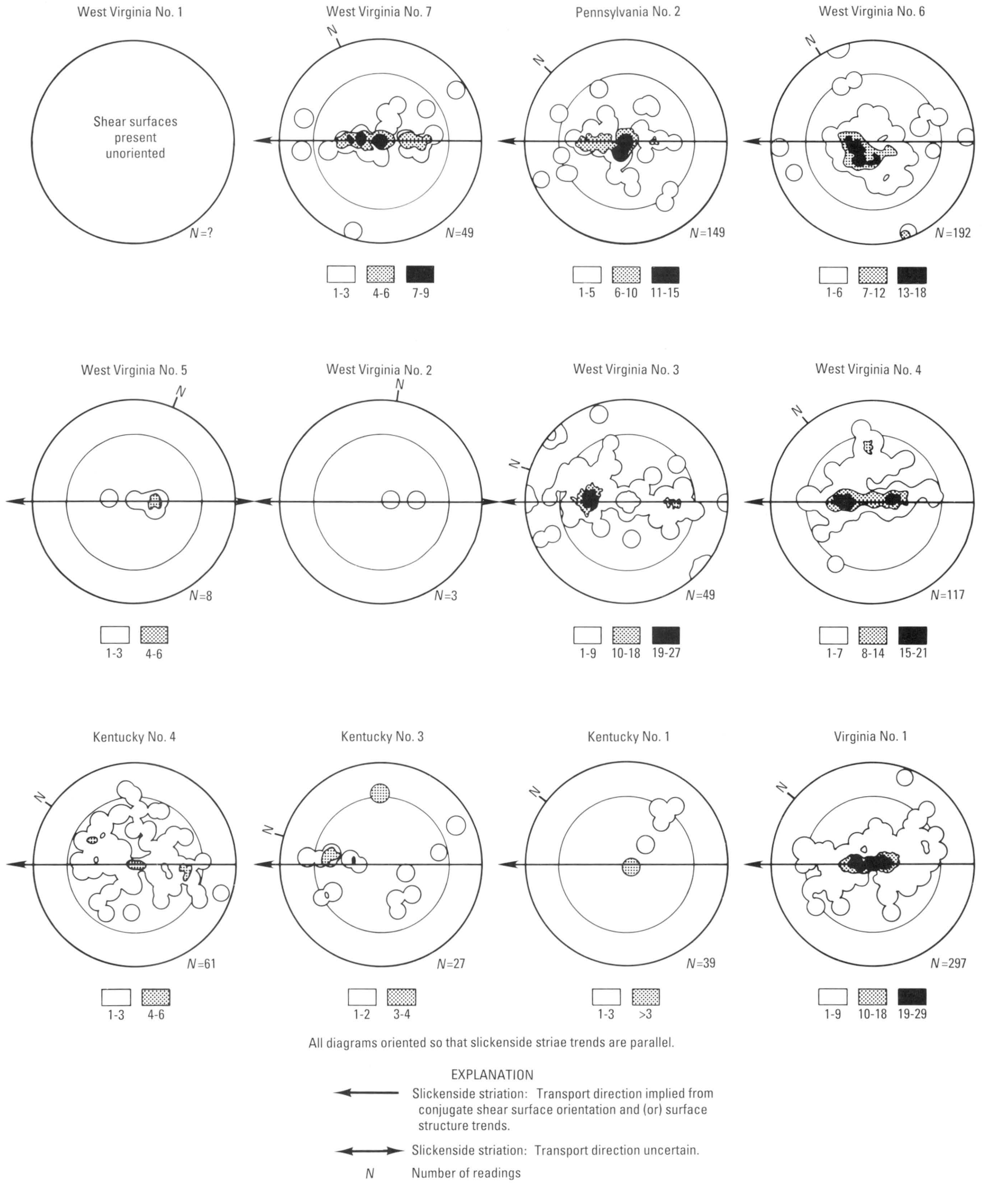


Figure 19. Poles to shear fractures found in oriented shale cores. See figure 5 for well locations. The northernmost wells are at the top of the page, and the easternmost wells are on the right side of the page. (Modified from Evans, 1979.)

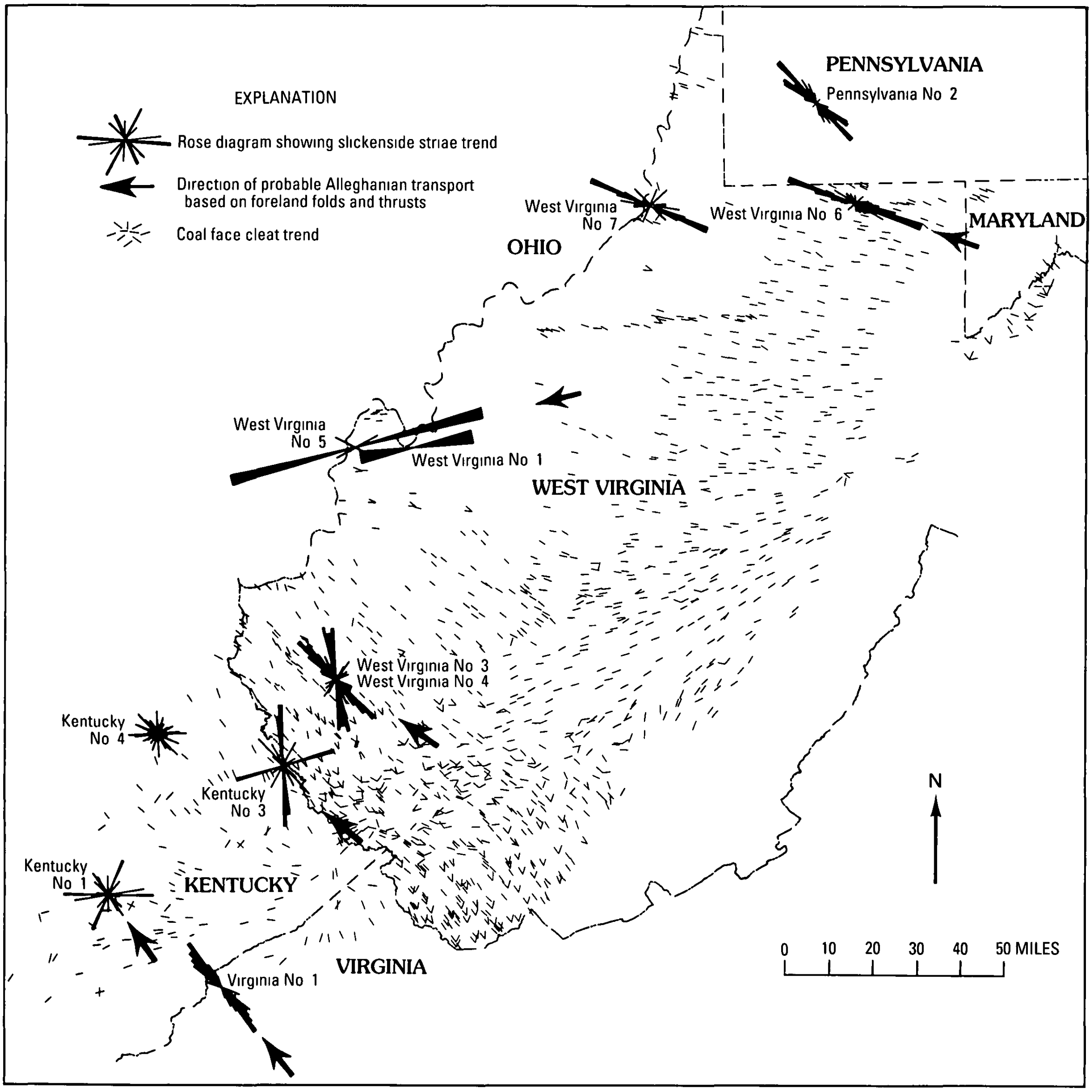


Figure 20. Slickenside striation trends in the oriented Devonian shale cores from the study area and the face cleat trends (pattern) from the surface coals (Modified from Evans, 1979)

analysis of the stratigraphic distribution of gas shows in 338 shale wells of eastern Kentucky by Moody and others (1987) confirms that natural production of gas comes primarily from the lower Huron

Evidence for the widespread presence of fracture permeability in the shale comes from the reported occurrence of slickensided shale fragments blown from wells that were drilled early in the history of the field (Lafferty, 1935) and the reported increase in the incidence of spar and slickensided shale in cuttings from wells that were drilled toward the center of the field, which is toward Floyd County, Ky (Negus-deWys, 1979) Oriented cores (Evans, 1979, Wilson and others, 1980, Shumaker, 1986b) that were taken outside the Floyd County center of production contain fractures similar to those described at the Cottageville and elsewhere in West Virginia The indications of open-fractures from sample examination, the localized and highly variable production, and the similarity of fracture patterns in eastern Kentucky cores to those described elsewhere suggest that the fracture permeability in the shale reservoir of eastern Kentucky is similar to that found in West Virginia

This distribution of permeability within a discrete and fairly thin unit, such as the lower Huron shale, which extends across the entire area of commercial production, has a direct bearing on the origin of the permeability This characteristic is not readily explained by local deformation or permeability associated with local basement structures

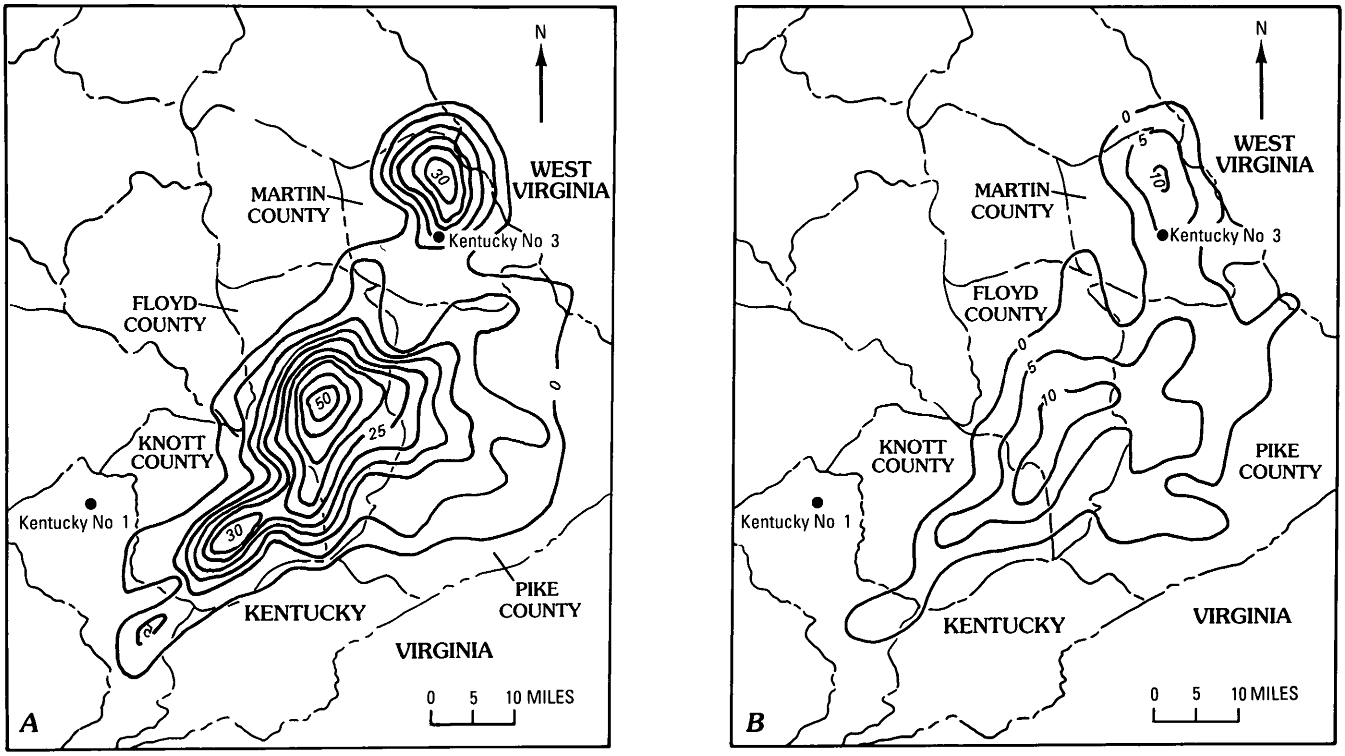


Figure 21. Contours of the number of high-volume wells per 25 square miles in eastern Kentucky *A*, 5 mmcf/d (Griffith, 1976) *B*, 1 0 mmcf/d (Negus-deWys, 1979)

such as those described at the Cottageville and Midway-Extra Fields Indeed, that the fracture permeability is widespread implies that it was caused by laterally continuous stress The presence of at least one low-angle shear system in the plane of Alleghenian transport indicates the importance of detached deformation to the formation of at least part of the fractures found in the reservoir

Centers of Elevated Production

Comparative analysis of geologic structure and gas flow in eastern Kentucky was limited to the two large areas, or centers, of high gas flow (fig 21) in Martin and Floyd Counties The Martin County center of production is situated at the change in the trend of the Rome trough that occurs at the intersection of the New York-Alabama lineament and the 38th Parallel lineament (fig 6) The surface structure of Martin County (Lee, 1980) consists of the broad east-west-trending Warfield and Inez anticlines and the Warfield fault, which enters the county at its eastern margin (figs 7, 24) Specifically, the Warfield and Inez anticlines plunge toward each other into the north-south-trending Little Blacklog syncline Lee (1980) reported that the Little Blacklog syncline occurs above a left-lateral strike-slip basement fault (fig 25), evidence for which rests on the apparent left-lateral offset of structures across the structural low Current work for this chapter by the author suggests

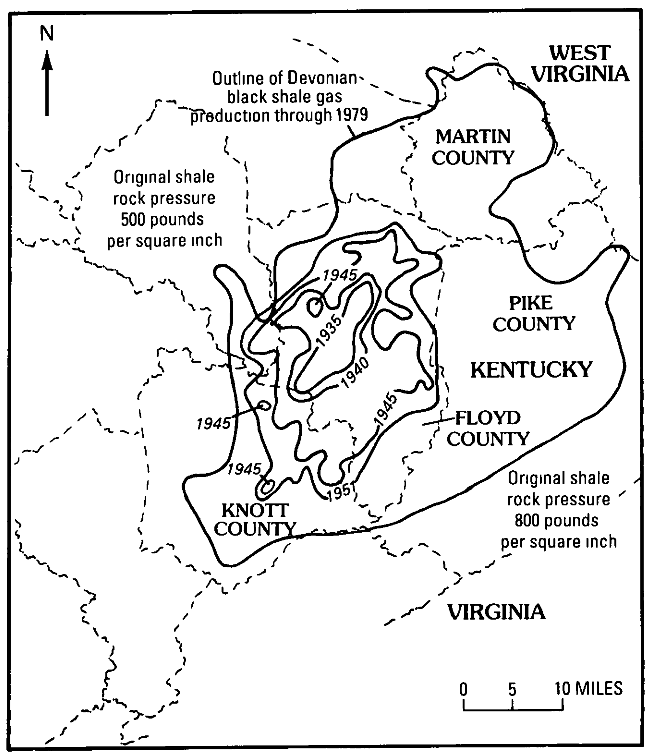


Figure 22. Devonian shale formation pressure decline (200-pound contour) in the eastern Kentucky field from 1935 to 1951 (From Negus-deWys, 1979)

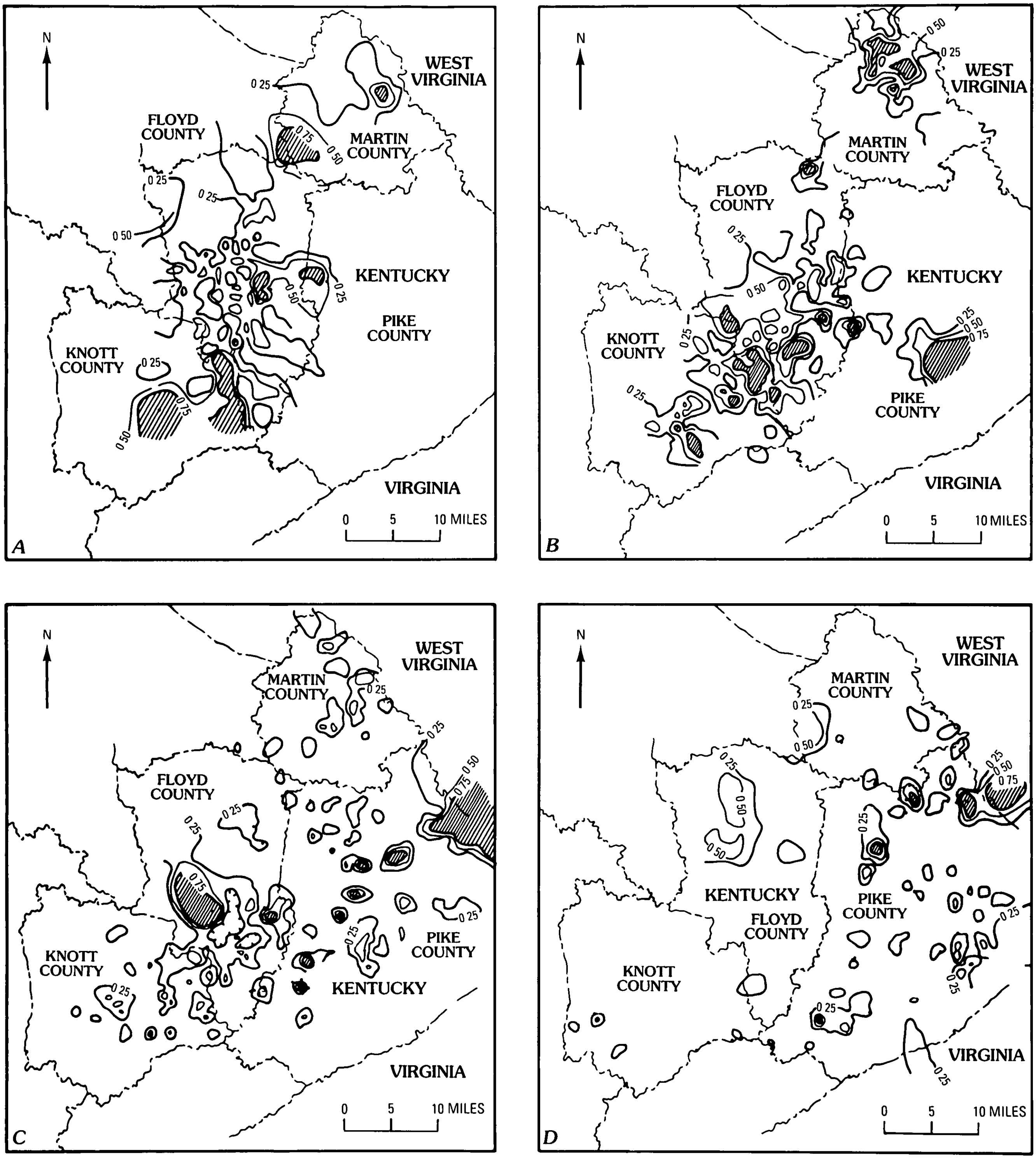


Figure 23. Historic development of the eastern Kentucky field as indicated by the contoured final open-flow values Contour interval 0 25 mmcf *A*, Pre-1930 *B*, 1931–40 *C*, 1941–50 *D*, 1951–60 The shaded areas contain wells that have final open-flows of greater than 750 mcf/d

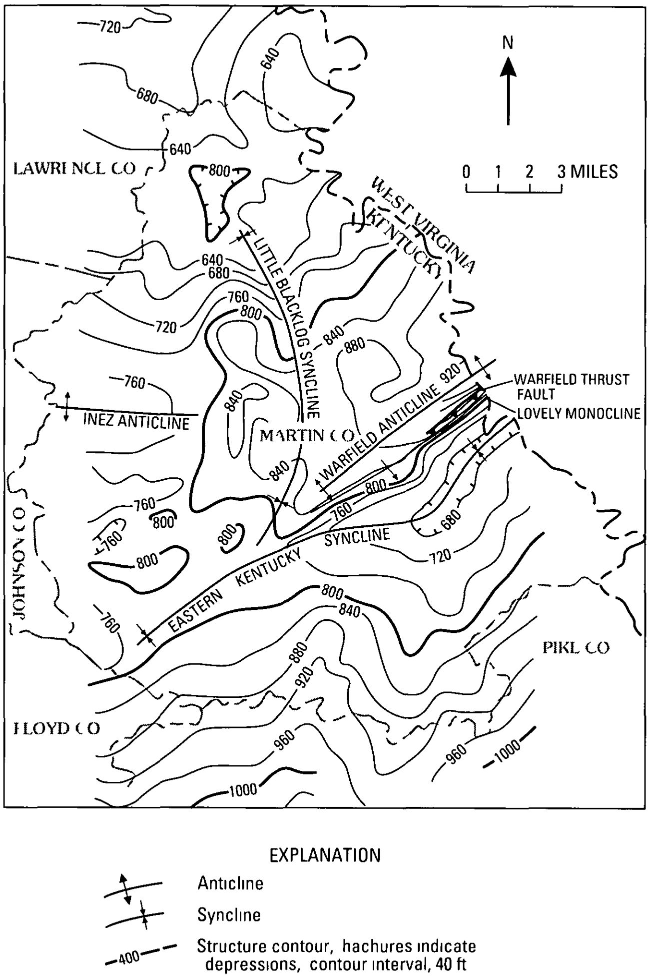


Figure 24. Surface structure of Martin County, Ky , contours on the Taylor Coal

an alternative interpretation that relates the offset to transtensional grabens formed in response to right-lateral movement along the 38th Parallel lineament The steep south-dipping Lovely monocline (fig 26) is not offset at its intersection with the Little Blacklog syncline, but it extends eastward several miles along the trend into West Virginia and westward with diminishing relief across Martin County to Floyd County The monocline has been interpreted as being the surface expression of a reactivated basement fault along the southern border of the Rome trough

Wells that have increased gas flows (figs 27, 28) are found along the Little Blacklog syncline and westward along the trend of the monocline (fig 28) Patterns of isopotential flow within the Little Blacklog syncline show that the areas of highest gas flow often occur near an intersecting east-west-trending low similar to that found at the Midway-Extra Field

It is likely that the structures of Martin County relate to basement movement because of their position within the 38th Parallel lineament (fig 6) at its intersection with the New York-Alabama lineament (fig 6) In addition, the Berea Sandstone follows the trend of the Little Blacklog syncline (Lee, 1980) The Warfield anticline and the Lovely monocline, in part, controlled late Devonian and early Mississippian sedimentation Such evidence of structural activity during deposition suggests that the structures relate to basement deformation

Detailed information on fracture patterns in the shale reservoir of the Martin County center comes from the Kentucky No 3 cored well (Evans, 1979), which is located near the structural intersection of the Lovely monocline (fig 25) and the Little Blacklog syncline As expected from its position near intersecting basement structures, this well had an elevated flow of gas after stimulation of 250 mcf/d from the middle part of the Huron and 370 mcf/d from the lower Huron (Evans, 1979) Note that the gas flows come from two discrete horizons in the Huron section Fracture patterns in the shale (Evans, 1979) of this well are subparallel to local structure (fig 25), but they appear to be part of a more regionally extensive pattern (figs 20, 29)

Appalachian shale gas production reaches its peak in the other center of high production in Floyd and Knott Counties (figs 21, 27) Relations between structure and production are less well defined than in the other areas studied The distribution of wells that have high gas flows of greater than 250 mcf/d is roughly triangular in shape (fig 27) and covers much of central and eastern Floyd and eastern Knott Counties and extends eastward into Pike County The western and southern boundaries of high flow are fairly sharp, but the northeastern border is ill defined A simple comparison of near-surface (fig 30) and subsurface (figs 26, 31) structure maps that show the distribution of high-gas-flow wells (fig 27) of this center fails to indicate any obvious relation between gas flow and structure At the shale level, the gas appears to be trapped, probably by a permeability barrier, on the gentle east-dipping flank of the Paint Creek uplift (figs 26, 31) Several linear trends of wells that have very high flows have been noted (Negus-deWys, 1979), but no clear patterns emerge The Bonanza-B and Carrie-A folds of figures 26 and 31 approximate the limits of the area where wells that have final flows of greater than 250 mcf/d (fig 27) are abundant, but no single fold or fault can account for this large area of gas flow

A relation between basement structure and high-gas-flow wells on a regional scale is suggested if the area of high production is compared with basement structure, as is inferred from gravity and magnetic maps (fig 32) The generalized outline of the area of wells that have a final open-flow of greater than 250 mcf/d curves around a magnetic and gravity anomaly that Ammerman and Keller (1979) called the Pike County uplift (fig 32*A*) Production extends southward along a basement low, the Floyd County channel, which they suggested is a graben that is, perhaps, an arm of the Rome trough

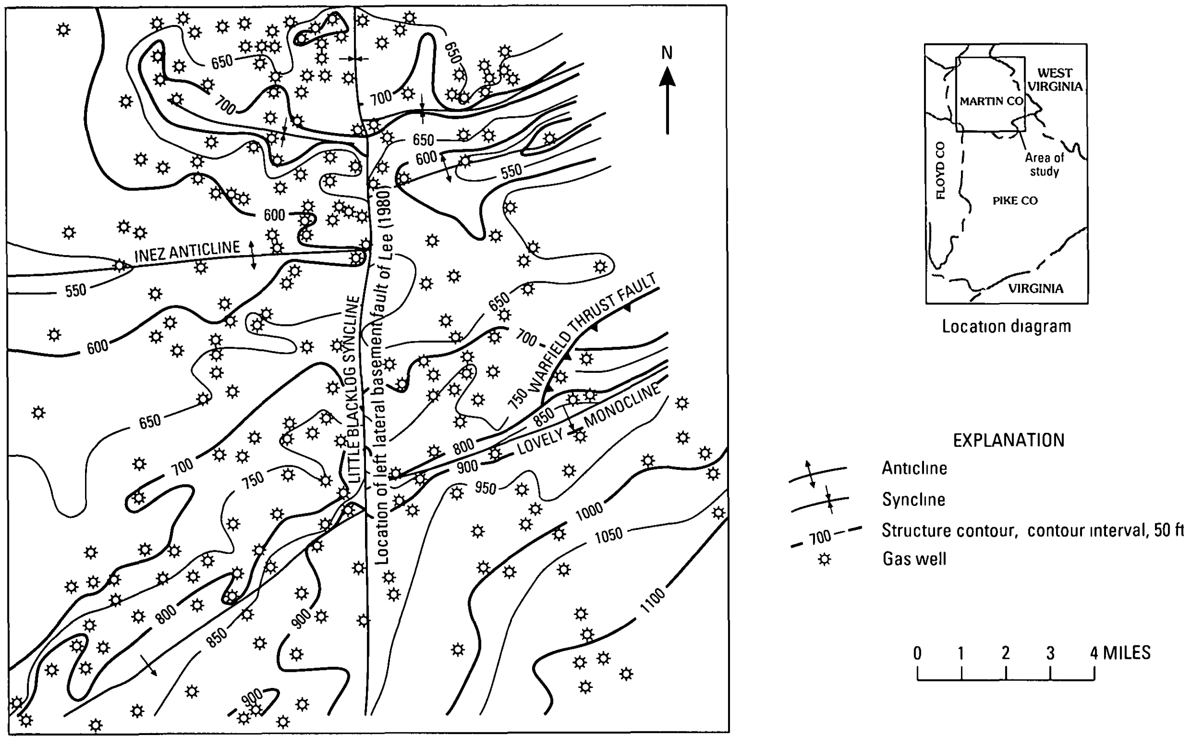


Figure 25. Subsurface structure on the base of the Mississippian Newman Limestone in Martin County, Ky (Modified from Lee, 1980)

The isopotential map (fig 27) shows that the trend of highest gas flow in Floyd County connects its northern end with the western end of production along the Lovely monocline This northward elongation and eastward swing of high gas flow in northern Floyd County are reminiscent of the northern trend and eastward swing seen on the pressure decline map (fig 22) Production along the Lovely monocline follows the southern margin of the Rome trough, and this connection of the two centers of high production along the margin of the trough suggests a physical connection of the underlying basement structure Black (1986) identified the Floyd County low as a faulted basement structure on a regional seismic line that crosses Perry County just south of the center of production The gravity and magnetic maps (fig 32) extend the low and, presumably, its faulted margin into the highly productive area of Floyd County This explains the extension of a basement fault into the region but not the large areal extent of the production found in the Floyd County center

A more specific relation between gas flow and geologic structure comes from a trend surface analysis of the regional structure maps Second-order residual maps of structure on the top and base (fig 33) of the Ohio Shale show a broad anticlinal fold of a northerly trend that terminates near the western end of the monocline at the Bonanza anticline If the second-order-trend surface map approximates the regional dip, then the positive anomaly from that surface (fig 33) outlines a broad anticline on the eastern flank of the Paint Creek uplift That anticlinal flexure approximately coincides with the north-south trend of highest gas flow (fig 27) and the basement low in Floyd County (fig 32) These relations indicate that a slight uplift of the Floyd County low created the anticline in the area of highest production Evidence favoring the basement origin for most of the named structures shown on the structure maps (figs 26, 31) comes from the isopach map of the Ohio Shale, which shows minor but systematic variations of thickness across the Lovely monocline, the Shelbians, the Bonanza-B, and the Carrie-A structures As noted above, these last two are the structures that approximately outline the area of highest production in the Floyd County center Likewise, the rapid thinning of the Berea Sandstone into the area of the Floyd County low was noted by Pepper and others (1954)

The relation between the basement structure and the area of elevated gas production in the Floyd County area is similar to that at the Cottageville and Midway-Extra Fields and in Martin County However, the highly productive area and the structure in Floyd County are considerably larger than those described in Martin County and many times larger than those at the Cottageville and Midway-Extra Fields In addition, production comes from the crestal area of a broad flexure rather than from the flank or adjacent syncline of a specific small structure The differences noted at Floyd County suggest a somewhat different origin for the fracture permeability found there Unfortunately, no shale

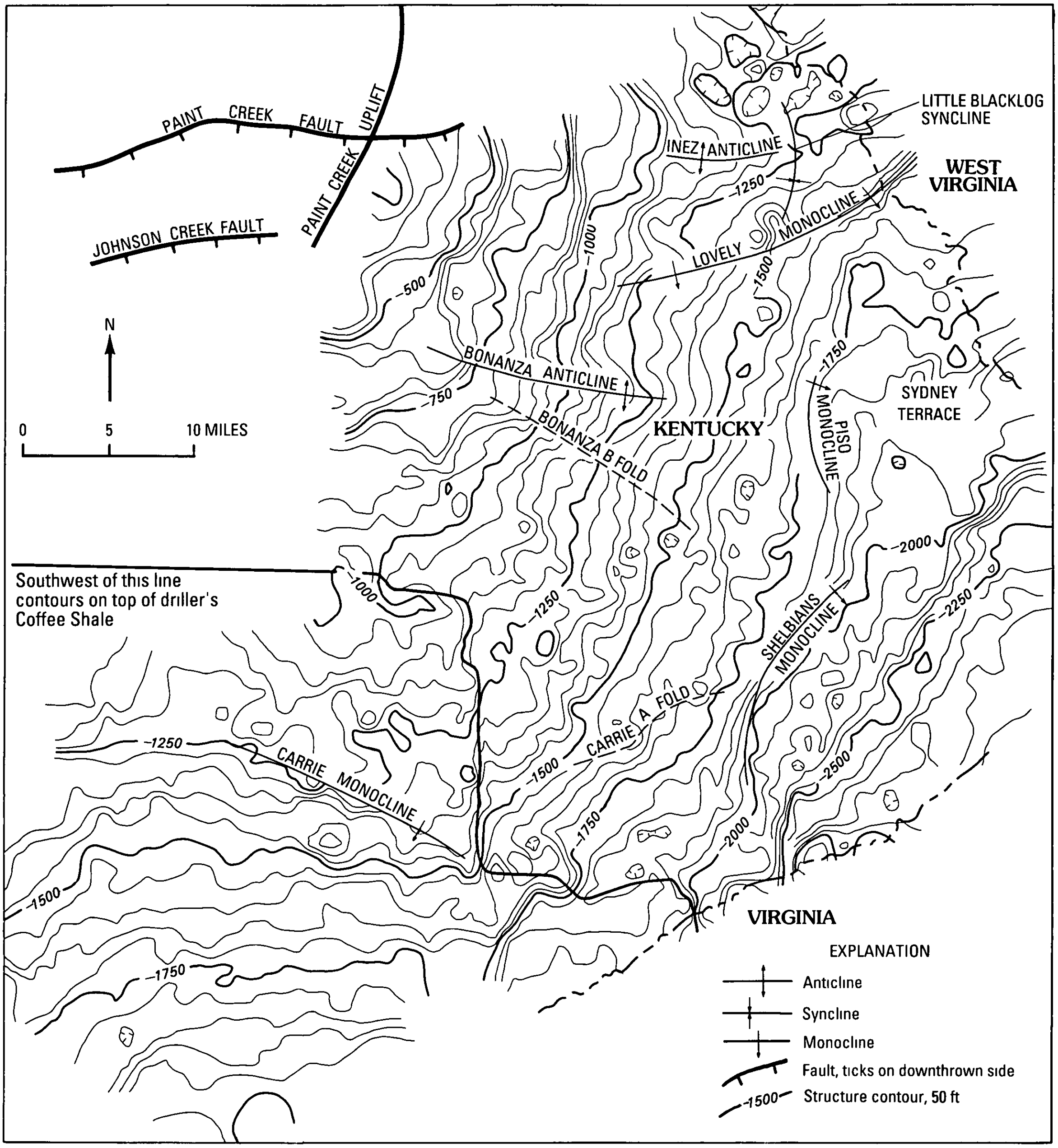


Figure 26. Geologic structure of the top of the Devonian shale (Ohio Shale), which is the base of the Berea Sandstone or the first organic shale (top of Sunbury Shale?) in the Big Sandy area (Data collected by Lee, 1980) For well control, see figure 33

cores are available within this area to assist in further defining that origin

Regional Production

Wilson and others (1980), Evans (1979), and Cliffs Minerals, Inc (1982) noted that the following aspects of the fracture pattern of the shale shed light on the origin of the regional production

- The primary reservoir is widespread and has its own unique fracture pattern
- The fracture patterns at the surface and in cores are more complex in eastern Kentucky than elsewhere in the marginally commercial areas of shale gas production in West Virginia and Ohio
- Optimum production occurs where low-angle shear fractures disappear from the shale

The increase in fracture complexity in eastern Kentucky probably plays a role in establishing high production The regional fracture pattern is more diverse in natural joints and in slickenside striation trends (figs 19, 20, 29, 34) To a lesser extent, coal cleat trends reflect the complex

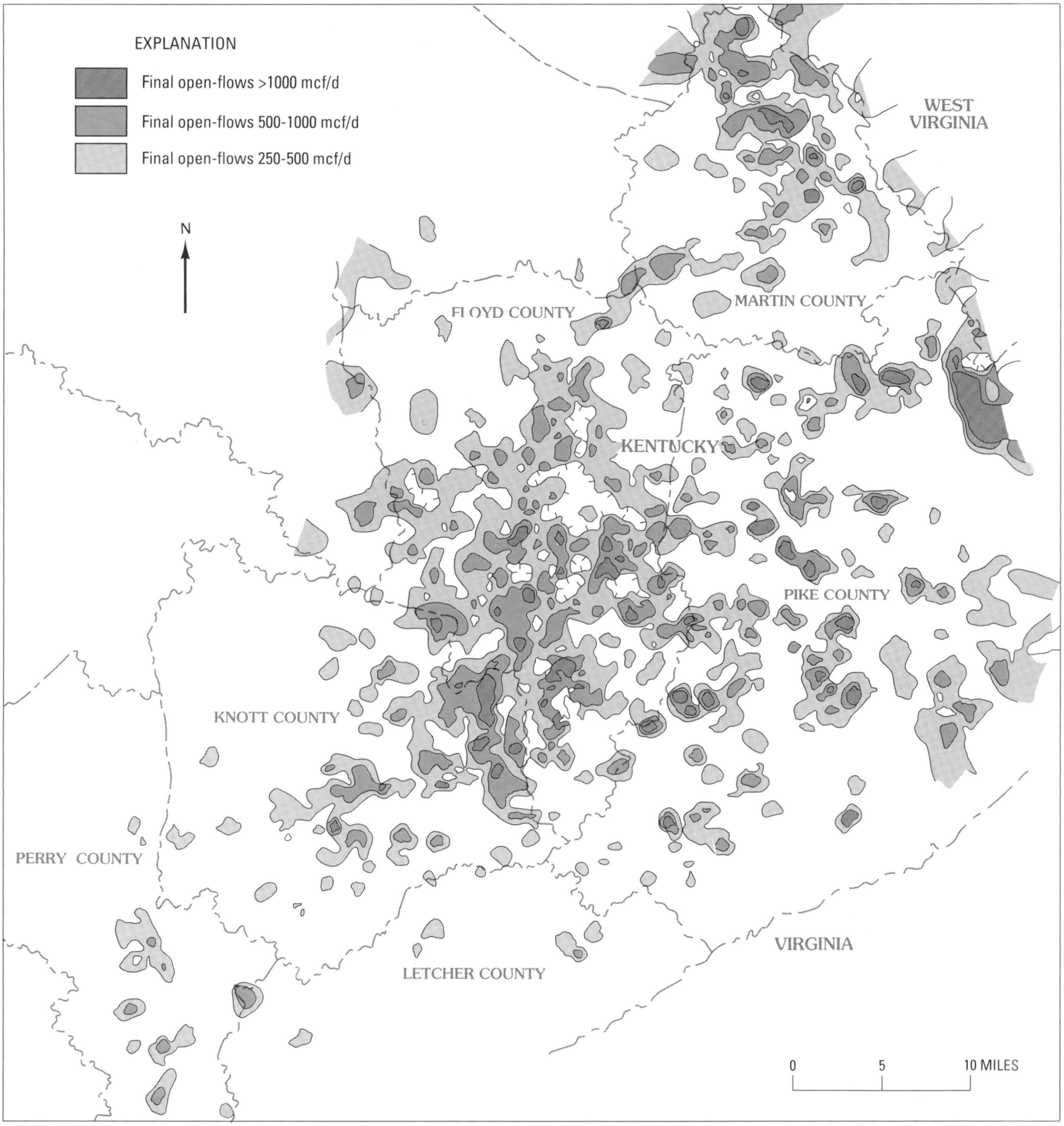


Figure 27. Isopotential values (final open-flows) from the shale gas wells in eastern Kentucky. This map was computer contoured by using the Surface II program. (Data collected by Negus-deWys, 1979.)

joint patterns found in the surface sediments (Shumaker, 1975b; Long, 1979) of eastern Kentucky and southern West Virginia (fig. 5). Although complex, fractures in the reservoir have defined maxima that often occur in orthogonal sets (figs. 20, 29). Vertical joints are commonly subparallel and (or) perpendicular to the slickenside striation trends found on horizontal and low-angle small faults (figs. 20, 29).

One of the cores, the Kentucky No. 4 well, shows a far greater diversity of slickenside striation trends (figs. 19, 20) than other Kentucky wells. This diversity relates to distorted shale caused by sedimentary compaction below the Berea Sandstone (Evans, 1979). The compaction fractures were unproductive, whereas fractures that produced a moderate show of gas in the deeper, lower part of the Huron produced at a low rate after stimulation (Evans, 1979).

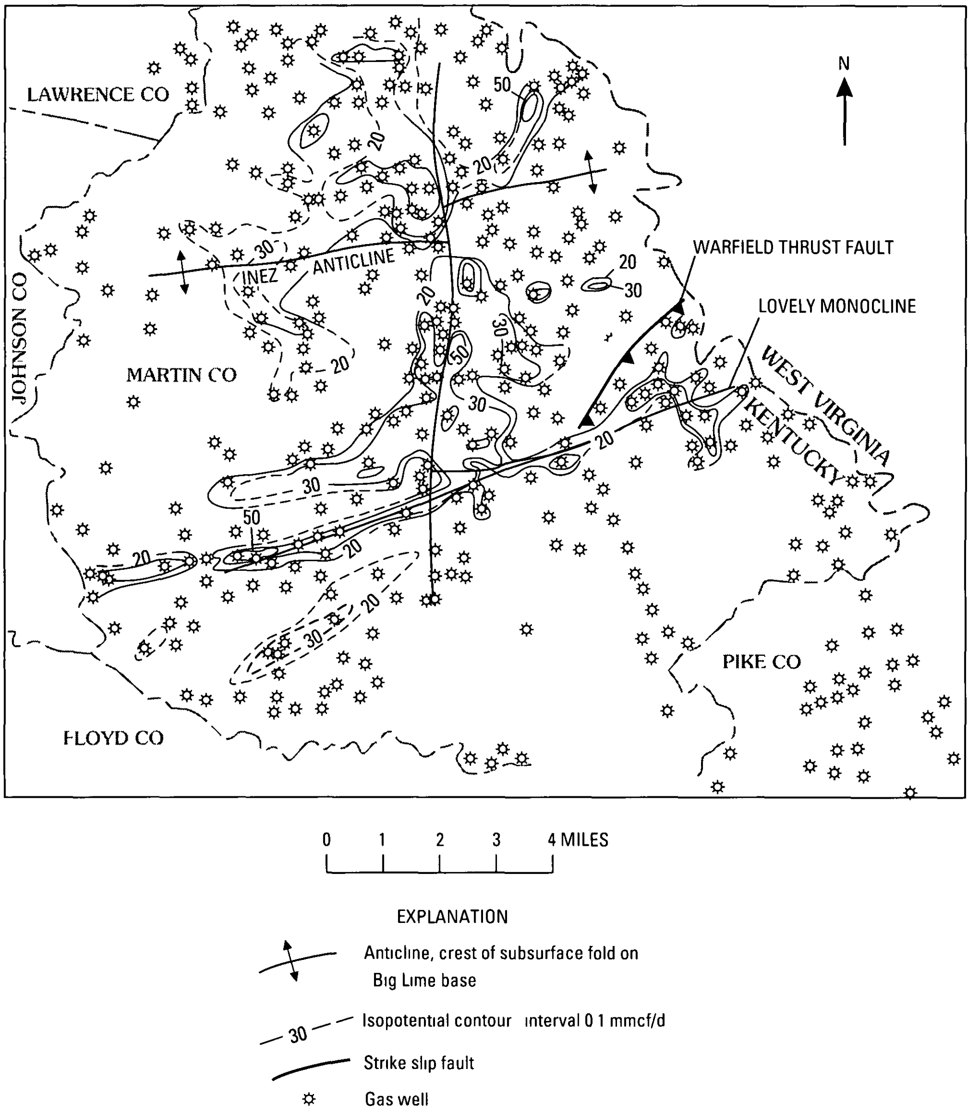


Figure 28. Isopotential values for the final open-flows in Martin County, Ky The structural axes and faults are from figure 25

Several more prominent trends of slickenside striations, which represent significant maxima, were statistically tested (Evans, 1979) and are tentatively correlated with trends found in the other cored wells of Kentucky (fig 20) The gas production from this well relates to the systematic joints of regional extent found in the lower Huron and not those formed by sedimentary distortion found just below the Berea Sandstone In a related observation, the thickest Berea Sandstone follows the Little Blacklog syncline in Martin County (Lee, 1980) and the trend of elevated shale gas flow found in that syncline (figs 24, 28) However, the trend of high production diverges from that of the thickest Berea beyond the Little Blacklog syncline to follow the structural trend of the Rome trough into West Virginia, again emphasizing the importance of tectonic rather than sedimentary influence on the formation of permeable fractures in the shale

Left unresolved are the reasons for the complexity of systematic fracture directions found in the shale cores of eastern Kentucky The trends of two orthogonal patterns are consistent with the implied direction of central and southern Appalachian tectonic transport, if one allows for some variation in tectonic transport and stress direction at the margin of the Alleghenian deformed belt However, the complex structural history of the region makes such a simple correlation suspect and certainly leaves the possibility open for other interpretations

Another characteristic of fractures in the reservoir that affects regional production is the increased intensity of low-angle shear fractures found in cores of wells drilled

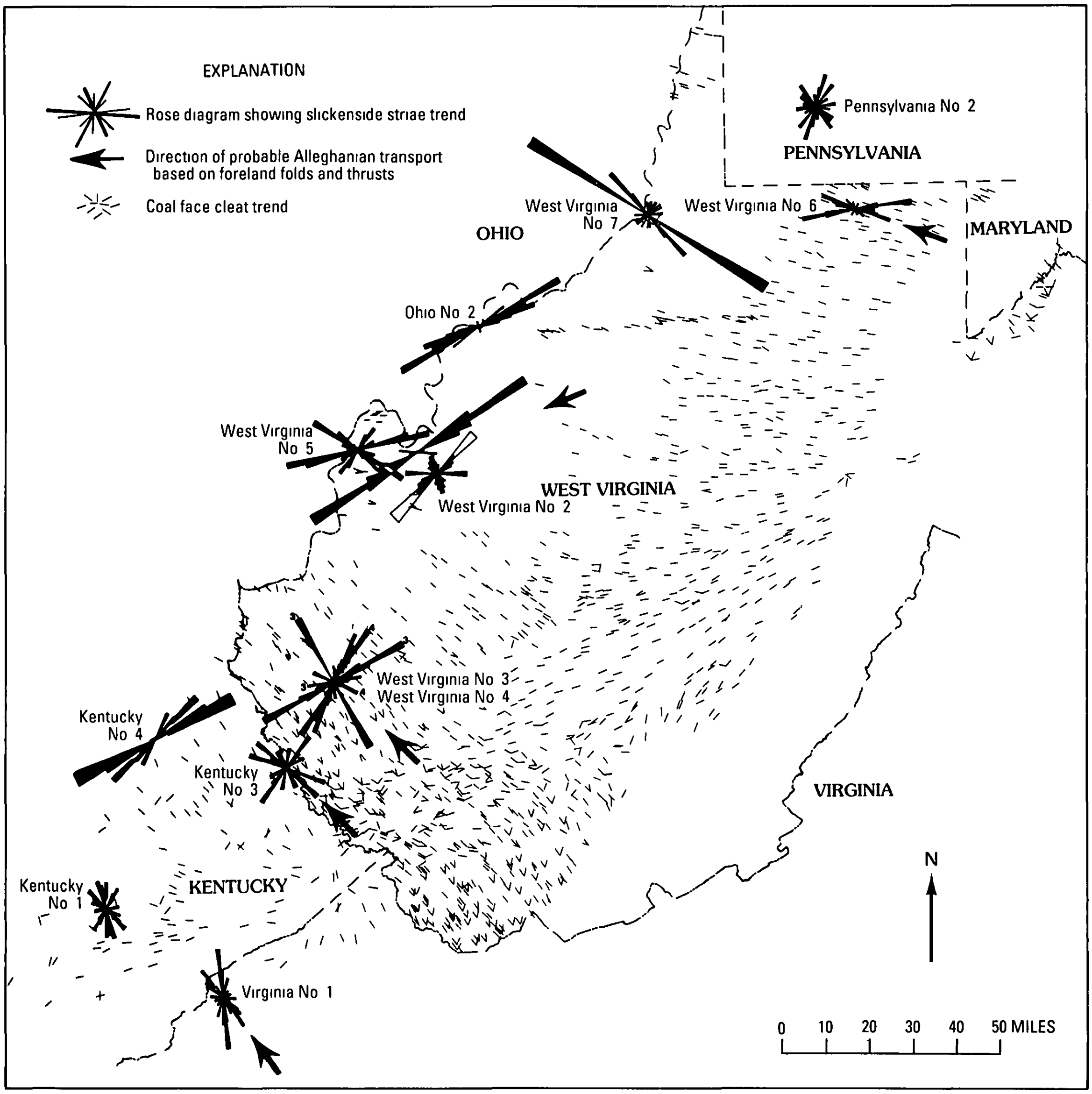


Figure 29. Natural fractures in the Devonian-shale-oriented cores and face cleat trends (pattern) from the surface coals (Modified from Evans, 1979)

closer to and in the fold and thrust belt This increased deformation of the reservoir is expected if the fractures were caused by the same Alleghenian stress that formed the thrusts and folds of the adjacent deformed belt The stereograms of fractures in the oriented shale cores shown in figures 19 and 34 have been rotated so that the orientation of the dominant slickenside striation trends, which usually imply Alleghenian transport, are parallel This realignment eliminates any effects of local deviation in the stress field at the core site, and it facilitates visual comparsion of patterns Shales in the western cores show less deformation than those in the eastern cores Cores taken along the eastern side of the producing area contain numerous horizontal and low-angle shear fractures that have a higher degree of preferred orientation (fig 19) The Virginia No 1 well was drilled through the decollement zone of a major thrust sheet that has been mapped at the surface near Pine Mountain in eastern Kentucky The orientation of fractures in the well is similar to that of other eastern wells, except that slickensides are greater in number and that slickenside striae maxima of the shear system have a slightly lower plunge Wells drilled near and in Ohio, which is west of the highest producing area, still have defined maxima for vertical joints However, they lack the number of shear fractures of the eastern wells (Evans, 1979, Cliffs Minerals, Inc , 1982) and had to be rotated by varied and greater amounts than the eastern wells to bring their slickenside striae trends parallel to those of other wells Even though this greater rotation

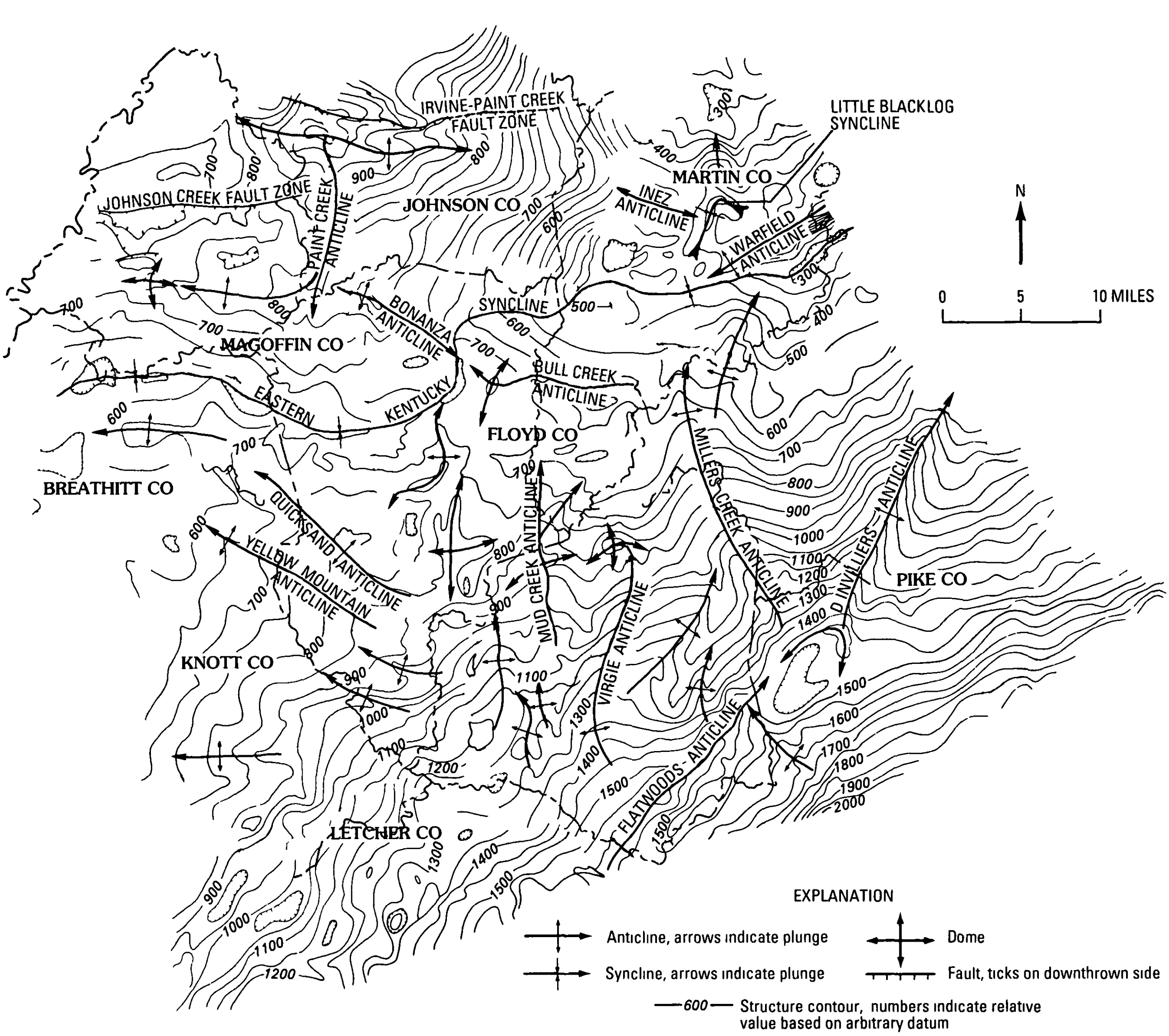


Figure 30. Near-surface form-line structure Relative contour values represent an approximation of the dip of the surface units Form lines represent various stratigraphic surfaces and may not join This map is based on Kentucky Geological Survey oil and gas maps of various counties published in the 1920's and 1930's

may indicate other origins for the faults, their occurrence in the organic shale section and their relation to regional structure suggests not Such local deviations in the stress field are expected at the margin of regional horizontal stress The observed decrease in production to the west is tentatively ascribed to the general westward decrease in fracture intensity and to the lack of mineral precipitants on vertical joints that prop fractures open in the shale of that area

Commercial shale gas wells decrease in number eastward from the area of commercial production (fig 7), partly because the shale is deeper and more expensive to drill and partly because the primary target often shifts to the laterally equivalent silt and sand reservoirs However, the eastward-trending decrease in production also relates to increased incidence of shear fractures associated with increased transport stress across the shale reservoir Vinopal (1981) noted sheared clays on the surfaces of the small faults in the shale and suggested that these clays effectively seal the microporosity of the shale matrix from the fracture porosity The increased intensity and dimensions of shear surfaces in shale decollement zones to the east would separate the fractured reservoir into innumerable shear-bounded pockets of porosity Evidence of this decrease in production comes from the data set of eastern Kentucky in an area where the shale does not change facies into coarser clastics (fig 2) Even though the shale thickens eastward toward the Pine Mountain thrust, production decreases in that direction Across the thrust itself, the increase in tectonic transport and the number of shear surfaces (small

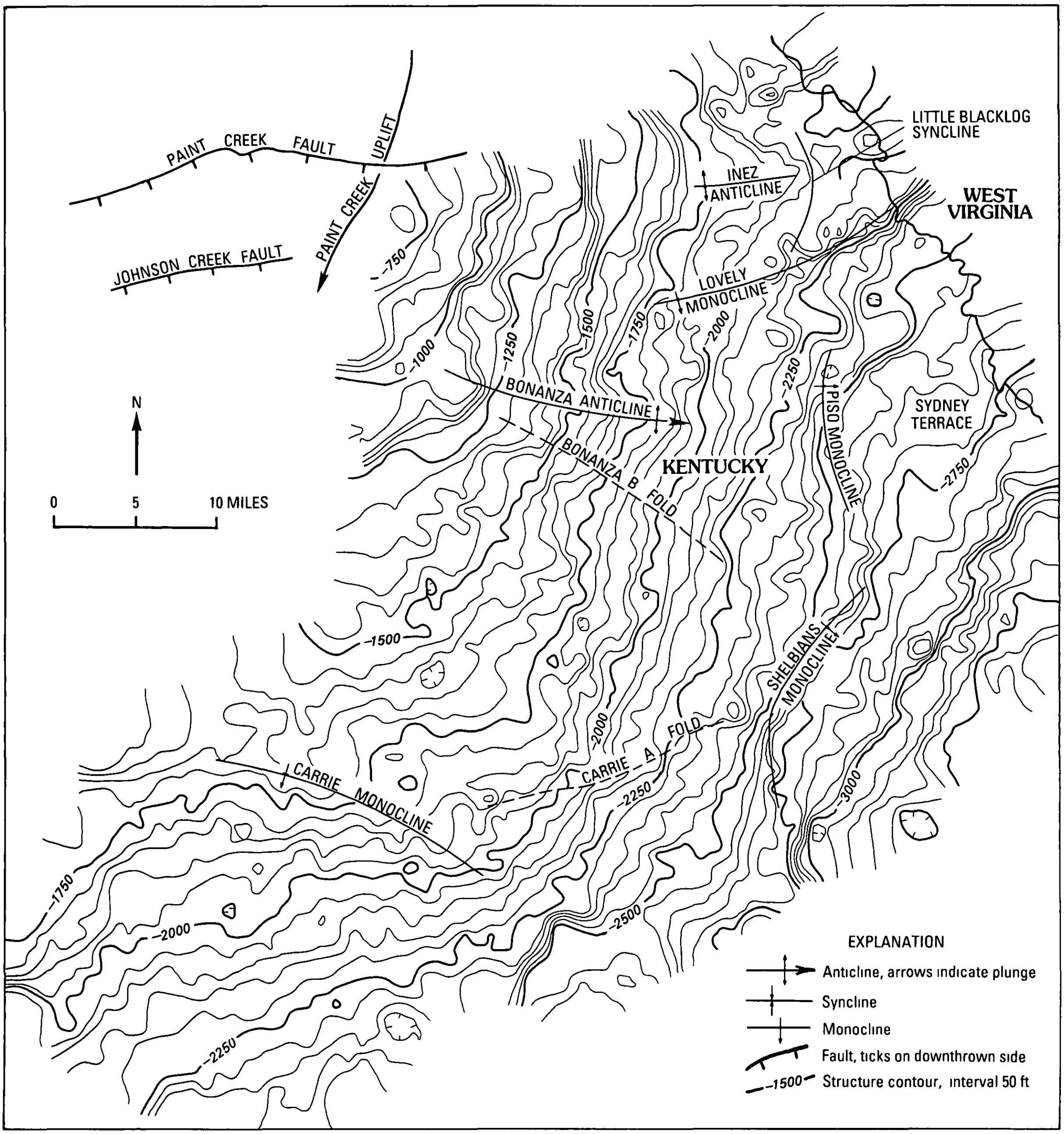


Figure 31 Subsurface structure of the base of the Ohio Shale in the Big Sandy area (Data collected by Lee, 1980) For well control, see figure 33

faults) in the reservoir are abrupt Shale from the decollement horizon in the lower part of the Huron of the Virginia No 1 well was strongly sheared and mineralized (fig 19), and, even though it was intensely fractured, it was a dry hole Young (1957) reported the occurrence of blow outs from numerous wells drilled through the thrust and little, if any, commercial production Increased shearing also is expected in a narrow belt of detached, low-relief folds that is visible on the detailed subsurface structure maps several miles west and in front of the Pine Mountain thrust This belt is precisely where gas flow decreases (fig 27) Northeastward along strike, gas flows abruptly increase where the Pine Mountain thrust terminates in an area where the small, low-relief folds in front of the thrust are likely to be replaced by cross-strike faults, such as the Pikeville, which was mapped by Lee (1980) Ryan (1976) noted a similar increase in production north of the Russel Fork fault at the northern terminus of the Pine Mountain thrust block He mapped surface lineaments associated with what he interpreted to be small strike-slip faults and reported a produc-

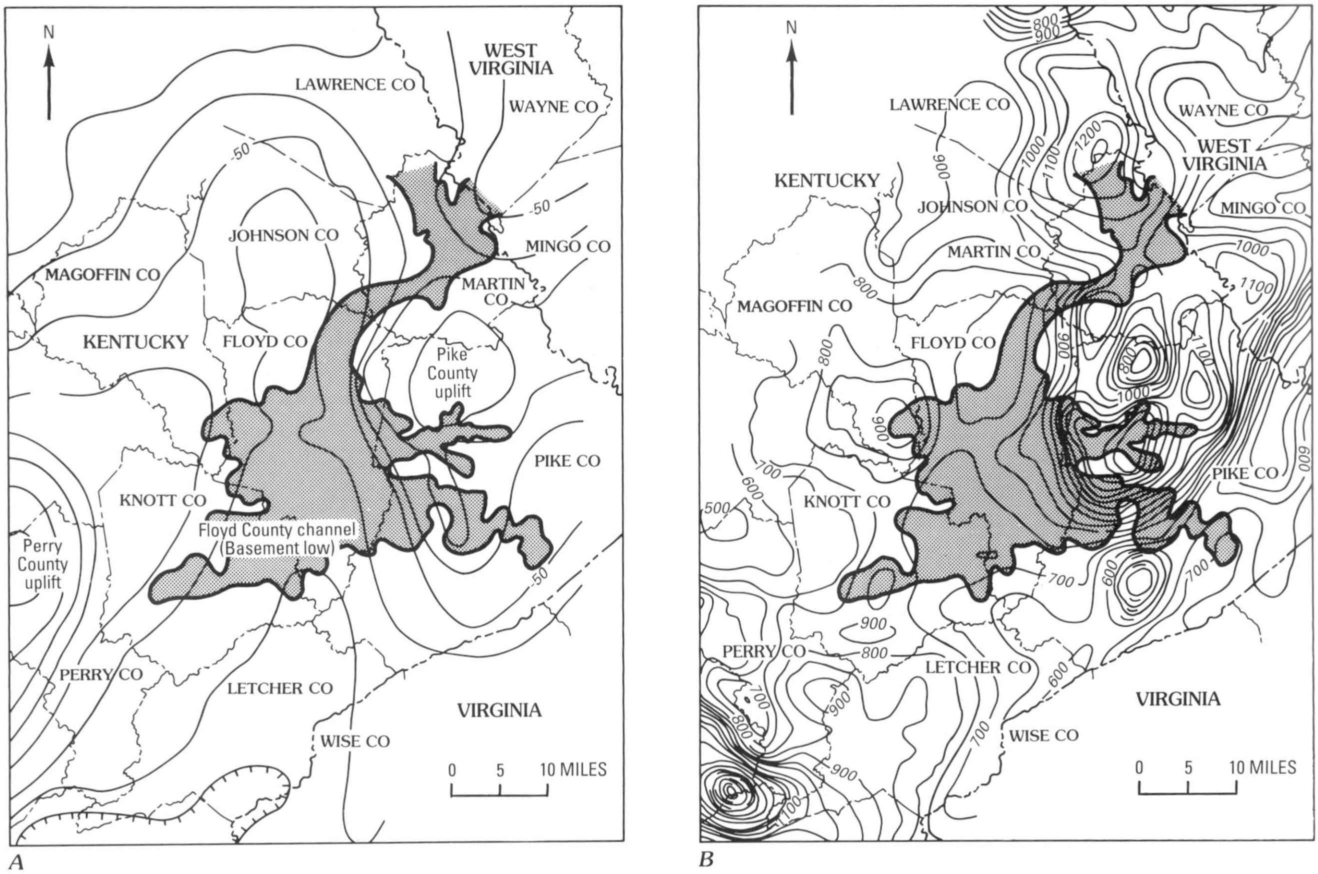


Figure 32. Eastern Kentucky field. *A*, Bouger gravity (Ammerman and Keller, 1979). Contour intervals in milligals. *B*, Aeromagnetic intensity. Contour intervals in gammas.

tion increase from wells drilled along these lineaments. Long (1979) noted that coal face cleats form a large fan across the part of the field that points toward the northern end of the Pine Mountain thrust (fig. 35); he also related the fan to the change in the Alleghenian stress field at the end of the Pine Mountain thrust. However, the face cleats that he mapped (fig. 35) parallel basement structures: the Carrie-A and Bonanza-B structures (figs. 31, 33), which are delineated for the first time here. It is possible, then, that the trends of face cleats relate to basement structures, as has been interpreted for cleat domain boundaries in adjacent West Virginia by Kulander and Dean (1980). Regardless of their origin, fractures and cross-strike tears could readily provide permeable pathways, particularly during periods of tectonic overpressure, for the migration of gas and mineralized fluids into the heart of the field.

CONCLUSIONS

Comparison of geologic structure with production from the Devonian shale in eastern Kentucky and southwestern West Virginia indicates that gas production from the Devonian shale relates to local and regional structures and that the proper mixture of both are prerequisites for the commercial flows of gas found in the southern part of the Appalachian basin.

The study found that the region of optimum production occurs at the margin of tectonic transport as indicated in shale cores by the disappearance of small thrust faults in the lower Huron. This organic shale is part of an established decollement zone in the adjacent folded Plateau and Valley and Ridge provinces, and it is the most extensive of several such organic shales that form reservoirs in the study area. Even though the lower Huron shale is the primary reservoir, other organic shales are productive from fracture porosity, and any part of the shale section can produce from small fractures or large joints. Analyses of cores taken through the lower Huron suggest that small vertical joints propped open by secondary carbonate minerals form the permeable pathways for the gas that slowly diffuses from adjacent organic shale. The more intense fracture pattern in the thick organic shales, as compared with the adjacent less-organic shale, indicates the greater susceptibility of the organic-rich units to fracture.

Detailed study of the Cottageville and Midway-Extra Fields, which are high-producing trends at the northern

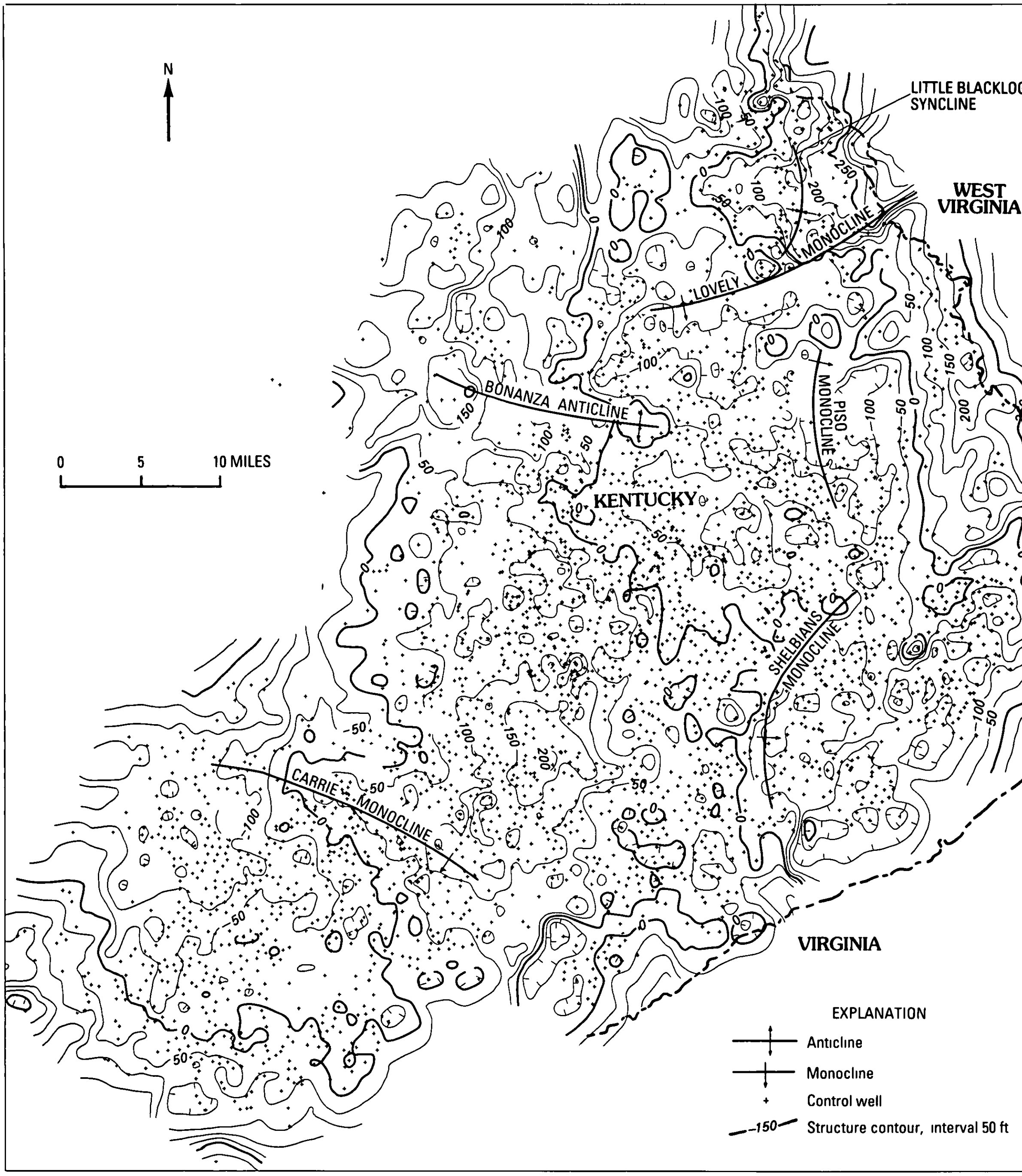
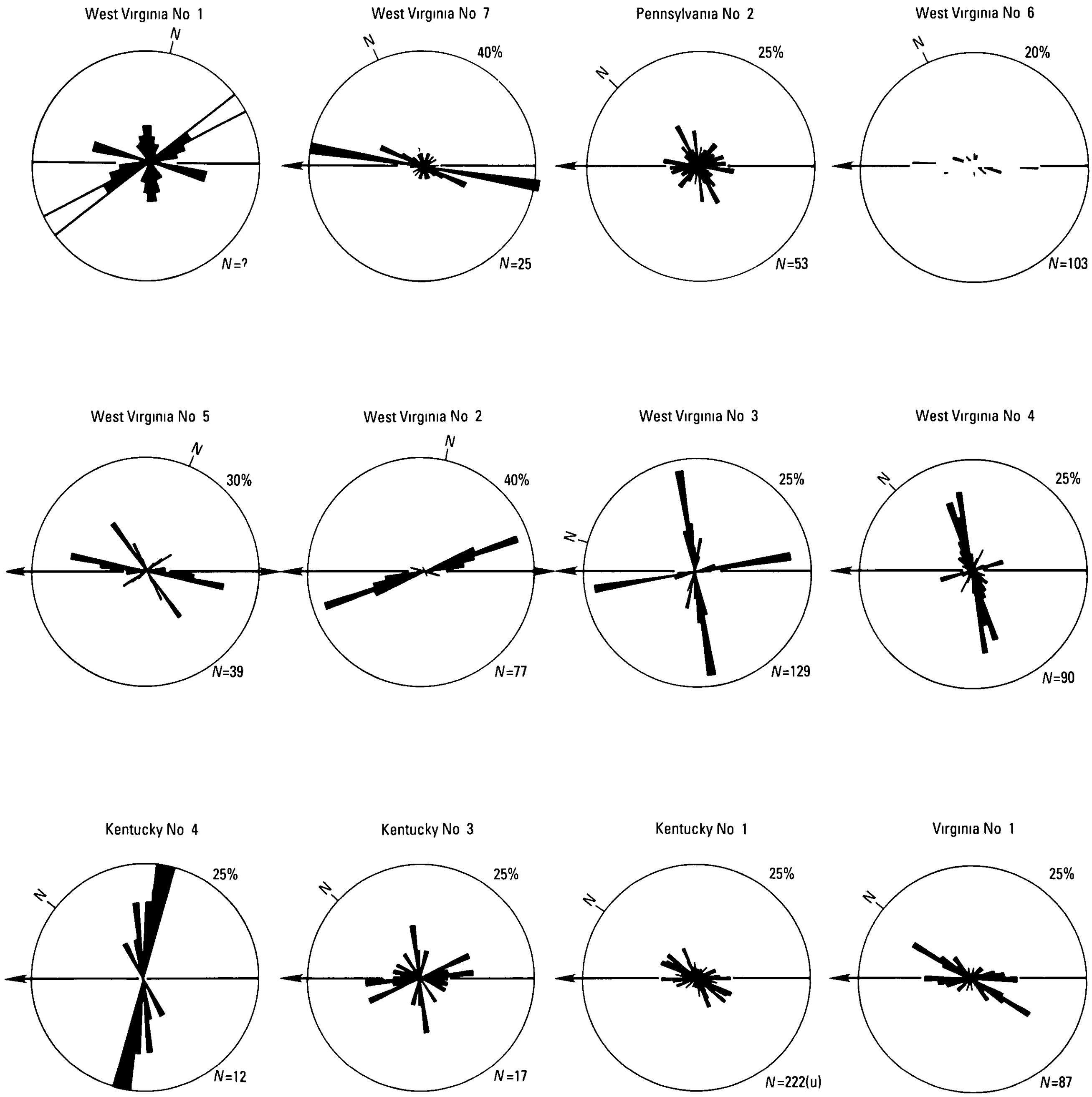


Figure 33. Contoured residual values from the second-order-trend surface map of the structure on the base of the Ohio Shale (fig 24)

margin of regional production (1978), shows that both lie adjacent to and above basement growth faults of the Rome trough system The highest producing wells in both fields are at the margin of synclines adjacent to very low relief folds Because seismic lines across both fields generally fail to show basement faults extending into the producing shales, part of the near-surface structural relief associated with production may be related to detached Alleghenian deformation Oriented cores taken in the Cottageville Field and studies of drill samples from both fields confirm the lateral continuity of the fracture zone in the lower part of the Huron and reinforces the importance of lateral changes of permeability as an important trapping mechanism

Recognition that enhanced production occurs along the flanks of low-relief structures, particularly at structural intersections correlated with basement fault zones, forms an



All diagrams oriented so that slickenside striae trends are parallel

EXPLANATION

◄——	Slickenside striation Transport direction implied from conjugate shear surface orientation and (or) surface structure trends
◄——►	Slickenside striation Transport direction uncertain
N	Number of readings
u	Undifferentiated

Figure 34. Vertical natural fractures of the cored wells The northernmost wells are at the top of the page, and the easternmost wells are on the right side of the page (Modified from Evans, 1979)

Figure 35. Coal face cleat trends (pattern) from the surface coals (Long, 1979) and Devonian shale gas isopotentials in eastern Kentucky. F.O.F., final open-flow.

empirical exploration rationale that can be applied in the Appalachian basin and tested in other foreland areas where the stratigraphy and organic geochemistry for shale production are suitable.

The center of highest commercial production is found in eastern Kentucky on the east-dipping flank of the Paint Creek uplift. Updip migration to a crestal position is impeded by impermeable (less permeable) shale. The origin of the fracture permeability in this part of the field is uncertain, but detailed mapping of the shale's structure, particularly after the removal of regional dip, demonstrates that this productive center lies on a broad anticlinal flexure that follows the Floyd County basement low.

Linear trends of high-flowing wells that extend downdip from the Floyd County center may outline permeable passageways for gas and fluid migration from the foreland basin These trends lie north of the Pine Mountain thrust block in an area of postulated cross-strike tears (Ryan, 1976, Lee, 1980) that may be confined to the rock section above a basal decollement zone in the shale

Viewed from a regional perspective, areas of highest gas flow are found along the southern and eastern margins of the Rome trough, where it turns from an east-west trend along the 38th Parallel lineament to a northeastern trend along the New York-Alabama lineament As of 1978, the highest commercial production lies on the western side of the New York-Alabama lineament and is nearly symmetrical to the 38th Parallel lineament

The unique structural setting at the intersection of basement structures at the margin of detached deformation suggests that production of similar magnitude will not be found elsewhere in other Eastern Interior basins or within other parts of the Appalachian basin The importance of the relation of detached deformation to the development of regional permeability inhibits application of results from this study to the Eastern Interior basins Separate exploration rationales based on structural style and thermal history should be developed for each basin

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Chapter L

Production and Production Controls in Devonian Shales, West Virginia

By DOUGLAS G. PATCHEN and MICHAEL ED. HOHN

U.S. GEOLOGICAL SURVEY BULLETIN 1909
PETROLEUM GEOLOGY OF THE DEVONIAN AND MISSISSIPPIAN BLACK SHALE OF EASTERN NORTH AMERICA

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Production and Production Controls in Devonian Shales, West Virginia

By Douglas G. Patchen[1] *and* Michael Ed. Hohn[1]

Abstract

Although shows of gas have been encountered throughout the thick fine-clastic interval that comprises the Devonian shale section in West Virginia, commercial production is stratigraphically confined to predominantly black shale units Within these black shales, fabric types that include silty or finer grained planar or lenticular laminations are more abundant than other fabric types in the pay zones of cored wells Cores also confirm the importance of natural fractures to gas production In some cores, the pay zones are highly fractured, and the orientations of fractures are more diverse The rate of gas flow depends on the density and the openness of fractures Because a certain lithology (that is, highly organic black shale) tends to fracture more easily, other workers have developed the concept of a porous fractured facies that is stratigraphically controlled The fractures are the reservoir, the encompassing black shales are the source beds and the seals Although fractures are important, they alone are not a sufficient factor Local structure, presence and thickness of black shales, amount and type of kerogen content, and thermal maturity of the shales also are important factors that determine the locations of commercial gas reservoirs

The typical shale well in southwestern West Virginia is a long-term low-volume producer Exceptional wells are produced naturally, however, most wells were shot, and, more recently, completed wells have been fractured by using a variety of techniques Some data suggest that fracturing enhances a well's productivity more than shooting, but other data do not

The geology of the Devonian shales in southwestern West Virginia is less complex than the geology of an equivalent interval in an emerging area of Devonian shale gas production in northwestern West Virginia In the historical area of Devonian shale gas production, two lithologies, black and gray shales, are predominant, siltstones or fine sandstones are uncommon in the relatively thin (1,000- to 2,000-foot) interval The shales have been deformed into broad, open, low-amplitude folds Faults are present but not as large-scale features In the emerging area of gas and oil production, the overall interval is much thicker (2,000–4,000 feet), more lithologically diverse (black and gray shales, siltstones, sandstones common), and structurally more complex (a major detached anticline, the axis of which is offset by transverse faults, dominates) In both areas, production is associated with structure but not in the conventional sense (that is, along anticlinal crests) Data interpreted by others suggest that the best production is associated with anticlinal flanks in the historical area and with offsets in the Burning Springs anticline in the emerging area

Our data indicate that the Huron Shale has the highest show ratio in both areas and that another black shale, the Rhinestreet, has the next highest These are the two main pay zones as well Because initial potentials of wells completed in these shales correlate with long-term production, they are predictive of a well's productivity Decline curves from the literature have been replotted at the same scale as new curves presented here In the historical area, all curves have generally the same shape, the initial (first-year) decline is not as rapid as previous assumptions, and the wells are long-term producers In general, production decreases from south to north—the Chapmanville area is better than the Midway-Extra Field, which, in turn, is better than the Cottageville Field The emerging area northeast of Cottageville apparently will not exhibit the long life typical of shale wells in the historical area, although some exceptional wells have been drilled In general, we have concluded that the emerging area of gas and oil production will not be economic unless detailed geologic studies are used to site wells, rather than the random drilling on small leases that has been the common practice in the past 5 to 6 years

INTRODUCTION

For nearly as many years as the Devonian shales have produced gas in the Appalachian basin, geologists and engineers have debated several points concerning gas production What controls shale production—structure, lithol-

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Figure 1. Historical area of gas production from Devonian shales in southwestern West Virginia.

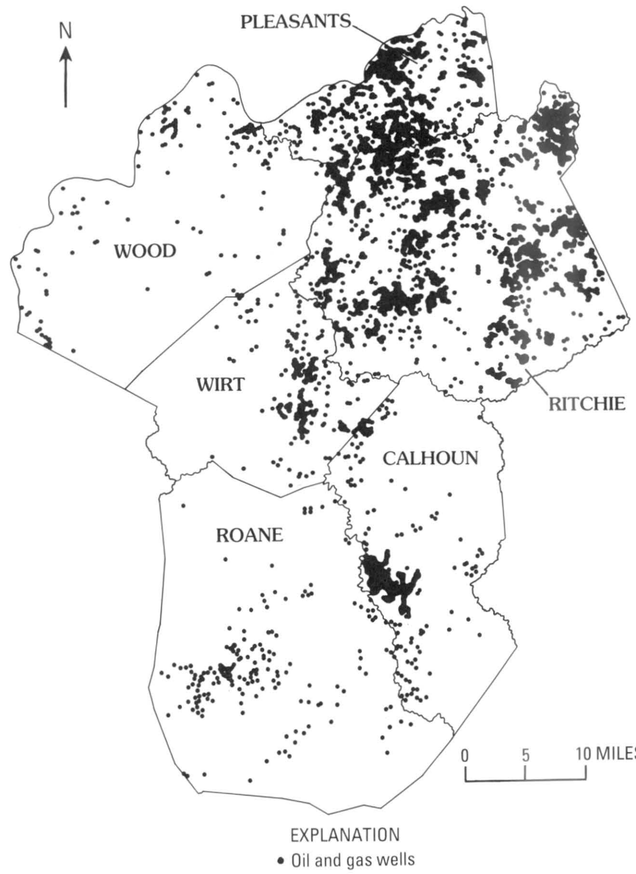

Figure 2. Emerging area of oil and gas production from Devonian shales in northwestern West Virginia since 1979.

ogy, primary porosity, natural fractures, or various combinations of these? Where does the gas occur within the thick shale sequence—in black or gray shales or siltstones, or is it dispersed throughout? If the gas is stratigraphically controlled (that is, from black shales) but is produced through a natural fracture system, then are these fractures stratigraphically controlled? What is responsible for the erratic nature and unpredictability of shale wells? Why are good wells often offset by failures? Why is a well's production affected by drilling offsets in some cases but not others? And, finally, how much gas is in the shales, how is it held, and how much can be produced given today's technology and current research for the future? Various sources have estimated that less than 10 percent of the original gas in place around a Devonian shale well will be produced. To increase this percentage, what are the best zones to complete and the best techniques to use to reduce drilling and completion costs and to increase gas production and reserves?

This report is divided into two parts—a summary of work that has been done in search of answers to the above questions and a comparison of the geology and production histories of two geologically diverse areas in West Virginia. These areas are the "historical" area of gas production in the southwestern counties (fig. 1) and an "emerging" area of gas and oil production in northwestern counties (fig. 2).

Acknowledgments

The authors are grateful to the Gas Research Institute (GRI) for funding an ongoing study of Devonian shale geology and production in West Virginia. This report resulted from that sponsored research (contract no. 5084–213–0983).

New production data analyzed in this report were obtained from State records, companies, and the Institute's Eastern Gas Data System, which is managed by the BDM Corporation. We are grateful to all of these sources. Maxine Fontana accessed BDM's data base and moved appropriate data over to our offices. Data were input into our data base by Nora Simcoe, Eileen Andre, and Peter Roberts. Cindy Williams (typist) and Renee LaValle (geological illustrator) produced the text and accompanying illustrations.

We appreciate Bob Shumaker's willingness to discuss structural control on shale gas production and to allow us to have prepublication access to his paper in this volume.

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CONTROLS, CHARACTERISTICS, AND ESTIMATES OF DEVONIAN SHALE GAS PRODUCTION

Stratigraphic Controls

During the past 15 years (yr), various workers have demonstrated that the thick, previously undivided shale sequence in the subsurface of West Virginia can be subdivided by using gamma-ray and density logs (Martin and Nuckols, 1976, Neal, 1979, Schwietering, 1979, Dowse, 1980), cable-tool drillers' logs, cores, and samples (Bagnall and Ryan, 1976, Patchen and Larese, 1976) Furthermore, these subdivisions can be refined and given formal stratigraphic names that correlate with Ohio and New York outcrops (Neal, 1979, Schwietering, 1979, Dowse, 1980) Once it was established that the shales could be subdivided and that these subdivisions were of regional extent, the question arose of whether the occurrence of gas could be correlated with stratigraphy, either within fields or on a regional basis

Some early workers suggested that gas in the Devonian shales is stratigraphically controlled (Avila, 1976) and that no definite relation exists between present structure and gas production (Browning, 1935) Martin and Nuckols (1976) were able to recognize three highly radioactive low-density shale zones (I, II, and III) in the Cottageville Field in Jackson County These zones were interpreted as containing kerogen-rich black shales that are the western facies equivalents of thicker gray shales to the east They also noted a high correlation of gas shows with zones II and III in the Huron shale, zone II, the lower part of the Huron, is the main pay zone throughout the field Hennington (1979) substantiated these correlations by statistical methods Farther south, Bagnall and Ryan (1976) identified three "brown" shale zones (termed "upper," "middle," and "lower") that correlate with the zones of Martin and Nuckols Furthermore, the total gas in the shale, as analyzed from cuttings, was highest in the "middle brown" (the lower part of the Huron) and "lower brown" (the Rhinestreet)

When cores of these various zones were taken under the U S Department of Energy's (DOE) Eastern Gas Shales Project, it became even more obvious that the occurrence of gas was controlled by stratigraphy and lithology Plots of gas occurrence versus depth (Snyder and others, 1978) revealed that initial gas release rates were inversely proportional to shale density and that shale density was a function of organic content, not porosity Thus, gas was concentrated in the highly organic black shales relative to gray shale Schlettler and others (1978) concluded that, on the basis of core descriptions, gas productivity correlated relatively well with the occurrence of black shales Cremean (1978) reported that free gas measurement data in the Lincoln County core (No 20403 of the Columbia Gas Transmission Corporation (hereafter referred to in text as Columbia Gas)) indicated that most gas was in the Rhinestreet and the Huron black shales Claypool and Threlkeld (1978) reported that, in cores from Virginia and Kentucky, black shales had higher gas yields than gray shales (1 2 versus 0 25 cubic feet of gas per cubic foot of shale (ft^3 of gas/ft^3 of shale))

Most studies of gas occurrence have examined vertical changes in a given well and the relative amount of gas in black versus gray shales Regional stratigraphic studies, however, have documented lateral west-to-east facies changes from black to gray shales across the basin Matthews (1985, 1986, unpub manuscript, 1985) noted that this facies change often is abrupt and occurs within a 20-mile (mi) area and that gas fields tend to occur along it He suggested that the best potential for shale gas will be at these shale-to-shale facies changes

Thus, it has been demonstrated by many workers that gas occurrence in the Devonian shales correlates with stratigraphy and lithology However, many of these same workers emphasized that production of gas depends on other factors

Fabric Controls

Petrographic studies by Larese (Patchen and Larese, 1976, Larese and Heald, 1977) identified quartz-feldspar lenses parallel to bedding in shales in the pay zones of two cored wells These lenses commonly occur at regular intervals in otherwise dark, homogeneous, organic-rich shales Within the organic-rich shale matrix, the gas that is able to reach these more permeable conduits can migrate laterally to natural fractures, which ultimately control production (Patchen and Larese, 1976, Larese and Heald, 1977)

Owen and others (1985) recognized that silt stringers and laminae within the shale increased the permeability of the shale unit They also stated that permeability is increased by bioturbation features and a microporosity network of crenulated illite grains, as observed in shale cores in southern Ohio They found little direct evidence of fractures in cores or the wellbore

More detailed petrographic work has shown that the shales can be divided into several fabric types, which correlate with stratigraphy and gas occurrence (Nuhfer and Vinopal, 1978, 1979, Klanderman and Hohn, 1979, Nuhfer and others, 1979) and include nonbanded, banded, finely laminated, and lenticularly laminated Cores taken through productive black shale units (the Huron and the Rhinestreet) illustrate the abundance of laminated fabrics versus banded and nonbanded types The intervening nonproductive Java and Angola Shales, however, are characterized by nonbanded bioturbated gray shales (Nuhfer and Vinopal, 1978, Nuhfer and others, 1979)

Laminations in black shale units are the result of the presence of fine sand- and silt-sized pyrite, quartz, and feldspar and abundant well-distributed organic matter Porosity in these shale fabrics (finely laminated and lenticularly laminated) is the result of voids associated with pyrite, pores between silt-sized quartz grains, and microfractures in organic matter (Nuhfer and Vinopal, 1978) Although their porosity is low, these fabric types enhance the horizontal continuity (permeability) of the porosity that is present (Nuhfer and Vinopal, 1979) and have higher organic content than other fabrics Thus, these workers concluded that petrographic properties are as important as fractures in determining the production of many wells What is needed, in their view, is a better correlation of physical tests (petrophysics) with petrographic characteristics

Fracture Controls

Early workers debated the importance of geologic structure in controlling gas production in Devonian shale fields Browning (1935) concluded that no definite relation exists between structure and production because gas was produced in some anticlines, synclines, and monoclines The better producing shale wells, however, were observed to be along the axes of anticlines and synclines (Lafferty, 1935) This suggested to Lafferty that gas moves in a system of fractures and that the best fractures formed near points of greatest stress (that is, along structural axes) Billingsley and Ziebold (1935) agreed that gas is held in vertical fractures that resulted from folding and that the areas of greatest fracturing occurred not on anticlines or in synclines but where "local characteristics" of the shale resulted in areas of weakness

Cores through productive and nonproductive shale zones have confirmed the importance of fractures in determining production rates In Jackson County, cores through zones II and III of Martin and Nuckols (1976) were highly fractured in the pay zones Furthermore, the orientations of these fractures changed with depth and lithology (Martin and Nuckols, 1976, Patchen and Larese, 1976) Fractures within the pay zones showed a greater diversity in orientation than fractures in either younger or older rocks These fractures commonly are propped open by dolomite (Patchen and Larese, 1976, Larese and Heald, 1977)

In southwestern West Virginia fields, gas production from shales generally is considered to be a result of fractured shales (Bagnall and Ryan, 1976) Consequently, the rate of flow depends on the density and openness of fractures, especially fractures in dark kerogen-rich shales Secondary dolomite has been observed to be an important propping agent in some fractures (Patchen and Larese, 1976) However, other workers (Vinopal and others, 1979) concluded that fracture frequency alone is not the only factor that controls gas production because a one-to-one correlation of fractures versus gas shows on temperature or sibilation logs could not be demonstrated in five cored wells in Virginia and West Virginia Also, no system of microfractures was found in a scanning electron microscope study of 400 core samples Thus, only macrofractures seem to be important (Vinopal and others, 1979)

High-angle to vertical macrofractures were observed to be more open and to have better permeability and higher gas production rates than low-angle fractures (Vinopal and others, 1979) Among cored wells, the best were those in which these high-angle fractures occurred in laminated organic-rich shale zones Their model is one that has a dual porosity reservoir wherein a fracture porosity system is recharged by diffusion from the shale matrix Silt layers may have acted as conduits for water charged with ions to reach these fractures Precipitation of calcite/dolomite then kept the fractures open (Vinopal and others, 1979)

Discussion

If gas occurrence is controlled by stratigraphy and lithology (fabric) but production is controlled by fractures, are the fractures stratigraphically controlled? Changes in the density and orientation of fractures within pay zones have been noted Histograms of fracture orientation versus depth indicate high diversity in organic-rich zones relative to organic-poor zones This suggested to Nuhfer and others (1979) that petrography can be correlated to fracturing These and other observations led Shumaker (1978) to the concept of a "porous fractured facies" that is stratigraphically controlled He noted that fractures in the seven shale cores are numerous, uniquely oriented, and often mineralized and have limited vertical extent because they were confined to the highly organic portions of the shale These fractures and commercial gas production occur together as a porous fractured facies of limited stratigraphic extent The fractures are the reservoir, and the encompassing shales are source beds and seal Outcrop studies in New York also suggest that black and gray shales do fracture differently, the density of fracturing is greater in the black shale (Patchen and Dugolinsky, 1979) The origin of these fractures has been attributed to reaction of the shale above basement faults (Martin and Nuckols, 1976, Shumaker, 1978), to thrust faulting above the Salina decollements (Sweeney, 1986), to reaction of the shale to movement related to the Rome trough (Patchen, 1977, Harris, 1978), and to flexure points on the flanks of structures (Schaeffer, 1979)

In summary, the following picture of Devonian shale gas has emerged Although gas shows have been recorded throughout the section, they are more common in black shales Zones chosen for stimulation (that is, pay zones) also are more commonly in dark shales Porosity and permeability in the shales are low, although silt lenses and laminated fabric in the dark shales tend to enhance horizontal permeability It has been stated that the black shales are source and reservoir for Devonian shale gas Shumaker (this volume) modified this by stating that fractures in the shale are the reservoir and that the shales are source beds and seals Thus, a well-developed fracture system is necessary to support commercial production, and the rate of production is dependent on the density and openness of fractures that are encountered Although fractures are a necessary condition, they alone are not sufficient Other important criteria are black shale thickness, kerogen content, and thermal maturity (Dean and Overbey, 1979)

Estimates of Gas Resources

The amount of gas trapped in Devonian shales in the Appalachian basin is enormous, regardless of whether you accept the top figure (2,400 trillion cubic feet (Tcf-))(Science Applications, Inc , 1977) or a lower one (834 Tcf) (Overbey, 1978) However, the amount that can be produced by using current technology is much lower Brown (1976) calculated a range of 876,100 to 1,159,000 million cubic feet (MMcf) for West Virginia In attempting to be more specific, he assumed reserves of 100 MMcf per well in sparsely drilled areas and 360 MMcf in densely drilled areas and discounted each by 15 percent to account for commingled production Thus, his final estimate of ultimately recoverable gas for West Virginia, which was based on a study of more than 3,000 wells in an area of nearly 1,500 square miles, was 893,128 MMcf

Recovery rate calculations for a Devonian shale gas reservoir have been very low If only 350 MMcf is recoverable per well and if assumptions are used for drainage area (150 acres), thickness of black shale to stimulate (400 feet (ft)) porosity (8 percent), shut in ("rock") pressure (700 pounds per square inch), and gas saturation (40 percent), then the calculated gas in place around a well is 4 27 billion cubic feet and recovery amounts to only 8 2 percent (Brown, 1976) Working independently in eastern Kentucky, Avila (1976) calculated a recovery rate of 8 4 percent of the original gas in place

These low recovery rates are attributed to three different modes of occurrence of gas in the shales Brown (1976) identified the following types V_1, free gas in pores and fractures connected to the well, V_2, gas adsorbed on exposed shale surfaces, and V_3, gas adsorbed within the shale matrix, the great majority of gas in place These types have vastly different production rates Production of V_1 gas is a function of the permeability and volume of connected space and is at a high rate Production of V_2 is related to the rate at which adsorbed gas is released V_3 gas is produced as a function of the rate and depth of diffusion of gas through the rock matrix to a permeable connection to the well bore Because this diffusion is very slow, this gas is not producible by means of current technology (Brown, 1976) Thus, the key to economic exploitation of the shale is technology How can we best drill and stimulate a shale well to release the adsorbed gas locked in the shale matrix nearby, but not connected to, the well bore?

Geochemistry

Because of the importance of this problem, much energy and money have been expended to determine gas composition and release rates for black versus gray shales in various structural settings Black shales have a higher content of mobile gas (0 6 ft^3 of gas/ft^3 of shale) and greater release rates, whereas gray shales contain only 0 1 ft^3 of gas/ft^3 of shale (Smith, 1978) Moreover, in areas of higher thermal maturity such as Wise County, Va , black shales contain as much as 2 0 ft^3 of gas/ft^3 of shale Gas content and release rates are inversely related to bulk density and are not related to porosity (Snyder and others, 1978) This suggests that the density of shale is related to organic content, not porosity, and that initial gas release volume is proportional to the carbon content (low-density high-organic black shales) (Snyder and others, 1978) The original gas-generating capacity of black shales has been calculated as 3 1 standard cubic feet per cubic foot (scf/ft^3) of shale (Claypool and others, 1978)

The hydrocarbon-producing potential of a shale depends on the following factors (1) the amount of organic matter, (2) the type of organic matter, and (3) the degree of conversion of organic matter to hydrocarbons (Claypool and others, 1978) Factors 1 and 2 depend on the original deposition of the shales, whereas factor 3 depends on the postdepositional burial and heating history Claypool and Threlkeld (1978) examined black shales from cores in Martin County, Ky , and Wise County, Va , and, by assuming uniform organic matter of marine origin across the basin, could attribute significant differences in gas composition to differences in thermal history of the shales in the two areas Kerogen in black shales from Wise County is postmature with respect to gas but only just mature in Martin County Thus, the shales in Martin County still have hydrocarbon-generating potential, whereas the black shales in Wise County are spent Claypool and others (1978) calculated the degree of conversion to be 76 percent in the Wise County core and 13 percent in the Martin County core They also calculated 40 and 13 percent for cores in Lincoln and Mason Counties, W Va , respectively These calculations were based on estimates of the original gas-generating capacity (3 1 scf/ft^3 of shale) and remaining gas potential from pyrolysis

It should be noted that all other indicators of thermal maturity for the Wise County core suggest that, between the top of the dry gas window and the oil generation floor, the Devonian shales are mature, not postmature Thus, the assumption that the organic matter is uniform across the basin may not be valid Organic matter of marine origin ("oil prone") is concentrated in the shales in the western side of the basin, whereas terrestrial "gas-prone" organic material is predominant to the east (Zielinski and McIver, 1982) This difference in the original composition of organic matter also may be a factor in the relative distribution of wet versus dry gas

On the basis of natural gas composition from wet gas in the west to dry gas in the east, Claypool and others (1978) showed that thermal maturity varied across the Appalachian basin Carbon isotope ratios of methane exhibit parallel trends—light methane to the west and heavy methane to the east Solid organic matter shows an increase in carbonization to the east, which reflects deeper burial history, higher temperatures, and increased metamorphism of organic matter Hence, conversion of solid and liquid organic matter to methane is in an early stage in the west and is nearly complete in the east Conversion rates have been calculated to be 15 percent in western West Virginia, 50 percent in central West Virginia, and 80 percent in eastern West Virginia (Claypool and others, 1978) Thus, while some thermally immature shales still have hydrocarbon-generating potential and can be retorted, others are more mature and are used as drilling targets

Tetra Tech, Inc (undated) prepared a report for the Morgantown Energy Technology Center in which various factors—vitrinite reflectance (R_o), outgassing rates, and organic carbon distribution—were compiled and mapped In general, R_o values increased to the east, and all known areas where gas is produced from the shales are between 0 6 and 1 5 percent R_o Organic matter distribution, however, was not as uniform Values for samples in the Rhinestreet increased from west to east, whereas samples from the younger Huron and Cleveland yielded values that increased from east to west These trends were combined with maps of stress ratios, organic shale thickness, and geologic structure to delineate areas of exploration potential, as well as to explain current production

Production Characteristics

Early gas producers noticed that, as production decreased, "rock" pressure also decreased but at a lower rate However, if a well was shut in, then the "rock" pressure recovered This led to the concept of primary and secondary porosity systems As the well produces, the secondary porosity system is drained, but the well is recharged by an effective primary porosity system (Avila, 1976, Brown, 1976)

A positive correlation of open flows to production also was noted by early workers Bagnall and Ryan (1976) presented four averaged shale decline curves that were grouped in ranges of 100 Mcf (thousand cubic feet) of initial open flows for wells in Lincoln, Mingo, and Wayne Counties In terms of higher initial potentials (IP's) and production, the best wells showed a rapid decline in the first 4 to 6 yr, whereas poorer wells are characterized by flatter curves However, the best-flowing wells remained the best producers over the 26-yr period of observation Bagnall and Ryan (1976) attributed this to more fractures being intersected by the better wells, thus yielding higher IP's and higher early "flush" fracture production These wells remained better throughout the productive history because the increased number of fractures provided a more extensive drainage system through the shales to produce V_2 (adsorbed gas on fracture surfaces) and V_3 (adsorbed gas in the matrix) gas

Further production data for wells in Lincoln County were compiled by Smith (1978), who studied 20-yr production histories of 35 shot wells near 2 shale wells cored by the DOE in the late 1970's Smith noted a positive correlation between initial open flows and 20-yr cumulative production and stated that stabilized open flows are probably the best method of preproduction testing Although no data were presented, cumulative production appeared to range from 50 to 900 MMcf, two-thirds of the wells appeared to be below 300 MMcf

Most of the early shale wells in southern West Virginia were shot, usually from the Berea Sandstone to total depth These older wells gained a reputation for being low-volume long-term producers, their life span was determined more by mechanical failures than by any geologic factor Even though productive rates were low, the long histories led to fairly high reserve estimates (by basin standards) Reserve estimates for shale wells, by counties, ranged from 568 MMcf per well in Cabell County to 310 MMcf per well in Logan County (Bagnall and Ryan, 1976)

Ray (1976) was one of the first to attempt to determine the effect of completion technology on shale production He presented data on 106 hydraulic fracture jobs on shale wells performed between 1965 and 1975 Shot and fractured wells were grouped by initial open flow ranges that had production histories of 4 to 5 yr He concluded that fractured wells outperform shot wells in all open flow ranges in terms of gas deliverability In all open flow ranges, the longer a well produced, the greater the production increase, fractured versus shot Thus, fracturing was shown to reduce significantly the payback period for these shale wells

Farther north, in Jackson and Mason Counties, Martin and Nuckols (1976) compiled production data for 37 wells drilled between 1948 and 1950 in the Cottageville Field The average natural open flow was 133 Mcf/d (thousand cubic feet per day) Most of these wells were shot, and the average after-shot open flow increased to 523 Mcf/d Mean first-year production for 37 wells was 74 8 Mcf/d, second year, 61 5 Mcf/d, third year, 47 3 Mcf/d, and fourth year, 42 9 Mcf/d After 27 yr, 18 wells still on line were producing at a rate of 17 Mcf/d

Negus-de Wys and Shumaker (1978) related gas production data for 63 wells in the Cottageville Field to several geologic factors Total accumulated production correlated best with structure mapped on the top of the Onondaga Limestone and with fracture facies inferred from a shale core in the field Mean production curves for 30 Cottageville wells that had at least 12- to 13-yr production histories were compared with Clinton wells in Ohio and with production curves from shale wells in southern West Virginia published by Bagnall and Ryan (1976) The upper portion of the decline curve for Cottageville wells more closely resembles the Clinton sand gas decline curve, whereas the lower portion tends to fit an average shale well curve The mean Cottageville curve approximates the 100- to 200-Mcf/d curve of Bagnall and Ryan (1976), the only exception being higher production in the upper end of the Cottageville curve A plot of annual production versus year of production yielded three families of production curves According to Bagnall and Ryan (1978), the best, family 1, was similar to the greater than 300-Mcf/d curve, whereas families 2 and 3 correlated with the 100- to 200-Mcf/d and the less than 100 Mcf/d curves, respectively, that had been developed for Lincoln, Mingo, and Wayne County shale wells

Completion Technology

In southwestern West Virginia, the standard completion before the 1960's was to drill to the Big Lime (the Greenbrier Limestone of Mississippian age), set pipe, and then drill through the "middle brown shale" (that is, the lower part of the Huron), leaving the Lower Mississippian as well as the Upper Devonian open to the well bore The entire open interval, including the Berea Sandstone, usually was shot If no shows occurred in the Mississippian before shooting, then the well was called a shale well If shows had been noted in younger zones, then the well was considered to be commingled If these Mississippian shows were large, then the Berea and the Devonian shale were produced separately (Brown, 1976)

According to Brown (1976), the average shale well would test 60 Mcf before shooting and would range between 150 and 400 Mcf after shooting Ray (1976) noted a further enhancement in deliverability when wells were hydraulically fractured rather than shot Thus, before the mid-1970's, when interest in shale wells increased significantly, the best shale wells were the unique natural wells, the majority of wells were shot, and a relatively few more recent wells were hydraulically fractured At that time, it generally was understood that shale wells, regardless of completion technique, were usually low-volume long-term producers that yielded less than 10 percent of the calculated gas in place within a "normal" drainage area (normal spacing for a more conventional reservoir, approximately 150 acres) Thus, the DOE, industry, and the Federal and various State geological surveys began looking at the real problems with Devonian shales—choosing the best stratigraphic intervals to complete and the best technology to reduce drilling and completion costs and to increase ultimate production As a first step in determining the best intervals and optimum techniques, a vast data base needed to be assembled to correlate stratigraphy and technology with short- and long-term well performance Even while this laborious task was being performed, the DOE began experiments in newly drilled wells, utilizing foam (N_2 and water), cryogenic liquids (CO_2) and gelled liquids, and other variations, including massive hydraulic and explosive fracturing This research is continuing

While drilling relatively shallow wells into the Upper Devonian rocks in eastern Ohio during the 1970's, operators discovered oil in a thin interval they called the "Gordon sand " In 1979, drilling on the West Virginia side of the Ohio River extended this oil play into Wood and Pleasants Counties Ultimately, drilling depth increased, and deeper zones were completed for oil and gas Many of these wells had high IP's, which created national interest in drilling shale wells in the area of the Burning Springs anticline in West Virginia

GEOLOGY AND PRODUCTION IN HISTORICAL VERSUS EMERGING AREAS

Stratigraphy

In southwestern West Virginia, the term "Devonian shales" refers to the fine-grained clastic interval between the Berea Sandstone (Lower Mississippian) and the Onondaga Limestone (Middle Devonian) In general, this section consists of gray and black shales and a few thin gray siltstone bundles in the upper part The Devonian shales, which thicken eastward, range from 900 ft in Wayne County to more than 3,000 ft in Kanawha County

Productive wells had been drilled into this interval for more than 50 yr before anyone attempted to subdivide the shales and to correlate them with established surface nomenclature However, even the early drillers noticed distinct differences in the shales and subdivided them accordingly Of special interest were the "brown shales," so called because the highly organic, actually black shale beds

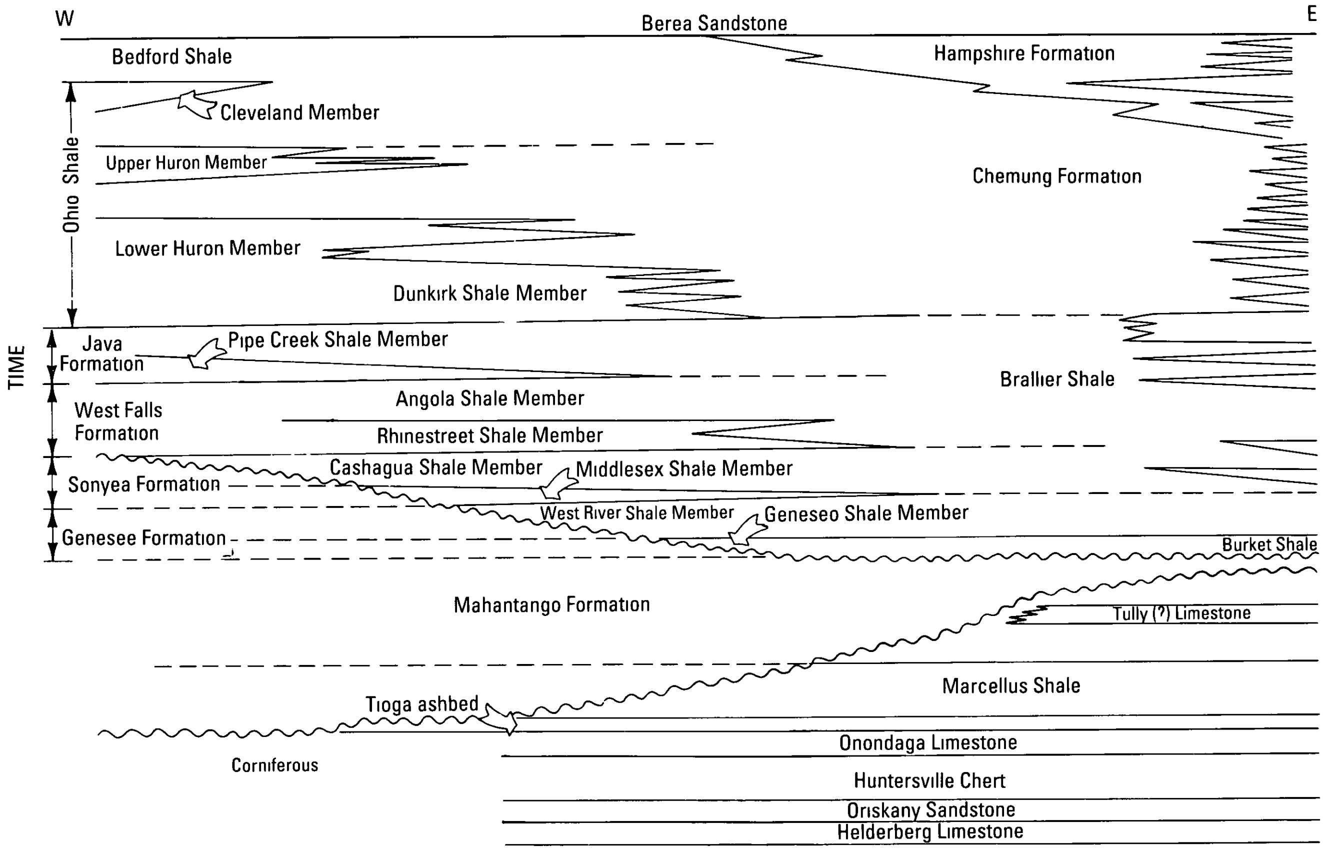

Figure 3. Nomenclature for Devonian units in West Virginia emphasizing stratigraphic position and extent of black shale tongues Vertical scale is time Note increasing magnitude of unconformity to west

yield brown cuttings when crushed ("streaked") by the cable-tool bits Thus, the cable-tool drillers divided the section into an upper green-gray shale, a brown shale, the Big White Slate (actually silty gray shale), and a lower brown or black shale above the Onondaga

During the 1970's, various workers (Schwietering, 1970, Bagnall and Ryan, 1976, Patchen, 1977, Neal, 1979) demonstrated the utility of cable-tool logs, sample descriptions, and wire-line logs in subdividing the section and correlating it with units exposed in Ohio and New York At present, the section is subdivided into a series of cycles, each with a black shale at the base and a gray shale at the top (fig 3) In West Virginia, the names used for units below the Huron Member of the Ohio Shale are taken from formations and members in the Devonian of New York State, from the Huron up, the names used are those of units exposed in Ohio In ascending order, the shale cycles are black Marcellus Shale–gray Mahantango Formation, black Geneseo Member–gray West River Member, black Middlesex Member–gray Cashaqua Member, black Rhinestreet Member–gray Angola Member, black Pipe Creek marker at the base of the gray Java Formation, and black Huron Member below the greenish-gray Upper Devonian undivided In the westernmost portions of Cabell and Wayne Counties, two younger black shale tongues are present—one that correlates with the upper part of the Huron above a gray middle Huron and another that correlates with the black Cleveland Member of the Ohio Shale However, in most of West Virginia, only the lower part of the Huron Member can be recognized and usually is referred to as "lower Huron "

This rather simplistic picture is complicated by two other factors—east-to-west facies changes from gray to black shales that migrated westward over time and the presence of a Middle-Upper Devonian unconformity that increases in magnitude westward Thus, to the west, black shales replace gray shales, and progressively younger units onlap progressively older units (fig 3)

In the six-county area (Pleasants, Wood, Ritchie, Wilt, Roane, Calhoun) around the Burning Springs anticline, the stratigraphy of Upper and Middle Devonian units is more complex Black shale units thicken and split to the east where they are interbedded with gray shales Distal tongues of fine sandstones and siltstones that are productive in north-central West Virginia are interbedded with these gray shales and interfinger with the easternmost tongues of black shales (fig 4) The introduction of coarser clastics tends to dilute the organic content of black and dark-gray

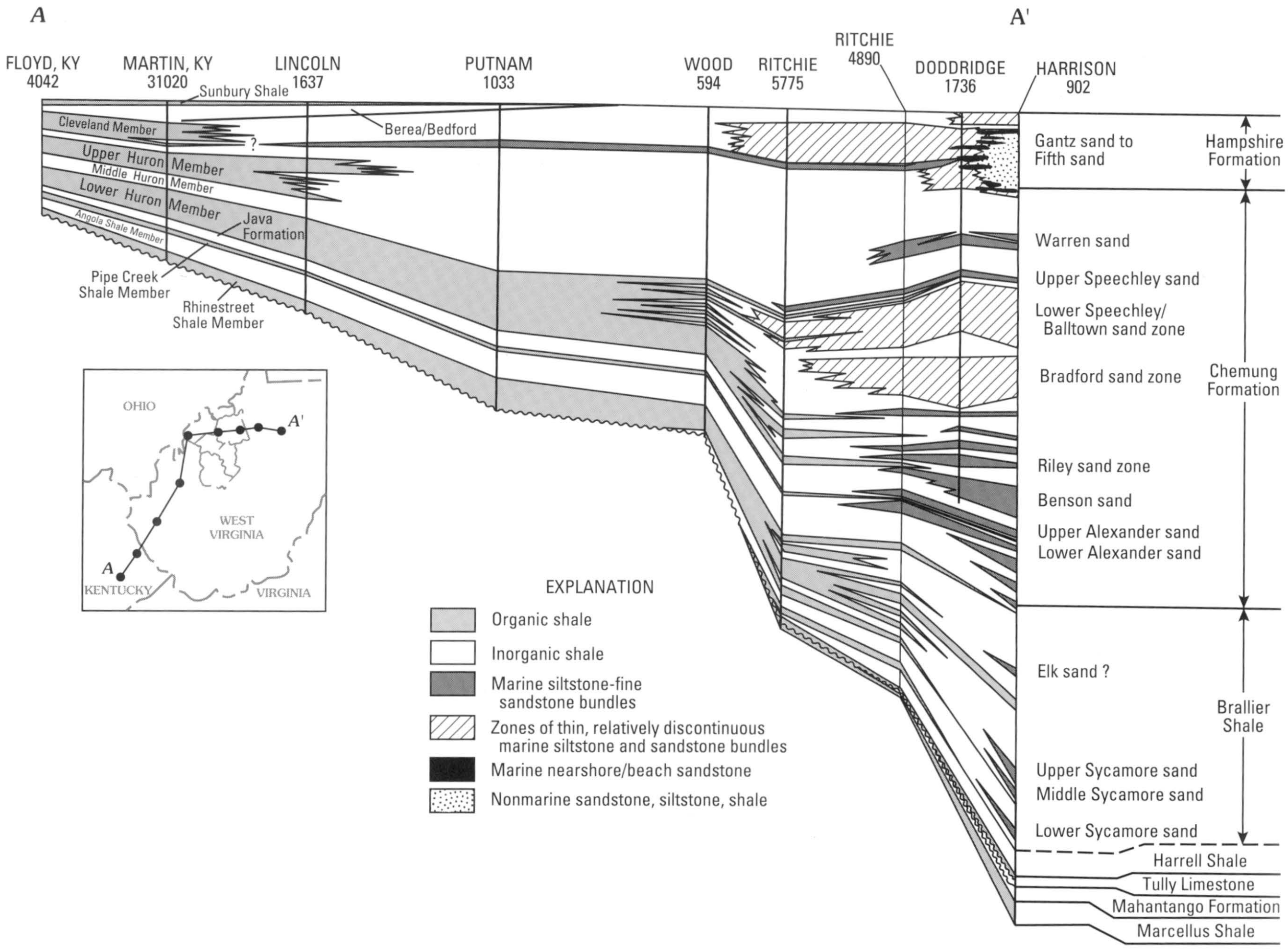

Figure 4. Upper and Middle Devonian clastic facies, central West Virginia to eastern Kentucky. Emerging area shown in inset map. (Section and inset map from Filer, 1985.)

shales and the associated uranium content; this reduces the natural radioactivity recorded on gamma-ray logs and increases the bulk density recorded on density logs. Thus, correlation is difficult in this expanded section, which is characterized by diverse lithologies and dramatic facies changes across relatively short distances.

In spite of these complicating factors, Dowse (1980), Filer (1985), and Sweeney (1986) subdivided the 2,000- to 4,000-ft Devonian shale section into formal units defined by black shale units overlain by gray shale and siltstone units. The sequence from bottom to top is the same, Marcellus-Mahantango to Huron-Upper Devonian undivided, but all units are thicker and more lithologically diverse, and the intervals completed by various operators reflect this diversity. In the historical area to the southwest, the 400-ft-thick Huron Shale is the main pay zone; in the emerging area of Devonian shale production, siltstones and black and gray shales commonly are completed, often in intervals exceeding 2,000 ft in thickness. In other wells, operators have chosen to complete thinner zones, thus attempting to establish production in either thin siltstones, black shales, or intervals with interbedded black and gray shales as well as siltstones.

Structure

Shumaker (this volume) summarized the regional structural geology and tectonic history of areas that produce gas from Devonian shales in West Virginia. Simplistically, the major regional structural features (fig. 5) and events are as follows: the New York-Alabama lineament (King and Zietz, 1978), which is a northeast-trending major shear zone of Grenville age; the Rome trough (Woodward, 1961), which is a Cambrian-aged graben that formed as part of a more extensive system of rifts (Shumaker, 1975) called the Eastern Interior aulocogen (Harris, 1978); reactivation along the Rome trough and other basement features throughout the Paleozoic (Donaldson and Shumaker, 1981) that affected sedimentation patterns and thicknesses of units in the Devonian shale section; the Alleghanian orogeny of

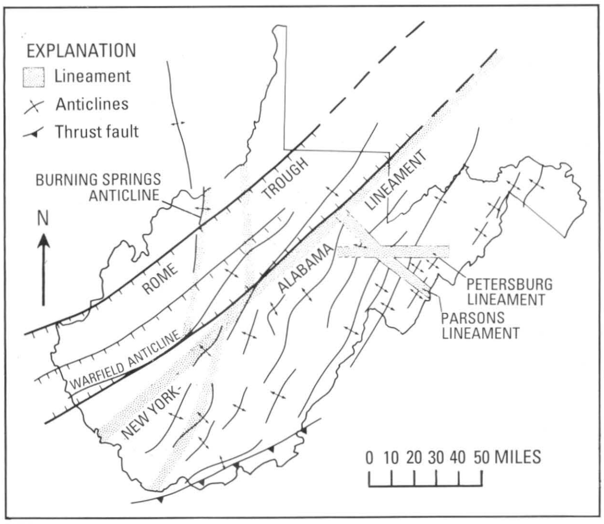

Figure 5. Major structural features in West Virginia. The Rome trough, the New York-Alabama lineament, the Warfield anticline, and the Burning Springs anticline are prominent features in areas where gas is produced from the Devonian shale.

Figure 6. Main anticlines in the area of gas production from the Devonian shales. Anticlines east of the Burning Springs and Mann Mountain structures are interpreted as being detached. (Modified from Shumaker, this volume.)

Permian age that thrusted and folded sediments in the foreland; the formation of low plateau folds by either detached deformation or basement faults; and detached movement in the organic-rich Devonian shale facies that was critical to creating fractured shale reservoirs (see Shumaker, this volume).

The Devonian shale fields in southwestern West Virginia are located in an area that has little structural relief and where large-scale broad, open, upright folds are locally developed and generally trend northeast-southwest on the regional dip, which is to the southeast (fig. 6). This area lies to the west of the area of detached folds. Here, fractured reservoirs were created in organic-rich black shales, like the black lower Huron shales, near the distal margin of major decollement zones in the foreland to the east. Evidence suggests that during times of overpressure, tectonic transport created vertical tension fractures, which are now held open by mineralization, whereas sealing shear fractures, which are more prominent to the east, have decreased to a minimum. This created the unique fracture patterns common to cores from organic-rich shale reservoirs noted by Shumaker (this volume).

In southwestern West Virginia, the major structural features at the Huron level are the Warfield anticline and fault, the Griffithsville syncline, the Midway anticline, the Guthrie syncline, and the Handley syncline. However, most shale fields lie above or adjacent to the margins of the Rome trough (Patchen, 1977), which continues under the Big Sandy gas field of eastern Kentucky. In eastern Kentucky, the trend of the Rome trough is more east-west until it intersects with the New York-Alabama lineament near the Kentucky-West Virginia border. The trough then follows the northeast-southwest trend of the New York-Alabama lineament through most of West Virginia.

Thus, the structural picture in southwestern West Virginia is relatively simple within the shales, although more complex at depth. The broad, low-amplitude folds are more likely the result of the reactivation of basement faults or a combination of basement faulting and the Alleghanian orogeny.

In northwestern West Virginia, however, the structural geology is more complex. The six-county study area (Pleasants, Wood, Ritchie, Wirt, Roane, Calhoun) is bisected by the north-south-trending Burning Spring anticline. This unique structural feature is located near the western side of the Appalachian Plateaus in an area of low-amplitude northeast-southwest-trending folds. The Burning Springs structure, however, has an amplitude of 1,600 ft and dips as steep as 70° on the western flank and on its north-south axial strike (Filer, 1984). Filer's (1984) map of the base of the Huron indicates that the axis of the anticline has been offset by a series of transverse or strike-slip faults within the Burning Springs thrust sheet. At least two of these, labeled "D" and "C" (Filer, 1984), can be traced eastward through Ritchie County, where they are identified as zones where axes of minor folds change strike, are offset, terminate, or decrease in relief.

East of the Burning Spring anticline, gentle, broad low-relief folds generally trend north-northeast in most of Ritchie County but swing more north-south adjacent to the Burning Springs structure and east-northeast along the Ohio River in Pleasants County (Filer, 1985) As mapped by Filer (1985), relief is generally less than 150 ft, and wavelength of folds ranges from 2 to 18 mi West of the Burning Springs anticline, folding is less pronounced, and the Parkersburg syncline is the only major structural feature

Sweeney (1986) mapped the southern half of the study area and documented the systematic step down on the Burning Springs axis to the south before it plunges out He also noted offsets in the axis and a distinct difference in the degree of deformation east and west of this major structure

Woodward (1959) interpreted the Burning Springs anticline as being a detached structure that was formed by thrust faults that repeated Middle and Lower Devonian carbonates in the core of the structure These repeated sections have overthickened the Lower-Middle Devonian carbonates by as much as 1,600 ft, thus creating most of the fold's amplitude Rodgers (1963) and Gwinn (1964) concurred and extended the concept of detached structures from the Burning Springs anticline eastward under low-amplitude folds to the major folds in the eastern edge of the Appalachian Plateaus They also placed the decollement zone beneath the Burning Springs structure in the Salina salt, which was identified as the F4 salt by Clifford and Collins (1974) Shumaker (1982) suggested a down-to-the-east basement fault under the structure that was activated periodically in the Paleozoic This fault could have determined the western edge of the F4 salt basin, which, in turn, resulted in upthrusts from the decollement that created the Burning Springs anticline Filer (1985) and Sweeney (1986) created more detailed structural cross sections based on better log control They were able to recognize repeated sections in various Devonian shale units and interpreted these repeated sections to be the result of a series of splay thrusts from the Salina decollement that died out within the shale section Thus, the Devonian shale fields to the southwest occur in an area interpreted by Shumaker (this volume) to be west of detachment, whereas production in the emerging area to the north is closely associated with a major detached structure

Controls on Devonian Shale Production

Schaeffer (1979) documented the relation of production to structure in the Midway-Extra Field in Putnam County As interpreted from an isopotential map of final open flows, the best shale wells are located on the northwestern flank of the Midway anticline and in a flanking syncline along the southeastern limb Various isopach maps of the lower Huron Member indicate that the Huron thickens in the syncline, which suggests growth of the Midway structure during sedimentation A seismic line confirmed the presence of the basement fault that was responsible for formation of the Midway fold

Farther to the south, Mao (1986) attempted to correlate gas production data (10-yr cumulative) from 448 wells to geologic structure He noted low values of production in the vicinity of the Warfield anticline and high values along the northwestern limb of the anticlinal structure south of the Guthrie syncline Mao concluded that correlations between geology and production and between geology and open flow data were not strong He did suggest that "rock" pressure and 10-yr production data are predictive in the area

Although Shumaker (this volume) presents a strong case for structural control on gas production, he emphasizes that fractures created above basement faults or by tectonic transport are stratigraphically controlled as well Thus, organic-rich black shales, particularly in the lower part of the Huron Member, are reservoirs because they contain a unique fracture pattern formed by tectonic transport at a time when the shales were overpressured These fractured reservoirs occur near the disappearance of shear fractures found in the distal portion of shale decollement zones Within the lower Huron black shale beds, vertical tension fractures, which are held open by mineralization, are the reservoirs, whereas the shale itself and any shear fractures are seals To the east, sealing shear fractures are dominant, and the shale is not productive in detached structures where the shale beds were decollement zones (east of the Mann Mountain anticline) (fig 6)

In northwestern West Virginia, however, the main decollement zone was lower, in the Salina salt, and the best shale production occurs along and east of the westernmost extent of detachment Filer (1984, 1985) divided oil and gas production from the Upper and Middle Devonian fine-grained clastics into three broad geographic areas— west of the Burning Springs anticline, where most production is gas, from the anticline east to 81°, where most of the oil is produced, and east of 81°, where primarily gas is produced, probably from siltstone tongues extending into the area from the east Filer explained these zones in terms of structural geology (fracture permeability), facies changes (black shale and siltstone content), and thermal maturity (organic types and maturity levels)

Rocks on and east of the axis of the Burning Springs anticline are situated favorably for the development of fracture permeability Eastward, the intensity of fracturing associated with the formation of the anticline is expected to decrease West of this structure, where little oil is produced from similar black shales, it appears that a well-developed fracture system is lacking

This area also lies in a transition zone where distal tongues of black shales from the west and siltstones from the east interfinger with gray shales, which are the dominant lithology in the area Furthermore, these differences in lithology are responsible for a difference in organic content as well. To the south and west, where black and gray marine shales are more abundant, the content of oil-generating marine-type organic matter increases. To the east, where sediments were carried into the area through the Catskill deltaic complex, gas-generating terrestrial organic material is more abundant. Total organic content decreases eastward as black shales thin and pinch out. Thus, according to Zielinski and McIver (1982), the area is in a transition zone between oil- and gas-prone organic material. Enough oil-prone organic matter was present to generate oil. To the south and west, where more marine (oil-prone) organics are present, less oil was generated. This was probably because lower levels of thermal maturity were to the west and south and higher levels of thermal maturity were along and east of the Burning Springs anticline (Filer, 1985).

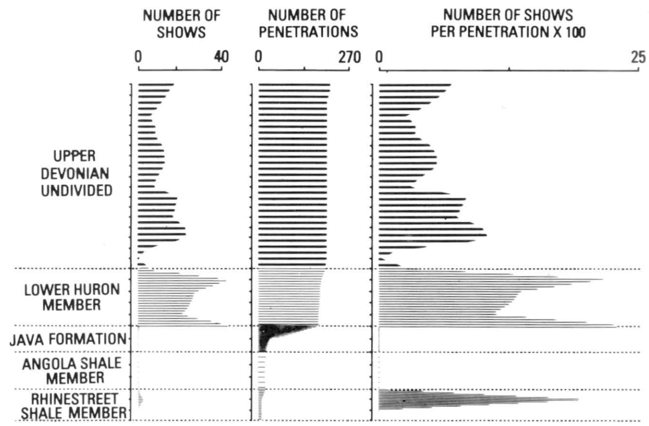

Figure 7. "Shows per penetration" ratio for Devonian shale wells in Mingo, Lincoln, and Logan Counties.

Shows and Pays

Throughout the historical area of Devonian shale gas production in southwestern West Virginia, many workers have pointed out that gas shows occur throughout the shale section and are not confined to the black shale intervals. However, the few attempts to quantify this general observation indicate that shows are more abundant in the black shale zones and that all older wells were drilled through and completed in either the lower Huron Member or the lower Huron and the younger gray shales. Bagnall and Ryan (1976) reported that, in the large operating area of Columbia Gas, total gas, as analyzed from drill cuttings, was greatest in the "middle brown" shale (the lower Huron) and the "lower brown" shale (the Rhinestreet).

In our current research sponsored by the GRI, Michael Hohn and Maxine Fontana have calculated "shows per penetration" and "show ratios" for four subdivisions of the entire shale interval (base Berea Sandstone to top Onondaga Limestone) for three counties in the southwestern area of historical production (Lincoln, Logan, Mingo) and two groups of three counties each in the area of emerging production in northwestern West Virginia (Wirt, Roane, Calhoun; Pleasants, Wood, Ritchie).

The ratio for "shows per penetration" takes into account the different number of penetrations to shallower versus deeper zones, rather than merely counting the number of gas shows recorded in each shale unit; also, the approximate stratigraphic position of each gas show within a shale unit is considered. Shows are tabulated in successive intervals and are divided by the number of penetrations through those intervals to yield shows per penetration figures. When the results are illustrated graphically, as in figure 7, the relative stratigraphic position of shows is evident. In the figure, the first column tabulates the number of gas shows within successive intervals, and the second column tabulates the number of penetrations through each interval; note the sharp decrease in penetrations below the Huron. Dividing the number of gas shows in column one by the number of penetrations in column two yields the "shows per penetration" ratio in the third column, which portrays the relative importance of each part of the stratigraphic sequence as far as shows are concerned.

Our "show ratio" goes one step further than that of the "shows per penetration" by taking into account variations in thickness of shale units and the number of penetrations. Hence, for any given shale formation, the number of gas shows divided by the number of penetrations divided by the thickness of the units equals the show ratio. In Lincoln, Logan, and Mingo Counties, more than 1,500 shows were analyzed by this technique. The lower Huron Member had the highest show ratio (9.94 shows per penetration per unit thickness) followed by the black Rhinestreet (7.77), the gray shales above the Huron (3.78), and the Java Formation and the Angola Member between the two black shales (1.38), as shown in figure 8. The significance of the show ratio can be seen by looking at the raw data for the number of shows—825 in the thick (1,000-ft) gray shale section above the lower Huron versus 752 in the thinner (325-ft) lower Huron. Also, only 25 gas shows were reported in the thinner (150-ft) Rhinestreet, whereas 35 wells penetrated that formation versus 411 through the upper gray shales and 405 through the lower Huron (table 1).

Thus, although shows are numerous throughout the shale section, we conclude that the black shale units, the lower Huron and the Rhinestreet, are the most significant zones in terms of gas content. This conclusion is supported somewhat by research recently completed by Columbia Gas. Columbia Gas chose nine unstimulated open hole wells that had no tubing and that were producing from the Devonian shale section exclusively to clean out and recomplete. When Columbia Gas reentered the wells, they found that all were bridged in the Pocono (Lower Mississippian) shale section. Following extensive clean-out operations, gas

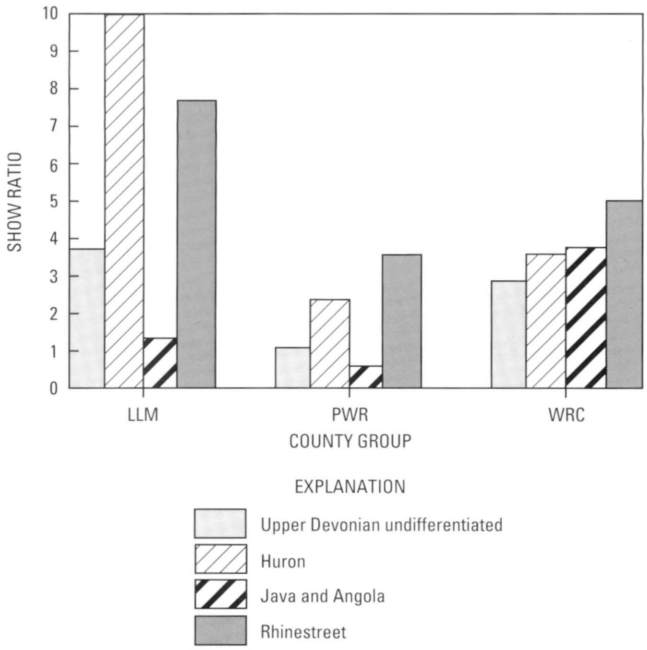

Figure 8. "Show ratios" for Devonian shale wells in Lincoln, Logan, and Mingo (LLM), Pleasants, Wood, and Ritchie (PWR), and Wirt, Roane, and Calhoun (WRC) Counties.

flows increased significantly—from as low as 15 Mcf/d before clean out to 1,039 Mcf/d after (Curtis and Lemon, 1985). Also, production leveled off at higher rates than before clean out (Wallace and others, 1986). Furthermore, it was found that most of the gas was entering the wells from a thin interval at the bottom of the wells, usually near the base of the Huron Member of the Ohio Shale.

In northwestern West Virginia, show ratios calculated for the Upper Devonian section above the Huron, the Huron, the Java-Angola, and the Rhinestreet in wells in Pleasants, Wood, and Ritchie Counties were consistent with our earlier results. However, because our data set was much smaller, fewer shows and penetrations were used in the calculations. The Rhinestreet (3.57) and the Huron (2.44) again proved to be the zones that had significant shows. The data for Wirt, Roane, and Calhoun Counties, however, did not duplicate those results (fig. 8, table 1). Again, the Rhinestreet was highest (5.34), but the Java-Angola section (4.16) appeared to exceed the Huron (3.58) when this criterion was used. Some shows in the Java-Angola may be in distal siltstone tongues that extend into the area from the east. When possible, shows in siltstones were removed from the analysis.

In this same general area, the GRI released results based on well tests that appear to contradict our data and that of Columbia Gas. Graham (1985), under a GRI contract, concluded that most of the gas in shale wells enters the borehole at the top of the perforated interval; very little is contributed from lower units, including dark shales. He suggested that operators may be wasting money by drilling deeper than is necessary and by completing intervals that are too thick. A possible explanation of this problem could be as follows. Columbia Gas was testing unstimulated wells and compiling data on the stratigraphic occurrence of natural shows, and Graham was testing stimulated wells after they had gone on production. It is possible that most of the gas in his wells actually was sourced from deeper beds and migrated vertically through the induced fractures until it reached the top of the mechanically fractured interval. At that point, the gas migrated

Table 1. Gas show summary

[S/P, "shows per penetration"; SR, "show ratios"]

	No. of shows	No. of penetrations	S/P	Average thickness	SR
Emerging area					
Pleasants, Wood, and Ritchie Counties:					
Upper Devonian undivided	12	26	0.461	1,226	1.10
Huron Shale	18	23	.783	939	2.44
Java Formation and Angola Member	2	22	.091	454	.59
Rhinestreet Shale	8	21	.381	313	3.57
Wirt, Roane, and Calhoun Counties:					
Upper Devonian Shale	17	15	1.13	1,167	2.88
Huron Shale	12	11	1.09	903	3.58
Java Formation and Angola Member	5	7	.71	507	4.16
Rhinestreet Shale	5	7	.71	395	5.34
Historical area					
Lincoln, Logan, and Mingo Counties:					
Upper Devonian Shale	825	411	2.01	935	3.78
Huron Shale	752	405	1.86	329	9.94
Java Formation and Angola Member	14	54	.26	331	1.38
Rhinestreet Shale	25	35	.72	163	7.77

laterally and entered the well bore at the top of the perforated interval Thus, it may be necessary to drill to and stimulate the deeper black shale zones because they may be the best reservoir in the thick interval completed In fact, confining the stimulation to a thinner, deeper zone may be more cost effective While examining records on hundreds of shale wells in this emerging area, we noted that some operators complete intervals in excess of 2,000 ft, whereas others confine their fracturing jobs to thinner intervals that are less than 100 ft thick

Completion Zones and Techniques

In our southwestern West Virginia data set, more than 98 percent of the wells were drilled through the lower Huron, but only 22 percent of these were drilled to deeper zones (that is, the Java-Angola or the Rhinestreet) The typical shale well was drilled through or to near the base of the lower Huron In many wells, drilling was stopped when a large flow of gas was encountered, usually in the lower Huron (Wallace and others, 1986) Casing often was set in the Big Lime, which left the Pocono shales, the Berea Sandstone, and the Upper Devonian shale section open to the borehole Unless a high natural flow was encountered, explosives were used to shoot the older wells (pre-1960)

In more recently drilled wells, zones to complete have been selected by noting gas shows and by choosing zones from gamma-ray and density logs or by gas entry interpreted from temperature or sibilation ("noise") logs The lower Huron is still the main completion zone, but, in deeper wells, the Rhinestreet Shale also has been treated These wells have been completed by using fracturing techniques, although a few operators still continue to shoot shale wells

In northwestern West Virginia, where the Devonian shale section is much thicker and lithologically more varied, operators have taken two approaches to completing shale wells—"thick" versus "thin" zones (Filer, 1985) Operators who choose to stimulate thick intervals often perforate 2,000 to 3,000 ft of section and complete in multistages Zones to perforate are chosen by using a variety of techniques, including the presence of organic shales or siltstones, suspected fractures, gas entry based on temperature or sibilation logs, and so forth, but, in the end, the entire section often is stimulated, which makes it impossible to determine the exact zone or zones from which gas actually is produced

Other operators have concentrated on selecting and treating relatively thinner zones These include siltstone bundles in the Upper Devonian undivided section, a thin interval in the upper part of the lower Huron that included interbedded siltstones and gray and black shales, organic-rich black shales, typically the basal section of the lower Huron and the Rhinestreet, and older siltstones in the Java and the Angola Oil production generally has been confined to the youngest of the zones listed above—siltstone bundles (the "Gordon sand") in the Upper Devonian undivided and the thin zone of interbedded lithologies near the top of the Huron However, some oil has been produced from the organic-rich basal Huron shales (Filer, 1985) Gas is produced from all zones listed above

The initial wells drilled in the northwestern study area were completed by hydrofracturing, which uses sand as a proppant However, because the shales were thought to contain water-sensitive clay particles that swell, thus reducing permeability, hydrofracturing was soon discontinued, and newer technologies were employed The most popular of these has been a straight nitrogen gas fracture, sometimes preceded by hydrochloric acid (Filer, 1985) This has the advantage that no water touches the shale reservoir However, because no proppant can be carried by the gas, fractures that are created cannot be propped open and may close quickly as pressure decreases Therefore, many operators have used a foam produced by mixing nitrogen gas with water (75- to 90-percent water and 25- to 10-percent nitrogen) With this technique, little water reaches the formation, but the foam can carry sand to prop open fractures that are produced

Rendova Oil Company of Midland, Tex , released data on 40 shale wells drilled in the study area, which were completed by using a variety of techniques in an attempt to improve production (Murray and others, 1984) Rendova's main exploration technique is to identify a thin "fracture prone stratigraphic zone" in each well that appears to be consistent and widespread in the area (Murray and others, 1984) This zone is present near the top of the lower Huron and consists of several interbedded lithologies that make the zone weaker and easier to fracture Thus, induced fractures penetrate further into the formation and have the potential to intercept more natural fractures

Rendova experimented with various techniques before selecting nitrogen alone as a fracturing fluid Because nitrogen is an inefficient fracturing fluid and is poorly suited to long interval completions, Rendova treated a single 10-ft interval in the zone described above As a preliminary step after the well was perforated, an explosive process, termed "stress frac," was used to produce numerous fractures in the perforated interval

Production histories from wells completed by using foam and nitrogen fracturing led Rendova to these conclusions Long-term flow rates are enhanced by foam fracturing, possibly because the ability to prop induced fractures open offset any damage caused by water However, initial flow rates for wells fractured by using straight nitrogen are higher than wells fractured by using foam Unfortunately, because induced fractures cannot be propped open, the enhancement of production is short term As a result of this, research is continuing to develop a nondamaging fluid that can carry proppants In some tests, a "stabilized foam" is made by reducing water from 25 to 10 percent and by adding a gelling agent that enables the foam to carry higher concentrations of sand per gallon of water. Thus, formation damage is reduced, and propping capability is enhanced by this more expensive technique.

In the historical and the newly emerging areas of shale production, some gas undoubtedly has been produced from many zones scattered throughout the shale sequence. However, because of older and current completion practices (shooting and long-interval fracturing, respectively), it is difficult to assess the relative importance of each zone. The recent successes by some operators in completing shorter intervals offers encouragement that we have the potential to reduce completion costs and to increase productivity by choosing the best zone (or zones) to complete and by utilizing the most appropriate completion technique for that zone (or zones).

Initial Potentials—Inital and Final Open Flows

Schaeffer (1979) compiled initial and final open flow data for wells in the Midway-Extra Field, Putnam County, and analyzed the effect of shooting on these open flows. For wells that have natural open flows of less than 100 Mcf/d, shooting increased the final open flows from 292 to 1,273 percent. However, for wells that have natural open flows of greater than 100 Mcf/d, shooting increased the final open flows from 141 to 167 percent. By using Schaeffer's data, the mean initial open flow for 80 wells is calculated to be 62 Mcf/d and to have a range of 5 to 377 Mcf/d. The mean final open flow for 156 wells is calculated to be 296 Mcf/d and to have a range of 14 to 2,499 Mcf/d. An isopotential map of final open flows (Schaeffer, 1979, fig. 20) indicates that commercial production in the Midway portion of the field follows the northeastern flank of the Midway anticline, whereas good portions in the Extra part of the field are not defined as clearly.

Schaeffer's data were used by Beebe and Rauch (1979) to prepare isopotential maps of initial and final open flows. Initial open flows were interpreted as being better indicators of reservoir permeability, whereas final open flows were interpreted as being better indicators of a well's productivity and fracture influence on well yield. According to Beebe and Rauch (1979), short photolineaments interpreted from low-altitude stereophotographs correlate with high-yield gas wells and water wells. Two main trends were observed—N. 60° W. and N. 30° E. Landsat lineaments, however, correlated with low-yield gas wells in the field (Beebe and Rauch, 1979).

Sweeney and others (1985, 1986) examined records of all wells drilled into or through the Devonian shale sequence in Wirt, Roane, and Calhoun Counties to ascertain if initial potentials (IP's), stratigraphy, and completion techniques could be correlated. They concluded that mean

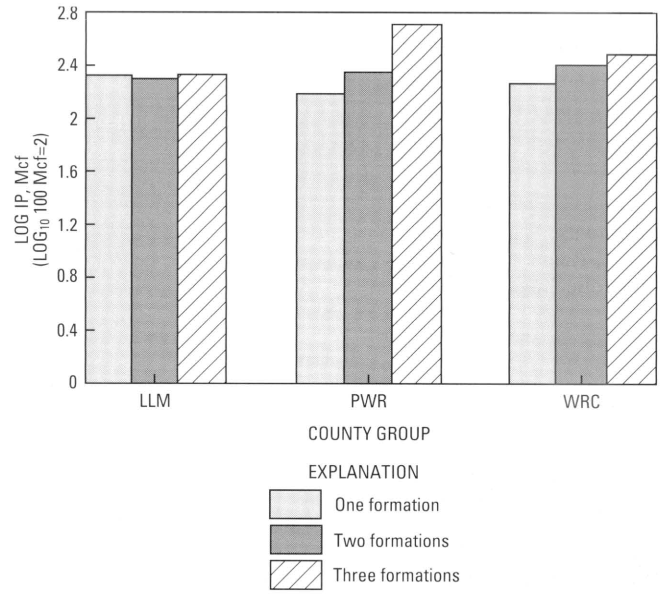

Figure 9. Average log of initial potential (IP) versus the number of formations treated for three areas of three counties each. LLM, Lincoln, Logan, and Mingo Counties; PWR, Pleasants, Wood, and Ritchie Counties; WRC, Wirt, Roane, and Calhoun Counties.

gas IP's for the 239 wells in the data set increased when three or more formations were completed, nitrogen fracturing was used, and the completed interval included the Marcellus Shale. The best zones from which to produce oil include the Upper Devonian undivided and the lower Huron Member of the Ohio Shale. The best oil wells were found to be in Wirt County. They also noted that the mean IP is greatly skewed because of the very large IP's of a relatively few wells. Thus, the majority of the wells in the data set had IP's lower than the mean calculated for all shale wells.

More recently, we have expanded our observations of IP's to include two three-county groups—Pleasants, Wood, and Ritchie and Lincoln, Logan, and Mingo. The average logarithm of IP was plotted against the number of formations completed for the three-county groups. This diagram (fig. 9, table 2) indicates that higher IP's result when more formations (thicker intervals) are completed, but the difference is marginal. In all examples, final open flows were used only for shale wells that had no commingled Mississippian production.

The mean log IP's for wells completed by using various stimulation techniques also were compared for each of the three-county groups (fig. 10, table 2). Wells that were fractured had higher IP's than those that were shot. Fractured wells were not subdivided by type of fracturing fluid for further analysis or by stratigraphy. Therefore, more recent wells in Mingo, Lincoln, and Logan Counties, for example, could have deeper, thicker completion zones than older wells commonly drilled to the Huron and then shot open hole. Also, there may be a problem in using

Table 2. Initial potential summary

[Expressed as logarithmic mean of IP in Mcf. Log_{10} 10 Mcf=1, log_{10} 100 Mcf=2, and so on]

Counties	Stratigraphy			Completion method			Number of units		
	Units above Huron	Huron	Units below Huron	Fracture	Acidize and fracture	Shot	1	2	3
Pleasants, Wood, and Ritchie	2.47	2.37	2.59	2.41	2.35	1.82	2.20	2.36	2.74
Wirt, Roane, and Calhoun	2.48	2.47	2.47	2.50	2.45	2.26	2.30	2.43	2.53
Lincoln, Logan, and Mingo	2.31	2.27	2.32	2.78	2.35	2.23	2.30	2.29	2.30

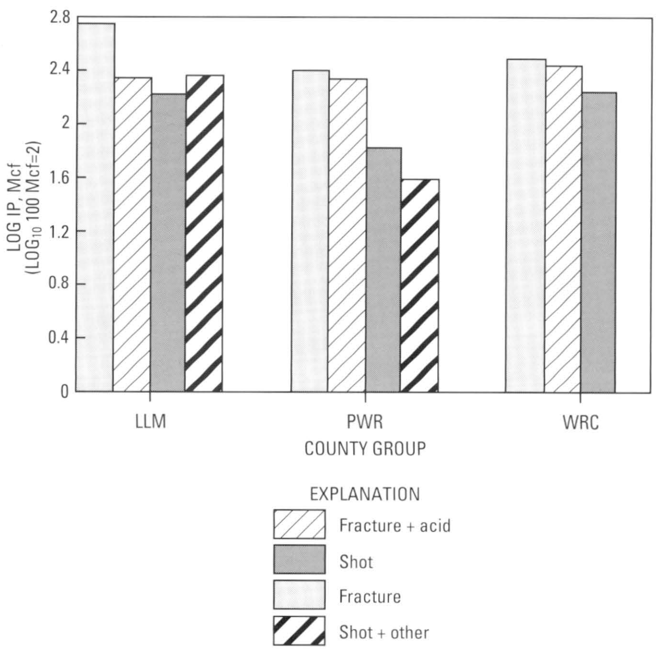

Figure 10. Average log of initial potential (IP) versus the type of completion in shale wells in the three county groups (fig. 8).

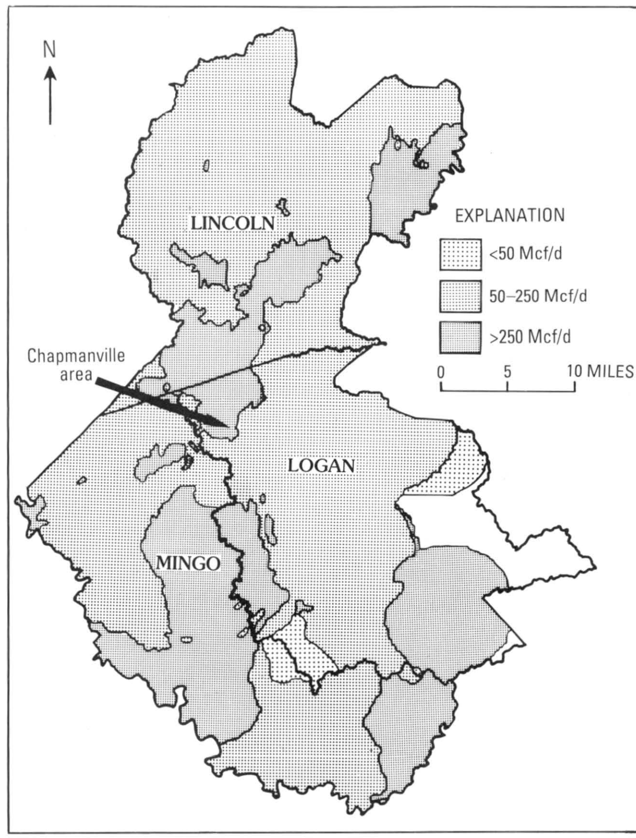

Figure 11. Isopotential (final open flows) of Devonian shale wells in Lincoln, Logan, and Mingo Counties.

nitrogen gas as a fracturing fluid because some of the gas measured during the initial test may be nitrogen flowing back into the well. Consequently, IP figures may be inflated for nitrogen-fractured wells.

For wells completed above, in, and below the Huron, IP's also were compared. No significant difference was found in two of the three-county groups—Wirt, Roane, and Calhoun and Lincoln, Logan, and Mingo. However, in Pleasants, Wood, and Ritchie Counties, wells in which zones below the Huron were completed (often with the Huron and even younger zones) had higher IP's than wells that were not completed below the Huron. Over 1,800 wells were used in the study—780 in Mingo, Lincoln, and Logan; 686 in Pleasants, Wood, and Ritchie; and 361 in Wirt, Roane, and Calhoun (updated from 239 in Sweeney and others, 1985).

Maps of final open flows (isopotential) were computer generated for the three counties in the historical area of shale production (fig. 11) and for the six counties that constitute the emerging area (fig. 12). Areas of good shale IP's are evident in the Chapmanville area of Lincoln and Logan Counties and along the Mingo-Logan boundary (fig. 11). In the area to the north, the wells that have the highest IP's are on and east of the Burning Springs anticline (fig. 12).

Production Studies

During the past decade, several authors have published production data for Devonian shale wells in south-

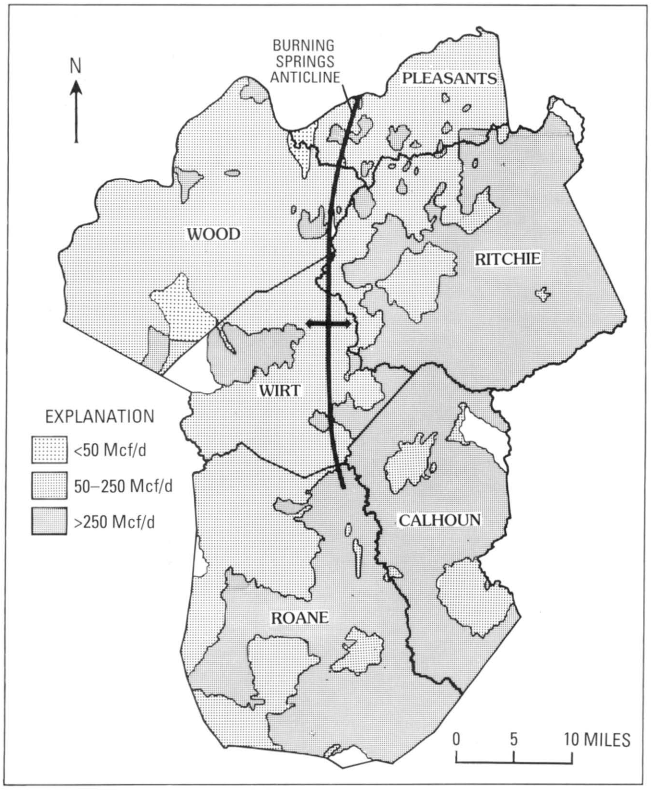

Figure 12. Isopotential (final open flows) of Devonian shale wells in the six counties that comprise the emerging area.

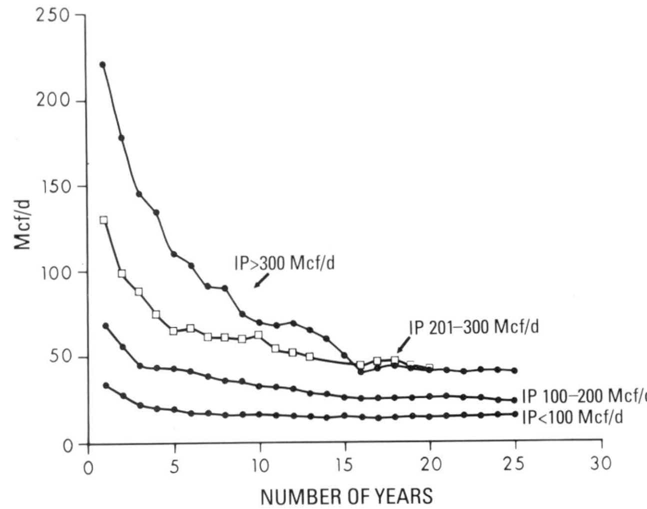

Figure 13. Nested production decline curves for Devonian shale wells in Lincoln, Mingo, and Wayne Counties segregated by ranges of initial potential (IP). (From Bagnall and Ryan, 1976.)

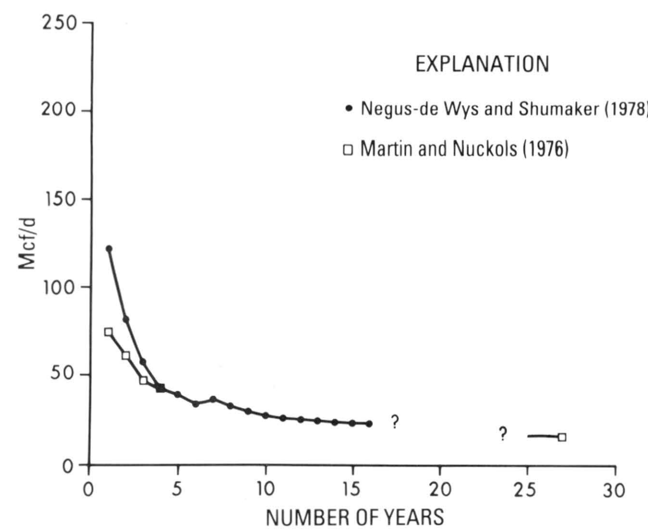

Figure 14. Production decline curves for Devonian shale wells in the Cottageville Field. The difference in the number of wells used accounts for discrepancies in the first 3 yr.

western West Virginia. The size and origin (that is, company sources) of the data sets varied, as did the way in which the data were analyzed (decline curves, isopotential maps, production maps, kriging). Most of these data are scattered in the literature. We will attempt to identify and summarize most of these before presenting our own analyses of production data.

Regional maps (scale 1:125,000) of isopotential have been published for the entire historical area of Devonian shale production in West Virginia (Patchen and others, 1981). In the absence of good (or any) production data, isopotential maps have been used by many operators in a regional evaluation of Devonian shale potential. This technique is justified somewhat by various studies that have shown that a positive correlation exists between IP and production performance (Bagnall and Ryan, 1976; Ray, 1976; Smith, 1978). In spite of this, the best measure of performance for a shale well is a plot of production versus time (Smith, 1978; Vanorsdale, 1985).

Decline curves for Devonian shale wells in southwestern West Virginia (fig. 13) have been published by Bagnall and Ryan (1976) and compared to similar curves for the Cottageville Field (fig. 14) by Negus-de Wys and Shumaker (1978). Typically, decline is rapid during the first several years and then slows significantly before stabilizing after about 15 yr. Two conclusions have been drawn from the nested curves of Bagnall and Ryan (1976)—IP and observed first-year production are good indicators of the future productivity of a well, and, because differences in decline curves for Devonian shale wells are ones of intensity rather than of kind, all classes have essentially the same shape.

Kucuk and others (1978) evaluated reservoir data from DOE's cored and offset wells in Lincoln County to determine how best to calculate gas in place and Devonian shale reserves. Although they presented only one pressure

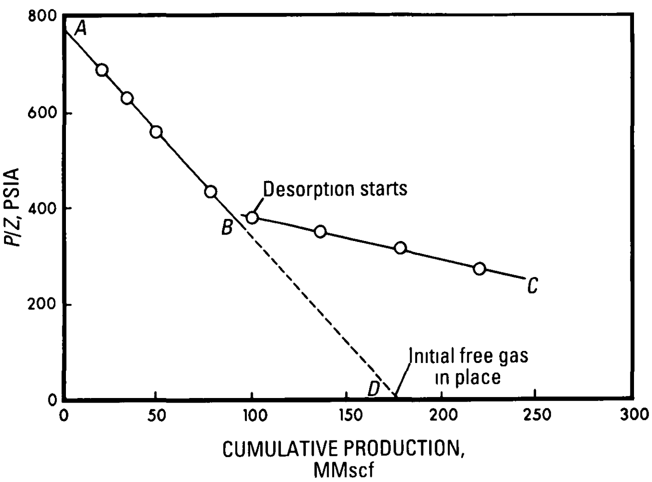

Figure 15. Theoretical values of the pressure to gas deviation factor ratio (*P/Z*) versus cumulative production from a dual porosity gas reservoir *A–B*, free gas produced from fractures before desorption, *B–C*, gas from fractures and desorption, D, estimated total free gas (From Kucuk and others, 1978) PSIA, pounds per square inch atmospheric

versus production plot for a well in Lincoln County, this curve was used to illustrate the dual porosity nature of the shale reservoir, a steep initial pressure drop was accompanied by production of free gas from fractures and was followed by a more horizontal curve after desorption began and gas was diffusing through the matrix to fractures and ultimately to the borehole (fig 15) They concluded that volumetric methods based on fracture porosity cannot be used to calculate gas in place in the shales because of the absorbed nature of the gas By using a plot of simulated values of production versus time for a dual porosity gas reservoir, they estimated that the production rate of a well is doubled in its later years as a result of gas desorption from the matrix

Vanorsdale (1985) prepared general decline curves for 162 wells in 20 contiguous counties in Ohio (10), Kentucky (54), and West Virginia (98) The data were plotted on a graph as a percentage of annual production rate relative to the best (initial) year of production He prepared a general curve for the entire area, curves for each of the three States, and curves for natural (19), fractured (11), and shot (132) wells All exhibited the same general slope, although initial decline rates (first-year decline) varied slightly After studying the data, Vanorsdale (1985) reached several conclusions First, initial decline rates are much less than the 60-percent figure often assumed, for all 162 wells, the initial decline was only 31 percent, for West Virginia wells, the decline was 27 percent (fig 16) Second, all curves were hyperbolic, and the "b" factor (the exponent that governs the curve) was greater than 1 0, which is indicative of a multiporosity system Finally, shot wells appear to be more productive than fractured wells, perhaps because of the small sample of fractured wells Natural

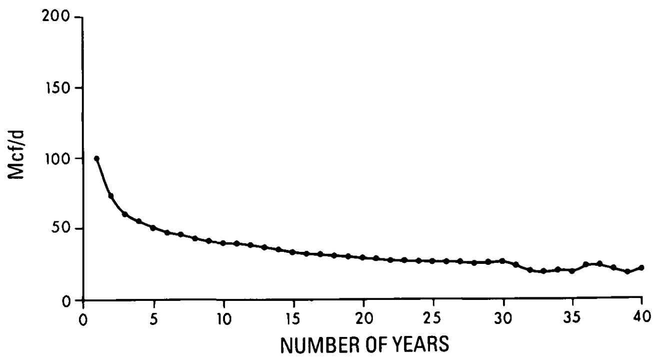

Figure 16. Gas production decline curve for 98 Devonian shale wells in West Virginia (from Vanorsdale, 1985) Well data are from 10 counties in historical areas and 4 in an emerging area

wells become increasingly more inferior after their sixth year on line Most wells in the three States produced for at least 20 to 22 yr and then were gradually abandoned during the next 20 yr

Through a contract with the BDM Corporation, the GRI created a data base of Devonian shale wells in Kentucky, Ohio, and West Virginia The BDM Corporation (1986) published decline curves for the entire area that were based on 1,508 wells and for the two smaller areas (quads 62 and 95) shown in figure 17 The southern cell (quad 62) includes most of the Chapmanville area of West Virginia Data on 166 wells, which had been online for an average of 28 1 yr, were used to prepare the decline curve (fig 18) for this quad The BDM Corporation's northern cell (quad 95) includes the Midway-Extra and Cottageville Gas Fields Data on 261 wells, which had been online for only 4 7 yr on average, were used to construct the decline curve for this cell Only 2 wells in quad 95 were still producing after 30 yr versus 75 wells in quad 62 Production from wells in quad 62 is significantly better than that from those to the north in quad 95 From the tenth year on, the production decline curve for the better area (quad 62) approximates the production decline curve for the entire 1,508 wells in the regional data base Thus, wells in the southern area begin as better than average and decline to average wells, whereas wells to the north are always less than average

Columbia Gas used data on hundreds of wells in a study of shale production in four counties (Wayne, Lincoln, Logan, Mingo) in West Virginia (Columbia Gas Transmission Corporation, 1984, Wallace and others, 1986) Four type curves (fig 19) that ranged from superior to poor were developed Open flows after treatment were contoured for 526 wells in an area covering four 7-minute quadrangles Areas of high final open flows (greater than 400 Mcf/d) are roughly aligned northeast to southwest and northwest to southeast A map of 10-yr cumulative production for these same wells better illustrates these two main trends, especially for cumulative production greater than 500 MMcf Two major shale production and several minor anomalies,

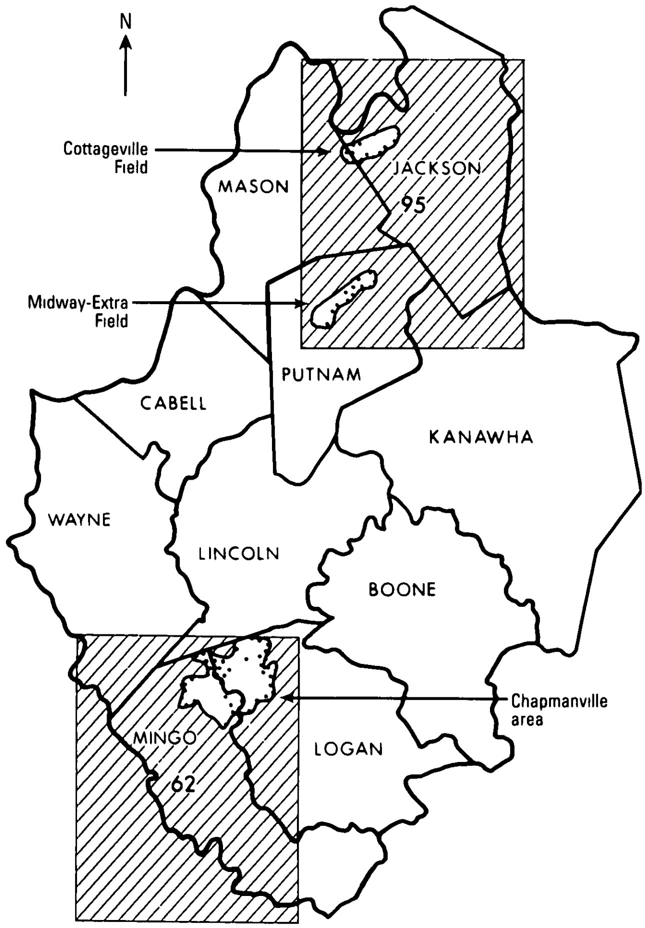

Figure 17. Quads 62 and 95 in the Gas Research Institute's Eastern Gas Data System, which is managed by the BDM Corporation

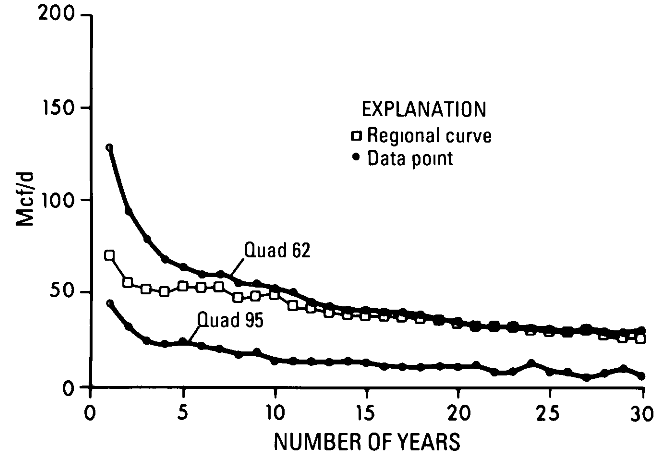

Figure 18. Gas production decline curves for quads 62 and 95 (fig 17) and the regional curve for 1,508 Devonian shale wells, mostly in West Virginia and Kentucky

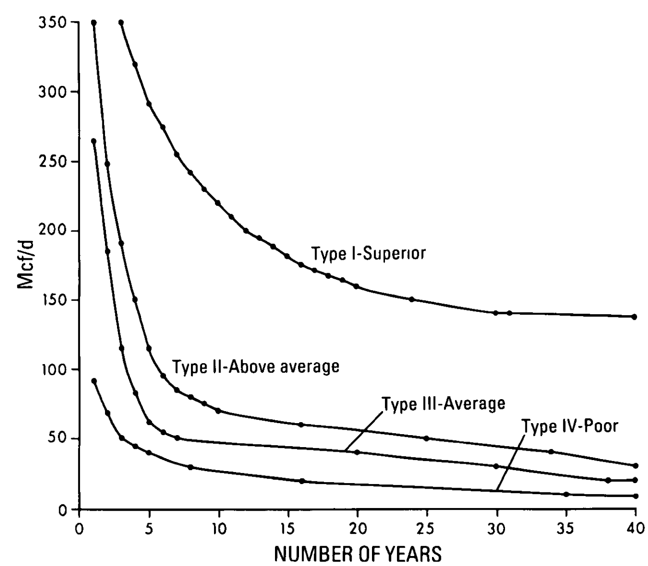

Figure 19 Gas production decline curves for four families of Devonian shale wells in Mingo, Lincoln, Logan, and Wayne Counties. Of the 95 wells used, 4 were type I, 14 were type II, 25 were type III, 34 type were IV, and 18 were transitional between types III and IV (From Columbia Gas Transmission Corporation, 1984)

which were mapped by Wallace and others (1986), occur on the flanks of anticlines mapped on the top of the Onondaga Limestone and on the downthrown side of interpreted basement faults However, other basement faults that extend into the shale section are not associated with high production (Wallace and others, 1986) Geologists from Columbia Gas concluded that high production is not related directly to basement faulting in this area but rather to anticlinal flanks (not crests)

Columbia Gas chose 10 unstimulated "untubed" shale wells for an in-depth study of production controls When the wells were reentered, all but one were bridged above the Berea Sandstone, and that one was bridged below the Berea Following cleanout, flow rates increased from twofold to thirty-fivefold in five of the wells Estimated ultimate recoveries were increased by as much as 22 percent On the basis of these data, Columbia Gas concluded that clean-out of naturally producing shale wells is cost effective

We used data on 405 shale wells and 51 wells that have commingled production provided by Columbia Gas to further evaluate the relation between IP's and production The mean IP for all shale wells, regardless of completion type, was 493 Mcf/d Most of these (374) were shot and had a mean IP of 303 Mcf/d, three fractured wells had a mean IP of 234 Mcf/d The relatively few exceptional wells that were produced naturally had a mean IP of 3,067 Mcf/d

Because a few wells that have high IP's can increase the mean to a nonrepresentative value, all data were converted to common logarithms (table 3) Thus, where average IP's appear to be significantly different (fractured

Table 3. Initial potential and 10-yr cumulative production summary for Columbia Gas Transmission Corporation data, southwestern West Virginia

[μ, mean, Med, median, Log, logarithmic value, Mcf/d, thousand cubic feet per day, MMcf, million cubic feet]

Subsets	No of wells	Initial potential (Mcf/d)				10-yr cumulative production (MMcf)			
		μ	μ Log	Med	Med Log	μ	μ Log	Med	Med Log
All shale	405	493 5	2 39	215	2 33	178 5	2 08	122	2 09
Shale and Berea Sandstone	34	269	2 31	183	2 26	183 4	2 15	119	2 07
Shale and Big Injun	2	333 5	2 48	333 5	2 48	276 5	2 44	276 5	2 44
Shale, Big Injun, and Berea Sandstone	4	308	2 46	241 5	2 38	238 3	2 35	268	2 43
Shale, Big Injun, and Big Lime	3	323 3	2 44	304	2 48	179 7	2 19	131	2 12
Shale and Big Lime	8	198 1	2 28	188	2 27	178 9	2 22	195	2 29
Shale									
Fractured	3	233 7	2 34	231	2 36	92	1 93	82	1 91
Natural	28	3,067 7	3 41	2,702 5	3 43	409 2	2 49	294	2 47
Shot	374	302 8	2 31	199	2 30	161 9	2 05	115	2 06
All shot	425	298 5	2 31	198	2 30	165 4	2 07	119	2 08
Commingled—shot	51	266 7	2 33	188	2 27	190 4	2 19	147	2 17

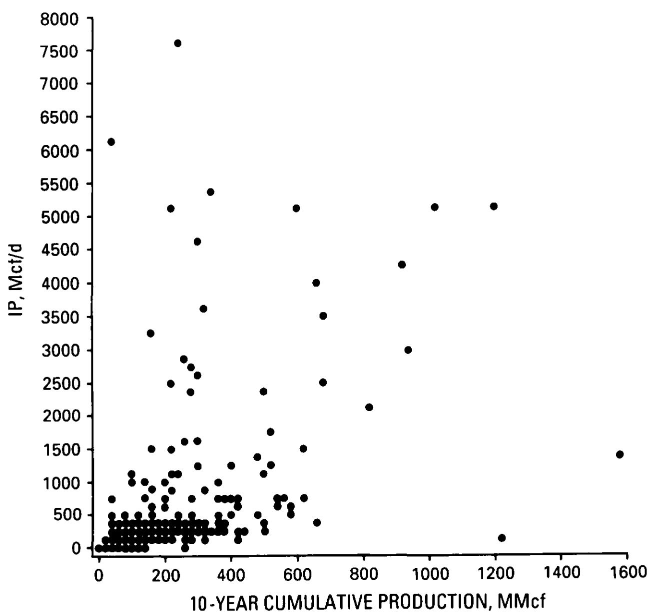

Figure 20. Initial potential (IP) versus 10-yr cumulative production for the data of the Columbia Gas Transmission Corporation Most data near origin represent multiple wells (2–20)

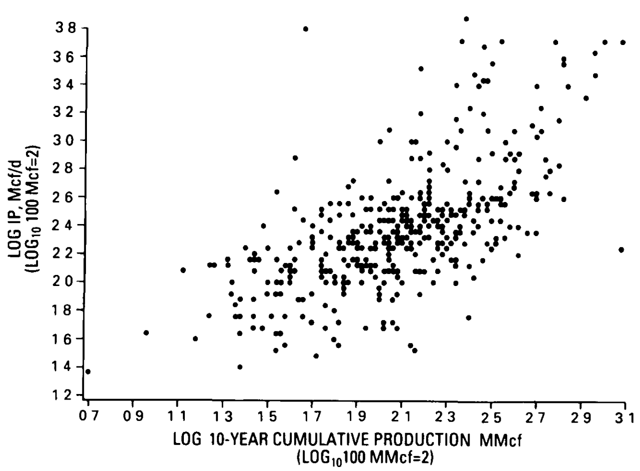

Figure 21. Log of initial potential (IP) versus log of 10-yr cumulative production, same data as in figure 20 Only a few solid circles represent multiple wells

versus shot wells, for example), the logarithms are quite close

Average 10-yr cumulative production for all shale wells was 178 5 MMcf per well For those wells that have commingled production, 10-yr production ranged from 178 9 (shale plus the Big Lime) to 276 5 MMcf (Devonian shale plus the Big Injun) Devonian shale plus the Berea Sandstone wells had lower IP's but comparable 10-yr production figures (table 3)

A plot of IP's versus 10-yr production (fig 20) was too crowded near the origin to illustrate if any relations among the data exist However, when all data were converted to their common logarithms and replotted, a positive correlation was apparent (fig 21) A plot for commingled shale and the Berea Sandstone (fig 22) shows the same general trend A plot of natural shale wells shows a cluster of points in the high-IP high-production area as compared with the plot of shale wells that were shot (fig 23) We can conclude from these various plots that there is a direct relation, on average, between IP's and cumulative production Thus, IP's, if measured carefully, should be predictive for most wells

Isopotential maps in this area (Columbia Gas Transmission Corporation, 1984) and other areas (Schaeffer, 1979, Shumaker, 1986) suggest a strong structural control on high-IP areas R C Shumaker (West Virginia University, oral commun , 1987) expressed the opinion that IP's do indicate a well's future potential, and, if production does not come up to that potential, then perhaps either something is mechanically wrong with the well or a proper completion was not achieved The recent experience of Columbia Gas

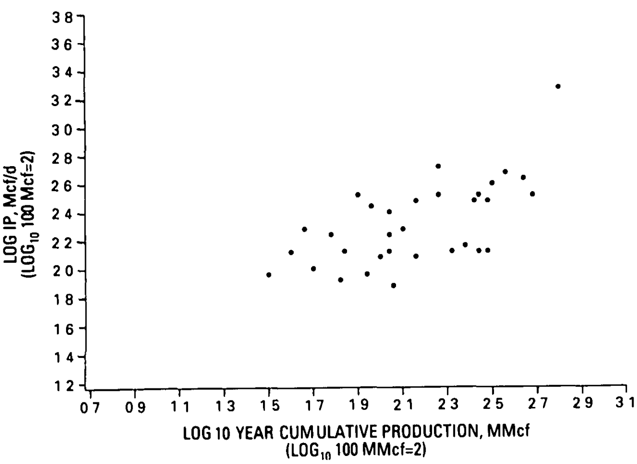

Figure 22. Log of initial potential (IP) versus log of 10-yr cumulative production for commingled shale and Berea Sandstone wells

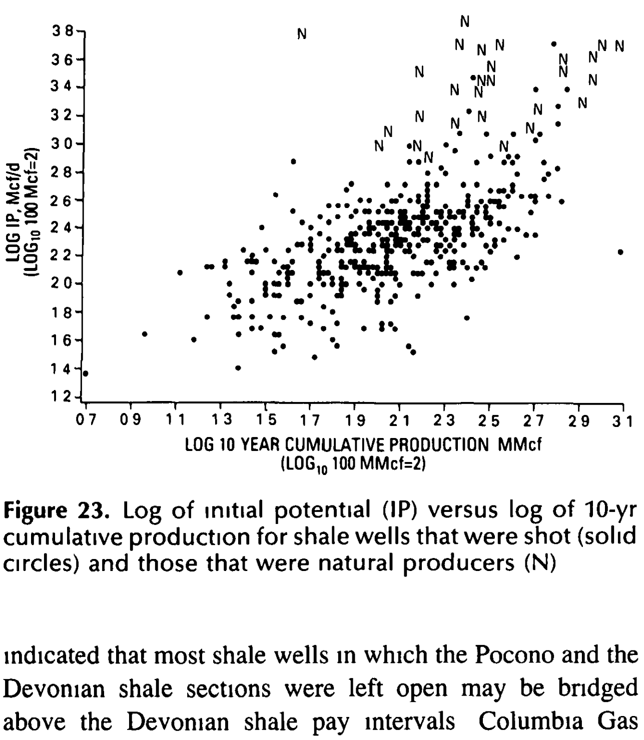

Figure 23. Log of initial potential (IP) versus log of 10-yr cumulative production for shale wells that were shot (solid circles) and those that were natural producers (N)

indicated that most shale wells in which the Pocono and the Devonian shale sections were left open may be bridged above the Devonian shale pay intervals Columbia Gas concluded that natural wells should be reentered and cleaned out to enhance production The best candidates for clean-out may be the "underachievers," which are those wells that have high IP's but below-average cumulative production (fig 23)

An average decline curve for 95 shale wells in Lincoln, Logan, and Mingo Counties (Neal and Price, 1986) shows the same distinctive shape, which is characterized by rapid decline during the first 5 to 6 yr and a flat tail after 14 to 15 yr (fig 24) During the first year that these wells were online, they averaged nearly 50 Mcf/d and declined 23 percent The 37 wells still producing 30 yr later averaged more than 24 Mcf/d during their thirtieth year,

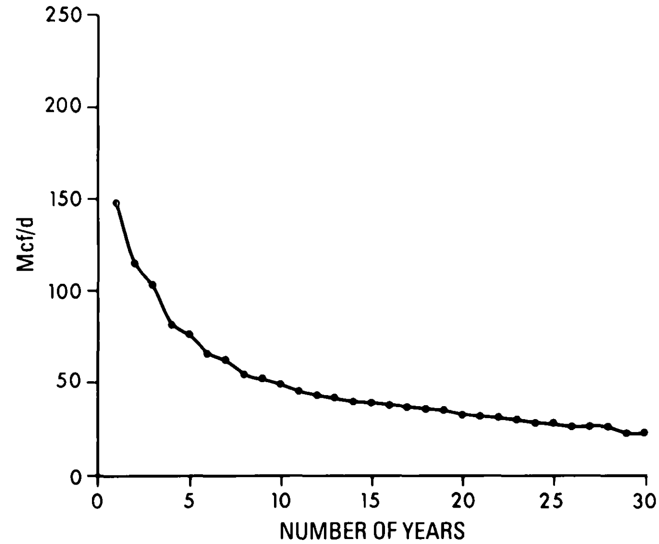

Figure 24. Gas production decline curve for 95 shale wells in the Chapmanville area of Lincoln, Logan, and Mingo Counties (From Neal and Price, 1986)

which is a decline from the peak (initial) year of 83 percent Averaged decline curves for each of the three counties (Neal and Price, 1986) did not show any significant differences in shape An increase in mean production during the 30th year in Logan County can be attributed to the abandonment of poor wells, which increased the average flow of those still online

Our attempt to quantify differences, if any, in long-term production between shot and fracture wells was not successful Because most of the wells in our data set were shot, the average decline curve for all shot wells is nearly identical to the overall mean decline curve However, the mean decline curve for fractured wells would of itself suggest that fracturing is a poor substitute for the older method of shooting (fig 25) Several reasons may account for this First, only a few wells in our data set were fractured, and only a few years of production data were available Second, a graph of the year in which each well went online (fig 26) illustrates that the fractured wells were drilled in the field between 35 and 40 yr after the initial shot wells were drilled Thus, normal field decline had occurred before these wells were drilled, fractured, and put online The rapid decline of these wells in the first 4 yr is similar to the initial portion of the average curve for shot wells

Plots of IP (final open flow unless natural) versus first- and tenth-year average daily production (fig 27) show a strong positive correlation Thus, in this area, on average, a well's IP is predictive of its short- and long-term production potential, this is in contrast to the study by Vanorsdale (1985) Because the distribution of this data was abnormal, production and IP values were converted to the common logarithmic scale A plot of first- versus tenth-year production (fig 28) again showed a high positive correlation In

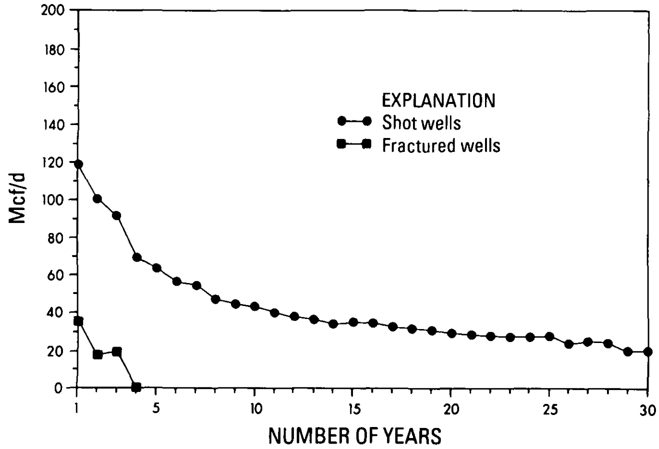

Figure 25. Gas production decline curves for shot versus fractured shale wells in Lincoln, Logan, and Mingo Counties (From Neal and Price, 1986)

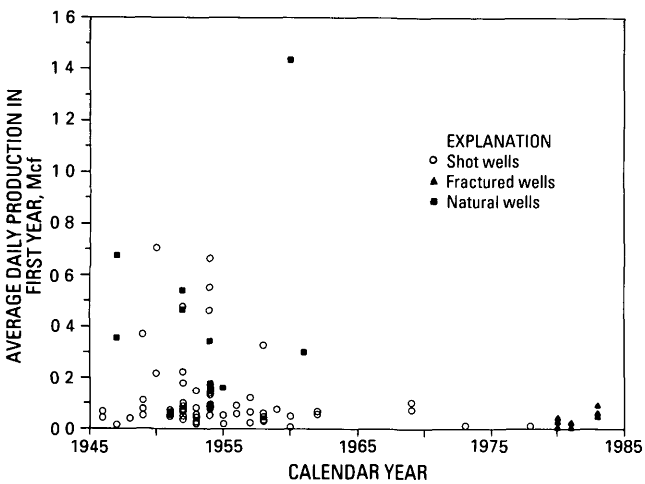

Figure 26. First-year production versus year of completion for shale wells in Lincoln, Logan, and Mingo Counties, subdivided by type of completion (From Neal and Price, 1986)

general, the best wells in the first year of production remain the best throughout the 10-yr period

The average cumulative production from these shale wells after their initial 5 yr online is 139,199 Mcf After 10, 20, and 30 yr, the average figures are 233,418, 366,263, and 460,998 Mcf, respectively, Therefore, the average Devonian shale well in Lincoln, Logan, and Mingo Counties produces about half of its 30-yr cumulative production after the tenth year The mean cumulative curve can be extrapolated to illustrate that, after 40 yr, the average shale well in the area will have produced 500,000 Mcf

A contour map of the logarithm of 5-yr cumulative gas production (fig 29) shows a northeast to southwest trend that cuts across the Warfield anticline However, the southwestern part of the trend parallels that of the Warfield fault The best production in the northeastern end of the

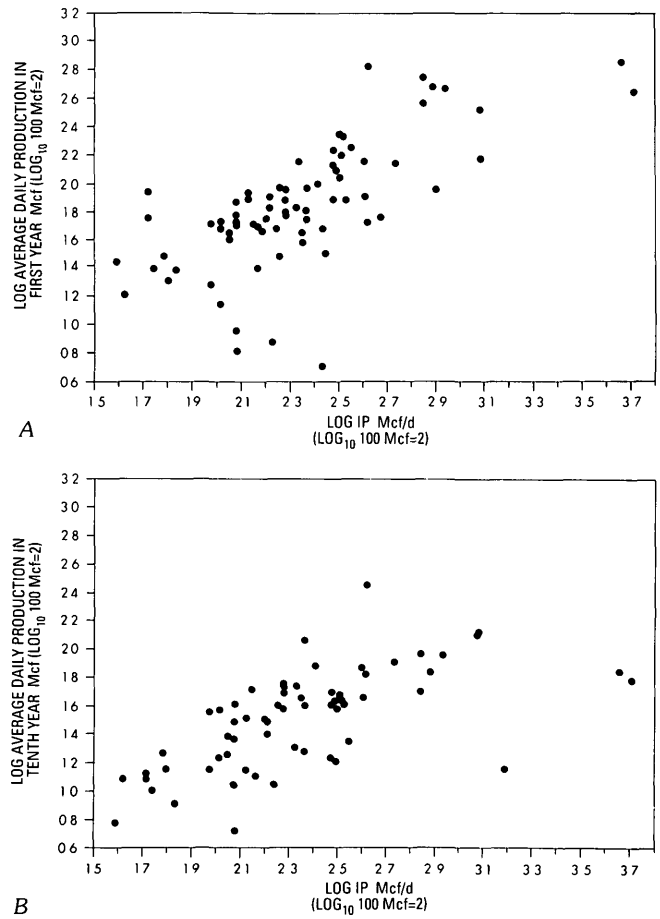

Figure 27. Initial potential versus average daily production for shale wells in Lincoln, Logan, and Mingo Counties *A*, Relation between initial potential (IP) and first year *B*, Relation between IP and tenth year Logarithmic scales

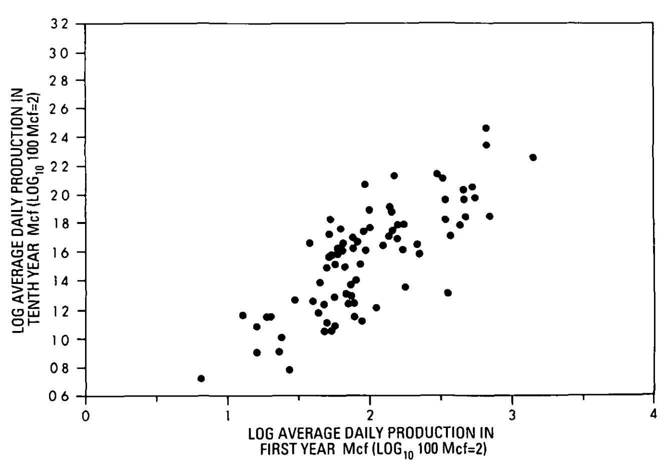

Figure 28 First-year versus tenth-year average daily gas production for shale wells in Lincoln, Logan, and Mingo Counties Logarithmic scales (From Neal and Price, 1986)

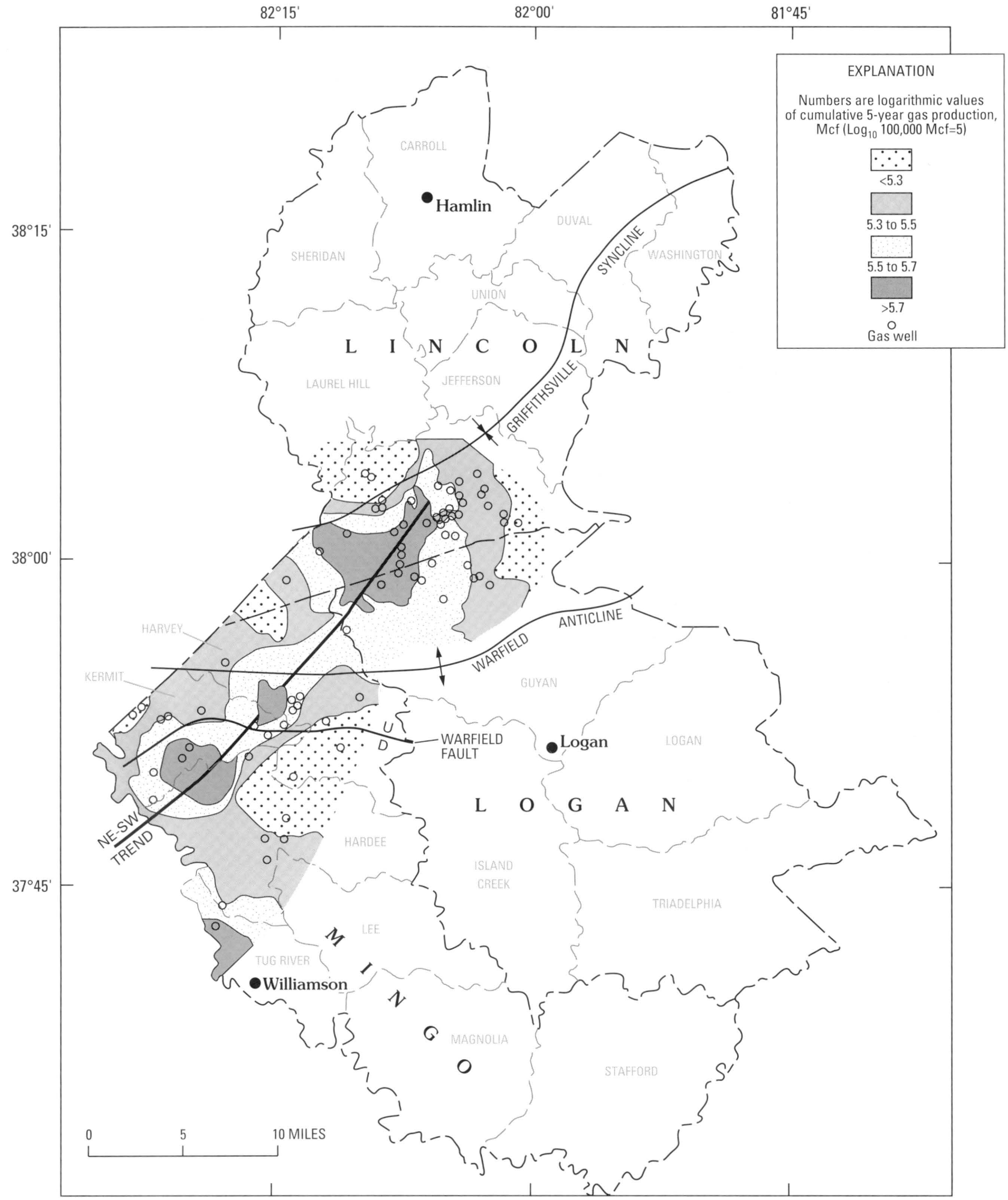

Figure 29. Kriged estimates of cumulative gas production after 5 yr in Lincoln, Logan, and Mingo Counties. (From Neal and Price, 1986.)

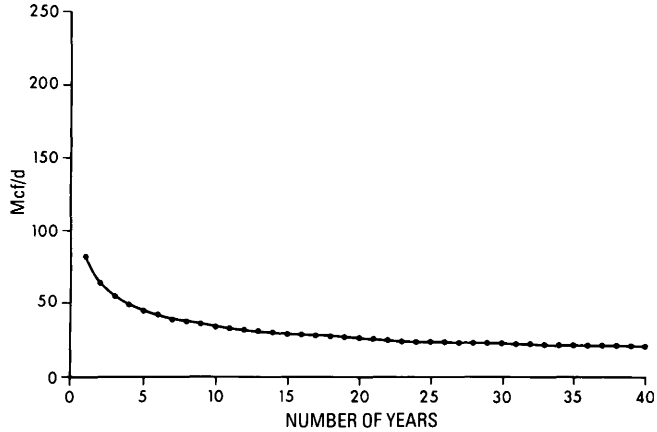

Figure 30. Production decline curve for Devonian shale wells in the Midway-Extra Field, Putnam County (From Schaeffer, 1979)

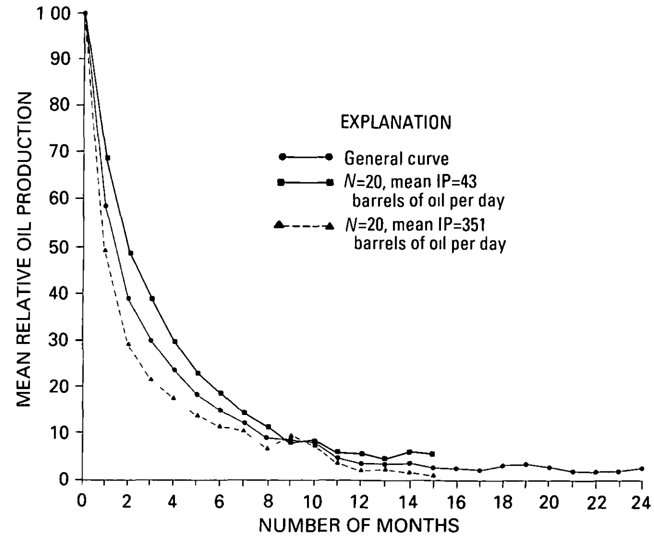

Figure 31. Oil production decline curves for Devonian shale wells in Ritchie and Pleasants Counties, separated by high versus low initial potentials (IP) *N*, number of wells in sample (From Filer, 1985)

trend lies off-structure between the Warfield anticline and the Griffithsville syncline (Neal and Price, 1986)

On the basis of production data from 39 wells, Schaeffer (1979) prepared an average decline curve for the Midway-Extra Field (fig 30) that can be compared with our curve for the Chapmanville area (fig 24) The average Midway-Extra well produced over 29 MMcf the first year and experienced an initial decline of 22 9 percent to 22 5 MMcf the second year After 10 yr, the average well had produced 170 9 MMcf, compared with 233 4 MMcf for wells in the Chapmanville area (Neal and Price, 1986) After 20 yr, the average Midway-Extra well had produced 274 5 MMcf, compared to 366 2 MMcf for an average Chapmanville well Schaeffer projected his data out to the fortieth year, at which time the average well would have produced 434 MMcf and would be producing at a rate of 20 3 Mcf/d Based on 160-acre spacing and 434 MMcf per well, Schaeffer calculated reserves of 39,063 MMcf for the 14,356-acre field

Although our curves and those of Schaeffer (1979), Columbia Gas Transmission Corporation (1984), and Vanorsdale (1985) illustrate the long life of a typical shale well, this may not be correct for the new area to the north An average Devonian shale oil-production decline curve for Ritchie and Pleasants Counties by Filer (1985) suggests that these wells are short-lived (fig 31) Mean production declined 96 percent during the first year that these wells were pumped and 98 percent over the initial 24-month (mo) period This was disappointing for an area that had attracted nationwide attention (and investment dollars) as a result of the very high IP's reported for many of the oil wells To see if the overall curve was being influenced strongly by wells that initially were not good producers, Filer (1985) separated his data set into more productive and less productive wells based on IP's The 40-well sample split evenly into two groups that had significantly different mean IP's (43 versus 351 barrels of oil per day (BOPD)) However, after 15 mo, actual production rates for the two groups were within 1 5 BOPD of each other Both groups showed rapid production decline (fig 31), such that the better wells were producing 3 5 BOPD after 15 mo (1 percent of IP) and the poorer wells were producing 2 0 BOPD (5 percent of IP) Thus, for oil wells in this area, IP's are not good indicators of future productivity

The influence of gas production on oil production in these wells was not evaluated by Filer (1985) However, the type of artificial fracturing technique used to stimulate the well was addressed, as was the concept of short- versus long-interval completion Of the 40 wells used in the study, 17 were completed by using a straight nitrogen frac in a single-stage short interval, and 16 were completed by using nitrogen in several stages over thick intervals There appears to be no significant difference between the two curves generated (fig 32) in terms of their decline However, the short-interval wells did continue to produce at higher daily rates than the long-interval wells

Gas production data for Devonian shale wells in the six-county area were difficult to obtain and difficult to deal with once available Two-phase (oil and gas) production, shut-in periods of up to 6 mo each year for gas, differences in reporting among operators, relatively short production histories, and the lack of data for days online for both oil and gas production were problems to overcome On top of this, we were attempting to see if any significant differences in production occurred when wells in the same area were completed in various formations by using different stimulation techniques Therefore, an already small suspect data base was split into too many subsets to warrant confident conclusions

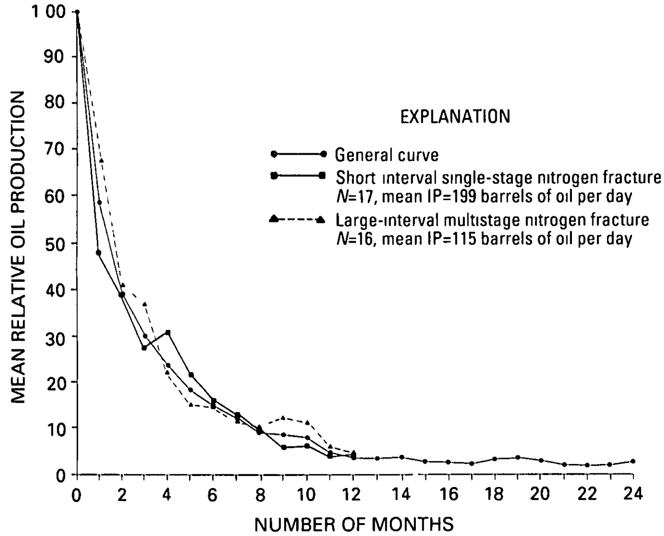

Figure 32. Oil production decline curves for Devonian shale wells in Ritchie and Pleasants Counties, separated by length of completion interval (From Filer, 1985) *N*, number of wells in sample

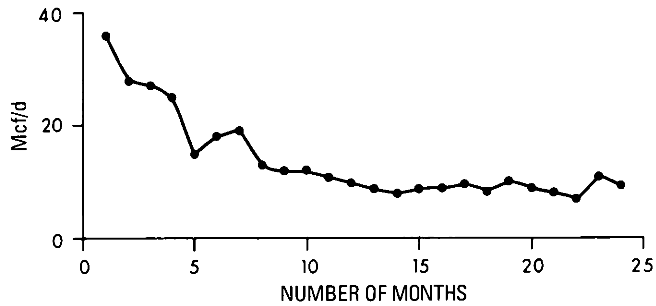

Figure 33. Gas production decline curve for Devonian shale wells in Ritchie and Pleasants Counties

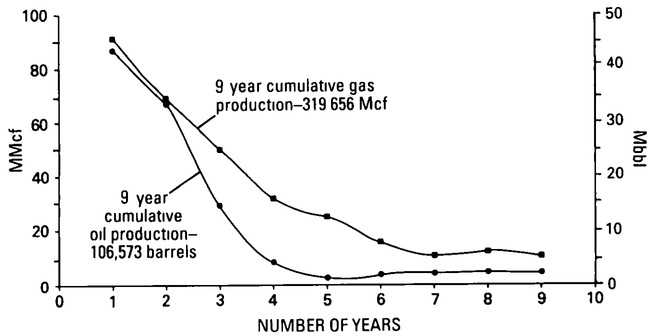

Figure 34. Production decline curves (oil and gas) for one of the first (and best) Devonian shale wells drilled in Calhoun County (Cal–2537)

Only 51 of the 239 wells used in the IP study for Wirt, Roane, and Calhoun County shale wells could be used in this production study Of these 51, 60 percent of these produced oil as well as gas The average well produced just 6 6 BOPD and 23 1 Mcf/d during its initial 365 days (d) online (excluding shut-in periods) Oil production averaged only 11 3 BOPD during the well's initial month of production and declined 28 percent to 8 2 BOPD during the twelfth month Gas production averaged 31 5 Mcf/d per well during the initial month of gas production and declined 30 percent to 21 9 Mcf/d per well during the twelfth month that the well produced The gas decline was comparable to that found by Vanorsdale (1985) for a larger area of West Virginia Thus, during the initial 365-d period that a well produced in this area, oil production declined to 26 percent of mean IP versus 5 percent in Filer's (1985) study area to the north, and gas production declined to approximately 9 percent of mean IP (Sweeney and others, 1986)

An attempt was made to generate mean gas decline curves for wells in Filer's study area by using different wells than he used for his oil decline data set The final curve (fig 33) is for all wells in Ritchie and Pleasants Counties and does not attempt to subdivide them on the basis of stratigraphy or completion technique To eliminate the problem of shut-in periods and still plot gas volume in thousands of cubic feet per day, all monthly totals (gas versus days) were plotted as a cumulative curve Production was read after each 30-d interval, and a decline curve was generated by using the differences in successive 30-d cumulative totals This entire process was accomplished by computer, and only the final mean decline curve for all wells was generated Although the resulting curve is erratic, it shows a rapid decline from 36 to approximately 10 Mcf/d (72-percent decline) after 12 30-d months, the decline was as low as 8 Mcf/d after 22 mo The mean increase noted in the twenty-third month is attributed to abandonment of poor wells, which increased the average of those still online

The significance of these studies, the averaging technique used in Wirt, Roane, and Calhoun Counties, and the decline curve technique used in Pleasants, Wood, and Ritchie Counties is that the average shale well in the six-county area is a poor well after only 1 yr on line The wells to the south (Wirt, Roane, Calhoun) appear to be better producers during their twelfth month (22 versus 10 Mcf/d) However, the average well in Wirt, Roane, and Calhoun Counties still makes less gas per day in its first year than the average well in Lincoln, Logan, and Mingo Counties is still making after 30 yr (23 1 vs 24 2 Mcf/d, figs 24, 33)

We realize that we do not have adequate production histories on all wells in this new emerging area of shale oil and gas production We also realize that exceptional wells have been drilled, some of which have produced at high levels for many years (fig 34) Furthermore, many of these better wells may be clustered geographically, which indicates that there are favorable areas that can be economically developed in the shale section if careful geology rather than random drilling is used However, based on the admittedly limited data that we have available, we can only conclude that the overall emerging area of Devonian shale oil and gas production has been overpromoted and will prove to be noncommercial to many operators and investors The historical area of Devonian shale gas production apparently can live up to its reputation as an area in which relatively low-volume long-term shale wells can be drilled, stimulated, and produced commercially

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Chapter M

Detailed Study of Devonian Black Shales Encountered in Nine Wells in Western New York State

By ARTHUR M. VAN TYNE

U.S. GEOLOGICAL SURVEY BULLETIN 1909
PETROLEUM GEOLOGY OF THE DEVONIAN AND MISSISSIPPIAN BLACK SHALE OF EASTERN NORTH AMERICA

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Detailed Study of Devonian Black Shales Encountered in Nine Wells in Western New York State

By Arthur M. Van Tyne[1]

Abstract

Late and Middle Devonian black shales from nine wells in western New York State contain a mineral suite of quartz, illite and mixed-layer clays, chlorite, calcite, dolomite, pyrite, and plagioclase feldspar and an accessory titanium mineral No consistent pattern of vanadium and nickel content was evident The organic matter in the Middle Devonian Marcellus Shale is composed of herbaceous, amorphous, woody, and coaly material In the Marcellus, total organic carbon ranges from 2 54 to 8 69 percent, thermal alteration indexes range from 3− to 3+, and mean vitrinite reflectances range from 0 55 to 1 95 percent The last two measures indicate that thermal conversion of organic carbon in the Marcellus has proceeded to the gas and light hydrocarbon liquid phase

Scanning electron microscope studies show that the clays are tightly packed Pores that range in size from 0 001 to 0 01 millimeter are present and appear to be more common in the Marcellus than in the other shales examined Mixed-layer illite-smectite contained in these black shales can expand in the presence of water This could decrease the permeability of the rock after a hydraulic fracture treatment Such treatments of these shales should be designed to use little or no water or specially treated water

Only two of the wells studied have produced appreciable amounts of gas None of the information derived from this study indicates why these two wells should have been better producers than the other wells studied Their superior gas production potential may be the result of their location in areas where natural fractures are likely to be present

INTRODUCTION

The Eastern Gas Shales Project of the U S Department of Energy began in 1976 and, by 1979, had produced data showing that trillions of cubic feet of indigenous natural gas are locked up in the Devonian black shales of the northern Appalachian basin Studies showed that, in areas where extensive natural fracturing occurred or where artificial fracturing techniques were effective in enhancing natural fractures, black shale gas production could be economically viable In response to those findings, the New York State Energy Research and Development Authority (NYSERDA) began a program to encourage exploration for gas in the Devonian black shales of western New York In the early 1980's, NYSERDA sponsored the drilling and the testing of several black shale wells (Donohue, Anstey & Morrill, 1981, Arlington Exploration Company, 1983) Of these, the data from eight are used in this study

This study was undertaken in an effort to ascertain if the lithologic and physical characteristics of the black shales, as observed in samples from nine wells, might relate to their productive potential The work was funded under a subcontract from the Arlington Exploration Company of Boston, Mass

Acknowledgments

Thanks are extended to NYSERDA and to the Arlington Exploration Company for funding this work Robert Lynch of Arlington was most helpful in approving the study and providing the samples and logs needed Daniel B Sass of Alfred University discussed procedure and made arrangements for sample processing during the early phases of this work The organic-carbon-kerogen analyses were provided by R E Zielinski of the Mound Facility of Monsanto Research Corporation at Miamisburg, Ohio, by authorization of Charles Komar of the Morgantown Energy Technology Center, U S Department of Energy Reviews and comments by John Hosterman on the X-ray and chemical analyses and the assistance and reviews of John Roen, Wallace de Witt, Jr , Laure Wallace, and Roy Kepferle are appreciated

The assistance of my family in sample preparation, transcription, and drafting is particularly appreciated

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WELLS STUDIED

This paper will focus on the results of studies of cuttings from NYSERDA-funded wells and a privately financed well, the Joyce Drilling Company No 1 Hammell, all of which are located in Allegany, Cattaraugus, Livingston, and Steuben Counties, N Y An unsuccessful attempt to take a black shale core was made in the Joyce Drilling Company No 1 Hammell The wells included in this study are as follows

St Bonaventure University
1 Fee
State ID No 31–009–16214
Town of Allegany
Cattaraugus County

Portville Central School
1 Fee
State ID No 31–009–16232
Town of Portville
Cattaraugus County

Houghton College
1 Fee
State ID No 31–003–14253
Town of Caneadea
Allegany County

Houghton College
2 Fee
State ID No 31–003–16202
Town of Caneadea
Allegany County

Allegany County Board of Cooperative Educational Services
1 Fee
State ID No 31–003–16227
Town of Amity
Allegany County

Alfred University
1 Fee
State ID No 31–003–16203
Town of Alfred
Allegany County

Joyce Drilling Co
1 Hammell
State ID No 31–003–13731
Town of Andover
Allegany County

Arlington Exploration Co
1 Meter Farm
State ID No 31–051–15480
Town of West Sparta
Livingston County

Arlington Exploration Co
1 Valley Vista View
State ID No 31–101–15268
Town of Rathbone
Steuben County

Locations are shown in figure 1

DESCRIPTIONS OF CUTTINGS FROM DEVONIAN BLACK SHALE SECTIONS

About 20,089 feet (ft) of cuttings from the nine wells were utilized in the study These were examined carefully for all lithologic details observable with a low-magnification binocular microscope At the same time, samples were taken for additional testing The purpose was to see if a detailed sample examination could find any lithologic clues to indicate that a certain well or area might have a better-than-average potential for black shale gas production

The sample studies show a generally excellent correlation with the lithology as interpreted from the gamma-ray logs The depth correlations between sample cuttings recorded by the drillers and the gamma-ray logs are not precise because of the difference between the more casual drillers' depth measurements listed for the sample depths and the accurate depths measured by the logging cable

The detailed sample descriptions (table 1) are grouped into three northeast-southwest-trending areas The western area includes the St Bonaventure University No 1 Fee in Cattaraugus County and the two Houghton College wells in Allegany County The central area includes the Portville Central School No 1 Fee in Cattaraugus County, the Board of Cooperative Educational Services No 1 Fee in Allegany County, and the Arlington Exploration Company No 1 Meter Farm in Livingston County The eastern area includes the Alfred University No 1 and the Joyce Drilling Company No 1 Hammell in Allegany County and the Arlington Exploration Company No 1 Valley Vista View in Steuben County This arrangement shows the possible west to east lithologic variations in the units studied

Of the shales in this area, only the Dunkirk, the Pipe Creek, and the Rhinestreet (stratigraphic sequence shown in fig 2) show any lithologic change across the study area The Dunkirk and the Pipe Creek show a transition from a grayish- and brownish-black color in the western part of the area to a dark- or medium-gray color in the eastern part These shales are thinner and somewhat less organic farther east where they wedge out The Dunkirk becomes siltier to the east, but the Pipe Creek shows no noticeable change in silt content across the area studied There is no production from either unit in the area of this study

Eastward across the area, the Rhinestreet shows a decline in the total amount of black shale present and an increase in thin interbedded siltstones There is no produc-

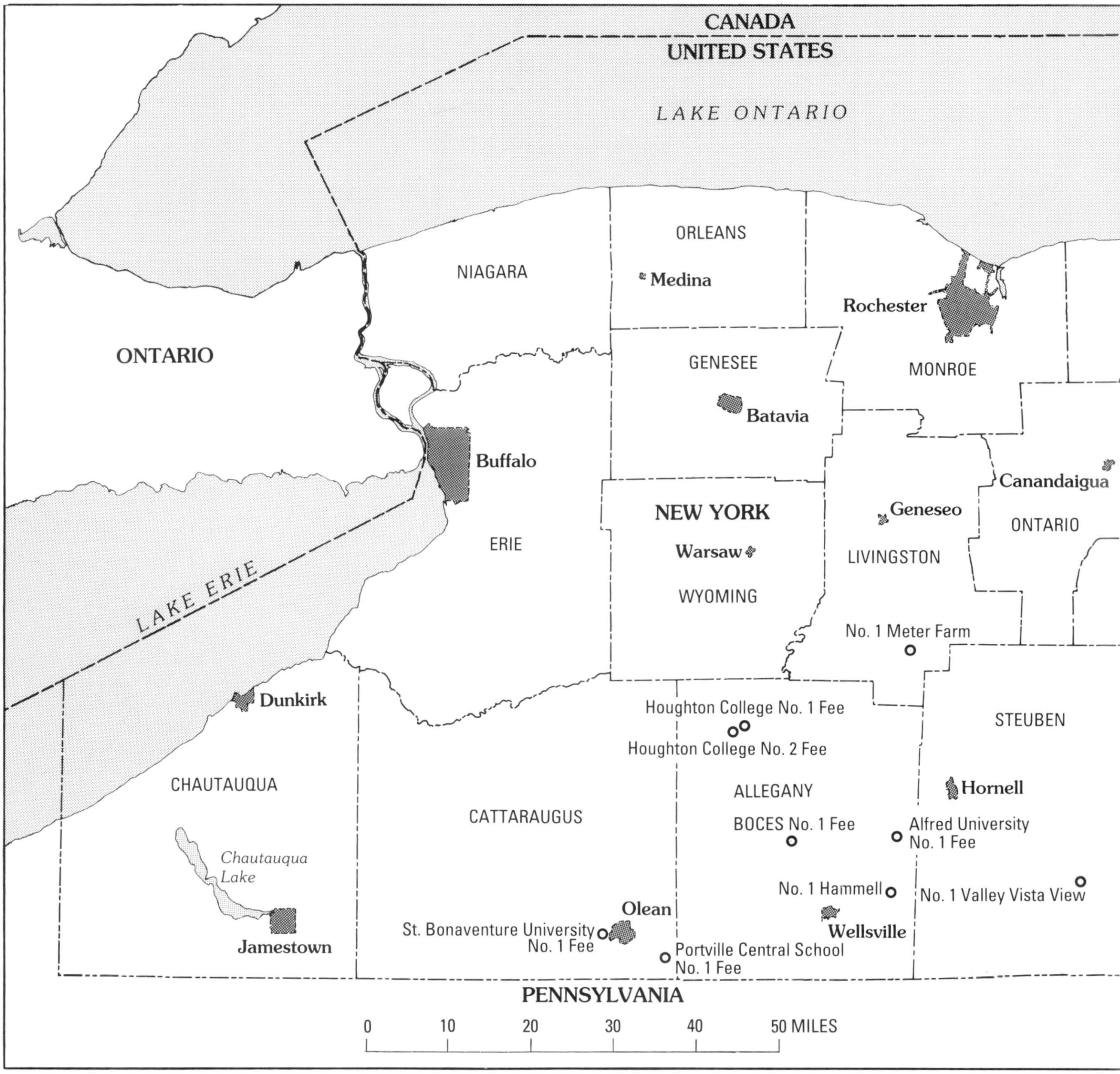

Figure 1. Well locations in Cattaraugus, Allegany, Steuben, and Livingston Counties, N.Y.

tion from the Rhinestreet in the study area. The other black shale units show little or no lithologic change throughout the area of study. There is no evidence in the lithology of the samples to account for any difference in the productive capacity of the wells within the area of this study.

X-RAY DIFFRACTION ANALYSES

Eleven representative samples of 10 shale zones from 7 of the wells (table 2) were analyzed at the New York State College of Ceramics at Alfred University. This was done to identify the mineral content of the shales and the types and amounts of clay minerals present. The analyses were made by using an automated Norelco X-ray diffractometer. The mineral constituents identified and the semiquantitative estimates of the mineral content are given in table 2.

The total amount of illite and mixed-layer clay minerals determined from X-ray analysis is less than 10 percent for each sample. This amount is believed to be too small relative to that found by Hosterman and Whitlow (1983), who determined the illite–mixed-clay content to be 40 to 85 percent in samples from the same shale units in other nearby wells. They stated, "Illite in this report is applied to a dioctahedral muscovite $(OH)_4K_2(Si_6Al_2)(MgFe)_6O_{20}$. It

Table 1. Summary of the lithology of well samples from black shale units across the study area

Black shale unit	Study area		
	Western	Central	Eastern
Dunkirk	Medium to dark gray, brownish gray, and grayish black, occasionally silty with scattered thin siltstone beds, abundant carbonaceous material and plant fragments, fine mica and pyrite	Medium to dark gray, mostly silty and hard, brownish black at base only	Medium to medium dark gray, silty, micaceous
Pipe Creek	Grayish black, silty	Brownish black, silty	Dark gray, silty
Rhinestreet	Scattered brownish black and dark gray to grayish black, interbedded siltstones, abundant carbonaceous material	Brownish gray, medium dark gray to grayish black and black, interbedded siltstones	Medium dark gray to grayish black and black at base, more siltstone
Middlesex	Dark gray to black, soft	Brownish black to black, soft, very calcareous at base	Dark gray to black and brownish gray, hard
Penn Yan	Dark gray to black, brownish black, slightly calcareous	Brownish black, hard	Grayish black to black, hard
Geneseo	Brownish gray, brownish black, grayish black to black, soft, pyritic	do	Brownish black to black, hard
Hamilton			
Ledyard	Dark gray, grayish black, brownish black	Grayish black, brownish black	Grayish black to black with pyrite
Levanna	Dark gray to brownish black and grayish black, hard, calcareous	Brownish black, grayish black to black, calcareous, some thin interbedded limestones	Grayish black to black, calcareous
Marcellus	Black, bituminous, noncalcareous	Black, bituminous, noncalcareous	Black, bituminous, noncalcareous

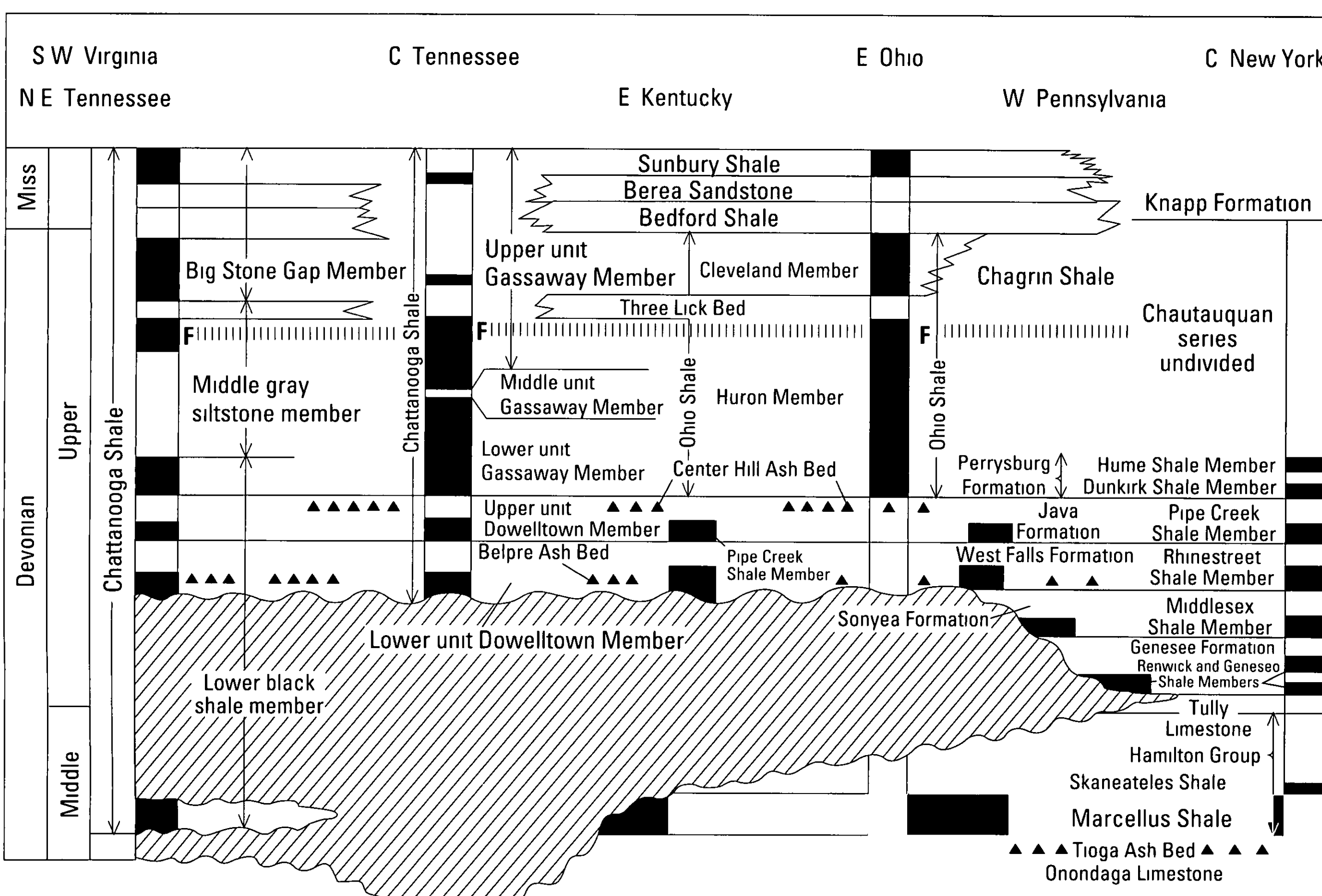

Figure 2. Devonian black shale units in the Appalachian basin (From Roen, 1984)

Table 2. Results of X-ray diffraction analyses of Devonian black shale samples from seven wells in Cattaraugus, Allegany, and Livingston Counties, N Y

[Major, more than 20 percent, large, 10 to 20 percent, small, 3 to 10 percent, very small, less than 3 percent, — not, present]

Well	Shale sampled	Depth (ft)	Quartz	Illite and mixed-layer clays	Muscovite	Chlorite	Calcite	Dolomite	Pyrite	Plagioclase feldspar
St Bonaventure University No 1 Fee	Rhinestreet	2,475–2,500	Major	Small	Small	Small	—	—	Very small	Small
		2,680–2,710	do	do	do	do	—	Very small	do	Do
Portville Central School No 1 Fee	Middlesex	3,400–3,500	do	do	do	Very small	—	do	—	Do
	Geneseo	3,690–3,710	do	Very small	do	do	Large	do	Small	Very small
Houghton College										
No 1 Fee	Marcellus	2,270–2,290	do	Small	do	do	—	—	do	Small
No 2 Fee	Middlesex	1,750–1,780	do	do	Very small	do	Large	—	do	Do
	Geneseo	1,910–1,930	do	do	Small	Small	do	Small	Very small	Very small
Allegany County Board of Cooperative Educational Services No 1 Fee	Middlesex	2,370–2,400	do	do	do	do	—	—	Small	—
Arlington Exploration Company No 1 Meter Farm	do	790– 800	do	do	do	do	—	do	do	Small
	Penn Yan	990–1,040	do	do	do	do	Large	Very small	—	Very small
Alfred University No 1 Fee	Geneseo	3,320–3,360	do	Very small	Very small	do	do	—	Very small	Small

Table 3. Chemical analyses (in wt percent) of Devonian black shale samples from New York

Well	Shale sampled	Depth (ft)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	TiO_2	Na_2O	K_2O	Total organic carbon	Ignition loss[1]
St Bonaventure University												
No 1 Fee	Rhinestreet	2,475–2,500	62 3	16 2	5 4	1 9	0 82	0 64	0 65	4 1	1 7	8 0
		2,680–2,710	62 9	16 8	5 7	2 1	56	68	68	4 3	2 2	7 8
Portville Central School												
No 1 Fee	Middlesex	3,400–3,500	59 7	15 0	5 5	1 9	84	64	68	4 1	2 3	8 5
	Geneseo	3,690–3,710	55 2	12 3	4 4	1 9	5 0	60	55	3 6	5 5	15 7
Houghton College												
No 1 Fee	Marcellus	2,270–2,290	54 1	13 8	6 5	1 7	1 9	64	60	4 1	7 3	16 4
No 2 Fee	Middlesex	1,750–1,780	46 0	9 8	4 2	1 7	16 3	54	45	3 1	3 4	18 5
	Geneseo	1,910–1,930	55 9	12 1	3 9	2 0	7 5	46	43	3 6	4 0	14 9
Allegany County Board of Cooperative Educational Services No 1 Fee	Middlesex	2,370–2,400	60 2	16 1	5 7	2 1	69	70	75	4 2	2 8	8 2
Arlington Exploration Company												
No 1 Meter Farm	do	790–800	60 4	16 0	5 7	2 4	72	60	70	4 4	2 8	8 7
	Penn Yan	990–1,040	52 1	13 4	4 3	2 3	8 5	60	54	4 0	2 4	13 8
Alfred University No 1 Fee	Geneseo	3,320–3,360	56 7	12 5	3 8	1 7	6 3	42	63	3 5	2 5	13 8

[1]Includes total organic carbon

contains approximately 12 percent K_2O, 39 percent Al_2O_3, 45 percent SiO_2, and 5 percent H_2O" (Hosterman and Whitlow, 1983, p 2) It is probable that the muscovite reported by the analyst should be included as illite

No kaolinite was reported from our analyses, although Hosterman and Whitlow (1983) found kaolinite in all but the Middlesex and Marcellus Shales They stated, "The presence of kaolinite in small amounts is extremely difficult to determine when chlorite is present" (Hosterman and Whitlow, 1983, p 5) The chlorite content also appears to be low compared to that found in the study by Hosterman and Whitlow J W Hosterman (U S Geological Survey, oral commun , 1986) examined our data and was of the opinion that not enough clay had been accounted for He believed that much of the SiO_2 should be assigned to the clays He also believed that some of the samples probably contain a little kaolinite and that calcite may be present in a slightly larger quantity than indicated

The suite of minerals found by X-ray diffraction in our samples is similar to that found in other studies of the Devonian black shales in this region The clay minerals are probably present in greater amounts than suggested, this will be discussed further in the following section The finding of mixed-layer clays in these samples is thought to be significant and may have a bearing on the productive potential of black shales The capacity of such clays for taking up water and expanding will be discussed in the section "Discussion of Mixed-Layer Clay Content of Black Shales "

CHEMICAL ANALYSES

Standard wet chemical analyses of samples from the same wells and intervals that had been examined by X-ray diffraction (table 2) were performed at Alfred University to ascertain the detailed chemistry of the shales and to calculate a predicted mineralogy The results are presented in table 3 The TiO_2 present may represent accessory ilmenite or titanite

J W Hosterman (U S Geological survey, oral commun , 1986) believed that, if all the alumina in these analyses were assigned to the clays, then it would take up most of the silica This would increase the clay content substantially from that shown by the X-ray results and, at the same time, would reduce the quartz content Hosterman and Whitlow (1983) showed that illite is the major clay constituent of these Devonian shales Chlorite is present in moderate amounts, and two types of mixed-layer clays are present in small amounts Kaolinite is occasionally present in trace to small amounts

Illite-smectite and illite-chlorite are the two types of mixed-layer clays found by Hosterman and Whitlow (1983) in Devonian black shales of the Appalachian area By using an ethylene glycol treatment, they were able to estimate the individual quantities of the mixed-layer clays and the illite present

J W Hosterman (U S Geological Survey, written commun , 1986) provided a semiquantitative determination of the minerals from samples from the wells studied (table 4) Although his data indicate an increase in the amount of clay minerals present, it still predicts the presence of about twice the amount of quartz found in his original study of shale samples from this area

The chemical analyses (table 3) and the stoichiometric mineralogy (table 4) of the study samples show that a higher level of clay mineral content than that shown by X-ray diffraction (table 2) is probable These data cannot

Table 4. Stoichiometric mineralogy (in percent) of Devonian black shale samples from New York

[tr, trace, —, not present Analyst J W Hosterman (U S Geological Survey, written commun , 1986)]

Well	Shale sampled	Depth (ft)	Illite	Chlorite	Quartz	Kaolinite	Calcite	Pyrite
St Bonaventure University								
No 1 Fee	Rhinestreet	2,475–2,500	38	13	47	2	—	tr
		2,680–2,710	40	14	45	1	—	Do
Portville Central School								
No 1 Fee	Middlesex	3,400–3,500	40	13	47	—	—	Do
	Geneseo	3,690–3,710	30	15	40	—	10	5
Houghton College								
No 1 Fee	Marcellus	2,270–2,290	40	10	40	—	5	5
No 2 Fee	Middlesex	1,750–1,780	32	—	34	—	34	tr
	Geneseo	1,910–1,930	32	14	40	—	14	Do
Allegany County Board of Cooperative Educational Services No 1 Fee	Middlesex	2,370–2,400	40	15	45	—	—	Do
Arlington Exploration Company								
No 1 Meter Farm	do	790–800	40	15	40	—	—	5
	Penn Yan	990–1,040	35	15	35	—	15	—
Alfred University No 1 Fee	Geneseo	3,320–3,360	33	10	45	—	2	—

Table 5. Analyses of the organic content of Marcellus black shales from eight wells in Cattaraugus, Allegany, Livingston, and Steuben Counties, N Y

[TOC, total organic carbon, TAI, thermal alteration index, R_o, vitrinite reflectance More than one value given indicates more than one sample evaluated]

Well	Depth (ft)	TOC (percent by weight)	Type of organic matter in sample	TAI (range)	R_o (percent)
St Bonaventure University					
No 1 Fee	3,600–3,640	4 86, 4 86	Herbaceous, amorphous, woody, some coaly	3– to 3	0 98, 1 19, 1 52
Portville Central School					
No 1 Fee	4,140–4,180	6 29	Herbaceous, woody, amorphous, coaly	3– to 3	1 08, 1 31
Houghton College No 2 Fee	2,380–2,410	6 82	Herbaceous, amorphous	3– to 3	0 55, 98, 1 30, 1 70
Allegany County Board of Cooperative Educational Services No 1 Fee	3,240–3,290	2 54	Herbaceous, amorphous, coaly, some woody	3– to 3	0 74, 1 09, 1 35, 1 89
Alfred University No 1 Fee	3,950–3,960	8 69	Herbaceous, coaly, amorphous, woody	3 to 3+	1 51, 1 79
Joyce Drilling Company					
No 1 Hammell	4,662–4,690	5 20, 5 18	Herbaceous, amorphous, woody-coaly	3 to 3+	1 52, 1 77
Arlington Exploration Company					
No 1 Meter Farm	1,570–1,600	6 7	Herbaceous, amorphous	3– to 3	0 92, 1 70
No 1 Valley Vista View	3,882–3,895	6 07	Herbaceous, coaly, amorphous-woody	3 to 3–	1 36, 1 63, 1 95

define the presence of mixed-layer clays The chemical characteristics of these shales therefore show no apparent relation to their productive potential

ORGANIC-CARBON-KEROGEN ANALYSES

Samples of the Marcellus Shale from eight of the wells were sent to the Mound Facility of Monsanto Research Corporation at Miamisburg, Ohio, to determine the potential for hydrocarbon production The analyses conducted were as follows total organic carbon (TOC), thermal alteration index (TAI), and vitrinite reflectance (R_o) values The information derived from these tests, including the organic matter description, is shown in table 5

All the samples show a relatively high TOC The TAI's show a small gradual increase from west to east and reveal that the Marcellus, in all cases, has undergone thermal alteration sufficient to convert organic carbon to gases and light hydrocarbon liquids The R_o values support the results of the TAI's

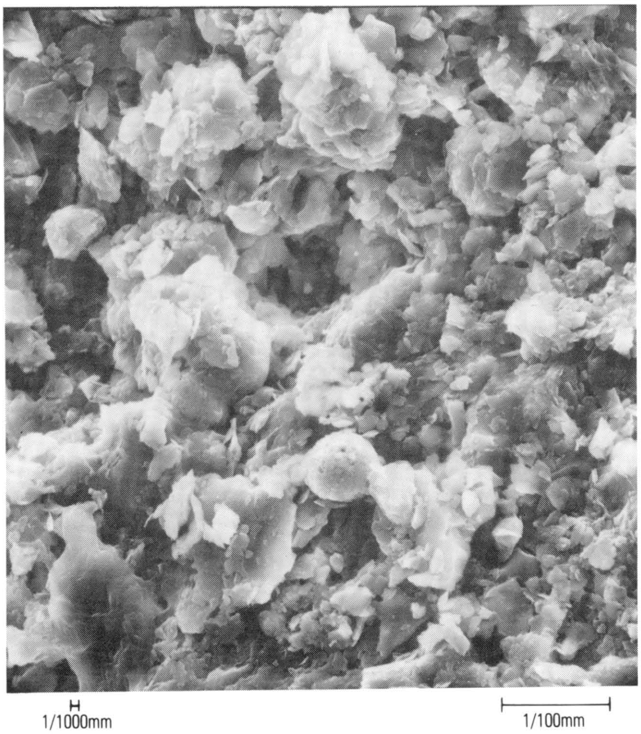

Figure 3. Rhinestreet Shale from the St. Bonaventure University No. 1 Fee, Cattaraugus County, N.Y., depth 2,488 ft, ×1,500. Flakes show a jumbled packing. Larger opening in center is about 0.006 mm in size, smaller pores are 0.002 to 0.004 mm in size, spherule is 0.006 mm in diameter.

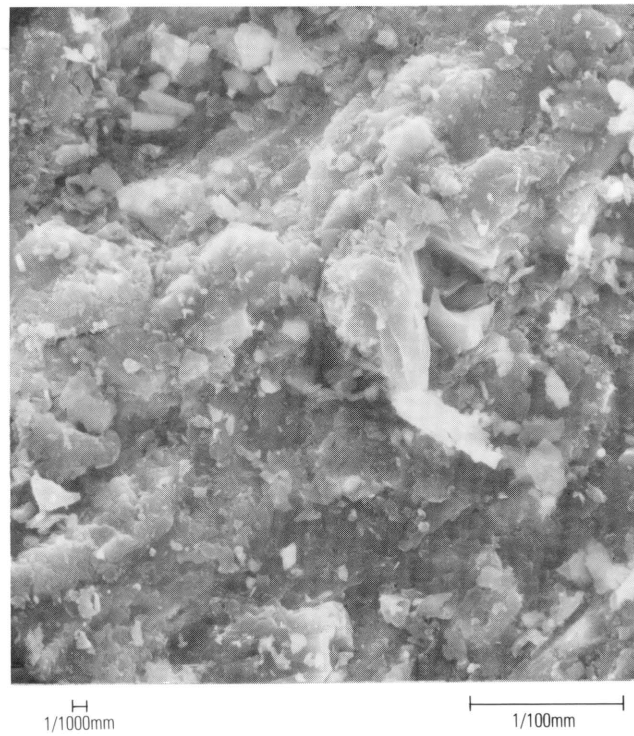

Figure 4. Rhinestreet Shale from the St. Bonaventure University No. 1 Fee, Cattaraugus County, N.Y., depth 2,695 ft, ×2,000. The matrix is very tightly packed. The few pores visible are in 0.001-mm or less size range.

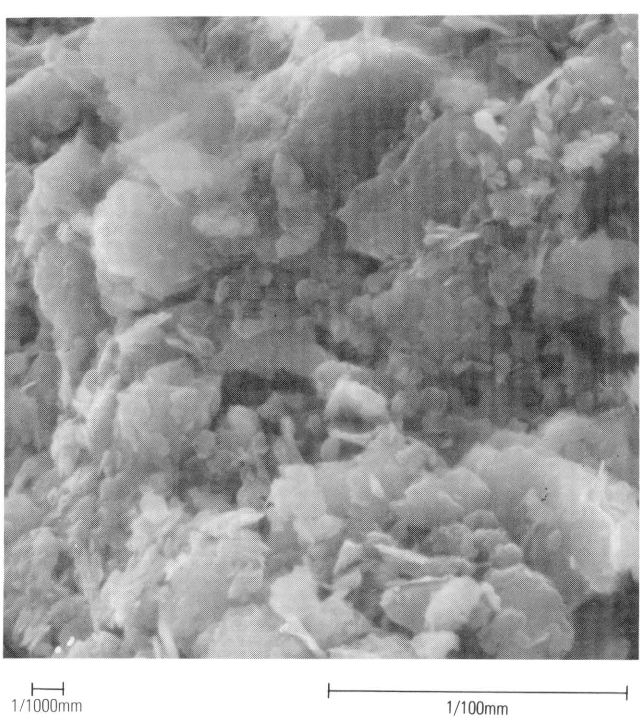

Figure 5. Middlesex Shale from the Houghton College No. 2 Fee, Allegany County, N.Y., depth 1,765 ft, ×4,000. Flakes show tight packing. Visible pores are 0.001 mm or less in size.

The various analyses of the organic content of these Marcellus Shale samples are quite similar. Although the analyses indicate that the Marcellus could generate gas, they do not appear to have any relation to the productive capacity of the shale.

SCANNING ELECTRON MICROSCOPE STUDIES

Because only a limited amount of scanning electron microscope (SEM) work has been done on black shale specimens, a program to study cuttings was undertaken. Of particular interest has been the detailed internal structure and the development of porosity.

Eighteen shale samples from 5 stratigraphic zones in 7 wells were prepared and examined by using an SEM at the New York State College of Ceramics at Alfred University. One to three shale chips were used from each sample. The chips were examined under low magnification to look for unusual features that might be present and also to find a suitable area that would represent the average appearance of the specimen. Polaroid photographs[2] were taken of each sample (figs. 3–22).

[2] The photographs are presented in stratigraphic order from youngest to oldest and in a west to east direction similar to the other data presented in this chapter.

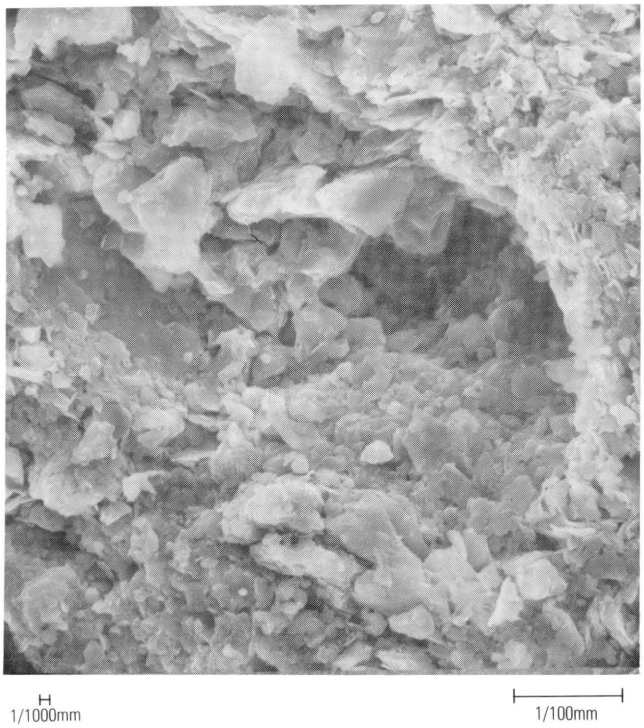

Figure 6. Middlesex Shale from the Portville Central School No. 1 Fee, Cattaraugus County, N.Y., depth 3,450 ft, ×1,500. The larger pore opening is about 0.02 mm in size; the smaller pore openings (dark) are 0.001 to 0.002 mm in size. Densely packed material visible at center left.

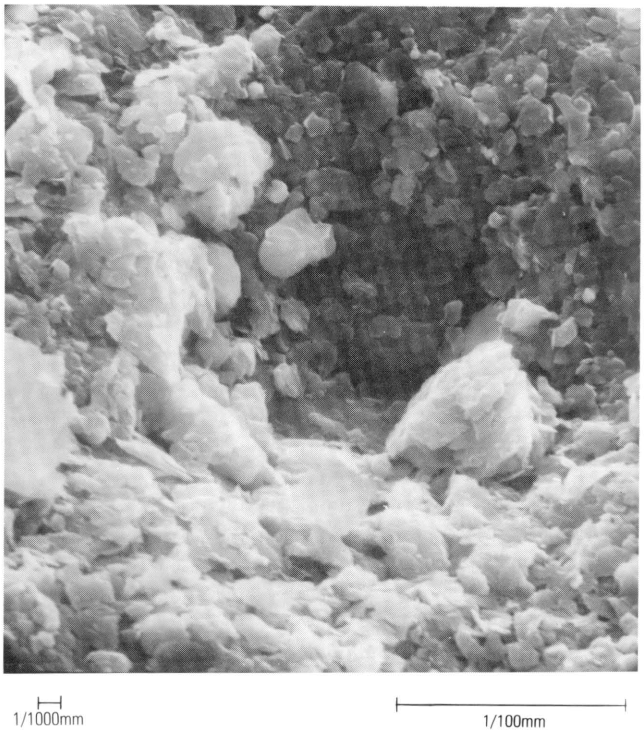

Figure 7. Middlesex Shale from the Allegany County Board of Cooperative Educational Services No. 1 Fee, depth 2,385 ft, ×3,000. The large opening in the center is smaller than 0.01 mm; the visible pores are about 0.001 mm or less in size. The light material is surficial debris. The darker flakes in the background average 0.015 mm in size.

The overall impression given by the SEM examination is one of exceedingly tight and interleaved packing of the clay and organic particles and occasional pores extending through this packing. The pore sizes are mostly 0.001 millimeter (mm) or smaller. Occasional pores and openings are larger but only rarely reach 0.01 mm in size.

The Marcellus appears to be characterized by a more random packing, possibly caused by the higher organic content of this shale, and by a larger number of pores than shown by the other shales. These pores are of the 0.001-mm size, but they could provide the entrapped gases a pathway for escape. The pores may have been formed by escaping gas during early diagenesis. The pores could bleed off indigenous gas into the natural fracture systems that might be present in some areas. Such fractures would form a reservoir for shale gas. The presence of these pores may be one of the reasons for the known productive potential of the Marcellus.

TRACE-ELEMENT STUDY

Studies have shown that vanadium and nickel are the most abundant trace elements (metals) found in crude oils (Tissot and Welte, 1978, p. 363). Because lighter fraction hydrocarbon liquids and black shale gas often are produced together in New York, it was decided to test several of the black shale samples for the possible presence of vanadium and nickel. Although the data base is minimal, it was examined to see if any regional trend of vanadium and nickel content might exist. Six well samples from the Geneseo and the Marcellus Shales were analyzed by standard atomic absorption spectroscopy methods at the New York State College of Ceramics; the results are shown in table 6.

Leventhal (1978), who investigated the concentrations of various trace elements in eastern Devonian black shales, reported an average concentration of 99 parts per million (ppm) nickel and 214 ppm vanadium in black shales from a core taken in a well in north-central Cattaraugus County. Because that core terminated in the Rhinestreet, the black shales he tested were in the Dunkirk, Pipe Creek, and Rhinestreet sections. Leventhal also gave data for concentrations of these elements in 121 Devonian black shale samples from six Eastern States in the Appalachian basin. The average of the values given for these samples is 114 ppm nickel and 242 ppm vanadium. No attempt has been made to relate these values to productive capacity.

Tests of samples (provided by the Mound Facility of Monsanto Research Corporation) from a black shale well drilled at Bath in central Steuben County, 25 miles northeast of the town of Alfred, show amounts ranging from 107

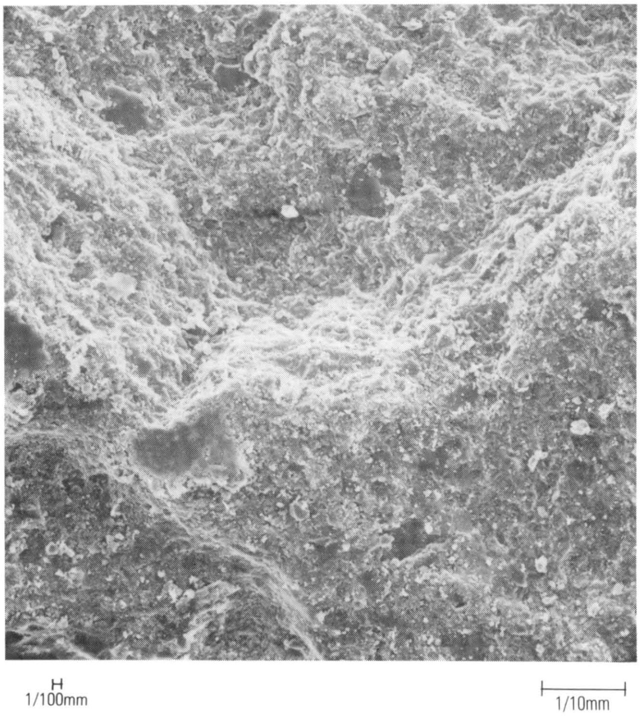

Figure 8. Middlesex Shale from the Arlington Exploration Company No. 1 Meter Farm, Livingston County, N.Y., depth 795 ft, ×150. The tightly packed structure of the shale is shown. This chip had a fair scattering of pores and pits; some are shown here. The pores are 0.02 to 0.03 mm in size, but they appear to be shallow.

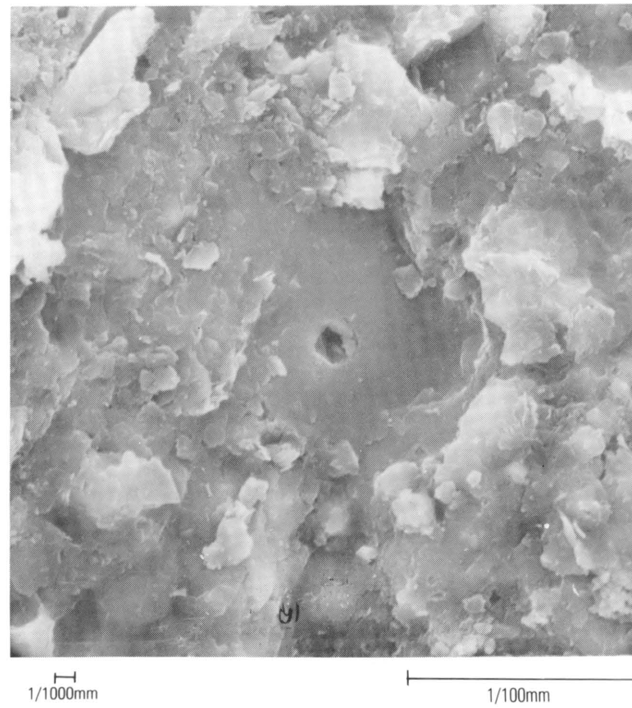

Figure 9. Penn Yan Shale from the Arlington Exploration Company No. 1 Meter Farm, Livingston County, N.Y., depth 1,015 ft, ×3,000. The tightly packed shale matrix material is shown. The pore in the center is 0.001 mm in size.

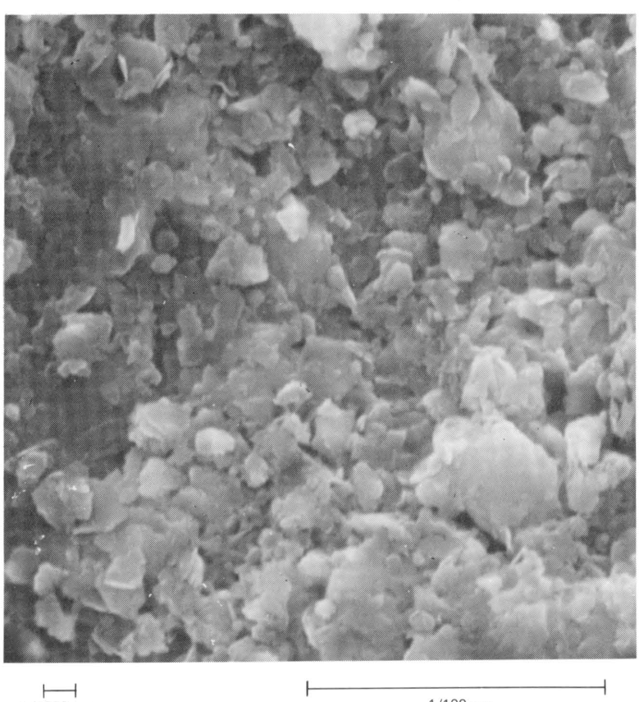

Figure 10. Geneseo Shale from the Houghton College No. 2 Fee, Allegany County, N.Y., depth 1,920 ft, ×4,000. Very tight packing is shown. The visible pores are 0.0005 mm or less in size.

Figure 11 Geneseo Shale from the Portville Central School No. 1 Fee, Cattaraugus County, N.Y., depth 3,700 ft, ×2,000. The lighter flakes are surficial debris, and the darker background is tightly packed matrix. The visible pores are 0.001 mm or less in size.

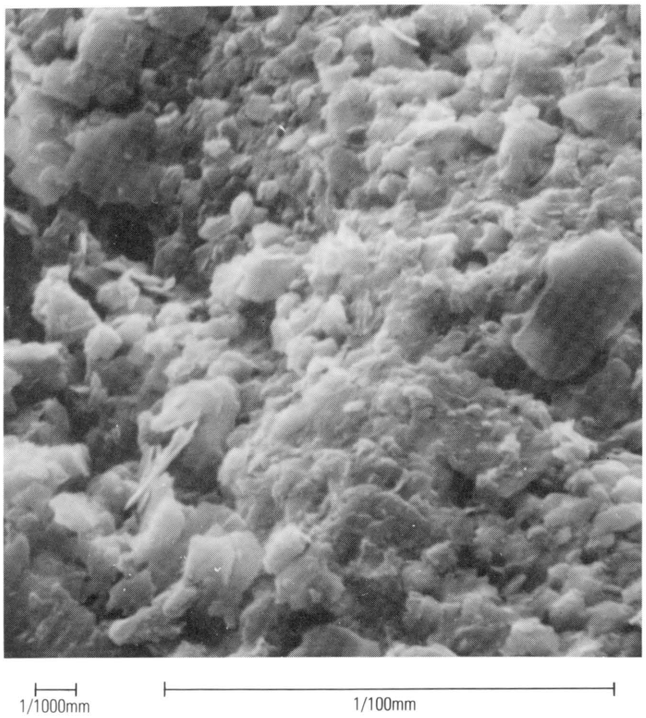

Figure 12. Geneseo Shale from the Alfred University No. 1 Fee, Allegany County, N.Y., depth 3,340 ft, ×6,000. The somewhat jumbled packing is tight. The pore throat just above center left is a little less than 0.001 mm in size; other pores are 0.0005 to 0.0003 mm in size.

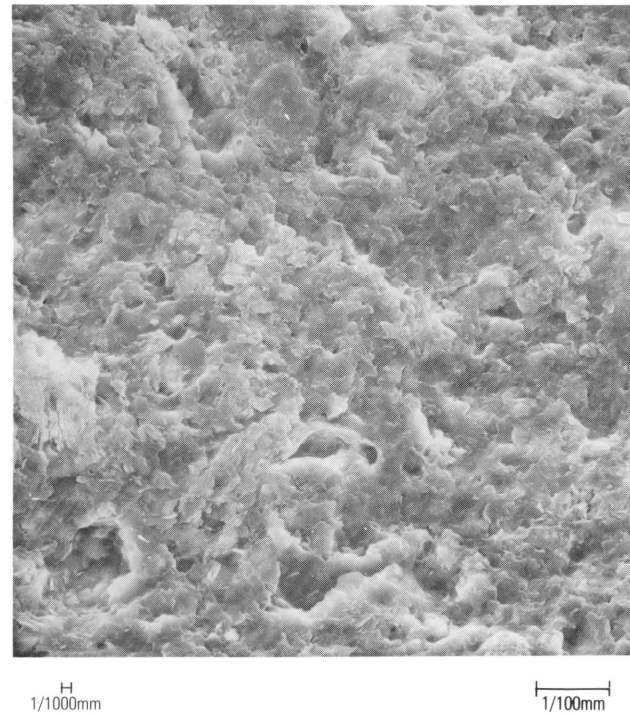

Figure 13. Marcellus Shale from the St. Bonaventure University No. 1 Fee, Cattaraugus County, N.Y., depth 3,635 ft, ×1,000. Many pores and somewhat jumbled packing are shown.

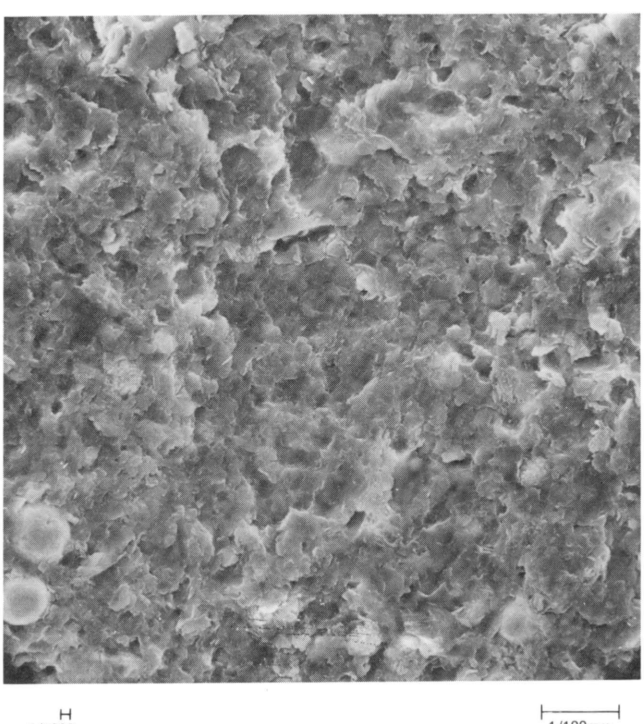

Figure 14. Marcellus Shale from the St. Bonaventure University No. 1 Fee, Cattaraugus County, N.Y., depth 3,635 ft, ×1,000. Numerous pores and pits are shown.

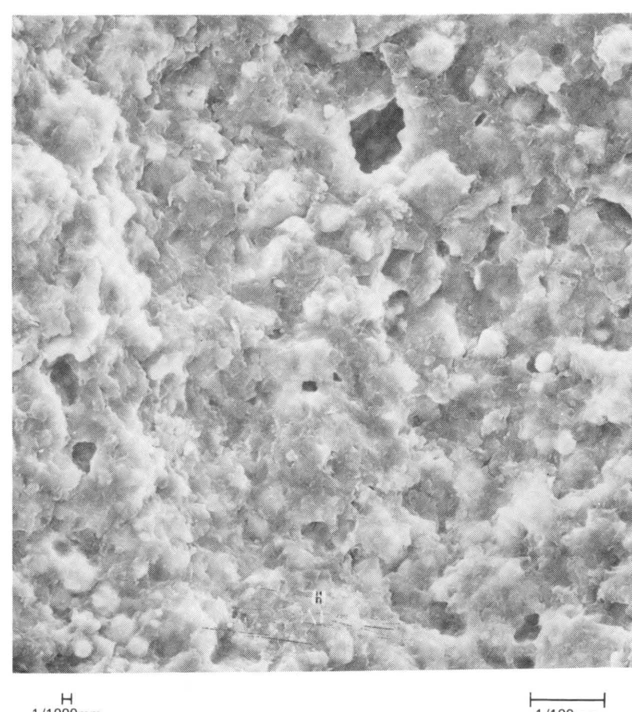

Figure 15. Marcellus Shale from the Houghton College No. 2 Fee, Allegany County, N.Y., depth 2,395 ft, ×1,000. Several pores, which are scattered over the surface, vary in size from 0.001 to 0.003 mm; the larger pore at top measures 0.01×0.005 mm.

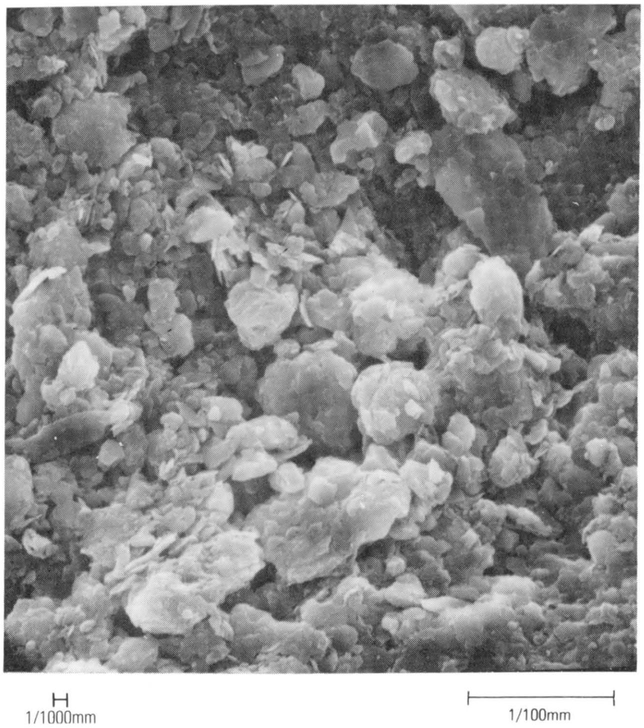

Figure 16. Marcellus Shale from the Houghton College No. 1 Fee, Allegany County, N.Y., depth 2,280 ft, ×2,000. Somewhat more jumbled particle packing and several pore throats are shown. The opening in the upper right corner is about 0.006 mm long.

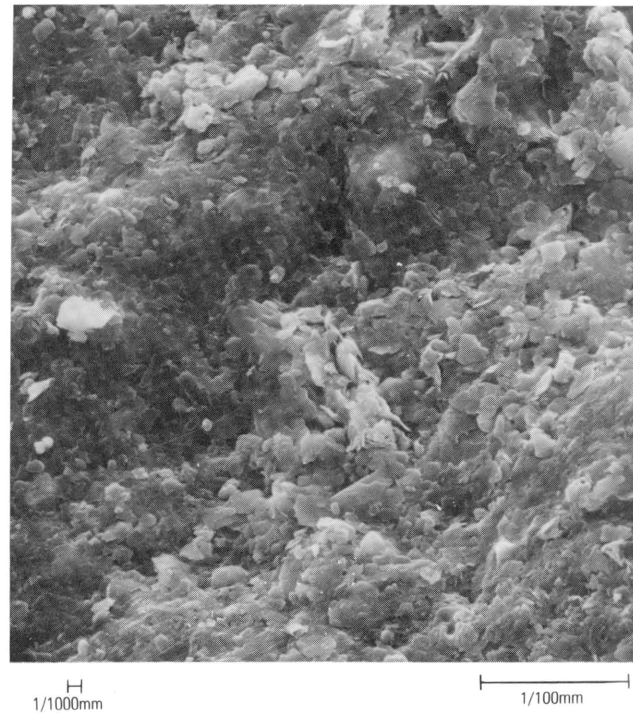

Figure 17. Marcellus Shale from the Houghton College No. 1 Fee, Allegany County, N.Y., depth 2,280 ft, ×2,000. The packing is dense, but numerous scattered pores are present. Pores range from 0.001 to 0.0005 mm in size.

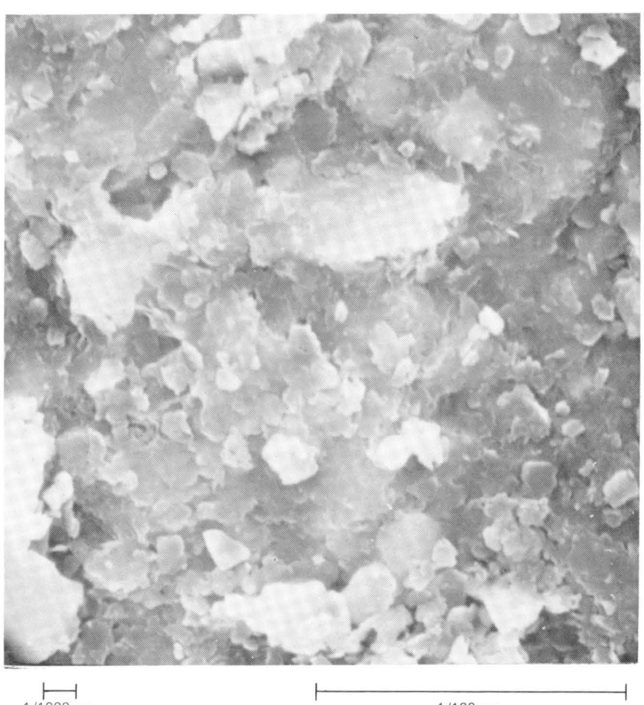

Figure 18. Marcellus Shale from the Portville Central School No. 1 Fee, Cattaraugus County, N.Y., depth 4,175 ft, ×4,000. Very tight packing is shown. The pores are much less than 0.001 mm in size.

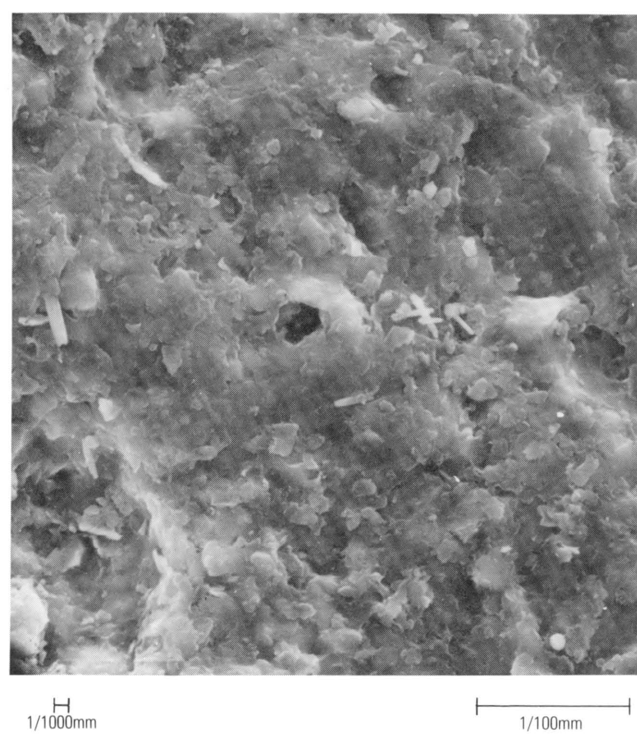

Figure 19. Marcellus Shale from the Allegany County Board of Cooperative Educational Services No. 1 Fee, depth 3,275 ft, ×2,000. The packing is exceedingly tight. The pore in the center is 0.002 mm in size.

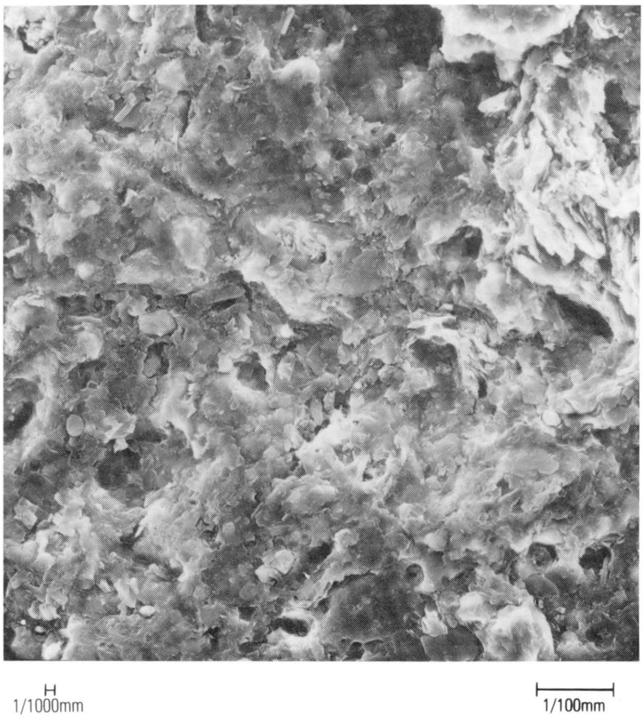

Figure 20. Marcellus Shale from the Arlington Exploration Company No. 1 Meter Farm, Livingston County, N.Y., depth 1,595 ft, ×1,000. Many pores are shown. The largest pore (at the top) is 0.005 mm in size.

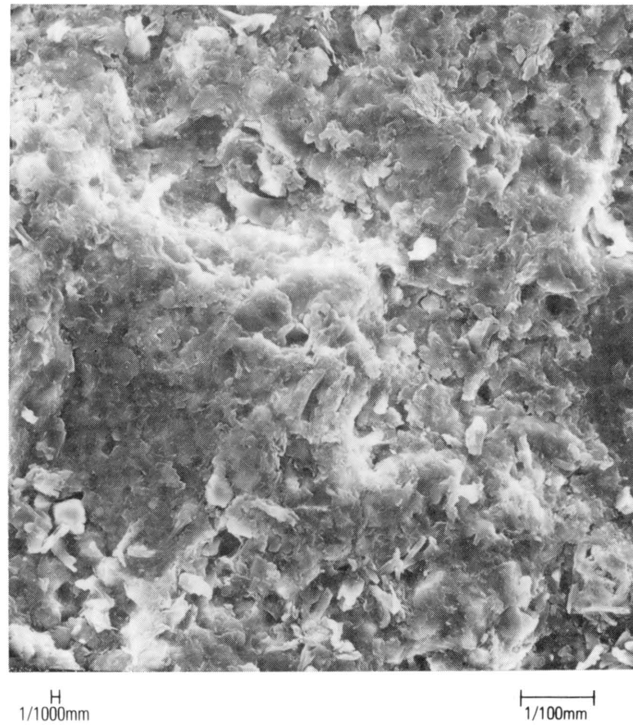

Figure 21. Marcellus Shale from the Arlington Exploration Company No. 1 Meter Farm, Livingston County, N.Y., depth 1,595 ft, ×1,000. Numerous pores and pits are shown.

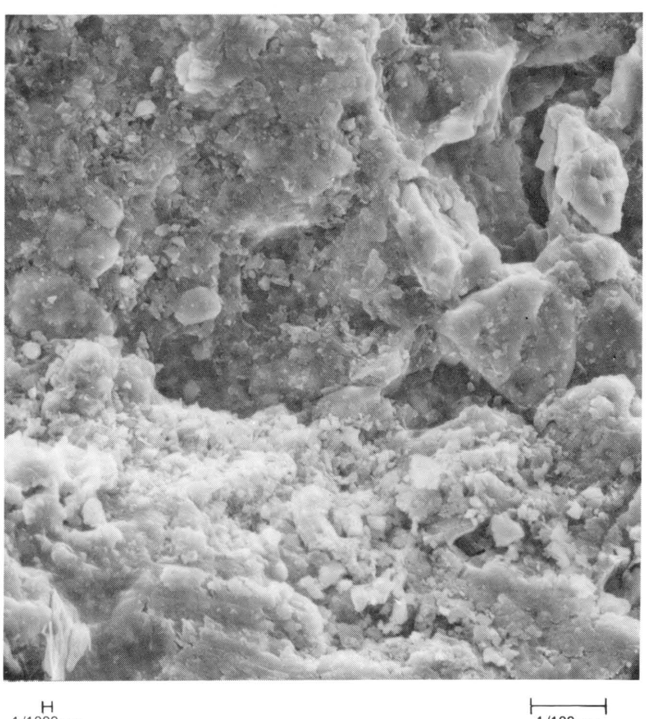

Figure 22. Marcellus Shale from the Alfred University No. 1 Fee, Allegany County, N.Y., depth 3,955 ft, ×1,000. Packing on a broken surface is shown. Several pores and pits are visible.

to 219 ppm (average, 175 ppm) nickel and from 292 to 358 ppm (average, 329 ppm) vanadium in five selected samples from the Marcellus. The average TOC for those samples is 6.43 percent.

Of the six wells tested for this study, four were tested for nickel and vanadium in the Marcellus (table 6). The average nickel content (145 ppm) is about the same as that reported for the Bath well. This is also reasonably close to the above-mentioned average of 114 ppm nickel for 121 Devonian black shale samples reported by Leventhal (1978). However, the average vanadium content (111 ppm) is considerably lower than that reported for the Bath well samples. This is less than half of the 121-sample average of 242 ppm vanadium reported by Leventhal (1978). The reason for the comparatively lower vanadium content in these four wells is not readily apparent.

Without information from a statistically significant number of tests for these trace metals in other black shale wells in western New York, one cannot be sure of the meaning of these results. In this study, the greatest nickel and vanadium concentrations were found in samples from the Geneseo and Marcellus Shales in the Houghton College No. 1 Fee and the Alfred University No. 1 Fee. The Houghton College No. 1 Fee had the highest reported values for nickel and vanadium in the Marcellus. It is suggested that this may be related to the liquid hydrocarbons produced by that well. Several gallons of high-fraction

Table 6. Nickel, vanadium, and total organic carbon in selected Devonian black shale samples in New York
[—, not analyzed Analyst R A Condrate, New York State College of Ceramics, Alfred University]

Well	Formation	Sample depth (ft)	Nickel (ppm)	Vanadium (ppm)	Total organic carbon (percent)
St Bonaventure University No 1 Fee	Geneseo	3,210–3,230	100	140	2 9
	Marcellus	3,625–3,648	110	85	4 86
Portville Central School No 1 Fee	Geneseo	3,680–3,700	126	140	[1]5 5
	Marcellus	4,140–4,170	—	—	6 29
Allegany County Board of Cooperative Educational Services No 1 Fee	Geneseo	2,700–2,730	94	120	1 8
	Marcellus	3,252–3,290	90	65	2 54
Houghton College No 1 Fee	Geneseo	—	—	—	—
	Marcellus	2,270–2,290	230	190	[1]7 3
No 2 Fee	Geneseo	1,912–1,930	156	210	[1]4 0
	Marcellus	2,380–2,410	150	105	6 82
Alfred University No 1 Fee	Geneseo	3,325–3,360	160	280	7 9
	Marcellus	3,950–3,960	—	—	8 69

[1] From table 3

hydrocarbon fluid were separated from the gas stream daily during the early phases of its production Vanadium and nickel became complexed to porphyrin during the early stages of alteration of organic debris into petroleum hydrocarbons (Hunt, 1979, p 485) This imprint is carried with the hydrocarbon during further maturation and accounts for the higher concentrations of vanadium and nickel found in crude oils as compared to other trace elements If, as it appears, there is a higher than normal percentage of liquid hydrocarbon present in the matrix of the Marcellus tested from the Houghton College No 1 Fee, then the vanadium and the nickel contents also might be higher

DISCUSSION OF MIXED-LAYER CLAY CONTENT OF BLACK SHALES

Analyses show that the major clay types present in the black shales in the study area are illite, mixed-layer clays, and chlorite As discussed in the section "Chemical Analyses," these are the same clays found by Hosterman and Whitlow (1983) in their broader study of Devonian shales Although the Alfred University analyses showed mixed-layer illite-smectite (montmorillonite) to be present in the 3- to 10-percent or less range in the samples studied, Hosterman and Whitlow (1983) found that mixed-layer illite-smectite constitutes 5 to 30 percent of their shale samples

The smectite clays are sometimes termed "swelling" clays, which means that they can take up water into their crystal structure and expand The water molecules are adsorped onto the electrically charged surface of the loosely bound clay sheets According to Hunt (1979, p 203), a smectite particle has an internal surface area about eight times as large as its external surface area and many times larger than the surface areas of such nonswelling clays as illite This characteristic of smectites can be a source of trouble if they are present in even small to moderate amounts in rocks that must be fracture treated with water-sand slurries to enhance oil or gas production The large amounts of water introduced into the formation can cause swelling of these clays, which will block off flow channels and decrease the permeability of the rock In addition, these clays tend to break down and crumble after absorbing water, and the resulting fine particles are flushed into the pores and tend to block off possible flow channels

The presence of "swelling" clay in the rock matrix presents a definite problem that should be considered when designing a fracture-treatment procedure for black shale wells According to Barnes (1982), the presence of smectite in the Dunkirk Shale in an Erie County, Pa , well that was treated with a water fracture may have been the cause of a drastic reduction in gas flow and eventual failure of the well With this in mind, it would appear to be of great importance to design stimulation treatments that use either little or no water or specially treated water for enhancing gas production from shale wells These treatments would include high foam content or compressed gas fracture and the use of water treated with organic polymers, alcohols, or other agents that can prevent the smectites from swelling

GAS PRODUCTION

The Marcellus section was fracture treated in eight of the wells studied, and the wells were placed on production, the Joyce Drilling Company No 1 Hammell was not treated or produced Only two of the wells, the Houghton College No 1 Fee and the Alfred University No 1 Fee, have produced any appreciable amount of shale gas (table 7) The other six wells have been uneconomic producers Nothing

Table 7. Gas production from Devonian black shale wells in Cattaraugus, Allegany, Livingston, and Steuben Counties, N Y

Well	Date production commenced (mo /yr)	Gross gas production reported through 1986 (MCF)	Status
Alfred University No 1 Fee	3/82	18,346	Shale plugged off, drilled deeper to the Oriskany in 1986
Allegany County Board of Cooperative Educational Services No 1 Fee	12/81	4,135	Producing
Houghton College			
No 1 Fee	11/80	24,750	Do
No 2 Fee	12/81	788	Plugged and abandoned
Portville Central School No 1 Fee	1/82	1,130	Do
St Bonaventure University No 1 Fee	12/81	2,592	Do
Arlington Exploration Company			
No 1 Meter Farm	4/81	4,914	Turned over to the farmer
No 1 Valley Vista View	5/81	3,453	Do

found in this study would appear to indicate why these particular wells are better gas producers than the others Either more natural fractures are present in the areas where these two wells were drilled or else the difference in their productive potential must be related to possible differences in completion techniques

The eight wells were treated with a foam fracture that used roughly the same amounts of sand, water, and nitrogen If there were less of the mixed-layer "swelling" clays in the shale matrix in the immediate area where the two best wells were drilled, then the artificially induced fractures would tend to stay more open than they might in areas where these clays are present in greater amounts In this study, the quantity and distribution of the "swelling" clays present, which were based on a limited number of samples, could not be defined on a regional basis to make this judgment

It is of interest to note the locations of the two good wells in relation to local geologic structure The Houghton College No 1 Fee is located on a joint and lineament trend that parallels the Genesee River This could well be an area of significant joint-related fracturing that resulted from postglacial rebound The Alfred University No 1 Fee is located on a prominent faulted anticlinal trend, which could be the site of significant fold and fault-related fracturing

SUMMARY

Physical and chemical characteristics of Devonian shale cuttings from nine wells drilled for natural gas in western New York were studied in an effort to relate gas production to these characteristics Various attributes of the Dunkirk, Pipe Creek, Rhinestreet, Middlesex, Penn Yan, Geneseo, and Marcellus were examined A detailed examination of sample lithology did not reveal any evidence that suggested any possible difference in the potential capacity of the nine wells to produce gas from the black shales within the area of this study

X-ray diffraction analyses (table 2) show that quartz, illite and mixed-layer clays, chlorite, calcite, dolomite, pyrite, and plagioclase feldspar are the principal minerals present in the shales An accessory titanium mineral also is present Chemical analyses confirm this mineral suite and also indicate that the clays are likely to be present in greater amounts than shown by the X-ray diffraction analyses

Mixed-layer illite-smectite clay present in these shales can expand if it comes in contact with water This can occur during a hydraulic fracture treatment to enhance gas production Clay expansion, as well as the numerous fine particles created by the disintegration of the clay, could block any flow channels created and decrease the permeability of the rock Fracture treatments used for enhancing gas production from Devonian black shale wells should be designed to use either little or no water or specially treated water

Organic-carbon-kerogen analyses of the Marcellus Shale reveal essentially herbaceous, amorphous, woody, and (or) coaly material The TAI range varies between 3− and 3+, and the mean vitrinite reflectance ranges from 0 55 to 1 95 percent These ranges indicate that the Marcellus has undergone sufficient thermal alteration to convert organic carbon to the gas and light hydrocarbon liquid phase These values exhibit a small increase from west to east across the study area TOC ranges from 2 54 to 8 69 percent All these values are quite similar within the study area and do not appear to relate to any possible differences in the productive capacity of the wells tested

SEM studies show that the clays in these shales are tightly packed and interleaved Occasional pores of 0 001 mm or less in size are present, it is rare that pores are as large as 0 01 mm in size The Marcellus appears to have more pores, which may partly account for its known productive potential

Samples were tested for the trace elements vanadium and nickel No consistent pattern of content was discerned that could be related to gas production or organic matter content

Only two of the wells studied, the Houghton College No 1 Fee and the Alfred University No 1 Fee, have produced appreciable amounts of gas The others have been uneconomic In this study of the lithologic, geochemical, and physical characteristics of black shales, no evidence was found that would indicate why these two wells should be better gas producers than the others

The uniformity of these characteristics of Devonian black shales in wells of the study area and the absence of specific anomalies associated with strata of the two productive wells indicate that the characteristics studied here are not critical to economically exploitable volumes of gas in western New York Instead, the data indirectly support the long-held contention that an extensive interconnected natural fracture system is essential to the economic production of natural gas from the Devonian black shales

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Chapter N

Estimates of Unconventional Natural Gas Resources of the Devonian Shales of the Appalachian Basin

By RONALD R. CHARPENTIER, WALLACE de WITT, JR., GEORGE E. CLAYPOOL, LEONARD D. HARRIS, RICHARD F. MAST, JOSEPH D. MEGEATH, JOHN B. ROEN, and JAMES W. SCHMOKER

U.S. GEOLOGICAL SURVEY BULLETIN 1909

PETROLEUM GEOLOGY OF THE DEVONIAN AND MISSISSIPPIAN BLACK SHALE OF EASTERN NORTH AMERICA

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Estimates of Unconventional Natural Gas Resources of the Devonian Shales of the Appalachian Basin

By Ronald R. Charpentier, Wallace de Witt, Jr., George E. Claypool, Leonard D. Harris,[1] Richard F. Mast, Joseph D. Megeath, John B. Roen, *and* James W. Schmoker

Abstract

The Devonian shales of the Appalachian basin are estimated to contain between 577 and 1,131 trillion cubic feet of in-place natural gas Recoverable amounts would be considerably lower In this study, the Appalachian basin was divided into 19 subareas, and a quantitative assessment of gas resources was made for each subarea by a play analysis method based on stratigraphic information and data from core off-gassing experiments Recoverability of the gas, which is primarily dependent on the nature of the fracture system in an area, was qualitatively assessed for each area

INTRODUCTION

The organic-rich Devonian shales of the Eastern United States are a potentially important unconventional source of natural gas To define, assess, and stimulate development of this resource, the U S Department of Energy initiated the Eastern Gas Shales Project As part of this program, this report presents an assessment of the in-place natural gas resources from Devonian shales of the Appalachian basin

Acknowledgments

The authors wish to thank Betty M Miller and Robert A Crovelli for comments and suggestions related to the assessment methodology The late John W Hosterman and the late Frank W Stead provided data and helpful comments Thaddeus S Dyman assisted in computerized data retrieval

GEOLOGIC SETTING

The Devonian gas shales, which constitute a sequence of predominantly Middle to Late Devonian age and are black, dark-brown, and dark-gray shaly rocks rich in organic matter, underlie most of the Appalachian basin Along the northern edge of the basin, the shale sequence is exposed at many localities from Albany, N Y , to Norwalk, Ohio, particularly along the southern shore of Lake Erie, as well as along the eastern flank of the Cincinnati arch from Norwalk southward to Pickwick Dam in Hardin County, Tenn The shale sequence dips to the east and south into the basin and is more than 12,000 feet (ft) below sea level near the anthracite fields of eastern Pennsylvania in the deeper part of the Appalachian basin On the eastern side of the basin, some of the shales, particularly those of Middle Devonian age, are well exposed in folds in the Valley and Ridge province from southeastern New York to southwestern Virginia To the southwest, in Tennessee, Georgia, and Alabama, dark, organic-rich Upper Devonian shales crop out at numerous localities in the Valley and Ridge province and in the Cumberland Plateau segment of the Appalachian Plateaus

The Devonian gas shale sequence underlies more than 160,000 square miles of the Appalachian Plateaus segment of the Appalachian basin and has a volume in excess of 12,600 cubic miles Surface and subsurface data are insufficient to determine accurately the area and thickness of the gas shale sequence in the structurally complex Valley and Ridge segment of the basin The thickness of the gas shale sequence varies considerably in the Appalachian basin as the result of (1) lateral and vertical interfingering of the dark shales rich in organic detritus and gray shale, siltstone, and mudrock low in organic matter, (2) depositional thinning of shale away from source areas or local centers of accumulation, (3) faulting, subsidence, and tectonic warping during deposition of the shaly sequence, and (4) extensive erosion of part of the sequence in the western part of the basin Thickness of the Devonian black shale facies ranges from zero in parts of Alabama, Tennessee, and Georgia to more than 1,400 ft in northeastern Pennsylvania (de Witt and others, 1975)

Recent stratigraphic studies show that the gas shale sequence contains several regionally extensive units of

Manuscript approved for publication September 13, 1989

[1] Deceased

black shale, each of which has a discrete depocenter Some units of black shale may contain several local areas of thick shale within a thinner, widespread sheet of black and dark-brown shale In general, the black shales interfinger to the east with eastward-thickening tongues of light-gray shale, mudrock, and turbidite siltstone (For an explanation of the paleogeographic and paleotectonic settings, see Ettensohn and Barron, 1981)

The Middle and Upper Devonian gas shales are dark, tough, laminar-bedded rocks Alternating light and dark laminae are commonly a few hundredths of an inch thick and have great lateral continuity The dark Devonian shales may contain as much as 20 percent organic detritus by volume, which is the source of the gas in the shale sequence In addition to the organic matter, the shales are composed mostly of clay minerals and clay- and silt-sized detrital silica Illite is the principal clay mineral present, whereas mixed-layer expandable clays, chlorite, and kaolinite occur locally (Hosterman and Whitlow, 1981b) Mixed-layer illite-smectite occurs sparingly in some of the thin ash-fall beds intercalated in the shale sequence Calcite and dolomite occur as concretions and nodules or in thin layers, beds, and laminae Pyrite, which is ubiquitous, occurs as euhedral crystals, masses of crystals, nodules, framboids, laminae, or replaced fossils, locally, pyrite may make up as much as 10 percent of the shale by weight A number of metallic elements, including barium, cadmium, calcium, cobalt, copper, lead, manganese, mercury, molybdenum, nickel, potassium, thorium, titanium, uranium, vanadium, and zinc, are present in trace amounts Of the trace elements, uranium is of special interest because it generally is associated with the organic matter of the gas shales, and its radioactive response on the gamma-ray log aids in mapping the extent and thickness of the gas shales Although relatively widely dispersed in amounts ranging from 5 to 100 parts per million, the quantity of uranium present in the Devonian gas shales makes up the country's largest low-grade uranium resource

Generally, the darker laminae contain a greater amount of organic matter and less detrital silica In contrast, the lighter colored laminae contain much clay and silica but little or no organic matter In addition to the laminae, the gas shales commonly show a crude cyclic layering in 0 5- to 4-ft intervals that are marked by differences in color and resistance to erosion The tough black shales weather in relief, whereas the lighter brown shales form reentrants between the more resistant black beds

The freshly exposed, unweathered rock of the shale sequence appears massive, although some lighter gray laminae or partings may suggest the shaly nature of the strata The rock is tough and weathers slowly to thin, sharp-edged, discoidal chips that commonly are stained reddish brown by iron oxides produced by the weathering of pyrite The black and brown shales of the shale sequence are commonly more resistant to weathering than the associated light-gray shale and mudrock At many places where the rocks are nearly horizontal, black shales cap small waterfalls or crop out as cliffs in gullies, gorges, glens, or canyons

The rocks of the black Devonian shale sequence do not contain typical clastic-reservoir strata that have abundant intergranular porosity The shales are tight rocks of very low permeability (0 005 millidarcy to less than 1 microdarcy) and low porosity (1–3 percent) Locally, siltstone and very fine grained quartzose sandstones are intercalated in the shaly sequence, however, these beds also have low porosity values that are comparable to those of the black shales The thin, brittle nature of the siltstones and sandstones relative to the enclosing organic-rich shales facilitates fracturing during tectonic stress, thus creating needed porosity, permeability, and better reservoir conditions

Commonly, joints and fractures that cut the shale sequence serve as reservoirs for gas evolved from organic matter in the shale A large volume of gas is contained in matrix porosity or is adsorbed by the organic matter in the shale Much of this gas is held tightly within the matrix of the shale, and, because of the very low permeability of the gas shales, only a small volume moves along permeability pathways from the matrix to microfractures and macrofractures The volume of matrix and adsorbed gas greatly exceeds the volume contained in the joint and fracture system (Brown, 1976) The long productive life, 50 years (yr) or more, and the relatively flat decline curves typical of shale gas wells have been attributed to the slow release of matrix and adsorbed gas and its slow movement along congested permeability pathways to the well bore

In terms of hydrocarbon resources, the organic matter in the shale sequence is the most important component of these rocks because it is the source of the gas Some methane was produced by bacterial action during the early stages of accumulation of the muds that contained organic matter Later, during the diagenetic transformation stage, the organic material was converted to kerogen at a relatively low temperature (less than 80 °C) within about 330 ft below the water-sediment boundary Through continued thermal maturation, which resulted from deeper burial at an approximate temperature range of between 80 and 150 °C, the kerogen passed to the catagenic stage and was transformed into liquid and gaseous hydrocarbons During thermal maturation, terrestrial kerogen yields mainly methane or dry gas Marine kerogen yields wet gas and oil at temperatures of between about 80 and 150 °C Beyond the catagenic stage (at temperatures in excess of 150 °C), the oil phase is progressively altered to the end products—dry methane and fixed carbon Thus, during the later stages of thermal maturation (between 150 and 300 °C), only dry methane is generated from both types of kerogens in the Devonian gas shale sequence

In the Appalachian basin, the degree of thermal maturation increases to the east and southeast from the western outcrop belt (Harris and others, 1978) as the Devonian black shales are buried under an increasing thickness of younger rocks This maturation pattern also is reflected in the systematic change of the composition of the gas and $\delta^{13}C$ of the methane generated from the organic matter in the shales In the western part of the basin, the gas composition is somewhat drier, is isotopically light, and has a $\delta^{13}C$ value of about -53 per mil In the central part, where the burial depth is 2,000 to 4,000 ft, the hydrocarbon composition is comparatively wet, and the $\delta^{13}C$ value ranges from about -51 to -42 per mil Farther east and buried below 6,000 to 9,000 ft of rock, the gas generated is low in wet, heavier hydrocarbons and has $\delta^{13}C$ values in the range of -41 to -26 per mil Thus, in the Appalachian basin, the shale sequence exhibits a full range of natural gas from mixed early biogenic thermal methane through midrange wet methane to upper maturation-level dry methane and, ultimately, in the easternmost metamorphosed segment of the basin, to black supermature carbonaceous slates devoid of methane

Drilling histories and production data from the Appalachian basin indicate that Devonian shales will yield gas abundantly only in areas where extensive natural fracture systems are well developed in the sequence One such area lies along the southern shore of Lake Erie in Chautauqua County, N Y , where natural gas was first produced commercially in the United States during the 1820's and 1830's Some of the wells in this area produced gas at low pressures and in small volumes from the shale sequence for more than 100 yr The area is undergoing rebound from loading by Pleistocene glacial ice, and the near-surface joint system has been enhanced and sprung open by the release of weight, which permits gas to escape more readily from the shale sequence The reservoir is only partly sealed by accumulations of glacial debris and recent lacustrine deposits As a result of incomplete seals, gas escapes from the fractured reservoir in many places, consequently, gas wells rarely show normal relations of pressure to depth

The Big Sandy gas field of eastern Kentucky and western West Virginia is associated with an extensive fracture system produced by repeated reactivation of basement faults of the Rome trough segment of the Eastern Interior aulacogen (Harris, 1978) Apparently, subsidence and normal faulting along the aulacogen generated the widespread and pervasive system of fractures and joints that make up the Big Sandy reservoir system Some shale gas wells have been productive for more than 50 yr in the Big Sandy area, and several of the more productive have yielded several billion cubic feet each The first wells were drilled in the Kentucky part of the field during the 1920's, and, by 1985, more than 10,000 wells produced more than 2 5 trillion cubic feet (ft^3) of gas, mainly from the Devonian shale sequence (Brown, 1976) In the Big Sandy field, as elsewhere in the Appalachian basin, the gas shale sequence is naturally fractured and is both source bed and reservoir rock

In some parts of the Appalachian basin, Devonian shales may be present, but apparently an extensive natural fracture system is not In these areas, wells drilled to the shale sequence by using existing stimulation and production techniques may yield gas but not in commercially extractable volumes

BASIS FOR ASSESSMENT

A number of major assumptions were made for this assessment Foremost was that, because the Devonian shale is an unconventional reservoir, the standard engineering equations for conventional porous-medium reservoirs are not strictly applicable Instead, an equation was used that divides the gas of the Devonian shale into three categories —macrofracture, microporosity, and sorbed Macrofracture gas is free gas that fills the major fracture and joint systems Microporosity gas is free gas that fills "small" fractures and other "small" matrix porosity Sorbed gas is gas that is either absorbed or adsorbed by organic matter in the shale

Some studies (for example, Lewin and Associates, 1979) have suggested that most of or all the gas produced from the shale was contained in the fracture system In contrast, Smith and others (1979) suggested that much higher fracture porosities than are seen in core examinations would be needed to contain the volume of produced gas Core examinations probably exaggerate the amount of fracture porosity because the cores include many fractures induced by the coring process as well as open fractures that would be closed under reservoir pressures In this study, large fractures are assumed to contain only a fraction of the total volume of in-place gas, this is not enough to explain most of or all the production Most of the gas contained in the shale is microporosity gas and the gas sorbed on organic matter in the matrix Large fractures are assumed to act mainly as permeability pathways rather than as reservoirs

Estimates of gas concentrations in the shale were based mainly on graphs of gas content versus organic-matter content from canned-core samples (fig 1) It was assumed that a linear relation existed between these two variables and that a line could be subjectively fit to the data on such a plot The slope of this line would be an estimate of the ratio of sorbed gas to organic matter, and the intercept would be an estimate of the effective microporosity gas content Because some amount of gas leakage from microporosity is expected, more weight was given to measurements showing higher gas contents for given organic-matter contents The line subjectively fit to the data, as illustrated in figure 1, thus tends to pass through the higher gas-content values of the data set and does not pass through the origin From the practical standpoint of these plots, macrofracture gas is from fractures large enough that the gas leaks out

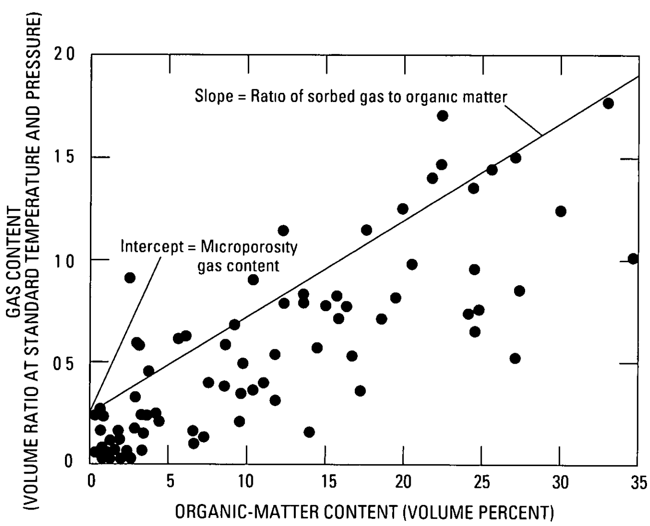

Figure 1. Typical plot of gas content versus organic-matter content based on data from off-gassing experiments Because a small, unmeasured volume of gas escapes from the microfractures during coring and canning of the core samples, the line defining the ratio of gas content to organic-matter content in the shales favors the higher gas-content values The line has been subjectively fit to the data points and intercepts the gas-content ordinate at a positive value equivalent to the gas content present in the microporosity

before canning Microporosity gas is from fractures and matrix porosity small enough that, for some of the samples, none of this gas leaks out before canning

Shales that have very low organic contents usually have little or no gas In this study, shale that has an organic-matter content of less than 2 percent by volume is considered to have only a negligible amount of gas

Certain areas of the basin have been assessed as having only negligible resource potential and were not included in this estimate They include Tennessee and Alabama, where organic-rich shale occurs, but the sequence is considered to be too thin to provide sufficient potential Negligible potential was assigned to the area east of the 4 conodont color alteration index (CAI) isograd (Harris and others, 1978) because of supermaturity Potential may exist in some of the deep synclines of Virginia, but information is insufficient for a quantitative appraisal

The estimate of most practical significance would provide the amount of economically recoverable gas from the shale However, the authors of this report feel that a quantitative estimate of recoverability is beyond the scope of a geological appraisal such as ours A major problem is lack of knowledge of the drainage volume of a single well Because of the complex drainage patterns and the unconventional nature of the reservoir, it is probably inappropriate to assume a standard well spacing (as was done by Lewin and Associates (1979)) as sufficient for drainage Another major problem is economics, which requires many further assumptions on use, costs, prices, completion techniques, and other factors However, on the basis of geologic data (primarily the extent of fracturing), we were able to make a rough qualitative estimate of shale gas recoverability

METHOD OF ASSESSMENT

Play Area Delineation

In resource appraisal by the play-analysis method, a play is defined as an area in which the main geologic and geochemical attributes are relatively consistent but differ significantly, or at least are hypothesized to differ significantly, from some of the attributes in other plays Basically, a play is a unit around which an exploration program may be generated

For this appraisal, the main part of the Appalachian Plateaus province and a small segment of the adjacent Valley and Ridge province were subdivided into 19 plays (fig 2) The subdivisions were based on structural and stratigraphic criteria (table 1)

Play 1—North-Central Ohio

The North-Central Ohio play is the area adjacent to the outcrop of the Devonian shale sequence from Lake Erie south to the vicinity of Chillicothe, Ohio The black Ohio Shale underlies the area in thicknesses that range from 350 to 600 ft (Wallace and others, 1977) The organic content of the shale, which is in the range of 10 to 15 percent of the shale by volume, is high for the Appalachian basin However, the maturation level of the shale as determined by the CAI is low—from about 1 0 to 1 5—which indicates that the shales have not attained maturation temperatures in the range for maximum oil or gas generation The area is structurally simple and lacks either large-scale normal or thrust faults Locally, the regional joint pattern has been enhanced by rebound from the loading of the area by Pleistocene glacial ice Gas in quantities sufficient for domestic use has been obtained from the gas shale sequence, particularly in the northern part of this play area Shallow depths to the Devonian shale sequence indicate low reservoir pressures The North-Central Ohio play thus appears to have a moderate recoverability for shale gas

Play 2—Western Lake Erie

The Western Lake Erie play is the area adjacent to Lake Erie from the vicinity of Norwalk, Huron County, Ohio, east to the Ohio-Pennsylvania border The Huron Member of the Ohio Shale and the older Rhinestreet Shale Member of the West Falls Formation are present at an aggregate thickness of about 600 ft (Wallace and others, 1977) The Middle Devonian Marcellus Shale is present locally in the eastern part of the play area The organic content of the shales, which is high to moderate, ranges

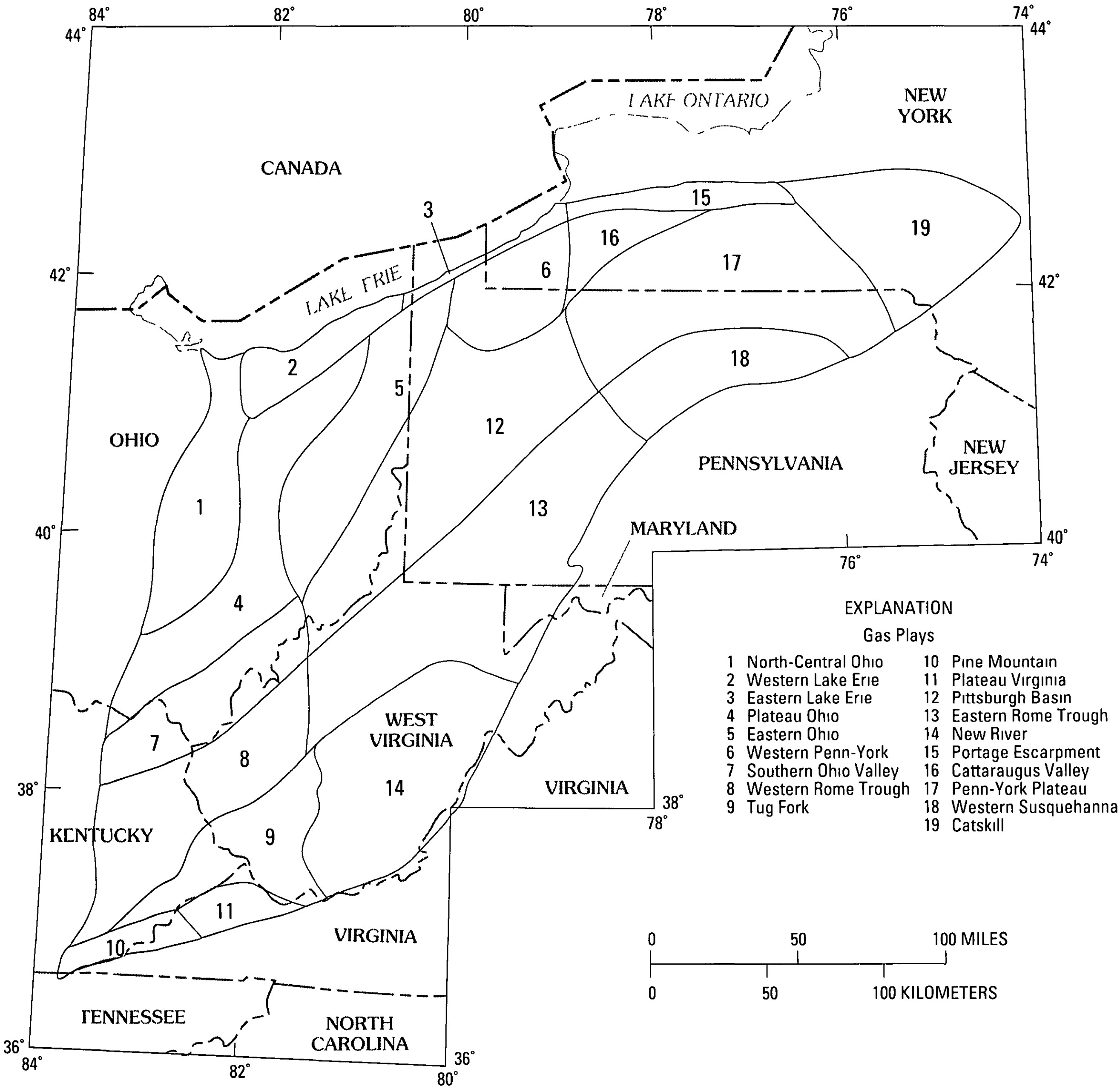

Figure 2. Devonian shale gas plays in the Appalachian basin

from about 11 percent by volume in the western part of the play to about 5 percent in the east near the State line The maturation level shown by the CAI is below 1 5, which indicates that black shales have not attained temperatures sufficient to release gas or oil in large volumes The area is structurally simple because it lies north and west of the western limit of the thin-skinned thrusting in the Appalachian basin The area has been and is rebounding from loading by Pleistocene glacial ice, and the near-surface joints have been accentuated as permeability pathways permitting matrix gas to migrate into the joint system The effective depth to which the joints have been sprung appears to be about 1,000 to 1,500 ft The Western Lake Erie play, which has produced Devonian shale gas in domestic and small commercial volumes for about 100 yr, has good recoverability for shale gas

Play 3—Eastern Lake Erie

The Eastern Lake Erie play is an area about 10 miles (mi) wide along Lake Erie in northwestern Pennsylvania

Table 1. Structural and stratigraphic features of shale gas plays in the Appalachian basin

Plays	Structural				Stratigraphic			
			Horizontal tectonics					
	Glacial rebound	Vertical tectonics	Thrust	Salt flow	Thick lobe	Brittle beds	High organic content	Aggregate thickness of black shale (ft)
1	X						X	350–600
2	X				X		X	600±
3	X				X		300–400	
4		X?			X	X		450–800
5			X?	X		X		500–900
6			X			X		400–600
7		X				X	X	200–600
8		X			X	X		500–1,000
9		X	X			X	X	400–900
10			X			X	X	100–400
11			X			X		400–600
12			X			X		300–600
13		X	X			X		400–900
14			X			X		400–1,000
15	X			X		X		400–1,000
16			X?					300–500
17		X?	X	X	X	X		600–1,000
18		X	X	X				600–1,400
19								400–800

and adjacent southwestern New York The Dunkirk Shale Member of the Perrysburg Formation, the Rhinestreet Shale Member of the West Falls Formation, and the Marcellus Shale are the principal black shales involved in the play (Wallace and others, 1977), their aggregate thickness ranges from 300 to 400 ft The organic content of the gas shales, which ranges from 6 to 7 percent of the shale by volume, is moderate for the Appalachian basin The maturation level, which is relatively low, ranges from CAI 1 5 to 2 0, which indicates that much of the organic carbon in the shales remains to be converted to oil and gas Similar to the Western Lake Erie play, this play area also is undergoing isostatic rebound from glacial loading, which enhances the surface joint system and opening permeability pathways in the shale sequence to depths of 1,000 to 1,500 ft Gas seeps are common in the play area This play differs from the Western Lake Erie play in that the eastern play has many beds of siltstone intercalated in the upper part of the Dunkirk Shale Member and in the overlying gray shale sequence During the Pleistocene and the Holocene, these hard, brittle beds were jointed and broken to a greater degree when the ice was being loaded and unloaded than the softer shales Fracturing of the hard beds produced an extensive fracture reservoir system, which makes the eastern area a slightly better play than its western counterpart Shale gas has been produced in domestic and commercial quantities from the Devonian shales of the Eastern Lake Erie play area for about 160 yr Several wells drilled into the Devonian shale sequence in the vicinity of Erie, Pa , have produced as much as 300,000 cubic feet per day after stimulation, which demonstrates good recoverability for the shale gas in this play area

Play 4—Plateau Ohio

The Plateau Ohio play is an elongated area extending from the Ohio River near Portsmouth, Ohio, northeast to the highlands of Geauga County on the southern side of the Western Lake Erie play The Cleveland and Huron Members of the Ohio Shale and the Rhinestreet Shale Member of the West Falls Formation are the principal black shale units present under the play area (Wallace and others, 1977) Their aggregate thickness ranges from 450 to 800 ft The organic-carbon content, which is high to moderate, ranges from 11 to 7 percent by volume northeastward across the play The maturation level, which is relatively low, ranges from CAI 1 0 to 1 5 Much of the organic carbon in the shales remains to be converted to oil or gas or both The play area is structurally simple Large faults are not known, although several small gas fields associated with marked surface lineations suggest that fracture porosity has been developed locally, particularly in the southern part of the play area Although this play has thick source beds, the low level of maturation and the absence of extensive structures suggest a low gas recoverability for the Plateau Ohio play

Play 5—Eastern Ohio

The Eastern Ohio play is an elongated area extending from the southern boundary of the Western and Eastern Lake Erie plays south to the northwestern corner of Washington County, about 20 mi northwest of Marietta, Ohio The Huron Member of the Ohio Shale and the Rhinestreet Shale Member of the West Falls Formation are the main black shales in this play area (Wallace and others, 1978, Roen and others, 1978a) The aggregate thickness of the two shales ranges from 500 to 900 ft, although, locally, some gray shale and siltstone are intercalated in the upper part of the Rhinestreet The organic-carbon content of the black shales, which is moderate, ranges from more than 7 to less than 5 percent by volume The maturation level, which is about CAI 1 5, is slightly greater than that in the Plateau Ohio play The increase in maturation level is the result of deeper burial of the gas shale sequence Although the shales lie in the maturation range in which kerogens are converted into gas and oil, these beds have not attained the stage of maximum gas and oil yield This play area lies along the western edge of thin-skinned folding in the Salina salt beds and in adjacent carbonate rocks a short distance below the Devonian gas shale sequence Faulting and folding of the gas shale sequence have produced zones of fracture porosity in the shales and in the brittle, silty, gray shale and siltstone sequence above the black gas shales Consequently, the Eastern Ohio play area appears to have moderate recoverability for its shale gas, particularly close to the western margin of the salt beds where small-scale splay faults may ramp up to the shale sequence

Play 6—Western Penn-York

The Western Penn-York play is a semicircular area that includes part of northwestern Pennsylvania and adjacent southwestern New York south of the Eastern Lake Erie play It includes much of the plateau country south of Lake Erie in the upper part of the Allegheny River basin The Dunkirk Shale Member of the Perrysburg Formation, the Rhinestreet Shale Member of the West Falls Formation, and the Marcellus Shale of the Hamilton Group are the principal black gas shales underlying this play The shales have an aggregate thickness of between 400 and 600 ft Their organic-carbon content, which ranges from 4 to 6 percent by volume, is moderate to low The maturation level, which is moderate, ranges between CAI 1 5 and 2 0, the maturation temperatures have been sufficiently high to generate gas and oil from the gas shales, but considerable type III organic carbon remains in the source beds Beds of siltstone are intercalated with or closely overlie the black shale sequence, and, locally, where the sequence has been broken by minor faulting and folding, considerable fracture porosity has been developed in the sequence of brittle beds This play area is structurally simple, a few small folds and some small-scale faults, which may be associated with the western edge of the thin-skinned tectonic belt, interrupt the southeastern regional dip into the Appalachian basin Considering the thickness of black shale and the presence of brittle-bed fracture-porosity reservoirs, the Western Penn-York play has moderate recoverability for shale gas

Play 7—Southern Ohio Valley

The Southern Ohio Valley play encompasses the main valley of the Ohio River from the vicinity of Marietta, Washington County, Ohio, southwest to the vicinity of Portsmouth, Ohio, at the mouth of the Scioto River and into northeastern Kentucky to outcrops of the Ohio Shale in Fleming and Rowan Counties The Cleveland and the Huron Members of the Ohio Shale are the principal black shales in the western part of the play In the eastern part of the play, the Cleveland Member of the Ohio Shale is absent because of a facies change, and the Rhinestreet Shale Member of the West Falls Formation is present above the mid-Devonian unconformity at the base of the gas shale sequence (Roen and others, 1978b) The aggregate thickness of black shale ranges from about 200 ft in the west to about 600 ft in the eastern part of the play The maturation level, which is relatively low, ranges from slightly more than CAI 1 0 in the west to slightly more than CAI 1 5 near Marietta at the eastern end of the play The increase in maturation to the east is a reflection of increased depth of burial of the gas shale sequence and the loss of the Cleveland Member of the Ohio Shale at the top of the sequence The organic content of the black shales ranges from a high of 16 percent by volume at the western end of the play to a moderate value of 5 percent at the eastern end of the play Throughout most of the play area, laminae and thin beds of siltstone are intercalated in the black shale sequence, locally, the brittle beds are shattered to form fracture-porosity reservoirs Structurally, the area is relatively simple The regional dip to the east is locally interrupted by small faults and low-amplitude folds, particularly along the southern edge of the play adjacent to the Rome trough and at the eastern end of the play area contiguous to the Burning Springs anticline The presence of an adequate thickness of black and brown shales rich in organic matter and of brittle-bed fracture reservoirs indicates that the Southern Ohio Valley play has moderate to good recoverability for shale gas

Play 8—Western Rome Trough

The Western Rome Trough play is the area containing most of the Big Sandy gas field of eastern Kentucky and contiguous western West Virginia The Ohio Shale and the older Rhinestreet Shale Member of the West Falls Formation or their lateral equivalents, the Gassaway and Dowelltown Members of the Chattanooga Shale, are the principal black shales in the Western and Eastern Rome Trough plays (Kepferle and others, 1978) The aggregate thickness of the black shales ranges from 500 to 1,000 ft in the play area The organic content of the black shales, which is moderate to high for the Appalachian basin, ranges from 5 to 16 percent by volume The maturation level, which is low to moderate, ranges between CAI 1 4 and about 1 8 Maturation temperatures were sufficient to generate oil and gas from organic matter in the gas shale sequence, particularly in the central and eastern parts of the play area Vertical tectonics, which consist of repeated rejuvenation of the normal faults of the Rome trough fault system in the late Paleozoic, shattered the gas shale and produced the extensive fracture reservoir system of the Big Sandy gas field Without the extensive natural fracture system, the gas shales are not capable of yielding gas in commercial quantities This play contains thick beds of black shale rich in organic detritus, an extensive natural fracture system, and maturation levels sufficiently advanced to generate much gas from the organic matter in the shale These conditions are most ideal for the production of shale gas Commercial volumes of Devonian shale gas have been recovered from this play area for the past 60 yr, and the Big Sandy gas field has produced more than 2 trillion ft^3 of gas mainly from the Devonian shale sequence The Western Rome Trough play area has good recoverability for shale gas

Play 9—Tug Fork

The Tug Fork play area is south of the Western Rome Trough play and includes much of the high Appalachian Plateaus from Harlan County, Ky , northeast to the vicinity of Charleston, Kanawha County, W Va The play area centers in the drainage area of the Tug Fork of the Big Sandy River along the Kentucky-West Virginia border The Huron Member of the Ohio Shale and the Rhinestreet Shale Member of the West Falls Formation are the principal black shales in the play area The aggregate thickness of the black shales ranges from about 400 to 900 ft The organic content of the sequence, which is moderate, ranges from a maximum of about 10 percent in Harlan County eastward to a minimum of 5 percent in Kanawha County The maturation level, which is moderate, ranges from CAI 1 5 to slightly more than 2 0 The rocks of the gas shale sequence are in the oil- and gas-generating maturation range In most of the play area, a 120- to 150-ft sequence of siltstones and sandstones of the Bedford Shale and the Berea Sandstone of Late Devonian and Early Mississippian age directly overlies the gas shale sequence These brittle beds have been fractured in part by the effects of subsidence along the Rome trough and in part by thrusting during the Alleghenian orogeny at the close of the Paleozoic Era Locally, they form fracture reservoirs that contain gas, which migrated from the underlying gas shale sequence The upper part of the Huron Member of the Ohio Shale grades eastward into a sequence of siltstone and shale Where fractured in the vicinity of small-scale faults, the brittle beds in the sequence form local fracture-porosity reservoirs The shale sequence also is fractured but not as greatly as in the Western Rome Trough play However, the combination of fracture reservoirs in the shale sequence and associated brittle beds suggests that the Tug Fork play area has moderate to good recoverability for shale gas

Play 10—Pine Mountain

The Pine Mountain play is confined to the Pine Mountain thrust block of southwestern Virginia, southeastern Kentucky, and adjacent Tennessee The Ohio Shale and the Rhinestreet Shale Member of the West Falls Formation or their equivalents, the Gassaway and Dowelltown Members of the Chattanooga Shale, are the main black shales underlying the Pine Mountain play The aggregate thickness of black shales ranges from 100 to 400 ft The organic content, which is high for the Appalachian basin, ranges from 9 to 15 percent by volume The degree of maturation, which is moderate, ranges between CAI 1 5 and 2 0 The rocks of the gas shale sequence are within the temperature range for generating gas and oil from their contained organic matter The play area is dominated by thin-skinned tectonics A large near-bedding decollement moved the Pine Mountain thrust block 4 to 12 mi to the northwest The master fault is near the base of the Devonian gas shale sequence, and many small faults splay upward to shatter and fracture the shales above the decollement The faulting produced many pockets of fracture porosity charged with gas Gas flows freely from the reservoir when it is opened by a well, but the volume of gas is small The well may cease producing in a few hours or a few days However, the Berea Sandstone overlies the gas shale sequence in the eastern part of the play area and forms an excellent fracture reservoir because it was extensively broken during Alleghenian thrusting The Mississippian age shale above the Berea seals the gas in the fracture-reservoir rock Because the individual fracture-porosity reservoirs appear to be small and not interconnected to any great extent in the area where the Berea Sandstone is absent, the Pine Mountain play appears to have only moderate recoverability for shale gas

Play 11—Plateau Virginia

The Plateau Virginia play area underlies most of the coal-bearing high plateau of southwestern Virginia contiguous to the eastern side of the Pine Mountain play area The Russell Fork fault separates the two play areas The main black shales in this play are the Cleveland and Huron Members of the Ohio Shale and the older Rhinestreet Shale Member of the West Falls Formation The aggregate thickness of the black shales ranges from 400 to 600 ft The organic content, which is moderate, ranges from 4 to 7 percent of the shale by volume The maturation level, which is moderate for the Appalachian basin, ranges from CAI 1 5 to 2 0, the rocks are within the maturation range to yield gas and oil from their contained organic matter The gas shale sequence is overlain by about 100 ft of siltstone and sandstone of the Berea Sandstone These hard rocks, which underwent considerable fracturing by thrusting and folding associated with the Alleghenian orogeny, are an extensive fracture reservoir that traps and holds gas migrating from the fractured black shale sequence below The Lower Mississippian shales above the Berea seal the gas within the Berea reservoir Because of the extensive fracture-porosity reservoir closely associated with adequate source rocks in the gas shale sequence, the Plateau Virginia play appears to have good recoverability for shale gas

Play 12—Pittsburgh Basin

The Pittsburgh Basin play underlies much of western Pennsylvania north of the Eastern Rome Trough play and extends south along the Ohio River Valley to the northern end of the Burning Springs anticline near Marietta, Ohio The gas shale sequence is buried at depths of between 5,000 and 7,500 ft in this play The older black shales—the Rhinestreet Shale Member of the West Falls Formation, the Geneseo Shale Member of the Genesee Formation, and the Marcellus Shale of the Hamilton Group—are the main gas shales in the play area (Roen and others, 1978b) Their aggregate thickness ranges from 300 to 600 ft The organic content, which is relatively low for the gas shale sequence, ranges from 4 to 6 percent of the shale by volume The maturation level, which is moderate to moderately high, is above CAI 2 0 The play is near the western edge of the area dominated by thin-skinned thrusting Zones of fracture porosity have developed locally in the black shales and associated silty shale and thin siltstone sequences Because the faulting and the folding in this play are relatively small scale, fracture porosity has not developed as extensively as it has to the east and south Vertical tectonics of the Rome trough do not appear to have affected the play area Because of the absence of extensive fracture reservoirs in the gas shale sequence, the Pittsburgh Basin play area has poor recoverability for shale gas

Play 13—Eastern Rome Trough

The Eastern Rome Trough play covers the extension of the Rome trough east of the Burning Springs anticline in northern West Virginia and the contiguous parts of western Pennsylvania The principal black shales in the play area are the Rhinestreet Shale Member of the West Falls Formation, the Geneseo Shale Member of the Genesee Formation, and the Marcellus Shale of the Hamilton Group The Huron Member of the Ohio Shale is present only in the western part of the play The aggregate thickness of the black shales ranges from about 400 to more than 900 ft The organic content of the black shales, which is low for the Appalachian basin, ranges between 3 and 5 percent by volume Because the gas shales are buried to depths of from 5,000 to 8,000 ft below sea level, their level of maturation, which is moderate to high for gas shales, ranges from CAI 1 5 to 3 0 As in the Western Rome Trough play, vertical tectonics produced an extensive fracture system in the black shales and associated hard beds In this play, thin-skinned thrusting of the Alleghenian orogeny has been superimposed upon the vertical tectonics Extensive fracture porosity that has developed is associated with splay faults and anticlinal folds produced by thin-skinned thrusting Although the organic content of the gas shales is relatively low, the greater level of maturation and the abundance of fracture-porosity reservoirs in the gas shales and the associated hard-bed sequences suggest that the Eastern Rome Trough play has good recoverability for shale gas

Play 14—New River

The New River play area underlies the Appalachian Plateaus of southern West Virginia east of the Tug Fork play and south of the Eastern Rome Trough play The Geneseo Shale Member of the Genesee Formation and the Marcellus Shale of the Hamilton Group, which are the main black shales in the play, have an aggregate thickness of from 400 to 1,000 ft and a relatively low organic content of between 3 and 5 percent of the shale by volume Their maturation level, which is relatively high for gas shales, ranges from CAI 2 0 to 3 0; this is at or beyond the temperature for the maximum generation of oil Structurally, the New River play is dominated by thin-skinned thrusting that has formed extensive zones of fracture porosity in the gas shales and associated brittle-bed sequences in the vicinity of splay faults, ramps, and anticlines Locally, small splay faults also may be associated with the troughs of synclines The depth to the gas shale sequence, the greater degree of maturation, and the relatively low organic content of the Devonian shales indicate that the New River play has low recoverability for shale gas

Play 15—Portage Escarpment

The Portage Escarpment play underlies the Portage escarpment and adjacent highlands from the meridian of Buffalo east across the Genesee Valley and the Finger Lakes district to the meridian of Syracuse and Tully in New York The Dunkirk Shale Member of the Perrysburg Formation, the Rhinestreet Shale Member of the West Falls Formation, the Middlesex Shale Member of the Sonyea Formation, the Renwick and Geneseo Shale Members of the Genesee Formation, and the Marcellus Shale of the Hamilton Group are the main black shales underlying the play area (Wallace and others, 1977) The aggregate thickness of these several black shales ranges from 400 to 1,000 ft The organic content, which is relatively low, ranges from 3 to 6 percent The maturation level, which is moderate, ranges from CAI 2 0 to 2 5, this indicates that maturation temperatures were near the upper level for the generation of oil but within the limits for generation of natural gas The area has been depressed by the weight of a thick sheet of Pleistocene glacial ice and is now isostatically rebounding from the release of the weight Consequently, the regional joint system is being sprung or enhanced, which increases the permeability pathways by which matrix gas escapes In the area of the larger Finger Lakes, the rocks of this play also have been affected by thin-skinned thrusting in the salt beds of the Salina Formation Splay faults rising through the Lower and Middle Devonian rocks have formed extensive zones of fracture porosity in the gas shales and the associated sequences of brittle beds Although the organic matter content is relatively low, the sufficient maturation level and the zones of extensive fracture porosity suggest that the Portage Escarpment play has good gas recoverability

Play 16—Cattaraugus Valley

The Cattaraugus Valley play underlies much of the drainage basin of Cattaraugus Creek in western New York It lies south of the western part of the Portage Escarpment play and east of the Western Penn-York play The Dunkirk Shale Member of the Perrysburg Formation and the Rhinestreet Shale Member of the West Falls Formation are the principal black shales underlying the play area The aggregate thickness of the black shales ranges from 300 to 500 ft The organic content of the shales, which ranges from 3 to 6 percent, is moderate to low The maturation level, which is moderate, ranges from CAI 1 5 to 2 2 The gas shales are more deeply buried in this play than in the Portage Escarpment play The near-surface effects of rebound from glacial loading do not appear to have enhanced the joint systems in this play The play also lies north and west of the main area of thin-skinned tectonics in the Appalachians In the northwestern corner of this play, some thrusting may be possible in an extension of the Bass Islands trend Consequently, this play lacks the tectonics needed to form much fracture porosity In the absence of extensive fracture porosity, the Cattaraugus Valley play has poor recoverability for shale gas

Play 17—Penn-York Plateau

The Penn-York Plateau play is the area underlying much of the high plateau of south-central New York and adjacent north-central Pennsylvania from the meridian of Olean, N Y , and Bradford, Pa , east to the meridian of Scranton, Pa The Geneseo Shale Member of the Genesee Formation and its lateral equivalent, the Burket Member of the Harrell Shale of Late Devonian age, and the Marcellus Shale of the Hamilton Group of Middle Devonian age are the main black shales in this play Locally in south-central New York, the Middlesex Shale Member of the Sonyea Formation may be sufficiently thick to be a source bed The aggregate thickness of black shale ranges from 1,000 ft in the west to less than 600 ft in the thickening sequence of gray clastic rocks in the east The organic content of the shales, which is generally low, ranges from 3 to 5 percent by volume The maturation level, which is moderate to high for the gas shales, ranges from about CAI 2 0 in the west to 3 0 in the east, maturation temperatures were mainly in the dry-gas range Structurally, most of this play is dominated by thin-skinned tectonics Decollements occur mainly in the Silurian salt sequence, and splay faults ramp into the Lower, Middle, and Upper Devonian rocks to develop extensive zones of fracture porosity in the gas shales and associated sequences of brittle beds Normal faults associated with several of the larger Finger Lakes, which project into the play area from the adjacent Portage Escarpment play, suggest that extensional as well as compressive forces have produced local fracture porosity Although the organic content of the shales is relatively low, the maturation level and the abundance of fracture porosity suggest that the Penn-York Plateau play has moderate recoverability for shale gas

Play 18—Western Susquehanna

The Western Susquehanna play underlies much of the West Branch and a smaller segment of the East Branch of the Susquehanna River in north-central Pennsylvania The Burket Member of the Harrell Shale and the Marcellus Shale of the Hamilton Group are the main gas shales of the play The aggregate thickness of the black shales ranges from 600 to more than 1,400 ft The organic content of the shales, which is low, ranges from 3 to 5 percent by volume Because the Devonian gas shales are relatively deeply buried adjacent to the Allegheny Front, the maturation level is high and ranges from CAI 2 5 to 3 5 The play area has been subjected to vertical tectonics along the eastern extension of the Rome trough as well as to the compressive stresses of thin-skinned tectonics of the Alleghenian orogeny The rocks have been greatly fractured, particularly in the vicinity of splay faults and antithetic faults rising from decollements in the evaporites of the Silurian salt sequence Although good fracture porosity may exist, the mature nature and the relatively highly dispersed organic matter as a result of facies changes and thinning suggest poor shale gas recoverability for the Western Susquehanna play

Play 19—Catskill

The Catskill play area underlies the Catskill Mountains of southeastern New York and the peripheral highlands in extreme northeastern Pennsylvania The Marcellus Shale of the Hamilton Group is the only Devonian gas shale in the play The black shales in the Hamilton Group have an aggregate thickness of from 400 to 800 ft Their organic content, which is relatively low, ranges from 3 to 5 percent by volume The maturation level, which is high, ranges between CAI 3 0 and 4 0 Structurally, this play is relatively simple Normal faults, which cut the Ordovician rocks south of the Adirondack Mountains, do not appear to have broken the Devonian rocks, and the thin-skinned faults and folds of the Penn-York Plateau and the eastern part of the Portage Escarpment plays are not present in this play The Catskill play has poor recoverability for shale gas because the shales have a relatively low organic content and a relatively high thermal maturity and lack an extensive fracture porosity system

Method of Calculation

The amount of gas in each play was calculated by using the following equation

$$G = \phi_{macro} \times TH_s \times \frac{P_r}{P_s} \times \frac{T_s}{T_r} \times \frac{1}{z} \times \text{area} \times [5{,}280 \text{ feet per mile (ft/mi)}]^2$$

macrofracture gas

$$+ \phi_{micro} \times TH_s \times \text{area} \times (5{,}280 \text{ ft/mi})^2$$

microporosity gas

$$+ \text{SOR} \times \text{ORG} \times TH_s \times \text{area} \times (5{,}280 \text{ ft/mi})^2$$

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 pounds per square inch atmospheric (psia))
- P_s = standard pressure (14 73 psia)
- T_r = average reservoir temperature (in degrees Rankine (°R))
- 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

The equation can be broken down into three parts for separate calculation of each of the three types of gas

The following two major factors affect the use of point-estimate input to the equation

1 Data are very limited for most of the assessed area, especially in the eastern part of the basin
2 The data that do exist are subject to large sampling errors and differences in interpretation

These factors make a deterministic point estimate of very limited value A better approach would be to accept a measure of the uncertainty of the input variables and to give some measure of the uncertainty of the resource estimate The approach chosen for this analysis was a probabilistic Monte Carlo technique, which allows the analyst to recognize and estimate variations or ranges of potential values for the variables

In using the Monte Carlo technique, each variable from the equation is entered in the form of a probability distribution Each of these distributions is randomly sampled, and the equation is solved to give a value for volume of gas This procedure is repeated many (in this study, 1,000) times, and the resulting gas-volume values are used to construct an empirical probability distribution for amount of gas Because the equation can be broken into three parts according to categories of gas, the procedure can provide probability distributions for each category as well as for the total amount of gas

The result of this approach is a probability distribution or interval estimate for the three components and for the total equation This allows an analysis of sensitivity and of variability of the potential amounts of gas In areas of sparse data, the probability distribution of a Monte Carlo approach yields much more potential insight than a deterministic point estimate

Derivation of Input

The basic configuration of gas shales in the basin was taken from published cross sections (Wallace and others, 1977, 1978, Kepferle and others, 1978, Roen and others, 1978a, b, West, 1978) as well as unpublished isopach and structure maps by J B Roen These maps and cross sections were used to estimate average depths that, when combined with estimated pressure and temperature gradients, yielded average reservoir pressures and temperatures The thickness of organic-rich shale was based on maps by de Witt and others (1975) and Schmoker (1980, 1981)

The organic content of the shale for the western part of the basin was estimated mainly from the map by Schmoker (1981) For the eastern part of the basin, data were taken from Claypool and Stone (1979) and Claypool and others (1980)

The microporosity- and sorbed-gas contents were estimated by using data from off-gassing experiments, as explained above Unpublished data from the U S Geological Survey, the Battelle Columbus Laboratories, and the Mound Facility were used for this purpose Because of sparse data, the estimate of macrofracture porosity was very subjective Sources such as Smith and others (1979) provided some help

The gas deviation factor (z) was calculated by using 60 U S Geological Survey gas analyses Gas deviation factors were calculated for each gas sample by the pseudocritical method, and one average figure was then used for the entire basin

This information was synthesized by members of the appraisal team, who were asked to provide a distribution for each variable for each play This distribution was described by a modal value and a measure of the distance between the mode and the fifth fractile When this distance is divided by 1 654, it gives an estimate of the standard deviation An average of the individual results gave one set of distributions (appendix A)

The computer program for the play analysis required that each distribution be represented by a number of fractiles The program would then interpolate between the given fractiles In this study, seven fractiles were used—1 00, 0 90, 0 75, 0 50, 0 25, 0 10, and 0 00 For simplicity's sake and because knowledge of the precise shapes of the distributions was not available, the distributions were assumed to be approximately normal To arrive at this approximation, the mode was input as the 0 50 fractile, and the other fractiles were functions of the mode and standard deviation (s d) as follows

1 00 fractile = mode − 2 326 × s d
0 90 fractile = mode − 1 282 × s d
0 75 fractile = mode − 0 674 × s d
0 25 fractile = mode + 0 674 × s d
0 10 fractile = mode + 1 282 × s d
0 00 fractile = mode + 2 326 × s d

In cases where the calculated fractile value was negative, zero values were substituted, thus effectively truncating the distributions at zero

Table 2. Estimates of in-place natural gas resources in Devonian shales of the Appalachian basin

[Because all tabulated values were rounded from original numbers, totals may not add]

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-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

RESULTS OF STUDY

Table 2 summarizes estimates of the in-place natural gas resources of the Devonian shale of the Appalachian basin A more detailed listing is available in appendix B For each of the 19 plays, the probability distribution for amount of gas in the play is represented by the 95th fractile (F_{95}), the 5th fractile (F_5), and the mean estimate The 95th fractile is a low estimate and has a corresponding 95-percent chance of there being a greater amount of gas than that The 5th fractile is a high estimate and has only a 5-percent chance of there being a greater amount of gas than that

Similarly, the 95th fractile, the 5th fractile, and the mean estimate are given for the entire basin In many other studies (for example, Miller and others, 1975, Dolton and others, 1981), subunits are fairly independent In those cases, the columns of fractiles are not additive In the present study, however, the individual plays are strongly dependent The simplest (linear) relation among distributions was assumed In this case, the columns of fractiles are additive For comparison, appendix B includes estimates for the total basin for the dependent and independent cases The means are additive under either assumption

Figure 3 presents the qualitative assessments of recoverability reported in the section "Play Area Delineation " These assessments are a rough estimate of the degree to which the in-place gas resource could be developed Thus, for example, play 12 is estimated to have a very large amount of gas in place, but, because of a probably low degree of reservoir fracturing, the play has been assessed as having poor recoverability for shale gas

Some recent estimates of gas resources of Devonian shale in the Appalachian basin are presented in table 3 Except for the estimate of the Federal Energy Regulatory Commission (1978), there is general agreement among the estimates in spite of the fact that very different assumptions and methods were used in the various studies

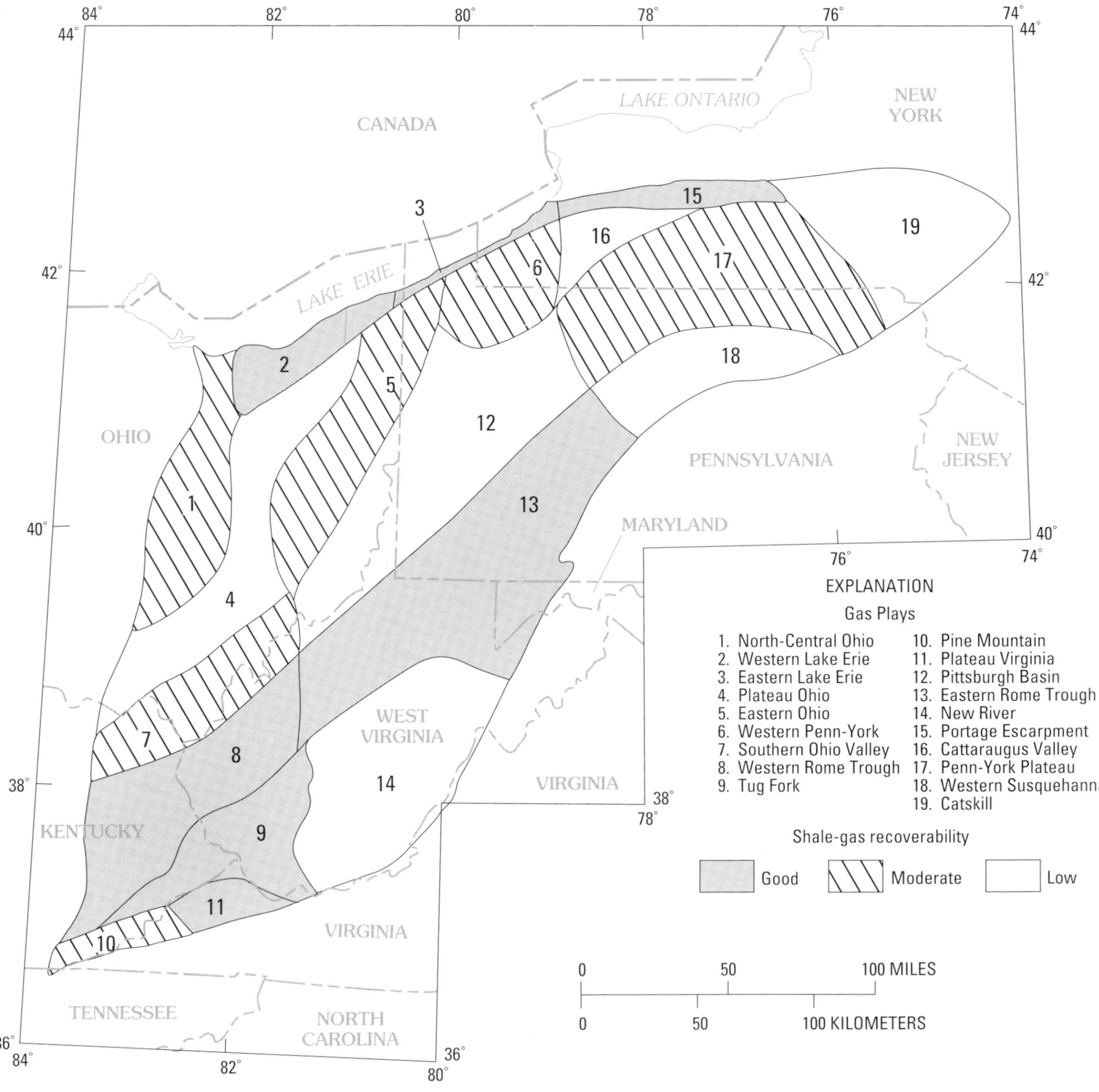

Figure 3. Qualitative assessment of gas recoverability from Devonian shales of the Appalachian basin.

Table 3. Comparison of several estimates of in-place natural gas resources in Devonian shales of the Appalachian basin

[In trillions of cubic feet]

Reference	Estimate
Smith (1978)	206–903
Federal Energy Regulatory Commission (1978)	285
Kuuskraa and Meyer (1980)	400–2,000
National Petroleum Council (1980)	225–1,861
This report	577–1,131

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APPENDIXES

Appendix A. Distributions of input variables for each play

[°R, degrees Rankine, psia, pounds per square inch atmospheric]

Play no	Average thickness of organic-rich interval (ft)		Average organic content of organic-rich interval (percent)		Average macrofracture porosity (percent)		Average effective microporosity (percent)		Average sorbed-gas to organic-matter volume ratio		Average reservoir temperature (°R)		Average reservoir pressure (psia)		Area (mi^2)
	Mode	Standard deviation	Mode	Standard deviation	Mode	Standard deviation	Mode	Standard deviation	Mode	Standard deviation	Mode	Standard deviation	Mode	Standard deviation	
1	493 0	30 0	10 60	0 59	0 0020	0 0025	10 0	4 3	3 00	0 55	530 0	2 6	236 7	35 1	4,528
2	627 3	30 9	8 40	56	0020	0025	37 5	5 5	5 05	68	546 0	2 9	383 0	46 2	1,903
3	339 3	20 8	6 20	34	0020	0025	40 0	6 8	3 35	76	534 3	3 0	355 0	40 6	464
4	558 7	33 8	8 73	50	0015	0028	20 0	5 5	4 30	71	543 7	3 6	651 7	67 2	6,668
5	552 7	30 6	5 13	25	0015	0028	30 0	5 5	4 50	71	559 3	4 2	905 0	97 6	5,461
6	464 7	26 7	5 67	29	0015	0028	50 0	4 3	2 15	58	553 7	3 9	815 0	75 3	3,008
7	543 3	31 5	8 03	49	0020	0025	22 5	5 5	2 85	68	544 3	3 5	651 7	64 9	3,970
8	558 0	34 2	9 33	53	0020	0025	20 0	6 8	3 50	76	559 0	4 6	1,030 0	104 5	6,845
9	562 7	32 5	6 23	33	0020	0025	15 0	4 8	2 70	55	576 3	4 9	1,569 3	135 6	3,893
10	372 0	25 4	10 13	29	0020	0025	60 0	14 0	6 25	1 42	565 0	4 6	1,285 0	129 7	1,129
11	451 3	22 8	5 40	27	0020	0025	30 0	12 3	4 00	1 42	593 7	6 4	2,201 7	209 9	1,074
12	702 7	69 5	5 00	76	0020	0025	40 0	5 5	2 15	64	587 0	6 7	1,625 0	168 3	10,266
13	841 3	85 1	4 50	78	0020	0025	26 0	5 0	1 85	55	609 3	8 0	2,241 7	234 8	12,334
14	978 0	101 6	4 00	74	0020	0025	20 0	5 5	2 00	78	607 0	8 3	2,275 0	231 9	8,266
15	525 3	59 1	5 67	95	0020	0025	60 0	15 2	1 65	70	531 3	3 1	248 3	30 4	1,420
16	594 7	68 1	5 57	99	0015	0028	60 0	13 6	1 30	70	554 3	4 1	798 3	78 0	1,479
17	1,013 3	95 9	4 17	81	0020	0025	47 5	8 6	85	68	571 0	6 0	1,245 0	124 9	10,001
18	1,248 7	127 3	4 10	81	0020	0025	25 0	8 2	2 00	76	597 0	7 8	1,878 3	180 7	3,863
19	726 0	85 1	4 17	92	0015	0028	32 5	11 0	1 00	96	561 0	5 3	1,078 3	129 7	6,229

Appendix B. Estimates of in-place natural gas resources in Devonian shales of the Appalachian basin

[Negl., negligible, less than 0.5 billion ft^3, in billions of cubic feet]

Fractile	Macrofracture gas	Microporosity gas	Sorbed gas	Total gas
Play 1—North-Central Ohio				
0.95	0	1,245	13,153	17,856
0.90	Negl	2,332	14,808	19,920
0.75	4	4,190	16,897	22,685
0.50	23	6,125	19,510	25,705
0.25	40	8,131	22,292	29,169
0.10	57	9,967	25,045	32,086
0.05	69	11,154	26,643	34,237
Mean	26	6,164	19,687	25,878
Mean gas content (percent)	Negl	24	76	100
Play 2—Western Lake Erie				
0.95	0	9,054	10,447	21,732
0.90	Negl	9,891	11,146	22,626
0.75	3	10,986	12,558	24,411
0.50	17	12,386	13,963	26,417
0.25	32	13,757	15,463	28,535
0.10	47	14,981	16,895	30,302
0.05	57	15,853	17,808	31,296
Mean	21	12,413	14,025	26,459
Mean gas content (percent)	Negl	47	53	100
Play 3—Eastern Lake Erie				
0.95	0	1,226	552	2,065
0.90	0	1,344	643	2,196
0.75	Negl	1,554	749	2,394
0.50	2	1,757	903	2,658
0.25	4	1,978	1,046	2,947
0.10	6	2,213	1,187	3,196
0.05	7	2,316	1,267	3,339
Mean	3	1,768	905	2,676
Mean gas content (percent)	Negl	66	34	100
Play 4—Plateau Ohio				
0.95	0	10,513	26,687	44,432
0.90	0	13,258	29,525	47,892
0.75	0	16,605	34,135	53,205
0.50	69	20,657	38,805	59,771
0.25	165	24,836	43,701	65,992
0.10	246	28,741	48,469	72,132
0.05	304	31,749	51,385	76,203
Mean	99	20,843	38,987	59,929
Mean gas content (percent)	Negl	35	65	100
Play 5—Eastern Ohio				
0.95	0	16,850	13,719	35,236
0.90	0	18,614	14,588	36,872
0.75	1	21,744	16,930	40,529
0.50	90	25,262	19,161	44,602
0.25	191	28,854	21,581	48,899
0.10	296	31,988	23,856	52,383
0.05	356	33,665	25,270	55,077
Mean	118	25,286	19,323	44,727
Mean gas content (percent)	Negl	57	43	100

Appendix B. Estimates of in-place natural gas resources in Devonian shales of the Appalachian basin—Continued

Fractile	Macrofracture gas	Microporosity gas	Sorbed gas	Total gas
Play 6—Western Penn-York				
0.95	0	16,155	2,581	20,410
0.90	0	16,957	3,146	21,092
0.75	0	18,076	3,860	22,599
0.50	32	19,458	4,714	24,293
0.25	75	20,755	5,672	25,881
0.10	116	21,979	6,588	27,322
0.05	141	22,838	7,023	28,154
Mean	46	19,451	4,775	24,271
Mean gas content (percent)	Negl	80	20	100
Play 7—Southern Ohio Valley				
0.95	0	7,774	8,062	19,687
0.90	1	9,193	9,233	20,969
0.75	10	11,254	11,424	24,203
0.50	60	13,672	13,715	27,569
0.25	108	16,171	16,192	30,826
0.10	156	18,283	18,619	34,300
0.05	184	19,878	20,373	36,245
Mean	68	13,710	13,881	27,659
Mean gas content (percent)	Negl	50	50	100
Play 8—Western Rome Trough				
0.95	0	8,697	21,007	37,975
0.90	1	12,212	23,891	41,339
0.75	20	16,647	28,726	48,423
0.50	146	21,014	34,270	55,964
0.25	287	26,112	39,760	63,430
0.10	414	31,177	45,195	70,235
0.05	478	34,137	48,562	74,044
Mean	179	21,371	34,471	56,020
Mean gas content (percent)	Negl	38	62	100
Play 9—Tug Fork				
0.95	0	4,246	6,305	13,665
0.90	0	5,554	7,322	14,985
0.75	20	7,265	8,637	17,074
0.50	128	9,335	10,211	19,640
0.25	249	11,202	11,750	22,175
0.10	346	13,389	13,102	24,579
0.05	414	14,278	14,075	25,931
Mean	153	9,314	10,249	19,716
Mean gas content (percent)	1	47	52	100
Play 10—Pine Mountain				
0.95	0	4,108	4,621	10,720
0.90	0	4,889	5,104	11,418
0.75	3	5,848	6,151	12,868
0.50	22	7,016	7,385	14,379
0.25	40	8,175	8,690	16,296
0.10	57	9,351	9,829	17,765
0.05	69	10,173	10,739	18,652
Mean	25	7,067	7,475	14,566
Mean gas content (percent)	Negl	49	51	100

Appendix B. Estimates of in-place natural gas resources in Devonian shales of the Appalachian basin—Continued

Fractile	Macrofracture gas	Microporosity gas	Sorbed gas	Total gas
Play 11—Plateau Virginia				
0.95	0	1,155	1,078	3,903
0.90	0	2,029	1,572	4,518
0.75	5	2,948	2,153	5,650
0.50	37	4,130	2,806	7,097
0.25	75	5,345	3,584	8,381
0.10	105	6,287	4,295	9,596
0.05	128	6,958	4,732	10,224
Mean	46	4,131	2,876	7,052
Mean gas content (percent)	1	59	41	100
Play 12—Pittsburgh Basin				
0.95	0	58,045	9,942	76,791
0.90	7	62,551	12,259	82,563
0.75	117	70,740	15,840	91,179
0.50	478	79,581	20,539	101,305
0.25	819	88,942	26,033	112,192
0.10	1198	98,826	31,324	123,719
0.05	1435	104,640	35,010	129,939
Mean	534	80,199	21,387	102,120
Mean gas content (percent)	1	79	21	100
Play 13—Eastern Rome Trough				
0.95	0	48,390	10,774	70,745
0.90	5	54,338	12,557	76,900
0.75	131	64,309	17,934	87,554
0.50	779	74,793	23,601	100,077
0.25	1494	85,435	29,381	111,933
0.10	2,210	96,760	36,238	124,828
0.05	2,600	103,190	40,141	132,498
Mean	956	75,146	24,178	100,280
Mean gas content (percent)	1	75	24	100
Play 14—New River				
0.95	0	22,317	4,613	38,493
0.90	0	27,762	7,494	42,516
0.75	105	35,455	11,396	51,757
0.50	637	44,611	16,347	62,454
0.25	1,265	53,477	22,648	74,393
0.10	1,858	62,941	28,697	84,603
0.05	2,214	68,623	32,831	91,737
Mean	796	44,912	17,431	63,139
Mean gas content (percent)	1	71	28	100
Play 15—Portage Escarpment				
0.95	0	6,676	431	8,542
0.90	Negl	7,888	838	9,778
0.75	1	10,074	1,291	11,952
0.50	8	12,400	1,843	14,447
0.25	16	15,057	2,540	17,170
0.10	23	17,692	3,236	19,793
0.05	27	19,102	3,711	21,320
Mean	10	12,662	1,953	14,625
Mean gas content (percent)	Negl	87	13	100

Appendix B. Estimates of in-place natural gas resources in Devonian shales of the Appalachian basin—Continued

Fractile	Macrofracture gas	Microporosity gas	Sorbed gas	Total gas
Play 16—Cattaraugus Valley				
0.95	0	8,592	308	10,428
0.90	0	9,953	526	11,668
0.75	1	12,145	1,058	13,907
0.50	22	14,427	1,761	16,394
0.25	48	17,260	2,476	19,167
0.10	76	19,641	3,239	21,571
0.05	92	21,162	3,735	23,225
Mean	30	14,700	1,840	16,570
Mean gas content (percent)	Negl	89	11	100
Play 17—Penn-York Plateau				
0.95	0	90,944	0	98,116
0.90	3	98,479	119	107,728
0.75	88	114,327	4,227	125,160
0.50	465	134,663	9,550	144,256
0.25	890	154,385	15,337	166,735
0.10	1,324	172,236	21,021	184,883
0.05	1,644	182,577	25,826	195,175
Mean	575	134,910	10,481	145,966
Mean gas content (percent)	Negl	92	7	100
Play 18—Western Susquehanna				
0.95	0	12,595	3,391	24,149
0.90	2	18,600	4,884	28,421
0.75	48	25,422	7,412	35,759
0.50	334	32,976	10,440	44,110
0.25	632	41,308	13,865	53,981
0.10	888	49,539	17,198	62,755
0.05	1,032	54,673	19,397	67,707
Mean	394	33,602	10,904	44,900
Mean gas content (percent)	1	75	24	100
Play 19—Catskill				
0.95	0	17,268	0	22,117
0.90	0	23,141	0	27,431
0.75	1	31,340	1,771	36,380
0.50	143	40,943	4,703	46,788
0.25	333	51,828	8,326	57,992
0.10	520	62,181	11,869	69,037
0.05	622	67,960	13,648	75,778
Mean	204	41,978	5,454	47,636
Mean gas content (percent)	Negl	88	11	100
Total Appalachian Basin—Plays Independent				
0.95	2,163	504,210	223,089	757,605
0.90	2,585	520,538	233,549	778,887
0.75	3,329	549,573	244,470	808,910
0.50	4,183	580,726	259,475	843,059
0.25	5,125	608,909	274,635	878,289
0.10	6,143	639,061	289,429	910,865
0.05	6,789	653,999	299,330	931,704
Mean	4,280	579,627	260,282	844,189
Mean gas content (percent)	1	69	31	100

Appendix B. Estimates of in-place natural gas resources in Devonian shales of the Appalachian basin—Continued

Fractile	Macrofracture gas	Microporosity gas	Sorbed gas	Total gas
	Total Appalachian Basin—Plays Dependent			
0 95	0	345,850	137,671	577,062
0 90	18	398,985	159,654	630,831
0 75	560	480,930	203,150	727,690
0 50	3,493	575,208	254,226	837,924
0 25	6,765	673,009	310,335	956,095
0 10	9,942	768,173	365,901	1,065,084
0 05	11,874	824,926	402,179	1,130,783
Mean	4,280	579,627	260,282	844,189
Mean gas content (percent)	1	69	31	100

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