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ANALYSIS OF STRATIGRAPHIC AND PRODUCTION RELATIONSHIPS OF DEVONIAN-SHALE GAS RESERVOIRS IN LAWRENCE COUNTY, OHIO

by

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ABSTRACT

The Devonian shales in Lawrence County, Ohio, have been analyzed to determine the relationships between natural gas production, geologic factors, and well-completion techniques. The study was initiated by compiling a comprehensive computerized Devonian-shale database for Lawrence County. A cross-section network, isopach maps, and structure maps were constructed on numerous stratigraphic horizons to determine stratigraphic and structural controls on the Devonian shales. Gas shows, completion intervals, stimulation techniques, and production data were analyzed to characterize Devonian shale reservoirs in Lawrence County. Integration of the geologic and production data indicated that the lower Huron Shale Member is the principal producing unit; there are no other obvious relationships between stratigraphy and production. Several structural features identified by the mapping indicated areas of increased fracturing where higher Devonian-shale gas production may be expected. Comparison of isopotential maps and cumulative-production maps showed little or no correlation between initial production rates and long-term performance of Devonian shale wells. This lack of correlation may be due to inconsistent reporting procedures and a small data set rather than natural conditions. The average decline curve exhibited typical shale-well characteristics, with initial rapid decline followed by a long stable period. This type of decline curve indicates a multiporosity reservoir system for the Devonian shales in Lawrence County.

INTRODUCTION

In late 1985 the Ohio Department of Natural Resources, Division of Geological Survey (ODGS) began a study of the Devonian shales in three areas of southeastern Ohio as part of a regional research project on the Devonian shales being conducted by the Gas Research Institute (GRI) of Chicago in Ohio, Kentucky, and West Virginia. The ODGS study is a detailed, computer-assisted look at the producing areas in Lawrence County (phase I), Meigs County (phase II), and Monroe, Noble, and Washington Counties (phase III) (fig. 1). The primary objectives of the study are to (1) establish a digitized database including stratigraphic, production, and completion data on the Devonian shales; (2) refine the stratigraphic framework throughout the area of Devonian-shale production; (3) identify Devonian-shale gas fields and pools; (4) determine relationships between production, stratigraphy, and completion techniques; and (5) provide the data to industry in forms usable for developing drilling programs.

This report presents the results of the first year of the study (Ohio Division of Geological Survey, 1987), which concentrated on Lawrence County. The digital database developed for Lawrence County was used to produce the maps and other figures in this report. The database is not reproduced in this report but is available at the Division offices. It consists of permit and completion data for 467 wells, geophysical-log tops for the study interval for 100 wells, and 1,193 annual production records from 93 wells.

ACKNOWLEDGMENTS

This investigation by the Ohio Division of Geological Survey was funded by GRI through Contract No. 5085-213-1154. John D. Gray was the Project Manager for the ODGS during this study. Lawrence H. Wickstrom developed the computer system for the project and structured the databases. Linda Dunbar handled much of the data entry and Angelena Bailey typed the manuscript. Dr. Paul E. Potter reviewed early drafts of this report and made helpful comments.

STRATIGRAPHY OF DEVONIAN-MISSISSIPPIAN SHALES IN LAWRENCE COUNTY

PREVIOUS WORK

A detailed study of Devonian shales in Lawrence County has not been performed in the past. However, many regional studies of Devonian shales involved records of wells in

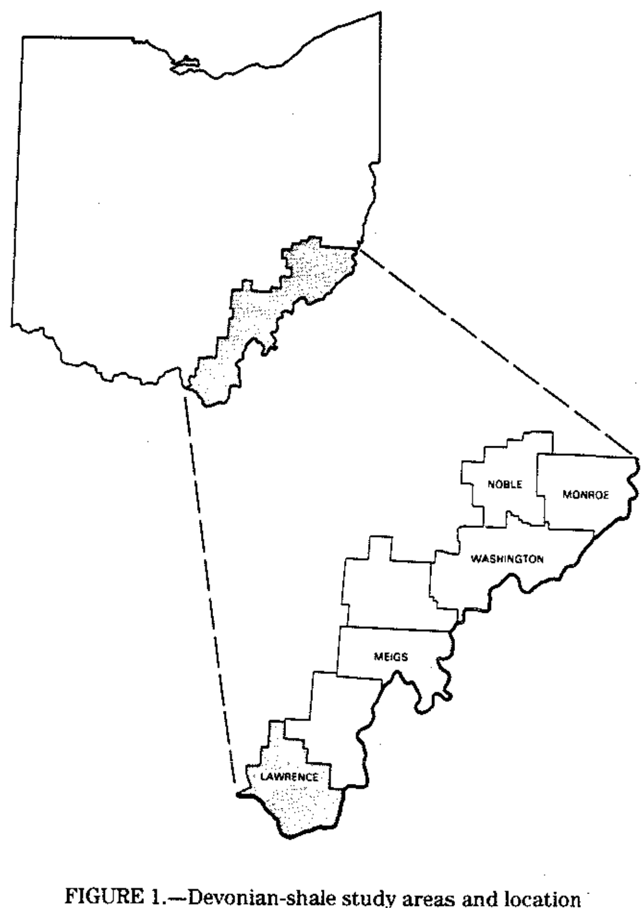

FIGURE 1.—Devonian-shale study areas and location of Lawrence County, Ohio.

Lawrence County. Prior to the widespread use of geophysical logs, Pepper and others (1954) used outcrops, well samples, and drillers' logs in a classic study of the Bedford Shale (Mississippian) and Berea Sandstone (Mississippian) in the Appalachian Basin. In addition to the Bedford and the Berea, the uppermost Devonian shales were examined by these authors. Schwietering (1970, 1979) used outcrops, sample cuttings, and geophysical logs in regional studies of Devonian shales in Ohio and adjacent states. In a study of the Cleveland Shale Member of the Ohio Shale in Ohio, Lewis and Schwietering (1971) used outcrops, sample cuttings, and geophysical logs. In another regional study, Janssens and de Witt (1976) used samples and logs to evaluate gas potential of Devonian shales in Ohio. Provo (1977) used samples and logs for a Devonian-shale study of the central Appalachian Basin. Charpentier and others (1982) did a qualitative assessment of production potential of Devonian shales in the Appalachian Basin based upon thickness of black shales, percentage of organic carbon, thermal maturation, and structural complexity. They recognized Lawrence County as having a moderate potential for gas production. In a regional study for the U.S. Department of Energy, Gray and others (1982) used outcrops, samples, and geophysical logs to study the Devonian shales of Ohio. Most recently, Roen and de Witt (1984) performed a comprehensive regional study of Devonian shales in the Appalachian Basin. Records from wells in Lawrence County were used to evaluate Devonian shales in all of these regional studies.

METHODS

The stratigraphic investigation of Devonian-Mississippian shales in southeastern Ohio was begun by constructing a cross-section network (fig. 2). Three detailed cross sections were constructed in Lawrence County and vicinity; these are on open file at the Ohio Division of Geological Survey (Baranoski, 1987a). The regional cross sections were made using published cross sections by the U.S. Geological Survey (Wallace and others, 1978; Roen and others, 1978) and by the Ohio Division of Geological Survey (Janssens and de Witt, 1976; Gray and others, 1982) and geophysical logs on file at the Ohio Division of Geological Survey. The cross sections were oriented to show the regional aspects of Devonian-Mississippian shales in southeastern Ohio, especially along the strike and dip of the Appalachian Basin. In order to maintain continuity of stratigraphic correlation across state boundaries, these lines were extended into West Virginia and Kentucky. The Geological Surveys of West Virginia and Kentucky are currently investigating Devonian shales under contracts with the Gas Research Institute. The contact of the Sunbury Shale and Berea Sandstone has been used as the stratigraphic datum because it is easily recognized on gamma ray and neutron/density logs and is present throughout the study area. The cross sections include the Onondaga Limestone (Middle Devonian) as a lower contact where it was penetrated and logged.

Throughout this report, names of creeks or rivers have been assigned to geologic features in Lawrence County. The creeks or rivers roughly parallel the subsurface features herein named: Symmes Creek Monocline, Ohio River Fault, Coffee and Tea Creek Fault, Little Storm Creek Trend, Rankin Creek Trend, Indian Guyan Creek Monocline, and Bear Creek Structure (see discussion of structure on p. 12).

Stratigraphic markers, based on log response, were chosen which could be traced throughout the study area. The Devonian-Mississippian sequence was subdivided into mappable units based on the gamma ray and neutron/density logs (fig. 3). Thus, the internal shale stratigraphy observed is a result of contrasting radioactivity on gamma

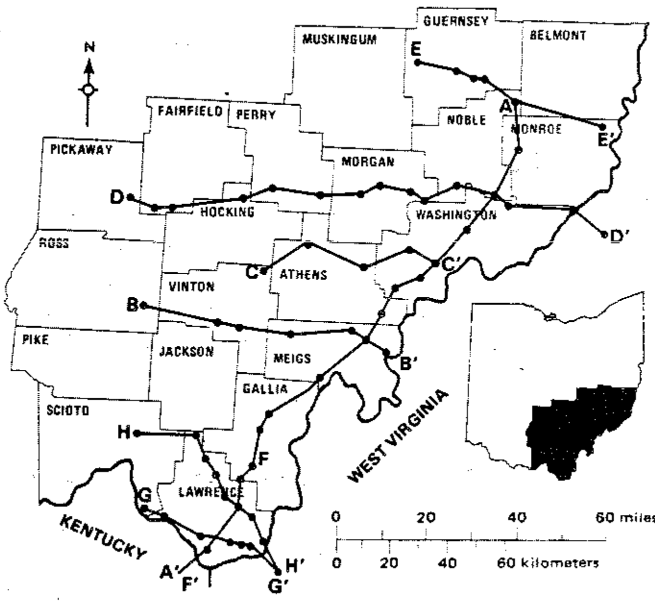

FIGURE 2.—Stratigraphic cross-section network of Devonian shales in southeastern Ohio.

ray logs, low bulk density, and bound water on neutron logs (Schlumberger Limited, 1972). Uranium concentration and its association with kerogen of black shales has been well documented by Swanson (1960, p. 4) and Merkel (1981, p. 78). Descriptions of samples and cores by other workers were utilized where possible. Both Ohio and New York nomenclature has been used to identify the stratigraphic units mapped for this study. However, many of the units described in this report have not been established as formal units in Ohio, following the revised rules of the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983, p. 850-851). Informal units are identified by quotation marks or lower case (*e.g.*, "Lower" Huron or lower Huron). The mixed nomenclature (formal and informal, New York and Ohio) used here has been used by Provo and others (1978), Roen and others (1978), Schwietering (1979), and Gray and others (1982). Such usage will continue until the stratigraphic nomenclature is formalized.

REGIONAL SETTING AND GENERAL STRATIGRAPHY

Lawrence County is Ohio's southernmost county and is bounded by the Ohio River to the south, which separates the county from Kentucky and West Virginia. Surface elevations range from 500 feet above sea level along the Ohio River in Hamilton Township to 1,036 feet in west-central Decatur Township. At the surface, rocks of Mississippian and Pennsylvanian age crop out. These rocks consist of a complex assemblage of sandstones, siltstones, shales, coals, and limestones which accumulated under predominantly marine and deltaic conditions.

The Devonian-Mississippian stratigraphic units included in this study are: upper Olentangy Shale (subdivided into New York-equivalent units: the Rhinestreet and Angola Shale Members of the West Falls Formation and the Java Formation and its Pipe Creek Member), Huron Shale Member (subdivided into lower, middle, and upper units) of the Ohio Shale, Three Lick Bed of the Ohio Shale, Cleveland Shale Member of the Ohio Shale, Chagrin Shale Member of the Ohio Shale, Bedford Shale, Berea Sandstone, and Sunbury Shale (fig. 3). The upper Olentangy is of Late Devonian

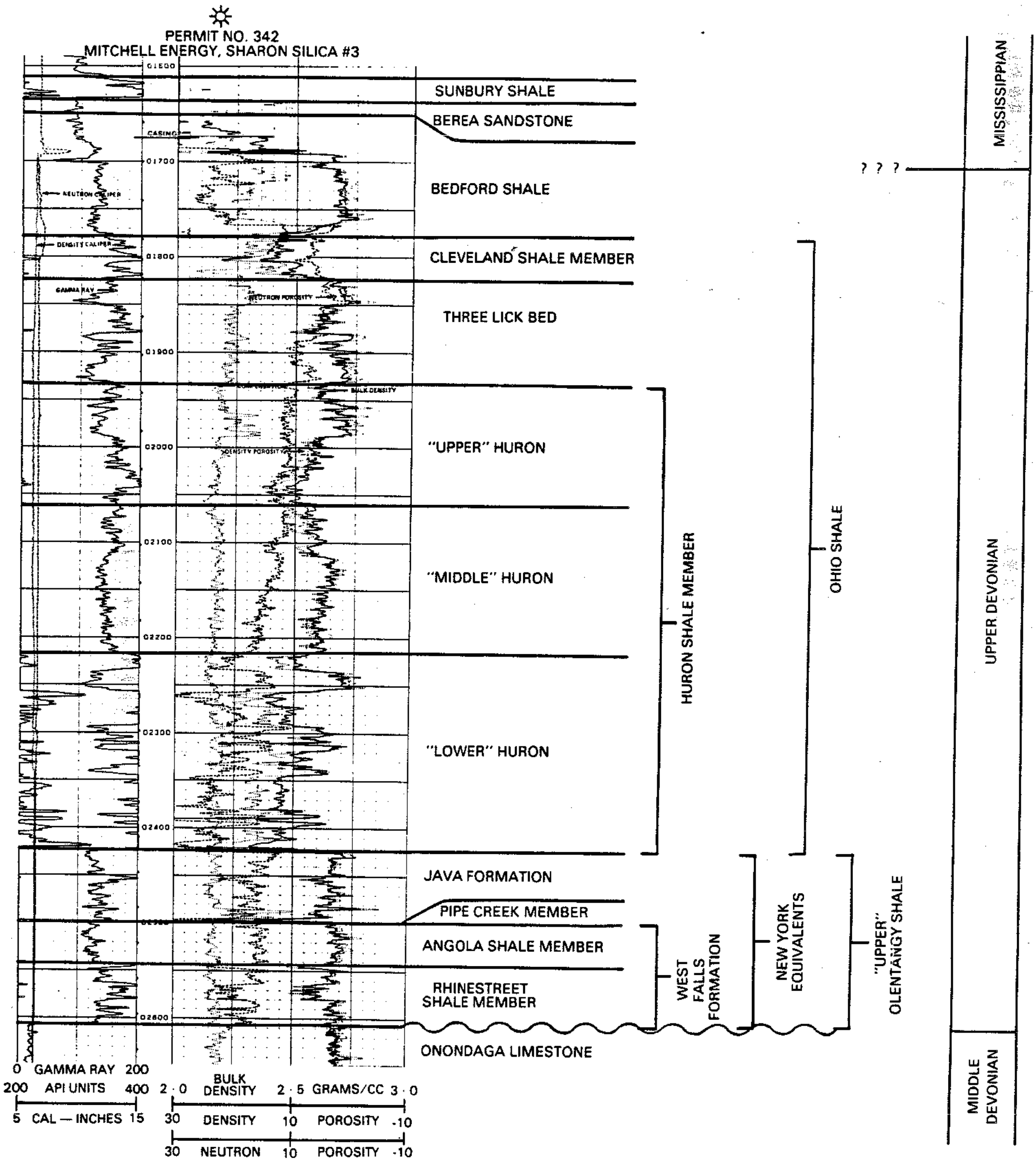

FIGURE 3.—Typical log for the Devonian-Mississippian shale sequence in central Lawrence County, Ohio. Chagrin Shale Member not present in central Lawrence County.

age and lies unconformably on the Middle Devonian Onondaga Limestone (Schwietering, 1979, p. 27). The interval from the base of the upper Olentangy to the top of the Sunbury is a continuous and conformable sequence. The lower, middle, and upper Huron, the Three Lick, the Cleveland, and the Chagrin are the only Devonian shale units exhibiting significant facies variations in Lawrence County. The Devonian-Mississippian boundary apparently lies within the Bedford Shale and cannot be precisely determined from geophysical logs.

From a regional perspective, Lawrence County is situated on the western flank of the Appalachian Basin (fig. 4). The Devonian shales of Lawrence County thicken eastward. Detailed stratigraphic studies of the Ohio Shale in Lawrence County show the same broad basinwide facies variations observed in Devonian shales by Potter and others (1982), Roen (1984), and Ettensohn (1985). In general, two lithologies dominate the shale sequence: black organic-rich shale and gray to greenish-gray shale. The black organic-rich shale accumulated in the moderately deep, marine, anoxic western portion of the Appalachian Basin (Ettensohn, 1985). The gray and greenish-gray shale, along with siltstone and sandstone, was deposited in the eastern to central portion of the basin as distal turbidites of the Catskill Delta (Potter and others, 1982, p. 294; Lundegard and others, 1985, p. 107).

During Devonian time, variations in terrigenous supply from an eastern source area resulted in deposition of tongues of greenish-gray oxidized mud, silt, and sand westward in the deep anoxic part of what was the Devonian black-shale basin (see diagrammatic cross sections by Potter and others, 1982, and Ettensohn, 1985). Isopach maps and cross sections of the shale units in Lawrence County show (1) the general north-south continuity of the

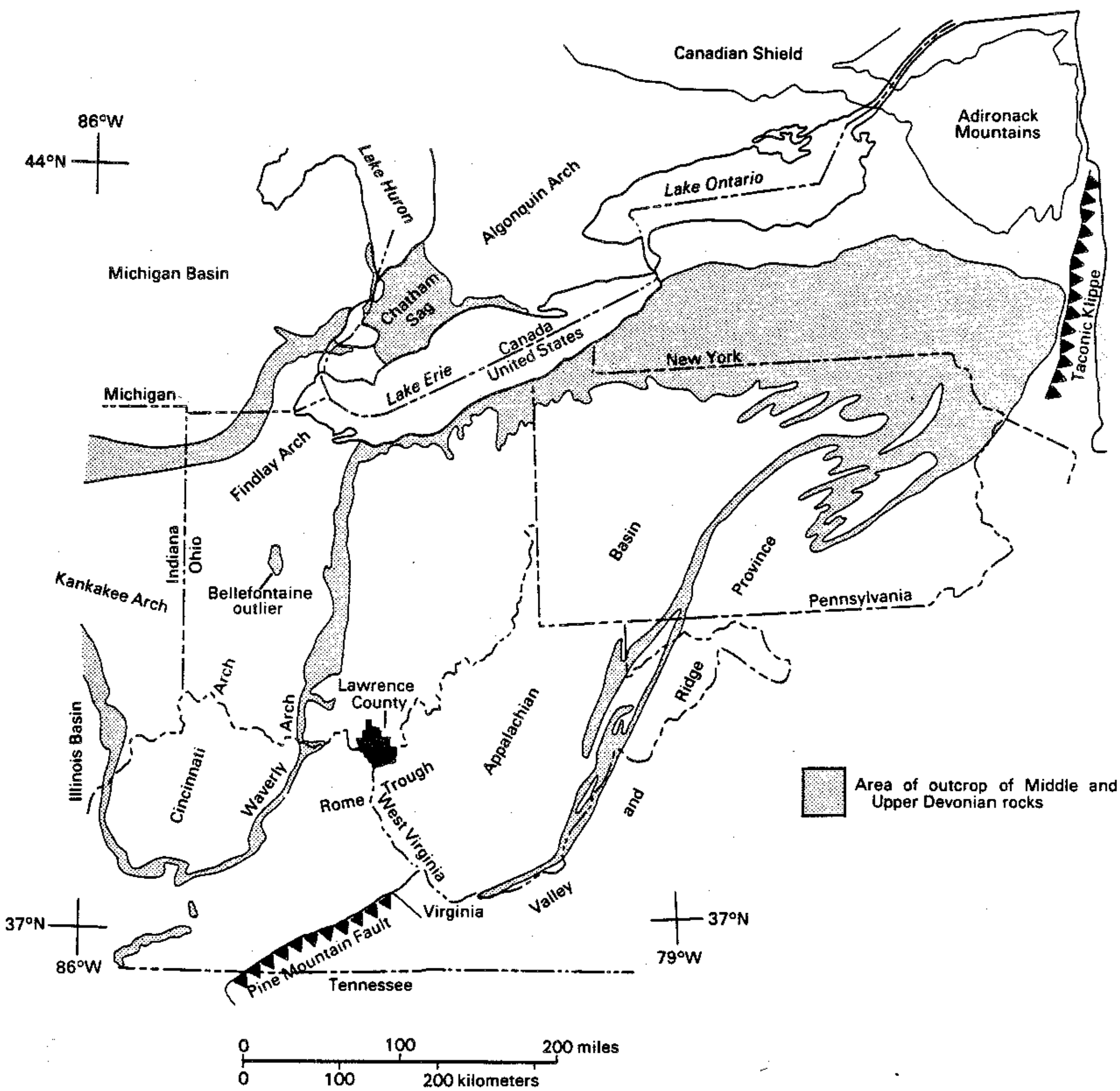

FIGURE 4.—Regional structural and stratigraphic setting and location of Lawrence County, Ohio (modified from Schwietering, 1979).

black-shale facies, (2) westward progradation of clastic sediments and resultant interfingering with black shales, and (3) eastward thickening of sediments during the Late Devonian.

"UPPER" OLENTANGY SHALE

The Olentangy Shale has been separated into lower and upper parts in central and southern Ohio (Tillman, 1970, p. 202; Schwietering, 1979, p. 27), but only the upper Olentangy Shale is present in Lawrence County. Lithologically, the upper Olentangy consists of medium- to dark-gray shale, greenish-gray shale, black shale, and minor amounts of limestone (Schwietering, 1979, p. 27).

In the subsurface the upper Olentangy has four marker beds, each with a characteristic log signature (fig. 3). These four marker beds can be traced into western New York (Roen and others, 1978) and are distal beds of the West Falls and Java Formations. In ascending order, these units are the Rhinestreet Shale Member of the West Falls Formation, Angola Shale Member of the West Falls Formation, Pipe Creek Member of the Java Formation, and Java Formation. These units are easily mapped, using gamma ray and density/neutron logs, from Lawrence County into neighboring Scioto, Jackson, and Gallia Counties, Ohio; Boyd and Greenup Counties, Kentucky; and Wayne and Cabell Counties, West Virginia.

The Rhinestreet Shale Member of the West Falls Formation, the lowest mappable bed of the upper Olentangy Shale, lies unconformably upon the Onondaga Limestone in Lawrence County. The Rhinestreet is recognized on logs by its high gamma ray response and corresponding high neutron/density porosity. The Rhinestreet consists of black shale interbedded with dark-gray and gray-green shale (Dowse, 1980, p. 51). As seen on the cross sections (Baranoski, 1987a), the gamma ray response is consistent across the study area, indicating no major facies changes.

The Angola Shale Member is characterized by a lower gamma ray response than the underlying Rhinestreet Member and overlying Pipe Creek Member. The cross sections (Baranoski, 1987a) show the gamma ray response to be consistent across the study area, indicating no facies variations. The Angola consists of gray to green-gray shale (Dowse, 1980, p. 53), which thickens eastward.

The Java Formation conformably overlies the Angola Member. This lower contact is very sharp and defined by the base of the Pipe Creek Member of the Java. The Pipe Creek is a thin persistent regional marker bed and is recognized on geophysical logs by its moderate gamma ray response and an especially high neutron/density porosity (fig. 3). This distinctive bed correlates with Schwietering's (1970, p. 29) "A" Horizon. Above the Pipe Creek Member the Java is characterized by a gamma ray response which is intermediate to the underlying Angola Member and overlying Huron Member. The Java consists predominantly of gray shale and siltstone (Dowse, 1980, p. 57). The unit is stratigraphically consistent across the study area and generally thickens eastward.

Total thickness of the upper Olentangy Shale, which consists of the four units described above, ranges from 130 feet in western Hamilton Township to 270 feet in eastern Rome Township (fig. 5). Depositional strike is generally north-south. No major facies variations occur (Baranoski, 1987a), and the unit can be traced into the adjacent counties of Ohio, Kentucky, and West Virginia. The most significant trend on the isopach map (fig. 5) is the NW-SE trend in Hamilton, Elizabeth, Lawrence, and Upper Townships. This thick trend is probably related to the Little Storm Creek Trend discussed below. A subtle N-S thick trend in eastern Windsor and Union Townships is evident on the upper Olentangy isopach map. This N-S trend possibly delineates a "down-to-basin" fault zone and is herein named the Indian Guyan Creek Monocline.

OHIO SHALE

The Ohio Shale in Lawrence County is subdivided into four units: the Huron Shale Member, the Three Lick Bed, the Cleveland Shale Member, and the Chagrin Shale Member. Unlike the underlying units, significant facies changes occur in these units in eastern Lawrence County. Lithologically they consist predominantly of carbonaceous silty dark-brown shale, with minor amounts of blue-gray to gray shale and rare beds of gray and dark-brown argillaceous limestone (Schwietering, 1979, p. 31). As with the underlying upper Olentangy Shale, several structural features apparently influenced deposition. The primary features that have been named are the Little Storm Creek and Rankin Creek Trends and the Ohio River Fault; secondary features are the Coffee and Tea Creek Fault and the Indian Guyan Creek Monocline (see fig. 19 and discussion on p. 12).

Huron Shale Member

In Lawrence County the Huron Member is subdivided into three mappable units, based on geophysical logs: lower, middle, and upper Huron (fig. 3). The lower Huron is easily mapped everywhere in Lawrence and adjacent counties because of its high gamma ray response, but the overlying middle Huron and upper Huron can only be mapped reliably in the western and central portions of the county (Baranoski, 1987a). In the eastern part of the county, correlation is difficult because black shales with high gamma ray response are replaced by shales of the Chagrin Shale Member, which have a lower gamma ray response.

"Lower" Huron.—The lower Huron is easily recognized on the gamma ray and neutron/density logs by the characteristic high natural radiation and corresponding high porosity response. The cross sections (Baranoski, 1987a) illustrate the consistency of the gamma ray response across the study area and the eastward thickening of the unit. A minor facies variation, 20 to 50 feet thick, in the upper part of the lower Huron is indicated by a lower gamma ray response in the eastern portion of the county (Baranoski, 1987a, dip cross section H-H′ from permit nos. 235 to 532). Similiar facies variations were noted on dip cross section G-G′ from permit nos. 291 to 532, and on strike cross section F′-F from permit nos. 18327 to 479.

The lower Huron conformably overlies the upper Olentangy Shale throughout Lawrence County and is traceable into adjacent counties of Ohio, Kentucky, and West Virginia. The lower Huron is predominantly brownish-black organic-rich shale (Provo, 1977, p. 45). Thickness ranges from 130 feet in the western portion of the county to 280 feet in the east (fig. 6). The lower Huron thickens basinward, as do the underlying units. However, its rate of thickening is more rapid and more irregular than older units. Consequently, the lower Huron exhibits local departures from the general N-S depositional strike.

Several W-E- to NW-SE-trending areas of anomalously thick lower Huron have been mapped. The trends have an irregular, lobate outline and are especially prominent in Perry, Lawrence, Fayette, Union, and Windsor Townships. Kepferle (1978, p. 22) observed "partly coalesced black shale lobes" in the western black-shale facies of Kentucky and West Virginia; these lobes may be related to gas production in the Big Sandy Field. Slight intertonguing of the upper part of the lower Huron with the overlying middle Huron is indicated in eastern Lawrence County (Baranoski, 1987a).

Slight thickening of the unit occurs along the Coffee and Tea Creek Fault in northeastern Aid Township. Thinning of the lower Huron is present over the Bear Creek Structure in north-central Union Township.

"Middle" Huron.—The middle Huron conformably overlies the lower Huron. It consists of brownish-black and gray shales (Provo, 1977, p. 43) and is recognized on gamma ray logs by a lower gamma ray response than either the underlying lower Huron or overlying upper Huron. However, the upper contact is somewhat difficult to pick in the eastern portion of the county as a result of fewer black shales (Baranoski, 1987a, G-G′, permit nos. 335 to 210; H-H′, permit nos. 351 to 221). This decrease in black shales may indicate a facies change from the middle Huron to the Chagrin Shale Member. Overall, the thickness of the middle Huron (fig. 7) is more irregular than that of the underlying lower Huron, so that a well-defined N-S depositional strike occurs only in the western part of the county. Thickness generally increases from 120 feet in the western portion of the county to 210 feet in northeastern Lawrence County.

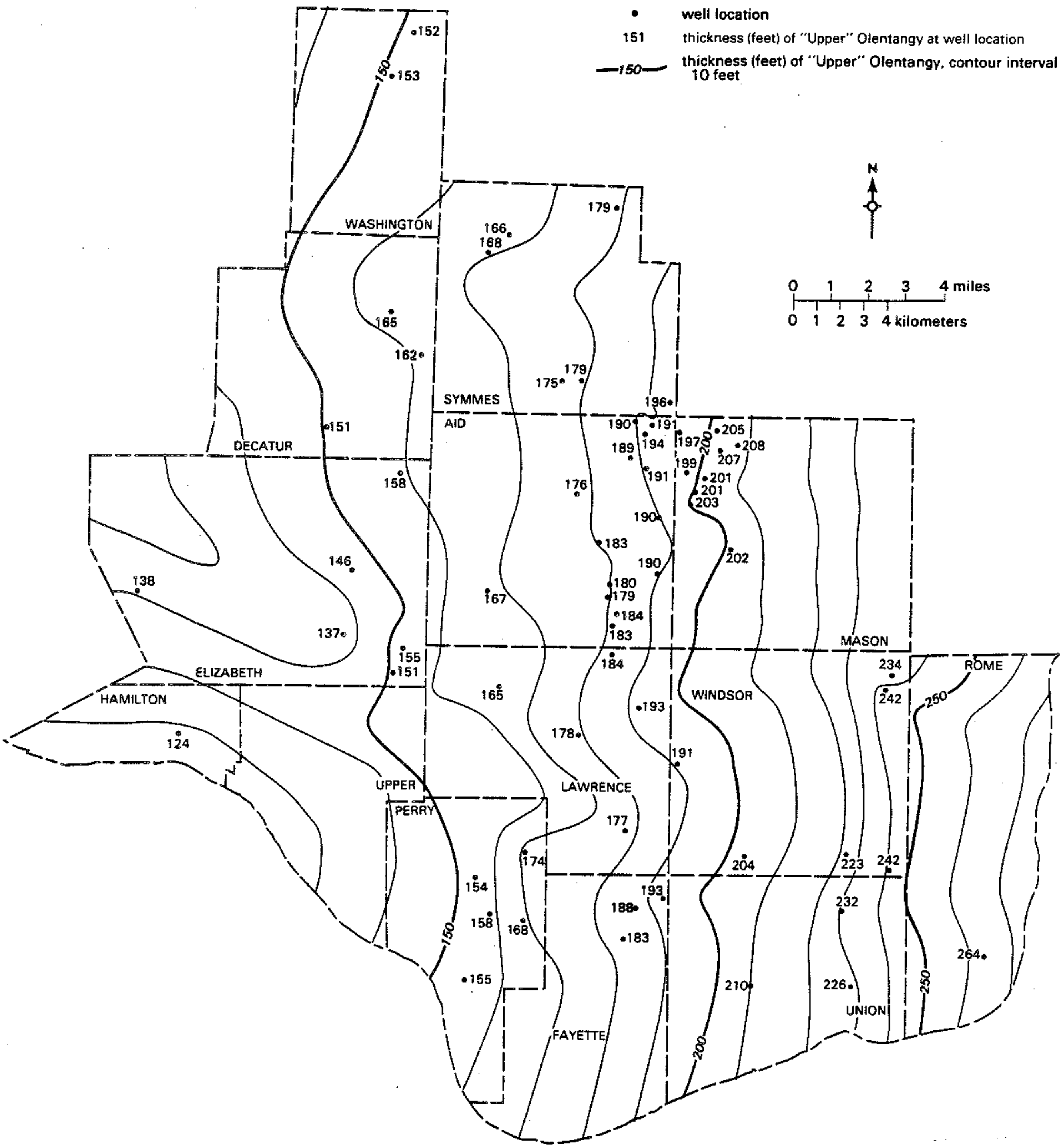

FIGURE 5.—Isopach map of the upper Olentangy Shale, Lawrence County, Ohio.

The NW-SE-trending thick areas of the upper Olentangy and lower Huron are not as prominent in the middle Huron. Several broad thin areas occur in Perry, Fayette, Lawrence, and Windsor Townships. The slight NW-SE thick trend associated with the Coffee and Tea Creek Fault is better developed in the middle Huron than in the lower Huron. A NE-SW thick trend is developed in central Rome and eastern Union Townships; it is 2 miles wide by 8 miles long and parallels the Ohio River Fault (discussed in the section on structural geology).

"Upper" Huron.—The upper Huron conformably overlies the middle Huron and is recognized by a slightly higher gamma ray response than that of the underlying middle Huron. The lower and upper contacts of the upper Huron are difficult to identify in the eastern portion of the county because of fewer black shales (Baranoski, 1987a, G-G′, permit nos. 335 to 210; H-H′, permit nos. 351 to 221). These tenuous contacts indicate a lateral facies change from the upper Huron to the Chagrin Shale Member. Provo (1977, p. 40) describes the upper Huron as a massive brownish-black

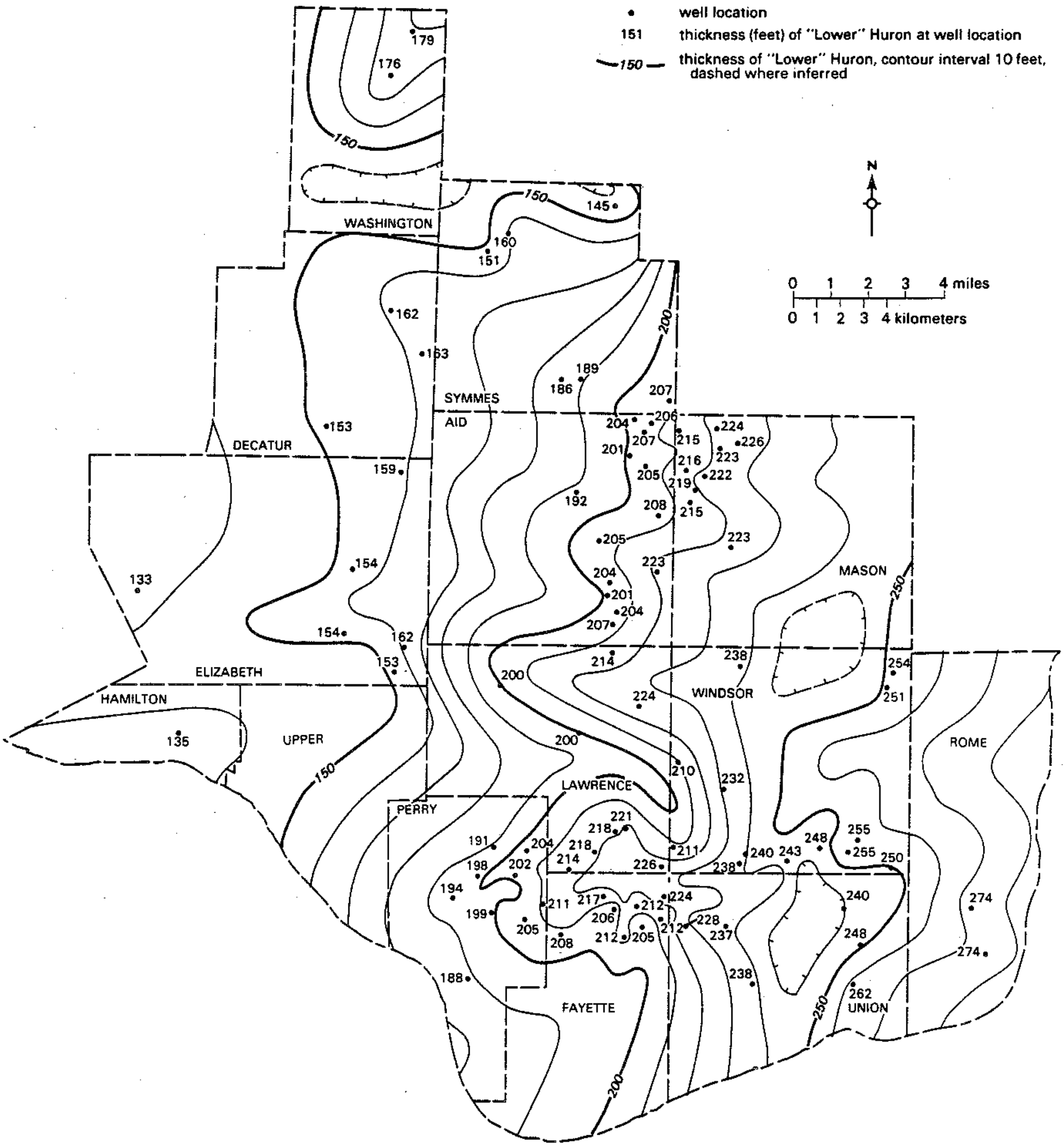

FIGURE 6.—Isopach map of the lower Huron Shale Member, Lawrence County, Ohio.

shale. However, in eastern Lawrence County the gamma ray response is indicative of the gray and greenish-gray shales of the Chagrin Member. The upper Huron generally thickens eastward from 90 feet in the western portion of the county to 200 feet in the eastern portion of the county (fig. 8). Thickness trends are more variable than those of the underlying units.

Several NW-SE-trending thick areas have been mapped and are well expressed in Elizabeth, Aid, and Lawrence Townships, Aid and Decatur Townships, and Symmes and Washington Townships. These thick areas are parallel to the Little Storm Creek Trend (see fig. 19). Thick trends related to the Coffee and Tea Creek Fault and the Ohio River Fault are better developed than in the underlying units. As with the lower Huron, thinning of the upper Huron occurs over the Bear Creek Structure in Union Township.

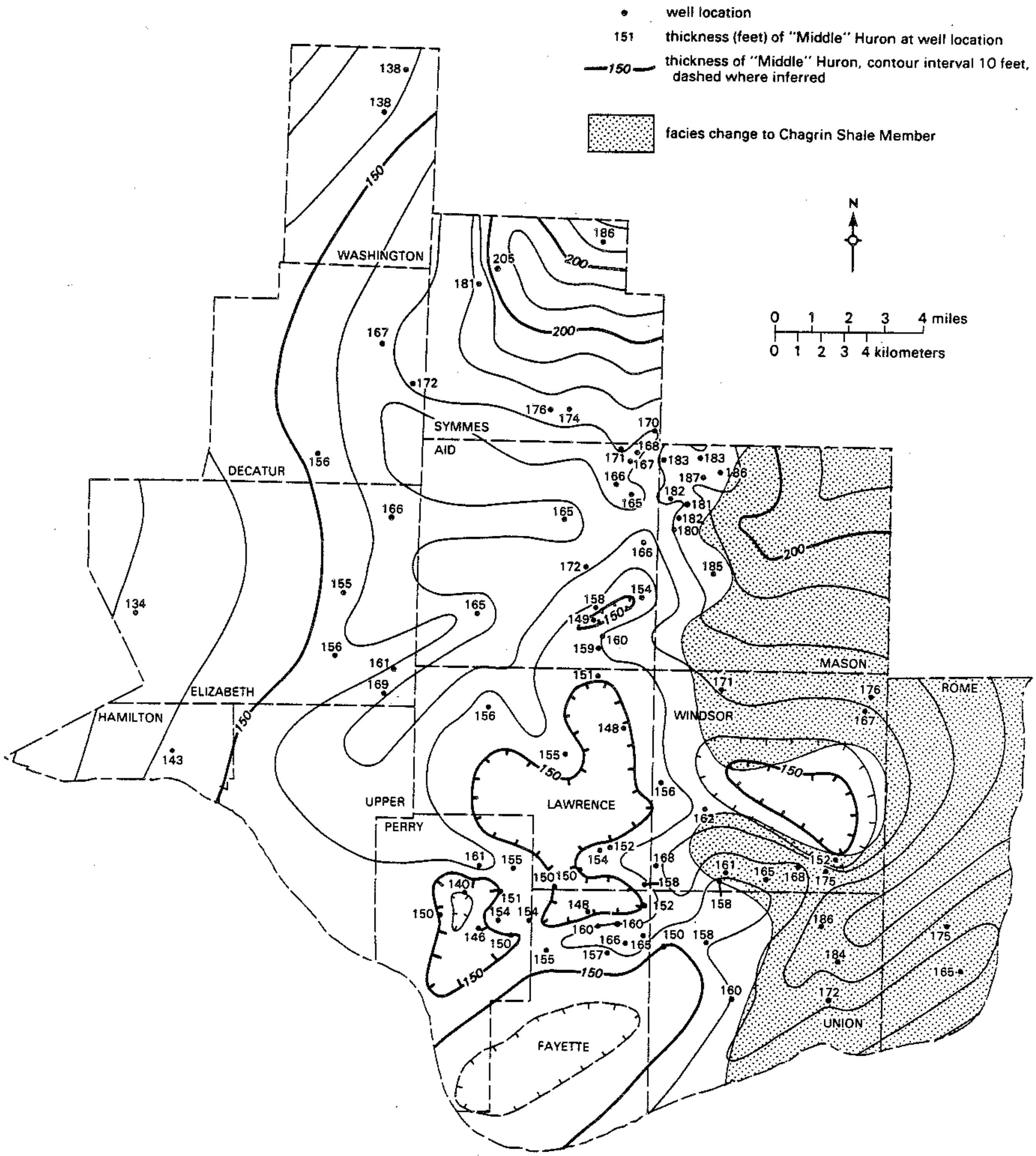

FIGURE 7.—Isopach map of the middle Huron Shale Member, Lawrence County, Ohio

Three Lick Bed

Provo (1977) orginally recognized this unit in southern Ohio and eastern Kentucky and named it the Three Lick Bed. Provo, on the basis of work by Lewis and Schwietering (1971), interpreted the Three Lick as a western tongue of the Chagrin Member. The Three Lick Bed consists of interbedded greenish-gray and black shales (Provo, 1977, p. 38) and conformably overlies the upper Huron. Log correlation of the Three Lick in the eastern portion of the county is difficult (Baranoski, 1987a).

The Three Lick Bed in Lawrence County contains three mappable subunits of greenish-gray shale, which are recognized on geophysical logs by alternating, but distinctive, low to moderate gamma ray responses (fig. 3). The lowest greenish-gray shale is the thickest (15 to 30 feet) of the

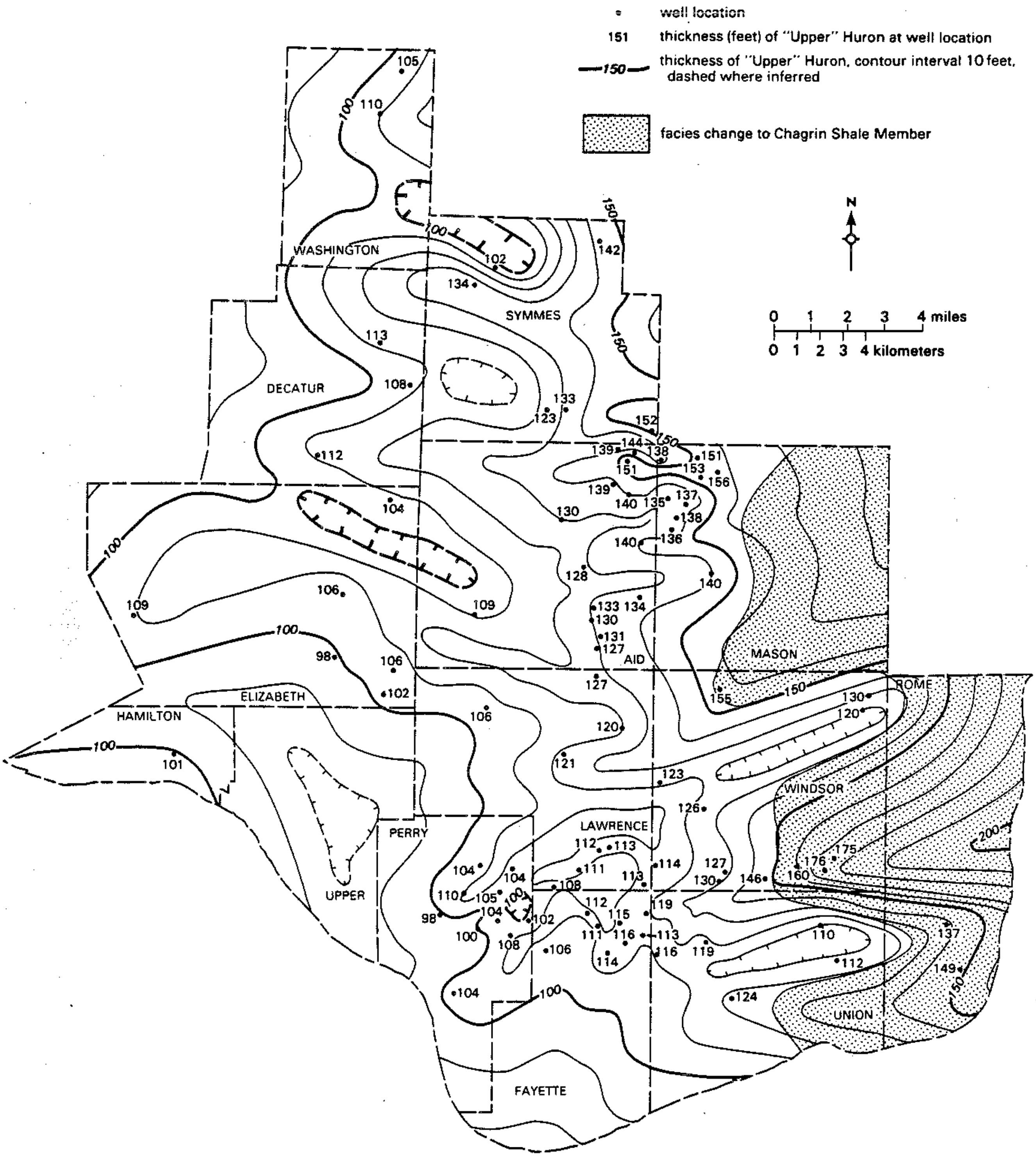

FIGURE 8.—Isopach map of the upper Huron Shale Member, Lawrence County, Ohio.

subunits. It extends farther east into the Chagrin than the overlying subunits before becoming unrecognizable on geophysical logs in Windsor, Union, and Rome Townships. The middle subunit is the thinnest; maximum thickness is 10 feet. It grades eastward into the Chagrin and pinches out to the west (Baranoski, 1987a). The upper subunit is 5 to 20 feet thick; it intertongues with the overlying Cleveland Member and merges eastward with the upper part of the Chagrin. This intertonguing relationship occurs in southern Lawrence County and northern Kentucky, where the black shales of the Cleveland Member thicken locally. Elsewhere in Lawrence County, there is a sharp break at the contact between the Three Lick Bed and the Cleveland Member on the neutron/density log.

The Three Lick Bed thickens eastward from 40 feet in western Lawrence County to 240 feet in the eastern part of the county, where it merges with the Chagrin Member (fig. 9). The unit thickens rapidly eastward from the 150-foot contour line. As is true of the older shales, several thick trends occur along W-E to NW-SE directions in Elizabeth,

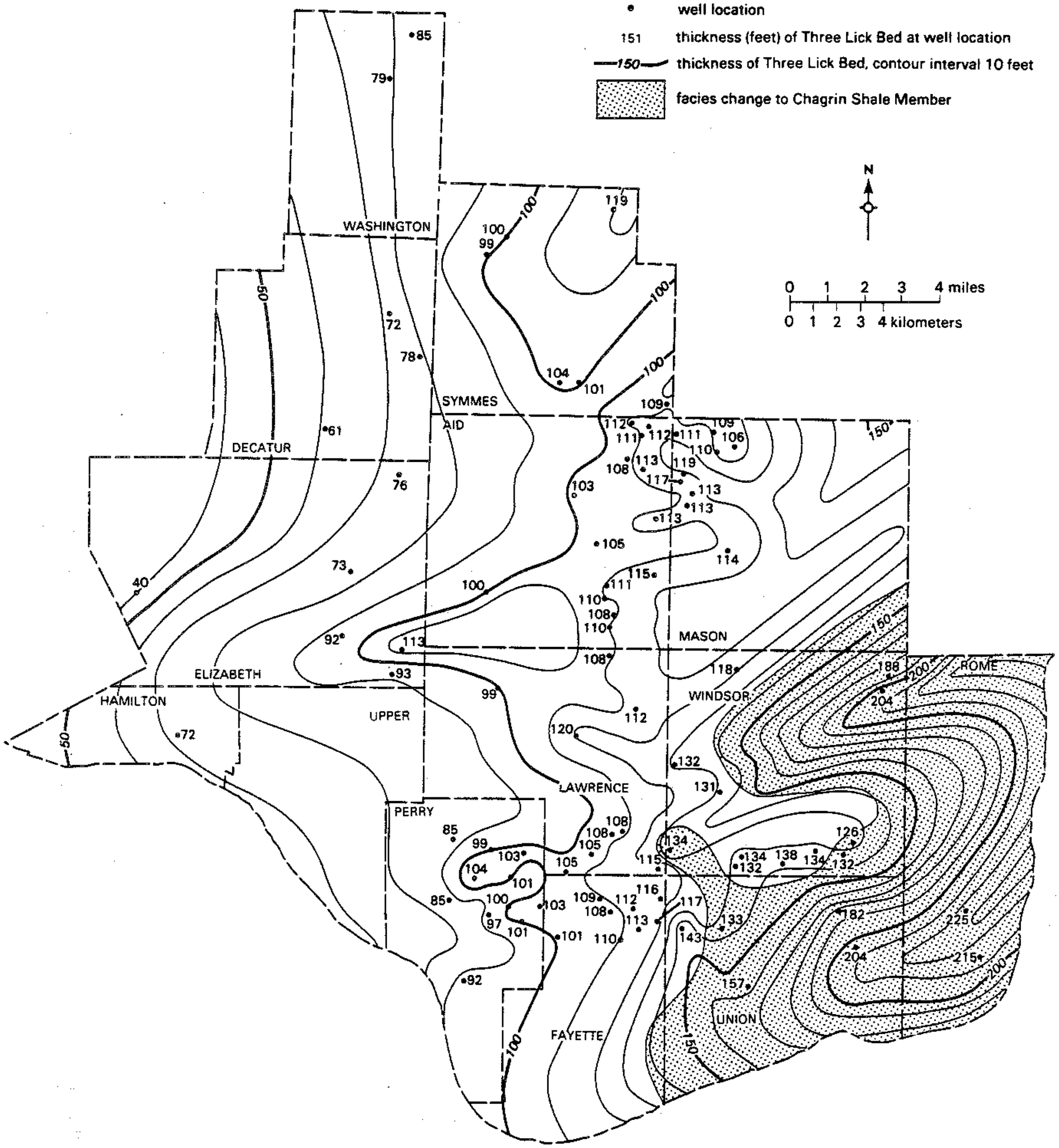

FIGURE 9.—Isopach map of the Three Lick Bed, Lawrence County, Ohio.

Hamilton, and Lawrence Townships and in Perry and Fayette Townships. These anomalies are proximal to the Little Storm Creek and Rankin Creek Trends. The NE-SW trend parallel to the Ohio River Fault, observed in the middle and upper Huron units, also is present in the Three Lick. As with older Ohio Shale units, thick areas occur along the NW-SE-trending Coffee and Tea Creek Fault.

Cleveland Shale Member

The Cleveland Shale Member in Lawrence County is recognized by a high gamma ray response and high neutron/density porosity. The Cleveland consists of brownish-black organic-rich shale (Provo, 1977, p. 34). The unit conformably overlies the Three Lick Bed, and, as discussed above, the base of the unit intertongues with the top of the Three Lick in the southern portion of the county. Along the N-S depositional strike (Baranoski, 1987a, F'-F) the Cleveland occupies a consistent stratigraphic position between the overlying Bedford Shale and underlying Three Lick Bed. The Cleveland merges with the upper part of the Chagrin Member in southeastern Rome Township (Baranoski, 1987a, G-G', H-H').

The Cleveland isopach map (fig. 10) shows very irregular thick and thin areas over most of the county. Thickness ranges from 30 to 100 feet. The W-E to NW-SE thick trend of older units along the Little Storm Creek Trend in Elizabeth, Upper, and Lawrence Townships also is apparent on the Cleveland isopach. A thick trend along the Coffee and Tea Creek Fault is evident, as are several broad thin areas in Perry, Upper, Symmes, Lawrence, and Windsor Townships. The N-S regional strike is present only in Washington Township.

Chagrin Shale Member

The Chagrin Shale Member of the Ohio Shale is recognized only in eastern Lawrence County. The complexity of the unit makes the Chagrin very problematic when attempting to map it in the subsurface. As a result, the Chagrin has been arbitrarily defined from geophysical logs where the stratigraphic contacts of the middle and upper Huron, Three Lick, and Cleveland become difficult or impractical to identify (Baranoski, 1987a).

The Chagrin has a much lower gamma ray response than black shales of the Huron Member, Three Lick Bed, and Cleveland Member because of a general absence of black organic-rich shales. The unit consists of gray and greenish-gray shales (Provo, 1977, p. 38) and intertongues both laterally and vertically with the Huron, Three Lick, and Cleveland. The contact between the top of the Chagrin and the base of the Bedford Shale (Mississippian) cannot be distinguished when the Cleveland is absent because of the vertical continuity of the geophysical log signature. Thickness of the unit increases eastward to as much as 650 feet in southeastern Lawrence County. Because of the complexity of the Chagrin, an isopach map could not be constructed for this report. However, Chagrin facies equivalents have been interpreted and are represented on isopach maps of the middle Huron (fig. 7), upper Huron (fig. 8), Three Lick Bed (fig. 9), Cleveland Member (fig. 10), and total Devonian-Mississippian (fig. 12). The relative position of these facies equivalents defines an area of rapid thickening of the Devonian shale sequence in Lawrence County.

BEDFORD SHALE

The Bedford Shale lies conformably on the Ohio Shale throughout Lawrence County. The Ohio Shale-Bedford Shale contact is defined by the high natural gamma ray response of the underlying Cleveland Member. The contact becomes less clear in the southeastern part of the county where the Cleveland pinches out into the Chagrin Shale Member (Baranoski, 1987a, G-G', H-H'). The Bedford-Chagrin contact cannot be traced farther east into West Virginia on geophysical logs because of an absence of black shales. The Bedford Shale in Lawrence County consists of red shale interbedded with gray shale and siltstone (Pepper and others, 1954, p. 26-27, fig. 13). A discontinuous 8- to 10-foot-thick bed of radioactive shale is present in Fayette, Symmes, and Washington Townships (Baranoski, 1987a, H-H', permit no. 373). Beds of siltstone are common in the Bedford throughout the county, but are more prevalent in the western portion. The Devonian-Mississippian contact lies within the Bedford, and the unit is included in the total Devonian-Mississippian shale isopach (fig. 12). Because the lower and upper contacts of the unit cannot be reliably mapped throughout the study area, the Bedford is not mapped separately.

BEREA SANDSTONE

The Berea Sandstone (Mississippian) lies conformably on the Bedford Shale. Throughout most of Lawrence County the Berea is 5 to 10 feet thick and very silty. However, sandstone beds 20 to 35 feet thick are present in Perry, Fayette, Lawrence, Union, and Windsor Townships. Generally only one bed of silty sandstone, in the upper part of the unit, is present. Because of the irregular distribution of sandstone bodies in the Berea, a Bedford-Berea contact cannot be traced on geophysical logs. Also, in western Lawrence County, siltstones of the Bedford and Berea interfinger, adding to the difficulty of tracing the contact. The Berea isopach map (fig. 11) shows elongate sandstone lenses striking 5° to 10° E of N. These lenses have been interpreted as offshore silty sand bars, on the basis of work by Pepper and others (1954, p. 54). In some areas the sand bars are connected by thin continuous sheets of silty sand. Where the sheets are absent, silty marine shale prevails. This is especially evident in southwestern and southeastern Lawrence County, where the Berea is very thin or absent.

SUNBURY SHALE

The Sunbury Shale (Mississippian) conformably overlies the Berea Sandstone and is readily distinguished on logs by its high gamma ray response and high neutron/density porosity. Because the Sunbury is regionally extensive, its base is used as a datum for all the cross sections (Baranoski, 1987a). The Sunbury consists of black bituminous shale (Pepper and others, 1954, p. 41). In Lawrence County the unit thickens eastward from 20 feet in Hamilton Township to 35 feet in Rome Township.

TOTAL DEVONIAN-MISSISSIPPIAN SHALE SEQUENCE

An isopach map for the total thickness of the Devonian-Mississippian shale sequence (fig. 12) was constructed using the base of the upper Olentangy Shale (top of the Onondaga Limestone) as the lower contact and the base of the Sunbury Shale (top of the Berea Sandstone) as the upper contact. Thickness of the sequence increases from 720 feet in western Lawrence County to 1,260 feet in the eastern part of the county. The isopach map of the total Devonian-Mississippian shale sequence indicates several dominant thick trends in Lawrence County. Most significant are the elongate NW-SE-trending Rankin Creek and Little Storm Creek Trends in Elizabeth, Lawrence, Perry, and Fayette Townships. There are several less prominent NE-SW and NW-SE trends in the county. With the exception of the

NW-SE trends, the total Devonian-Mississippian isopach map indicates progressive thickening of the sequence from west to east. This progressive thickening of the total Devonian-Mississippian shale sequence is in contrast to the thickness variations observed in the individually mapped units.

STRUCTURAL GEOLOGY OF LAWRENCE COUNTY

SETTING

Lawrence County is located on the western flank of the Appalachian Basin, approximately 100 miles east of the Cincinnati Arch (fig. 4). The nearest regional structural

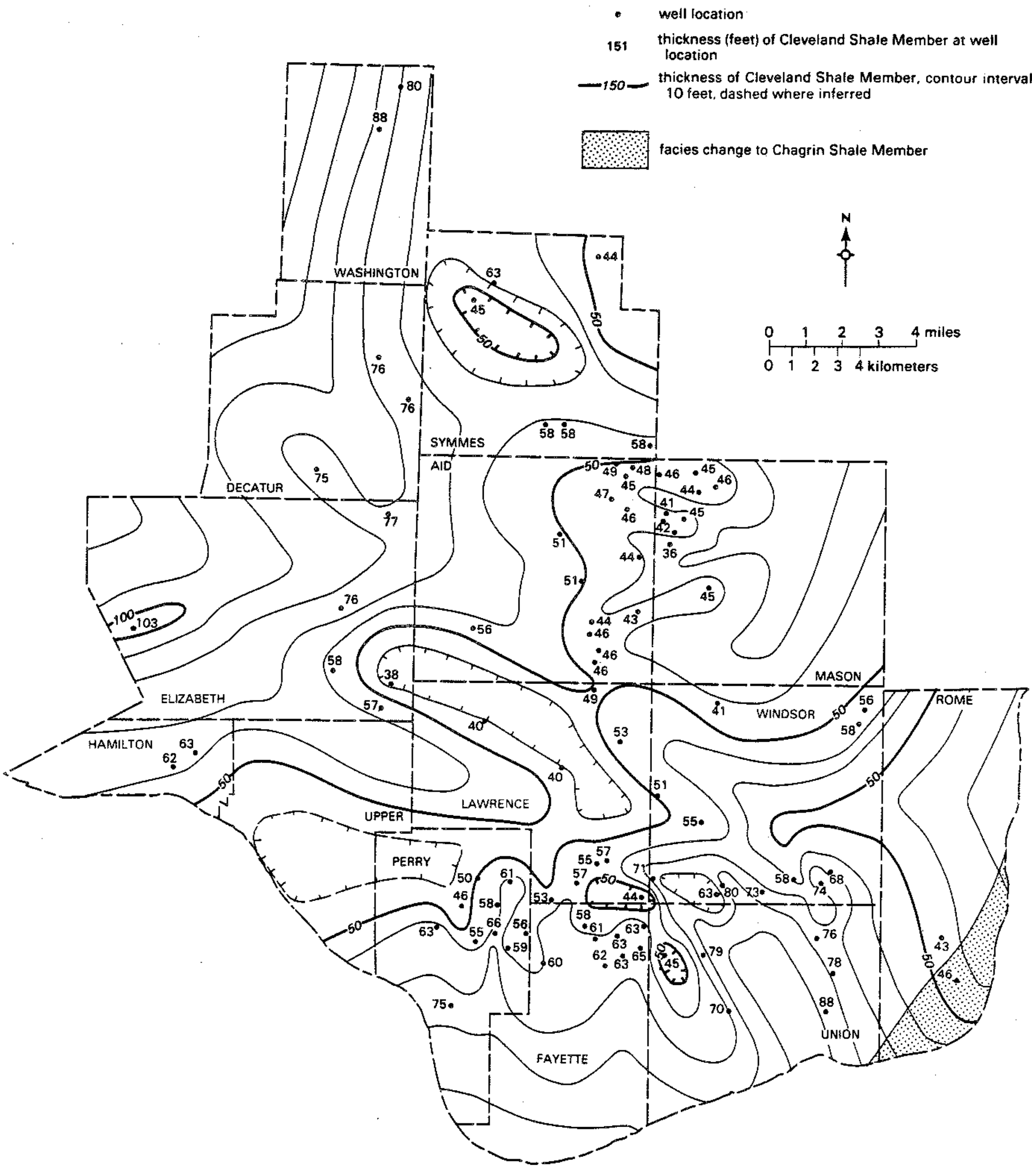

FIGURE 10.—Isopach map of the Cleveland Shale Member, Lawrence County, Ohio.

features are the NE-SW-trending Rome Trough ("lower Cambrian coastal declivity" of Woodward, 1961), which lies approximately 10 miles to the southeast (Ammerman and Keller, 1979, p. 350, fig. 8), and the N-S-trending Waverly Arch (Woodward, 1961; Tankard, 1986, p. 854, fig. 1), 40 miles to the west. No major structural features are present in Lawrence County, but six smaller structures have been mapped which appear to have affected Devonian shale deposition. These smaller structures are discussed below.

On a local scale the average strike at the surface is N 20° E and dip is approximately 25 feet per mile to the southeast (Maxey, 1940). Maxey (1940) located several subtle structural features at the surface. He named one of these the "Symmes Creek terrace" and described it as a 2- to 3-mile belt where dip increased from 26 to 50 feet per mile. This structure, referred to as the Symmes Creek Monocline (fig. 19) in this report, parallels regional strike and is located in central Lawrence and eastern Aid Townships. Maxey also mapped numerous subtle southeast-plunging structural noses. It should be noted that Maxey only mapped the

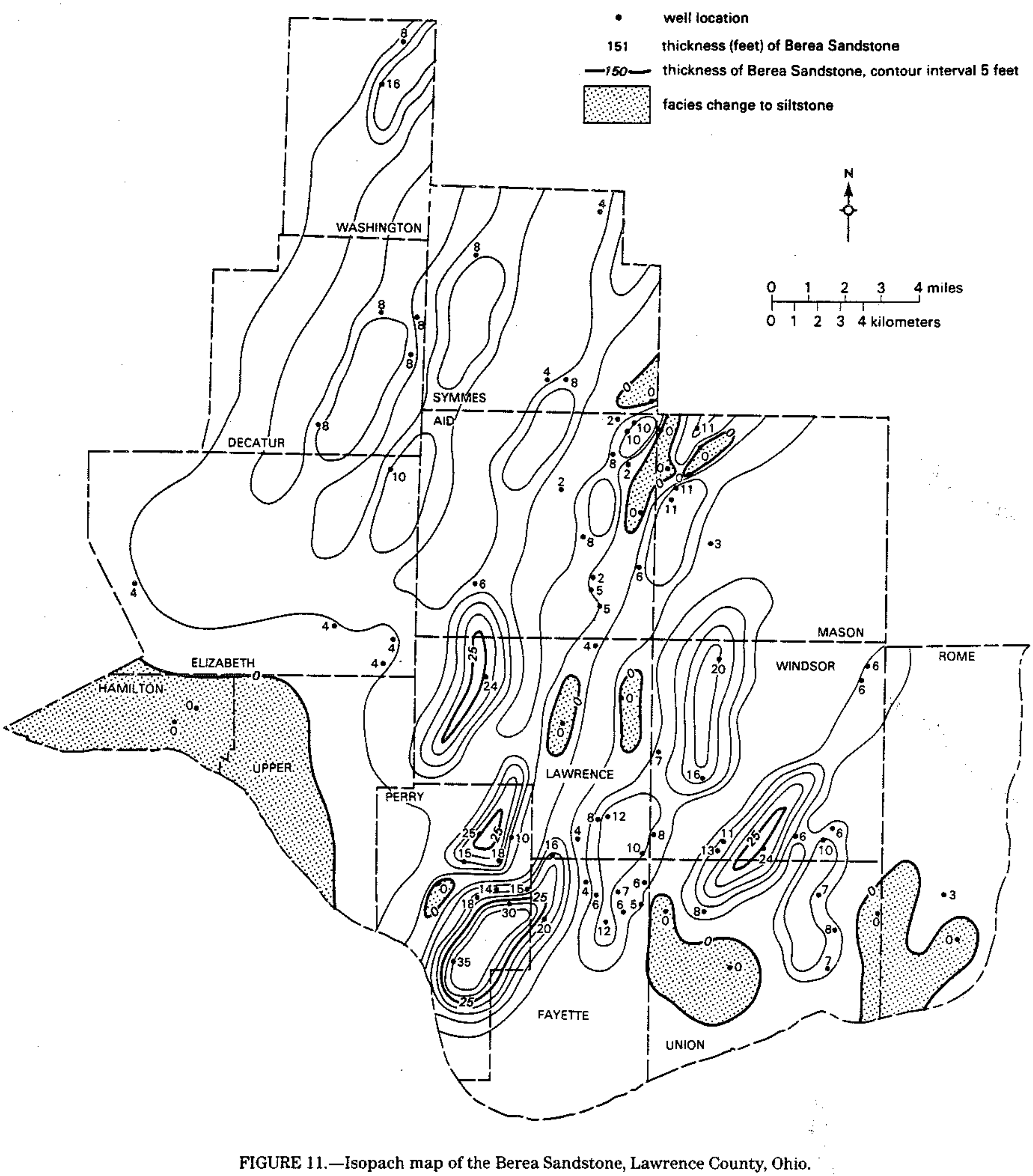

FIGURE 11.—Isopach map of the Berea Sandstone, Lawrence County, Ohio.

central portion of Lawrence County. He did not include eastern Mason, eastern Union, western Hamilton, Washington, Upper, Perry, Fayette, and Rome Townships in his study.

METHODS

Structural contour maps for Lawrence County have been constructed using geophysical logs from 100 wells drilled and completed prior to 1985. Where possible, drillers' stratigraphic tops were used for the Berea and Onondaga maps in areas where data were lacking. Geophysical logs were correlated with the regional cross-section network which established the regional stratigraphy for the Devonian-Mississippian shale sequence of southeastern Ohio. Structural contour maps on the following units were con-

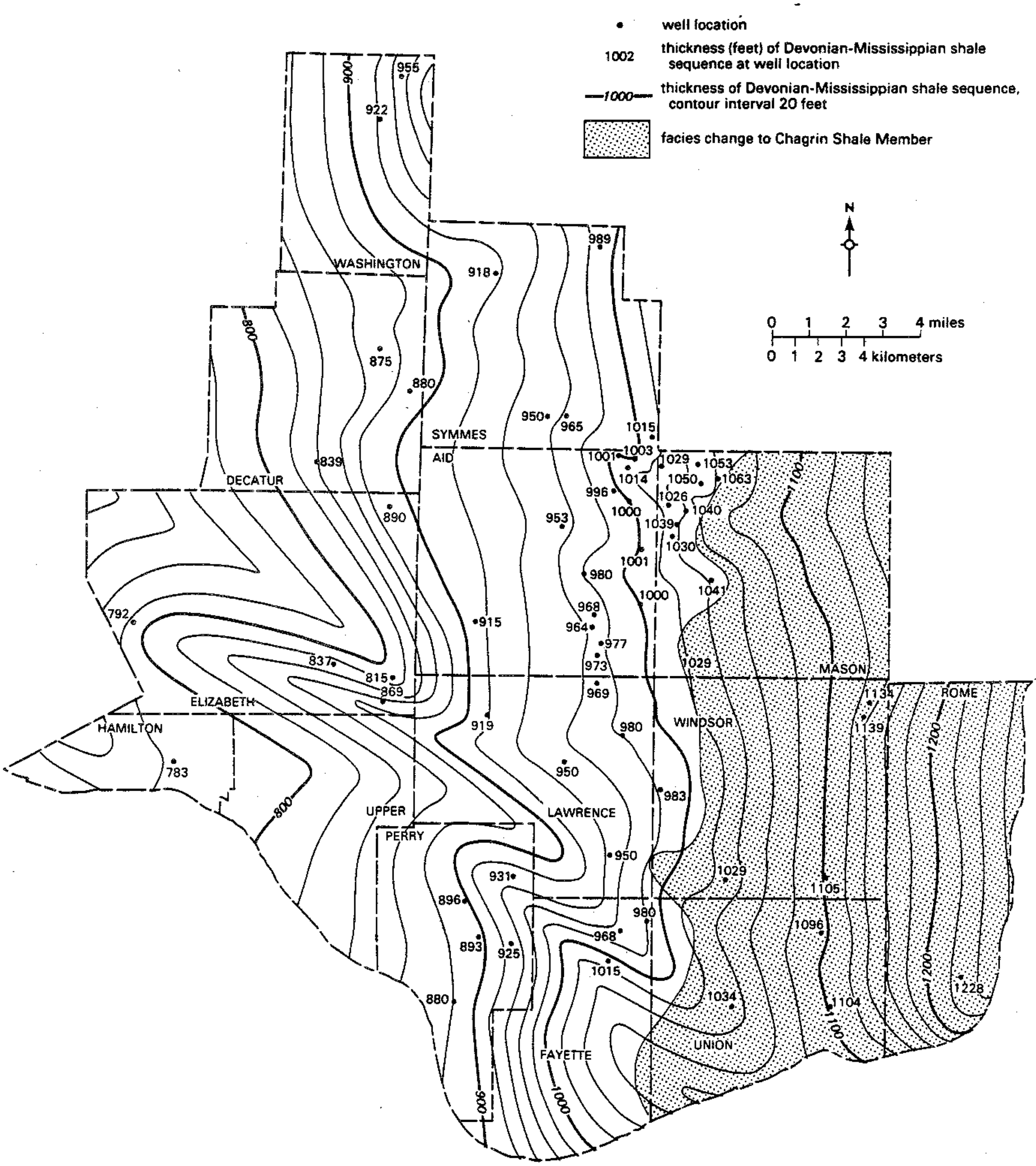

FIGURE 12.—Isopach map of the total Devonian-Mississippian shale sequence, Lawrence County, Ohio.

structed at a contour interval of 20 feet: "Packer Shell" (Silurian); Onondaga Limestone, Rhinestreet Shale Member, Angola Shale Member, base of the lower Huron Shale Member, and top of the lower Huron Shale Member (Devonian); and Berea Sandstone (Mississippian). All of these maps show virtually the same structural configuration throughout the county. Only the structure maps on the base of the lower Huron and on the top of the Berea are included in this report—the lower Huron because it is the primary gas-producing unit of the Devonian shale sequence, and the Berea because greater well density provides better definition of subsurface structures.

STRUCTURE ON "LOWER" HURON SHALE MEMBER

Regional strike on the structure map (fig. 13) on the base

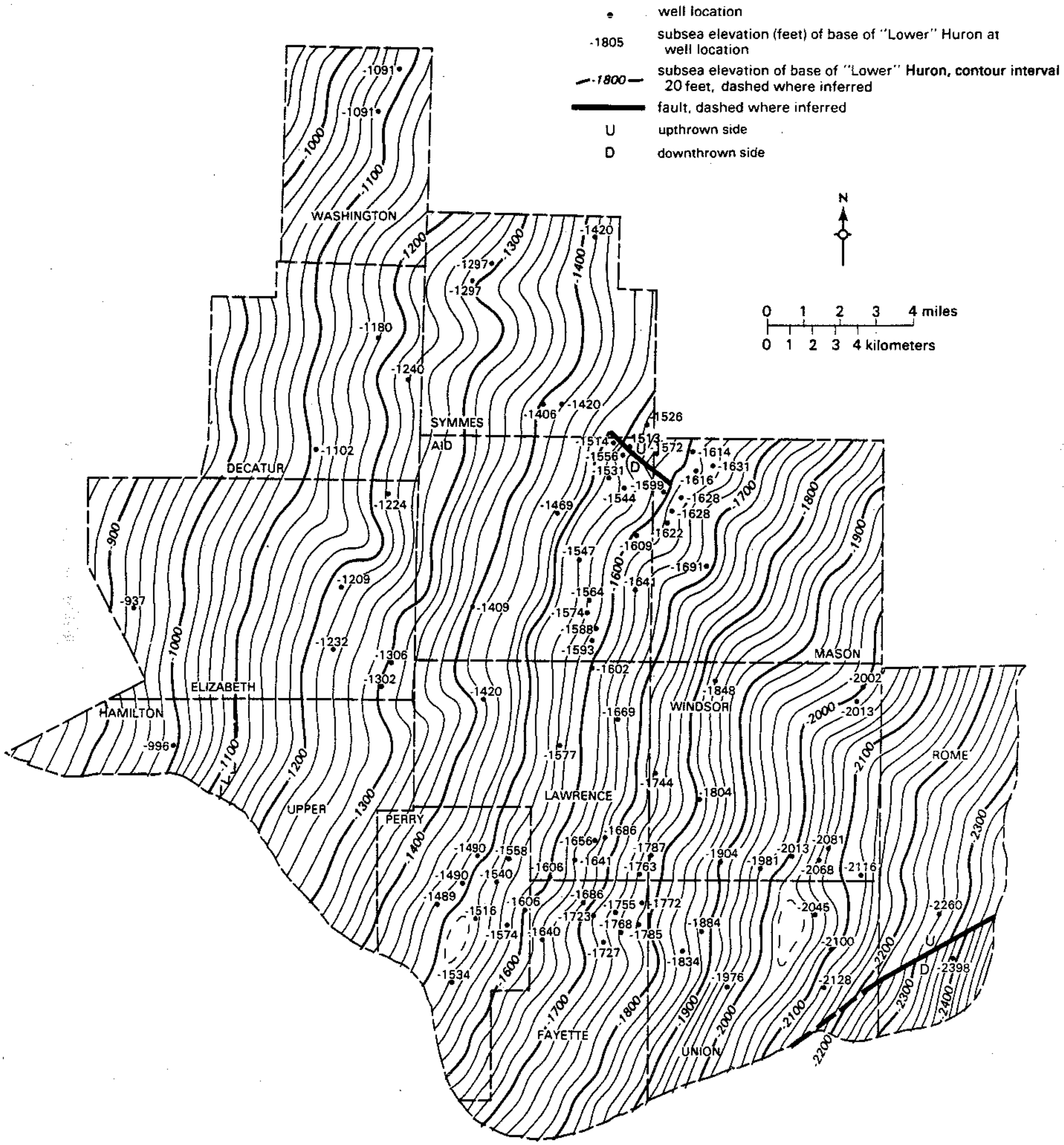

FIGURE 13.—Structure on the base of the lower Huron Shale Member, Lawrence County, Ohio.

of the lower Huron is N 10° to 20° E. Dip averages less than 1° to the east-southeast, ranging from 40 feet per mile in the western portion of the county to 80 feet per mile in the eastern portion. Subsea elevation is -820 feet in the west and -2480 feet in the east. Several southeast-plunging structural noses, the Symmes Creek Monocline, and the Coffee and Tea Creek Fault are evident in eastern Elizabeth, central Lawrence, eastern Aid, northwestern Mason, and southeastern Symmes Townships. A small terrace is present in central Perry Township. This feature is structurally lower than and aligned with the Symmes Creek Monocline to the northeast. Additional southeast-plunging structural noses occur in northern Fayette and eastern Union Townships. The Indian Guyan Creek Monocline is evident in eastern Windsor and northeastern Union Townships. In northern Union Township another feature has been named the Bear

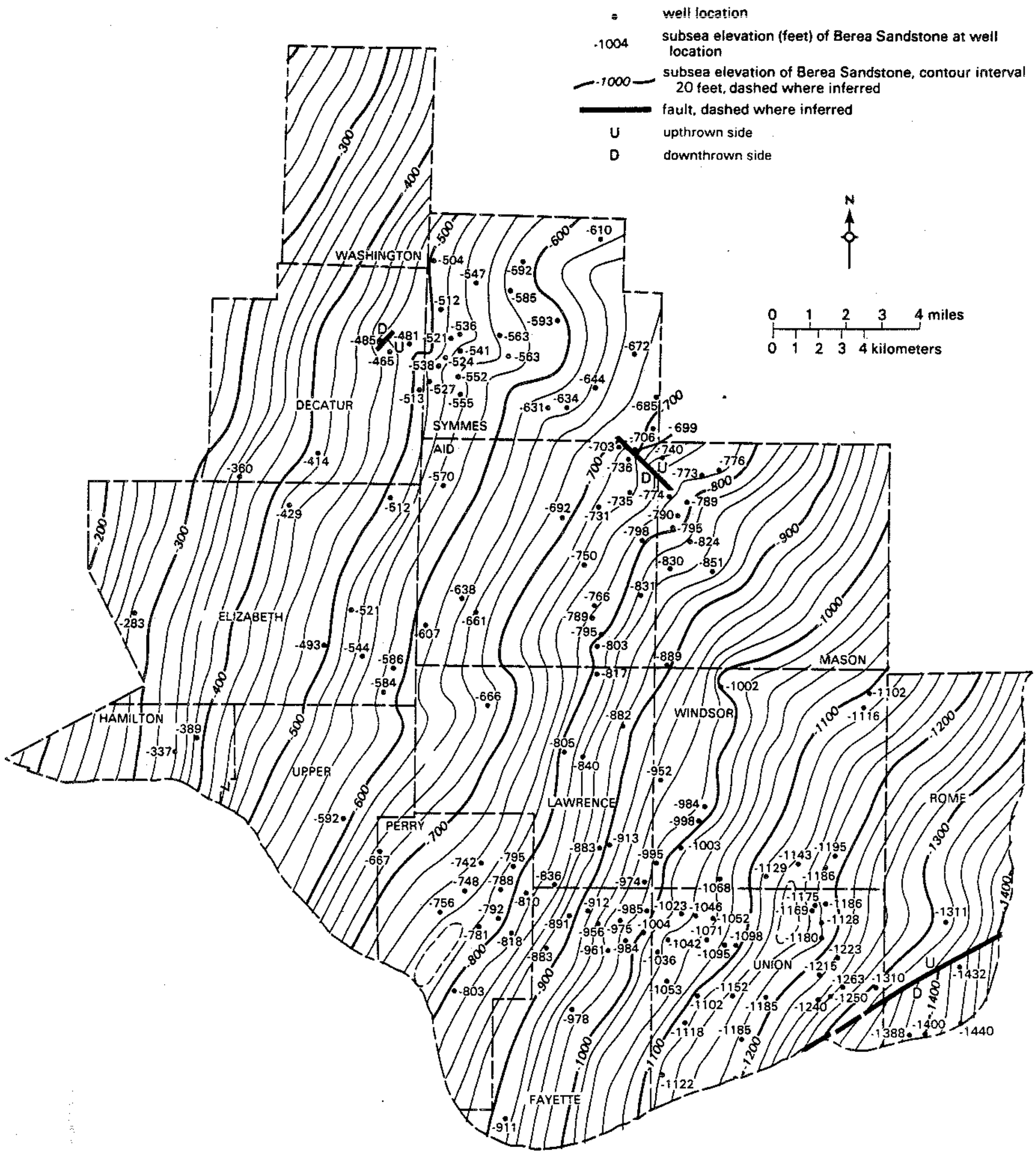

FIGURE 14.—Structure on top of the Berea Sandstone, Lawrence County, Ohio.

Creek Structure. This elongate feature parallels regional strike for approximately 2 miles. In southern Rome and Union Townships a NE-SW-trending fault has been named the Ohio River Fault. Throw is approximately 50 feet, down to the southeast.

STRUCTURE ON BEREA SANDSTONE

The structural contour map on the Berea (fig. 14) generally reflects the regional strike as well as all of the structural features discussed above. The Berea surface dips less steeply than the lower Huron surface; dip ranges from less than 40 feet per mile in the western portion of the county to 60 feet per mile in the eastern portion. Increased well control delineates a strong east- to southeast-plunging structural nose across Symmes Township.

DISCUSSION

Interpretation of the structure maps constructed for Lawrence County indicates several subtle structural trends which may be significant in the exploration and development of Devonian shales. The trends include several southeast-plunging noses, the NW-SE-trending Coffee and Tea Creek Fault, the NE-SW-trending Ohio River Fault, and the Symmes Creek and Indian Guyan Creek Monoclines. The Little Storm Creek and Rankin Creek Trends are not well defined on the structure maps.

Movement of the basement proximal to these structures may have taken place during deposition of Devonian shales, thus affecting the isopach trends observed on units mapped for this study. NW-SE-trending thick and thin areas along the Coffee and Tea Creek Fault are apparent on all of the mapped horizons. The NNE-SSW-trending Indian Guyan Creek Monocline has a thick area parallel to it in eastern Windsor and northeastern Union Townships on isopach maps of the upper Olentangy Shale and total Devonian-Mississippian shale sequence. The Bear Creek Structure has a thin area associated with it on the lower Huron and upper Huron isopach maps. Thick and thin elongate areas parallel and subparallel to the NE-SW-trending Ohio River Fault are evident on the isopach maps of the middle Huron, upper Huron, and Three Lick Bed. The Ohio River Fault parallels faulting along the Rome Trough in Boyd County, Kentucky, as interpreted by Ammerman and Keller (1979). Roen and de Witt (1984) have mapped a fault in Devonian shales in Boyd County, Kentucky, which is on trend with the proposed Ohio River Fault.

DEVONIAN-SHALE COMPLETION AND PRODUCTION IN LAWRENCE COUNTY

DRILLING HISTORY IN LAWRENCE COUNTY

Drilling for hydrocarbons in Lawrence County had taken place during the 1860's (Stout, 1916, p. 690), although no significant reserves were recovered. Newberry (1873, p. 158) observed the Huron black shale as a "vast repository of solid hydro-carbonaceous matter" that could be an excellent energy resource should petroleum supplies diminish. Such a conclusion was reached by Newberry from his empirical observations of black carbonaceous material on the outcrop, and related oil and gas fields discovered in Ohio and adjacent states. His observations included the following: (1) a line of oil and gas springs marks the outcrop of the Huron from central New York to Tennessee, (2) the rock is saturated in many places with petroleum or seeping natural gas, and (3) porous, permeable fractured strata above the Huron contain hydrocarbons. Newberry also viewed the Cleveland Shale Member as a hydrocarbon source rock. Production from Devonian shales was recorded during the early 1900's. According to Stout (1916, p. 692-693), "the next rock above the 'Clinton' [Silurian] in which production has been obtained is a gas bearing stratum lying in the body of the Ohio shales." Stout termed this stratum the "Ironton gas sand" and noted (p. 693) that it "is about 570 feet below the top of the Berea formation and about 280 feet above the top of the Devonian limestones." Based upon the stratigraphic position of the unit, this interval is believed to be in the lower Huron.

Over 180 Devonian-shale tests have been made in Lawrence County (fig. 15). As seen in the histogram, the greatest exploration for Devonian gas occurred during the 1930's. Drilling activity gradually decreased from the 1940's until 1970, when it came to a halt. An increase in well drilling to the Devonian occurred during the late 1970's and early 1980's as a result of the increase in gas prices.

The Ashland Field in nearby Boyd County, Kentucky, has produced from Devonian shales since the mid-1920's. Hunter (1955, p. 11) reported 233 wells drilled in the Ashland Field with 80 percent of these being commercial wells. Ninety percent of the commercial wells produce from Silurian sandstones ("Clinton") and Devonian shales, with the remaining 10 percent from Mississippian and Pennsylvanian sandstones. Wilson and Zafar (1978, p. 150) examined drillers' logs from the Ashland Field and concluded that gas production occurs from the Huron Member of the Ohio Shale. The discovery of "Clinton" gas in 1946 (Watson, 1983, p. 37) resulted in extensive development of the Ashland Field, which led to additional exploration activity in the Devonian shales.

The Ashland Field in Kentucky is an example of a field with multiple producing zones and provides a good analogy for exploration methods to be used in drilling oil and gas prospects in Lawrence County, Ohio.

GATHERING OF PRODUCTION DATA

Production data were gathered and correlated to the

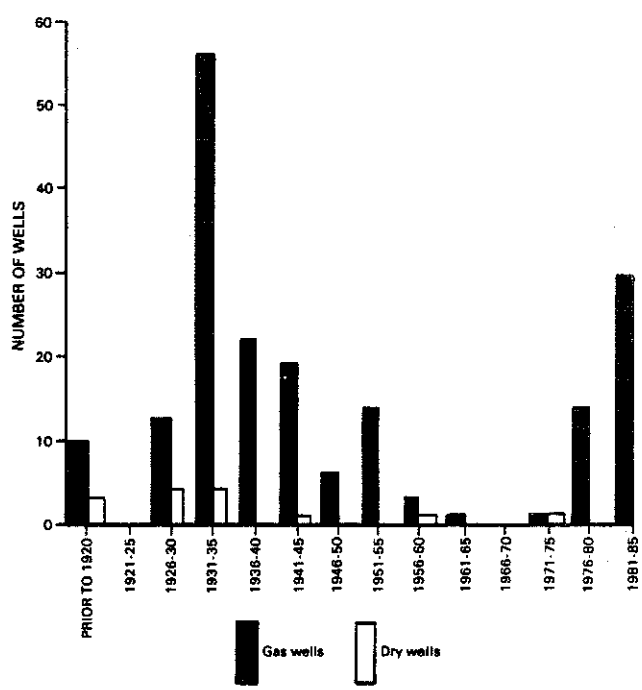

FIGURE 15.—Historical distribution of Devonian-shale well drilling Lawrence County, Ohio.

internal stratigraphy of the shales and the local structural features. Isopotential and cumulative-production maps were compared to the isopach and structure maps to determine what factors were controlling production and where the most favorable areas for production were located.

Historical production data in Lawrence County were gathered from four sources: (1) production records on microfilm at the Ohio Department of Natural Resources, Division of Oil and Gas, (2) county auditor's reports (Form 6a) for oil and gas properties on file at the county courthouse in Ironton, Ohio, (3) historical production records from Columbia Gas System Service Corporation, and (4) production records from various operators of Devonian shale wells in Lawrence County. Usable production data were obtained for 93 wells; 67 wells were completed in the Devonian shales, and the remaining 26 wells were completed in other horizons or were undetermined.

County auditor's reports for oil and gas properties are received by the Division of Oil and Gas. Much pertinent production information is not included on this form. Information such as producing unit, the date the well was put on line, the number of days on line, line pressure, and rock pressure needs to be added for these reports to be useful.

Historical production records for 29 wells were received from Columbia Gas System Service Corporation. These records were the most complete, with historical records going back as far as 50 years. The number of days on line, line pressure, rock pressure, and date put on line are included in these records. A survey of other operators in Lawrence County produced very few production data for Devonian shale wells.

COMPLETION TECHNIQUES

The primary stimulation methods that have been used for Devonian-shale completions in the Appalachian Basin include shooting with gelatinated nitroglycerine (gel), hydraulic fracturing, foam fracturing, and cryogenic fracturing. A statistical summary of the stimulation methods used in Lawrence County is shown in figure 16. This information was taken from completion cards on file in the Subsurface Geology Section of the Division of Geological Survey.

Shooting with nitroglycerine has been the most common stimulation method in Lawrence County and was used in 87 wells. This technique was prevalent in wells drilled prior to the mid-1960's and is presently used by some operators. Terry's Well Service completed the No. 1 Schneider (Union Twp., sec. 7, permit no. 354) with 50 sticks of 5-inch nitroglycerine spaced 10 feet apart (Terry Schneider, 1986, verbal communication). This well has averaged 600 mcf per month over a five-year period.

Commonly, the procedure for shooting involves filling the open hole with 80 percent gelled nitroglycerine. The explosive energy is contained by a sand or water pack. The short duration of shooting limits the radial distance in which the fractures are propagated into the formation. This stimulation method is most effective in wells where a natural fracture system already exists. Extensive wellbore cleanout commonly is necessary because of the crushing and caving in of rock adjacent to the wellbore.

Hydraulic fracturing has been used with caution by operators because of potential formation damage caused by the interaction between clays and fluids (Komar, 1978, p. 3). Two wells in Lawrence County used hydraulic fracturing. Sand was used as a proppant to hold the fractures open after the applied pressure dissipated. Holditch and Associates (1985) studied the effect of stimulation methods on Devonian shale wells and determined that vertical hydraulic fracturing is the optimal stimulation method if

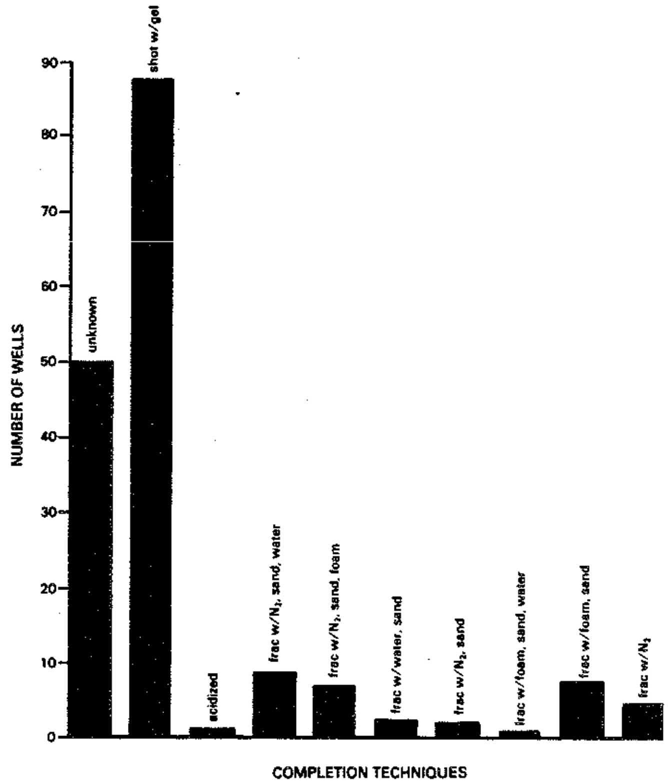

FIGURE 16.—Statistical summary of completion techniques used in Devonian shale wells, Lawrence County, Ohio.

the fractures intersect high-permeability features. Owen and others (1985, p. 224) also concluded that hydraulic fracturing of the entire lower Huron is the best stimulation method for Devonian shales.

Foam fracturing has been used recently as an alternative to hydraulic fracturing (Komar, 1978, p. 3). Twelve wells in Lawrence County have used foam stimulation techniques. Seven wells used foam, nitrogen, and sand; one well used foam and sand; and four wells used foam, water, nitrogen, and sand. Foam fracturing has two primary advantages: the recovery of fracturing fluid is more rapid and more complete than a water fracture, and formation damage is minimized because of less water-shale reaction. Doran and Associates (Mark Leidecker, 1986, verbal communication) have used nitrogen (N_2) in a 75-quality foam fracture, which consists of 75 percent N_2 with 25 percent liquid (water and NWAR additive) and 50/50 proppant (50 percent 20/40 sand and 50 percent 10/20 sand). Apparently, the large-diameter proppant enhances production by keeping the fractures open after stimulation. Doran and Associates have had better results with a 75-quality foam fracture than with explosive gel. J.D. Drilling (Spence Carpenter, 1986, verbal communication) completed the No. 1 Lang (Windsor Twp., sec. 32, permit no. 384) with 1.2 mmcf of N_2 with no proppant. This well produced 684 mcf with some brine during a 30-day test.

Cryogenic fracturing also has been used to stimulate Devonian shales in the Appalachian Basin (Horton, 1984, p. 46). This procedure commonly involves a mixture of liquid CO_2 mixed with either methanol or water. The primary advantage of this process is that it provides a highly energized fluid that can carry large quantities of proppant to the far limits of the fracture system, and then transport this fluid out of the fracture and into the wellbore in a short time.

An analysis of water fracturing versus shooting for

Devonian shales in the Eastern Kentucky Gas Field region was conducted by Yost (1983). Production rates for hydraulically fractured wells were significantly higher than wells shot with explosives. After five years of production, the cumulative production for hydraulically fractured wells averaged 113 mmcf, while the cumulative production for shot wells after five years averaged only 60 mmcf.

Comparisons between the various completion techniques in Lawrence County were difficult to make because of the paucity of historical production data. The only wells with enough production data to calculate decline curves were all shot with nitroglycerine. Most of the wells which used hydraulic fracturing, foam fracturing, and nitrogen fracturing were completed within the last three to four years and did not have enough production data available to construct a representative decline curve.

DRILLERS' SHOWS

Historically, gas shows within the Devonian shale sequence have been noted by operators in their completion reports, but the specific stratigraphic unit(s) within the Devonian shales are not generally known or given. Our major goal was to determine which stratigraphic units within the Devonian shale sequence actually contain the most shows. By use of structure maps prepared for each stratigraphic unit within the Devonian shales and reported depths, all gas shows were related to their corresponding stratigraphic unit. Shows in the Pennsylvanian sandstones, Berea Sandstone, and "Clinton" sandstone also were noted in this analysis.

A total of 176 gas and/or oil shows were noted from the completion cards. Drillers' shows were subdivided into two categories: reported shows within individual stratigraphic units (fig. 17), and reported shows covering multiple stratigraphic units (fig. 18).

The lower Huron had the greatest number of shows, with a total of 85 reported (fig. 17). In addition, there were three wells with shows of gas covering multiple stratigraphic units which included the lower Huron (fig. 18). Most of the wells which contained gas shows within the lower Huron also were completed within the same zone. A number of wells which were completed in the "Clinton" also contained shows within the lower Huron. Many of these "Clinton" wells may have potential for shallow gas production from the lower Huron. The lower Huron also has been shown to have the greatest potential for hydrocarbon production in the Devonian-shale play in West Virginia (Filer, 1985, p. 42) and Kentucky (Wilson and Zafar, 1978, p. 150).

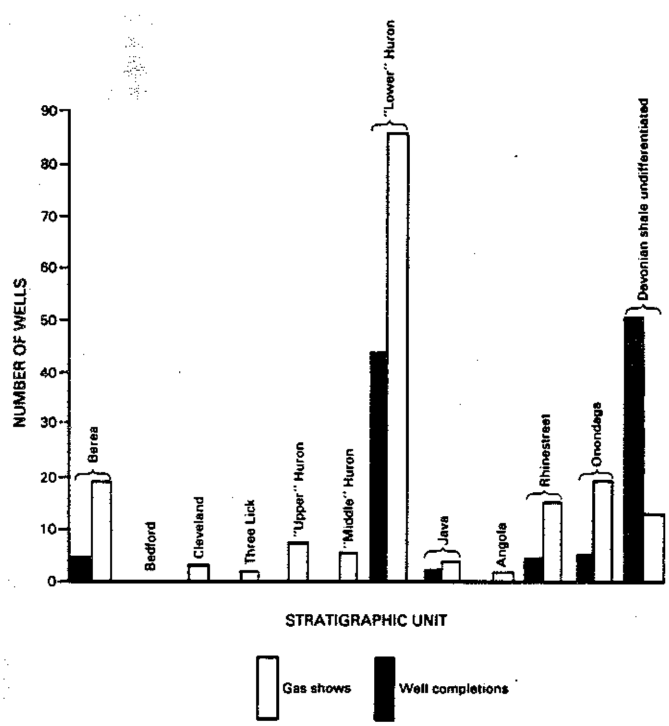

FIGURE 17.—Frequencies of completions and shows reported within individual stratigraphic units of the Devonian shale sequence.

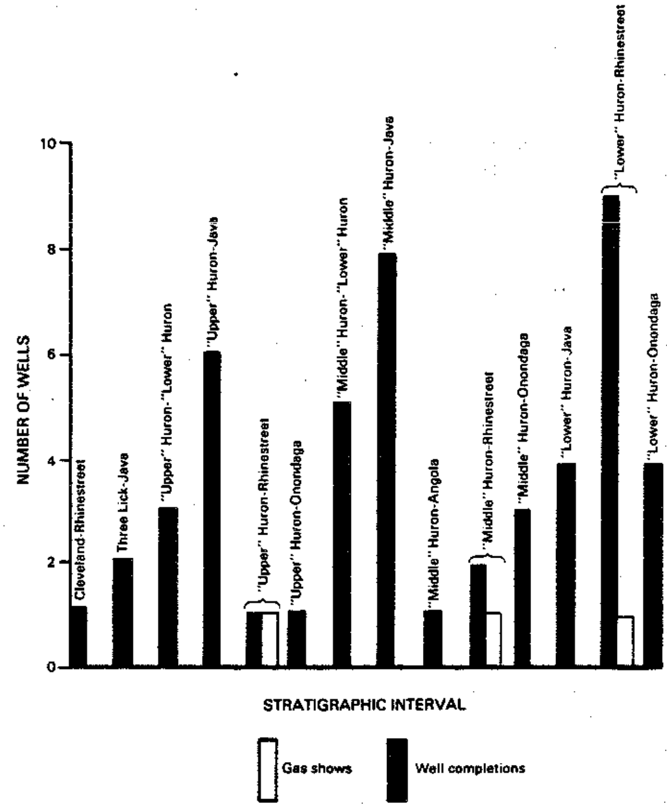

FIGURE 18.—Frequencies of completions and shows reported within multiple stratigraphic units of the Devonian shale sequence.

The Rhinestreet was the next most significant shale unit in terms of drillers' shows. Fourteen shows were reported within the Rhinestreet. Based on historical production, the Rhinestreet does not appear to offer as much potential for commercial gas production as the lower Huron.

Scattered shows of gas have also been reported in the shales of the Cleveland, Three Lick, upper Huron, middle Huron, Java, and Angola. On the basis of historical production in Lawrence County, these stratigraphic units do not have great potential for commercial gas production. Thirteen shows reported within the Devonian were not assigned a specific stratigraphic unit and are listed as Devonian shale undifferentiated in figure 17. The Berea Sandstone and the Onondaga Limestone had 19 shows reported from each unit.

Identifying the stratigraphic location of gas shows within the Devonian shale sequence is essential to determine those stratigraphic units having the greatest potential for commercial gas production and should be a part of every exploration program. Areas of "Clinton" production may also offer potential for Devonian-shale gas production.

These areas of exploration interest will be outlined later in this report.

COMPLETION INTERVALS

Completion cards were examined for all Devonian shale wells. A record of the interval which was acidized or shot generally is noted on the completion card. Completion intervals were analyzed using the same method that was used for studying drillers' shows. By comparing the subsea depth of the completed interval to the set of structure maps, it could be determined which stratigraphic unit within the Devonian shale sequence was actually completed.

Devonian wells generally are completed either by small intervals within one stratigraphic unit or by large intervals covering hundreds of feet and several stratigraphic units. Therefore, two histograms were used to illustrate the analysis; figure 17 shows completions from individual stratigraphic units and figure 18 shows completions from multiple stratigraphic units.

A total of 162 wells in Lawrence County were noted on completion cards or were inferred as being Devonian-shale completions. It should be noted that many of the older wells did not specify the producing horizon or give the interval which was shot or acidized. Thus, the producing horizon was inferred for some wells on the basis of shows of oil and/or gas within the drillers' logs.

The lower Huron is the most prolific producing stratigraphic unit within the Devonian shale sequence. Forty-three wells were determined to have been completed in the lower Huron, and all 50 wells which were completed in multiple stratigraphic units contained the lower Huron. Many of these wells completed in multiple stratigraphic units contained shows of gas within the lower Huron. These results suggest that the majority of the wells which were completed in multiple stratigraphic units were producing gas from the lower Huron. Similarly, in a study of Devonian-shale exploration and production in Jackson and Vinton Counties, Ohio, Owen and others (1985, p. 224) noted the lower Huron as the primary zone for gas production.

Other Devonian production included five wells completed in the Rhinestreet and one well completed in the Java. An additional 57 wells were listed as Devonian completions, but the producing stratigraphic unit could not be determined. The majority of the Devonian gas production was confined to the southern half of Lawrence County. The well completions in the northern half of Lawrence County are primarily "Clinton" producers. In addition, seven wells were completed in an unnamed Pennsylvanian sandstone, four wells in the Berea Sandstone, and five wells in the Onondaga Limestone.

A map at a scale of 1:62,500 was constructed illustrating the producing intervals in Lawrence County (Baranoski, 1987b). Gas fields producing from Devonian shales and from below the Devonian shales are summarized on a page-size map (fig. 19). The relationship of gas fields to structural features in Lawrence County also is shown in figure 19. Comparisons of the oil and gas fields with the structure and isopach maps may help establish relationships between production and stratigraphy.

ISOPOTENTIAL AND CUMULATIVE-PRODUCTION MAPS

Isopotential and cumulative-production contour maps for Lawrence County were drawn based upon all available data for Devonian shale wells. Only the southern half of Lawrence County was contoured for the isopotential and cumulative-production maps because of limited data available in the northern half of the county. Relationships between production and stratigraphy were established on the basis of comparisons of the isopotential and cumulative-production maps to the structural contour and isopach maps. Table 1 lists all of the major structural and stratigraphic features analyzed in this report and lists the relationship to the isopotential and cumulative-production maps.

TABLE 1.—*Relationship between isopotential and cumulative-production maps and structural and stratigraphic features*

Structural and stratigraphic features	Relationship to isopotential and cumulative-production maps
Rankin Creek Trend	Isopotential map has numerous areas of initial potential which exceed 200 mcf
Bear Creek Structure	Isopotential map has high initial potential over southern half of structure. Three-year cumulative-production map shows an area of high production reaching 60.4 mmcf over the structure. Ten-year cumulative-production map shows an area of high production reaching 451 mmcf over the structure
Indian Guyan Creek Monocline	Isopotential map has one well within Indian Guyan Creek Monocline with an initial potential of 531 mcf, showing a possible relationship between structure and production. There are no cumulative-production data over this structure
Ohio River Fault	Isopotential map displays two areas of high initial potential surrounding the fault, but the three-year and 10-year cumulative-production maps are inconclusive as to long-term trends

Isopotential map

An isopotential map (fig. 20) was constructed using initial-potential data (from open-flow tests) from completion cards on file at the Division of Geological Survey and production data obtained from Columbia Gas System Service Corporation. The isopotential values used for contouring were measurements after the well was stimulated. A contour interval of 200 mcf was used. It should be noted that open-flow tests, as reported on completion cards, are not standardized as to the amount of time that the tests are measured. Many of the older wells did not report the measurements from the open-flow tests. This lack of standardization decreases the validity of the values used for the isopotential map. In spite of this lack of standardization, an attempt was made to establish relationships based on available data.

The isopotential map has localized areas of initial potential greater than 200 mcf. These isolated areas may reflect regions of localized fracturing which enhanced production. One such area of high initial potential coincides with the Bear Creek Structure in northeastern Union Township. This structure may have produced a localized system of natural fractures. Two areas of initial potential greater than 400 mcf are located along the Ohio River Fault. Along the Indian Guyan Creek Monocline, there is one well with an initial potential of 531 mcf, demonstrating a possible relationship between stratigraphy, structure, and production. Several areas of initial potential exceeding 200 mcf are associated with the Rankin Creek Trend.

Cumulative-production maps

The three-year cumulative-production map (fig. 21) has

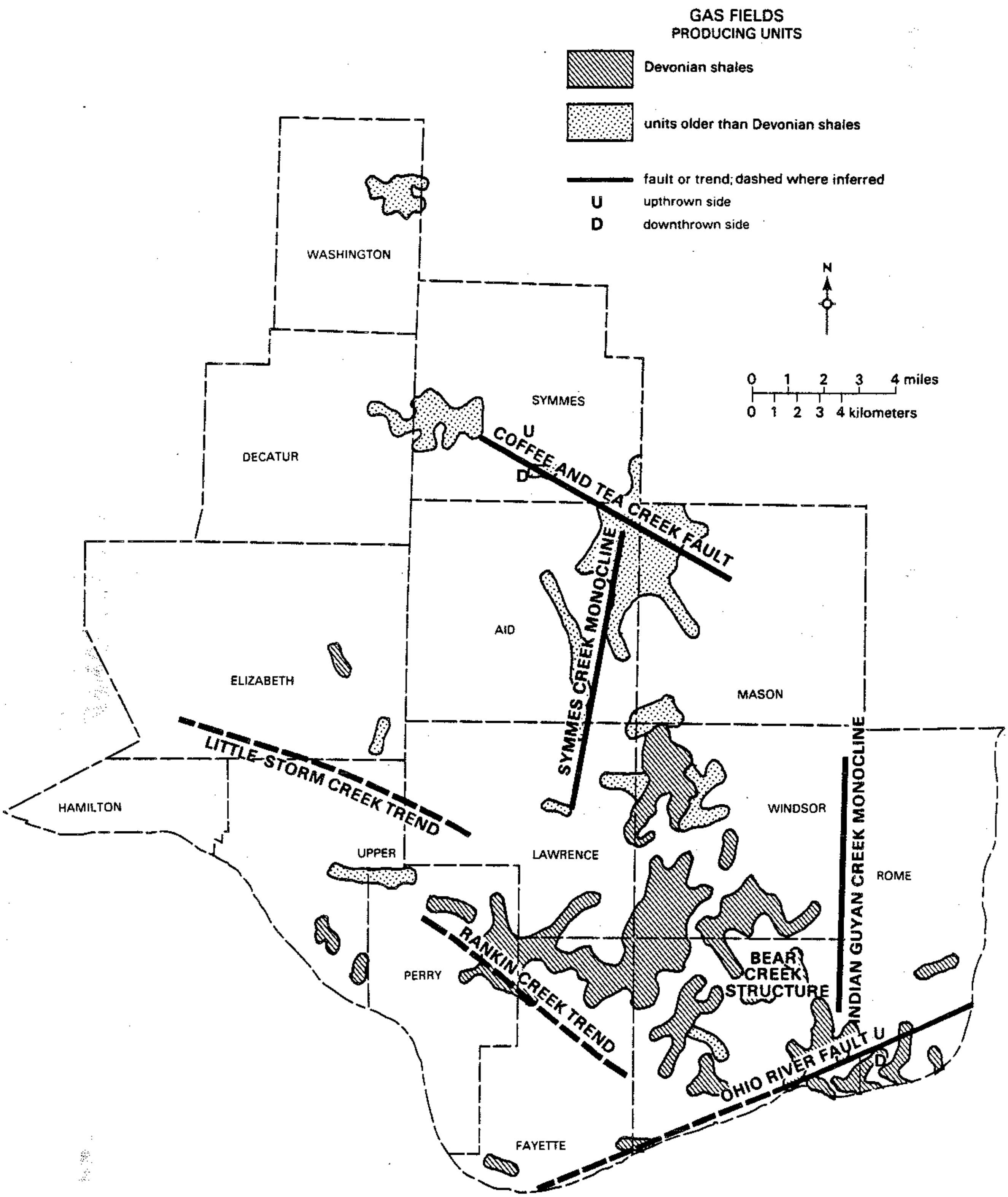

FIGURE 19.—Gas fields in Lawrence County, Ohio, and relationship to structural features.

several localized areas of high (≥40 mmcf) cumulative production. It should be noted that many of the three-year cumulative-production values were taken from auditor's reports, which do not report the number of days of production. For these wells it was assumed that the wells were producing 365 days a year, which is generally not the case.

An area of high cumulative production is coincident with the eastern flank of the Bear Creek Structure in Union Township. The three-year cumulative-production values along the Ohio River Fault range from 10 to 33 mmcf, and are significantly less than other producing areas in the county. The high initial potentials along the fault (discussed in the previous section) are probably a result of liberated gas which was being released from fractures. Apparently, there was not enough gas within the shale matrix to sustain long periods of high production once the fractures had been drained. There were no cumulative-production data available in the vicinity of the Indian Guyan Creek Monocline.

As with the three-year cumulative-production map, the 10-year cumulative-production map (fig. 22) shows a correlation between structure and production on the Bear Creek Structure in Union Township. Ten-year production values surrounding the Ohio River Fault range from 24 to 157 mmcf. These low cumulative-production values are further evidence that there is not enough gas within the shale matrix to sustain long periods of high production. There were no cumulative-production data available near the Indian Guyan Creek Monocline.

DECLINE CURVES

Methods

Decline-curve analysis is one of the most widespread diagnostic tools used for estimating oil and gas reserves. The rate at which gas production declines is important for determining the relative volumes of gas to be obtained during different periods of the life of the well. Such information provides a basis for determining the economic feasibility of

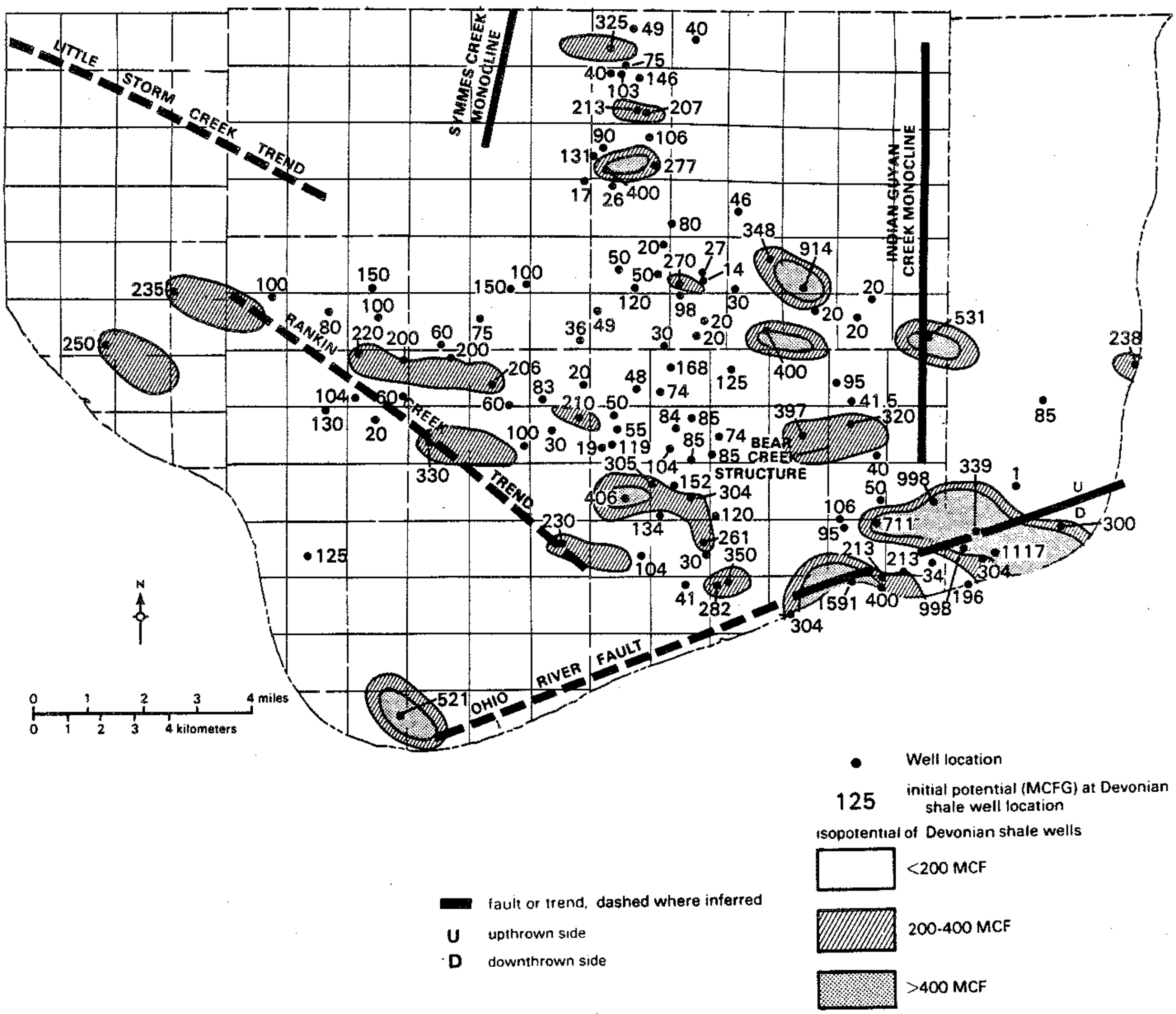

FIGURE 20.—Isopotential map of Devonian shales in Lawrence County, Ohio.

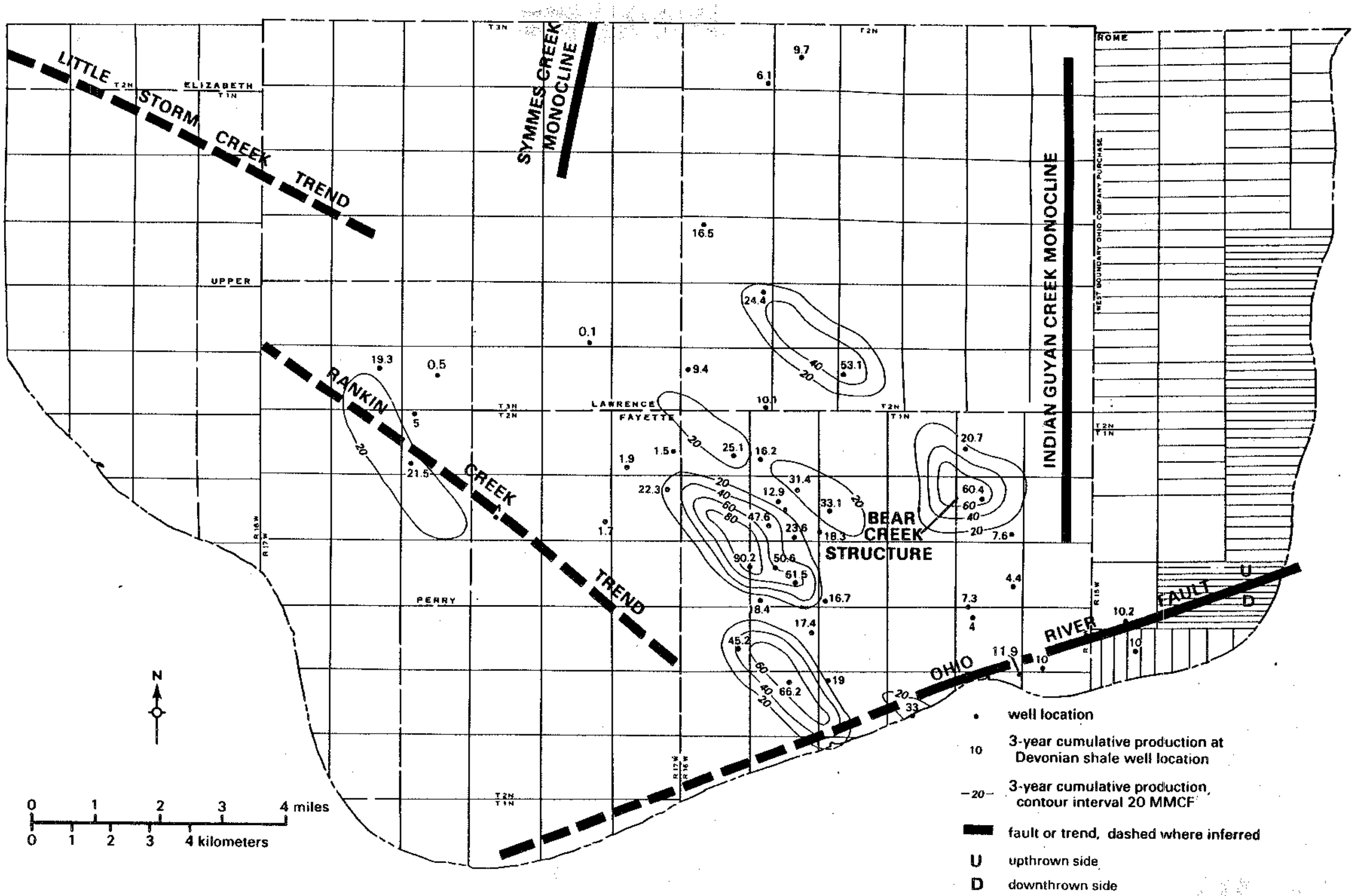

FIGURE 21.—Three-year cumulative-production map of Devonian shale wells in Lawrence County, Ohio.

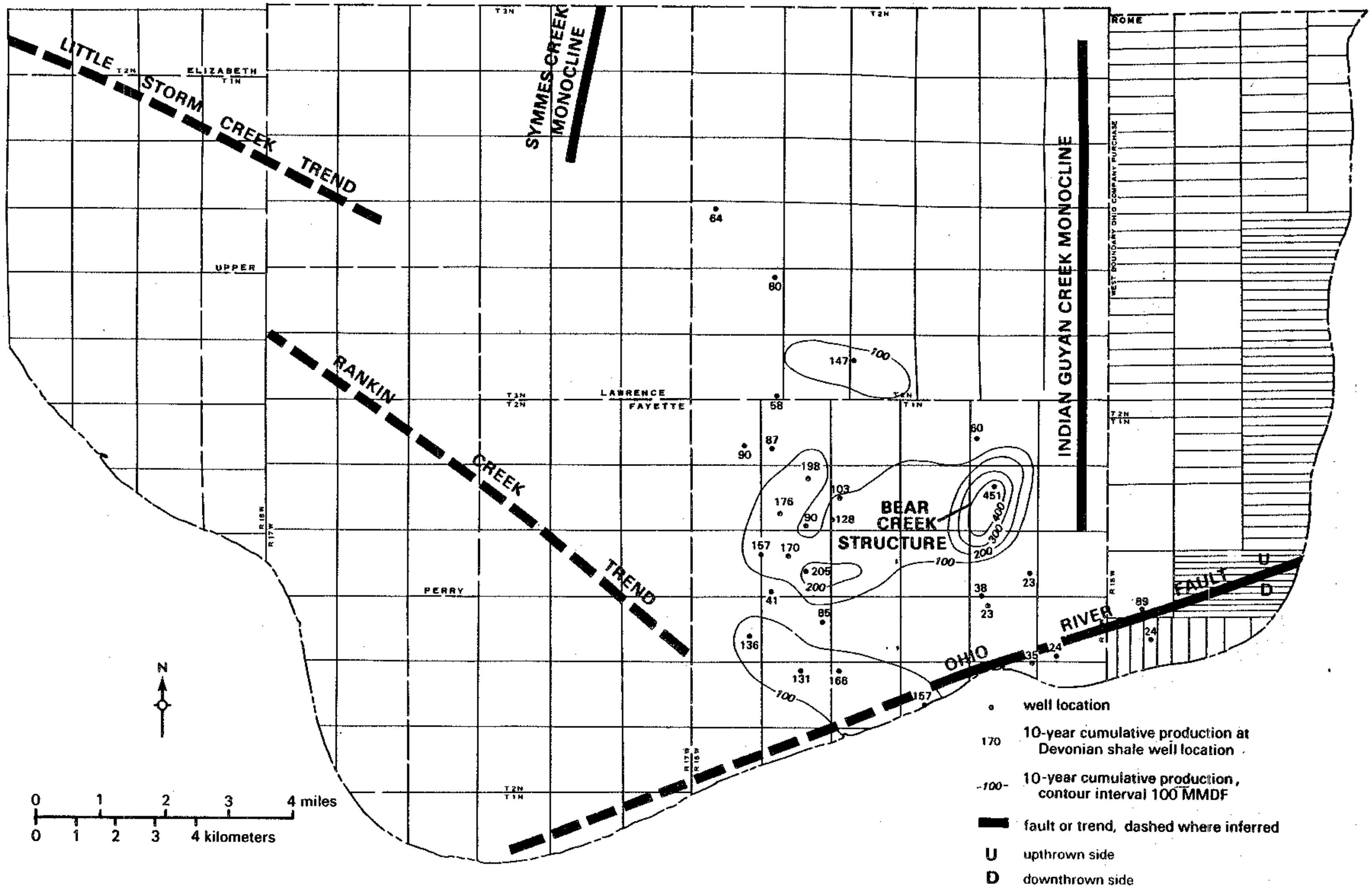

FIGURE 22.—Ten-year cumulative-production map of Devonian shale wells in Lawrence County, Ohio.

drilling an oil or gas prospect. An analysis of the decline curve also provides valuable insight into the reservoir characteristics in the vicinity of the well.

Additional screening criteria were employed on the 67 Devonian shale wells. To qualify for decline-curve analysis, a well needed at least five years of historical production data. In order to normalize the data to a common standard measurement, it was necessary to know the number of days on line of production. After these screening criteria were applied, only the 29 Columbia Gas wells were left in the sample set.

All 29 wells were shot with nitroglycerine and were completed in multiple stratigraphic units. There were not enough years of production for fractured wells to include in the decline-curve analysis. Thus, it was not possible to do a comparison of shot wells versus fractured wells for Lawrence County.

Results

An average decline curve was calculated for the 29 wells in Lawrence County (fig. 23). On the basis of information from completion cards on file at the Ohio Division of Geological Survey, all of the wells were completed as gas wells within the lower Huron, or were completed in multiple stratigraphic units containing the lower Huron. The average daily rate of gas production began at 45 mcf for the first year. After 30 years of production, the average well in this data set had an average daily rate of 24 mcf. The average decline curve exhibits the typical reservoir characteristics of Devonian shale wells in the Appalachian Basin, with an initial rapid decrease in production followed by a period of stabilization.

Wells characterized by an initial rapid decrease in production followed by a period of stabilization have been described as being a dual- or multiple-porosity system (Vanorsdale, 1985). Gas is released in a stepwise manner, with the liberated gas from the fractures being released first, then the adsorbed gas on the fracture surface being released, and finally the adsorbed gas within the shale matrix being bled off last. The initial rapid decline in production, or flush production, is a result of the release of liberated gas from the fractures. The release of the adsorbed gas from within the shale matrix can result in exceedingly slow production rates, allowing shale wells to produce for as long as 50 years (for example, permit no. 40-A-1, the No. 1 Ash, Rome Twp., sec. 34, and permit no. 112-A-1, the No. 1 McNeely, Union Twp., sec. 11).

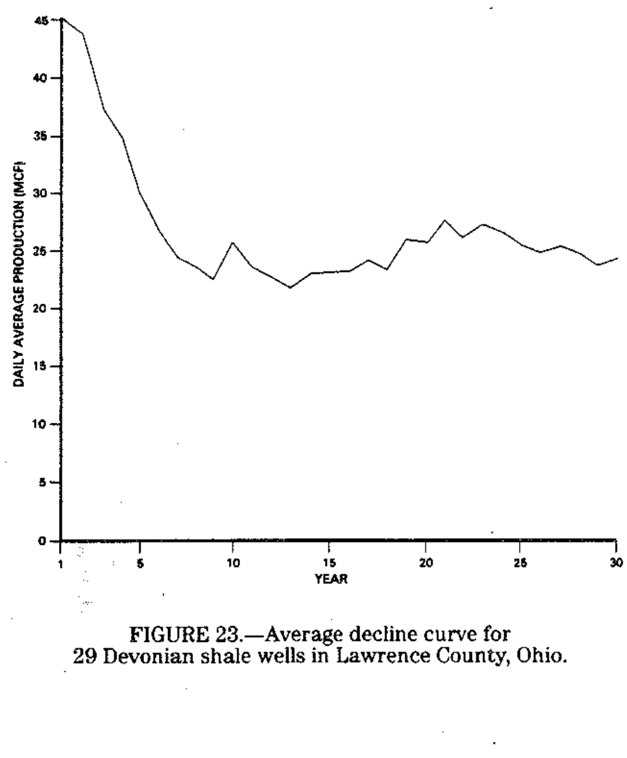

FIGURE 23.—Average decline curve for 29 Devonian shale wells in Lawrence County, Ohio.

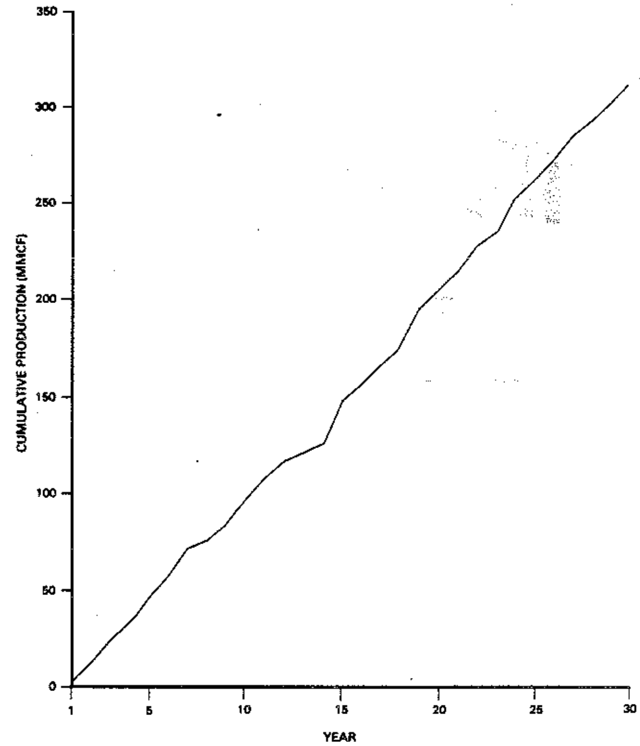

FIGURE 24.—Average cumulative production for 29 Devonian shale wells in Lawrence County, Ohio.

The average cumulative production of gas from Devonian shale wells in Lawrence County is illustrated in figure 24. After 30 years the average cumulative gas production for a Devonian shale well is 311 mmcf.

A plot of initial potential versus cumulative production (fig. 25) was constructed to determine if a relationship

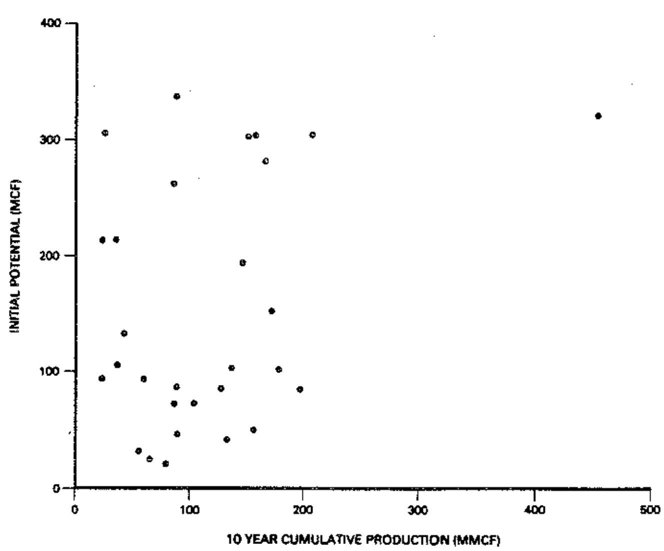

FIGURE 25.—Plot of 10-year cumulative production vs. initial potential for Devonian shale wells in Lawrence County, Ohio.

exists between the variables. As seen from the graph, there is excessive scatter, indicating no direct relationship. In contrast, a direct linear relationship between initial potential and cumulative production in Devonian shales has been found to exist in Kentucky and West Virginia as reported in studies by the West Virginia Geological and Economic Survey (Hohn, 1986) and the Kentucky Geological Survey (W. Frankie, 1986, verbal communication). Lack of correlation in the Lawrence County data could be a result of inaccuracy and lack of standardization of measurement for open-flow tests or insufficient data in the analysis to yield statistical significance.

MISCELLANEOUS GEOLOGIC TOOLS

There are numerous geologic tools that are used in exploration; these include: gravity, magnetics, seismic reflection, electrical resistivity, remote sensing, surface mapping, geochemical mapping, and joint studies. Only remotely sensed airborne imagery will be discussed, as this tool is readily available for this study. In this report, airborne imagery is used to approximate the location of subsurface faults and fracture systems which could provide reservoirs for the entrapment of hydrocarbons.

Fracture systems are features which develop as a result of mechanical failure from stress (Kulander and others, 1979). The location of fracture systems is especially important in exploration and development of Devonian-shale reservoirs. Fracture systems provide excellent reservoirs for oil and gas provided the proper structural and/or stratigraphic containment seals are present.

No single hypothesis pertaining to the origin of fracture systems is universally accepted. The literature is replete with postulated factors which may control the development of fracture systems. Many past and current workers assume that all fracture systems propagate vertically from the Precambrian basement, through overlying sedimentary rocks, and finally to the surface. Although this may be the case for some structural settings, it is not the situation for all structural settings. In Lawrence County the interpreted lineaments are probably the result of stresses originating in the basement. The coincidence of some of the lineaments with the stratigraphic and structural anomalies reinforces the hypothesis of basement involvement and is discussed below.

Struble and Hodges (1982) used Landsat satellite imagery to locate fracture systems in southeastern Ohio. Their interpretation of Landsat imagery covering the Huntington 1:250,000 quadrangle was used for this study. Overall, their map indicates four regional lineament trends in Lawrence County (fig. 26). In order of dominance these are (1) NE-SW, (2) N-S, (3) W-E, and (4) NW-SE. Pertinent to the present study is the alignment of lineaments with faults and structures that have been interpreted in the subsurface on the basis of isopach and structure maps of Devonian-Mississippian shale units. These features are: the NE-SW-trending Ohio River Fault in Rome, Union, and Fayette Townships, the NW-SE-trending Little Storm Creek Trend in Elizabeth, Upper, and Lawrence Townships, and the Indian Guyan Creek Monocline in Union and Windsor Townships. The lineaments mapped by Struble and Hodges are well defined and may be related to the subsurface features mapped during the present study. The N-S-trending Symmes Creek Monocline in Aid and Lawrence Townships, the NW-SE-trending Coffee and Tea Creek Fault in Mason, Aid, and Symmes Townships, and the NW-SE-trending Rankin Creek Trend in Fayette and Perry Townships do not have a well-defined lineament associated with them at the surface.

Synthetic aperture radar (SAR) imagery covering the Huntington 1:250,000 quadrangle was interpreted for lineaments in Lawrence County. A west-looking, far-range mosaic was used. Four regional lineament trends in Lawrence County (fig. 27) similar to those on Struble and Hodges' map (1982) are observed. In order of dominance these are: (1) NW-SE, (2) NE-SW, (3) N-S, and (4) W-E. As with the Landsat interpretation, lineaments pertinent to the present study are proximal to or in alignment with faults and structures discussed above.

NW-SE-trending lineaments dominate the SAR map. The Little Storm Creek Trend in Elizabeth, Upper, and Lawrence Townships and the Rankin Creek Trend in Fayette and Perry Townships are parallel or subparallel to this dominant trend, suggesting a possible relationship. N-S-trending lineaments are parallel to the Symmes Creek Monocline in Aid and Lawrence Townships and the Indian Guyan Creek Monocline in Windsor Township. The Coffee and Tea Creek Fault does not have an SAR lineament parallel to it.

POTENTIAL EXPLORATION AREAS

The primary objective of this study was to evaluate Devonian-shale production and its stratigraphic and structural relationships in Lawrence County. As a result of this study the authors have delineated areas with favorable exploration potential. The integration of all available information should minimize the risk taken by operators and maximize the economic benefits when exploring and developing Devonian shales for oil and natural gas.

The exploration parameters for natural gas production used in this report include studies of internal stratigraphy, structural relationships, production statistics, location of fractured zones, gas shows, and surface lineaments.

As shown on the gas fields map (fig. 19), the Coffee and Tea Creek Fault is situated within an area of "Clinton" production. Shows of gas, however, have been noted within the Devonian shales, indicating potential for gas production in this interval. This NW-SE-trending fault, and a structural flexure associated with it, are present on all of the structure maps. The isopach maps of the lower Huron, the middle Huron, the upper Huron, the Three Lick, the Cleveland, and the total Devonian-Missisippian shale sequence show a thick trend along the Coffee and Tea Creek Fault. The presence of a structural flexure and faulting along with shows of gas indicate this feature is a favorable area for a fractured reservoir.

The Symmes Creek Monocline is a sparsely drilled area containing some scattered "Clinton" production. There were no Devonian shows reported in this area. However, this structural feature could be an area of possible fracturing and therefore of exploration interest.

The Bear Creek Structure is evident on all of the structure maps and is situated within an area of established Devonian production. The isopotential map (fig. 20) shows an area of high initial potential over this structure. Both cumulative-production maps (figs. 21 and 22) indicate areas of good production over this feature. Established production and possible closure make this a promising area for exploration.

The interpreted feature named the Indian Guyan Creek Monocline is based upon a N-S thick trend observed on the upper Olentangy isopach map (fig. 5). The isopotential map (fig. 20) shows this area to have favorable production. On the basis of airborne imagery, there is an alignment of lineaments parallel to this feature. High initial potential and surface lineaments makes this an area of exploration interest.

The Ohio River Fault is evident on all of the structure maps generated for Lawrence County. This fault may be associated with the NE-SW-trending Rome Trough, which

has been established by previous investigators. The straight-line course of the Ohio River in this area is further evidence suggesting a fault. An alignment of regional lineaments indicates the presence of surface joints and fractures along this fault trend. The isopotential map (fig. 20) indicates several areas of high initial potential adjacent to this feature. Subsurface faults and surface lineaments suggest that this area should be favorable for gas production from Devonian shales.

The Little Storm Creek Trend may also be an exploration area for Devonian-shale production. This W-E to NW-SE thick trend in Elizabeth and Lawrence Townships is present on isopach maps of the lower Huron, the upper Huron, the Three Lick, the Cleveland, and the total Devonian-Mississippian shale sequence. This interpreted trend is proximal and parallel to surface lineaments and may represent an area of increased fracturing.

The Rankin Creek Trend is a NW-SE-trending feature in Fayette and Perry Townships. This feature is present on isopach maps of the lower Huron, the upper Huron, the Three Lick, the Cleveland, and the total Devonian-Mississippian shale sequence. NW-SE-trending lineaments are

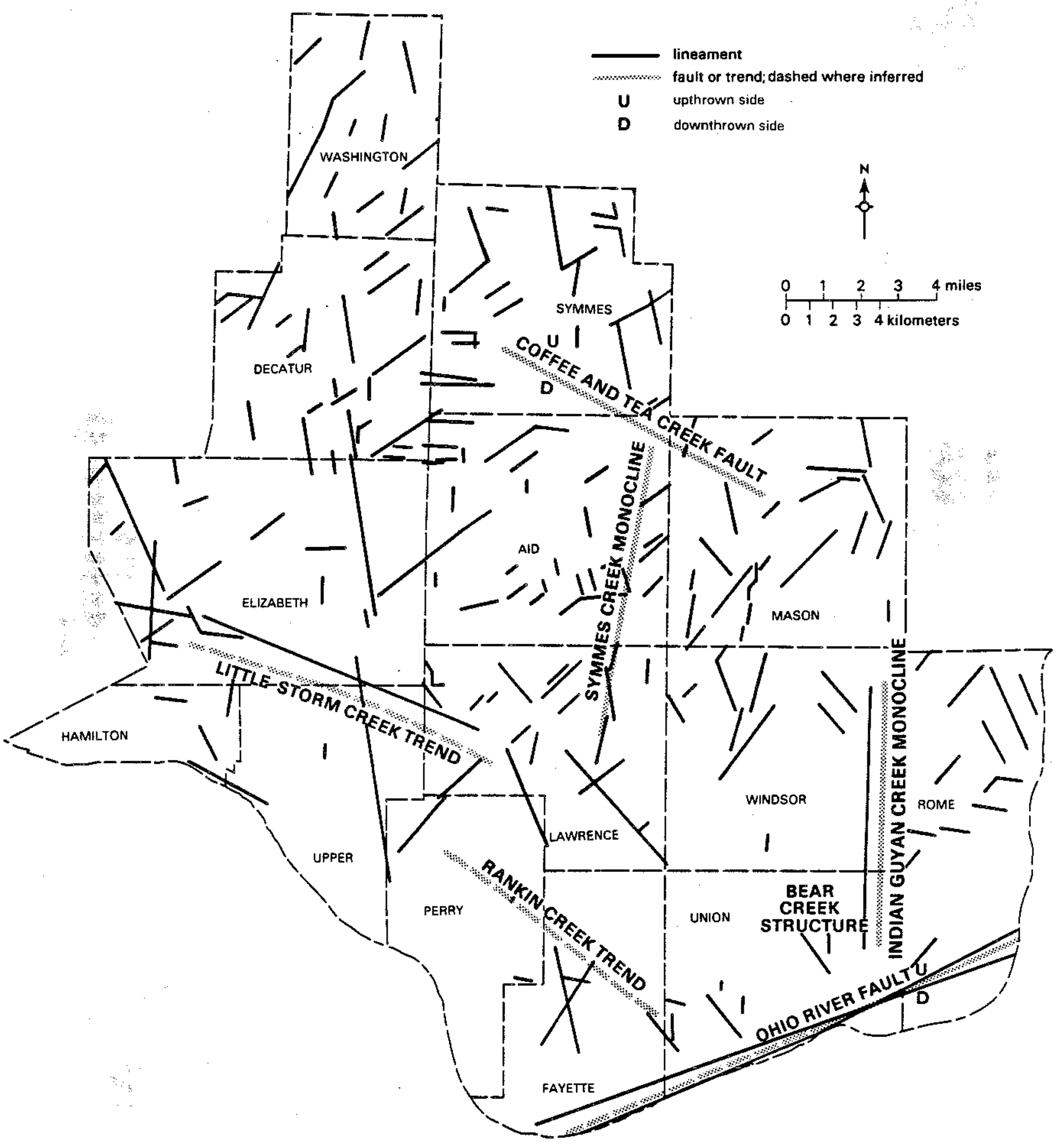

FIGURE 26.—Lineaments mapped from Landsat imagery, Lawrence County, Ohio (after Struble and Hodges, 1982).

subparallel to the Rankin Creek Trend. Thick accumulations of shale and subparallel lineaments indicate that the Rankin Creek Trend may be a prospective area for faulting.

This study describes two-dimensional areas of exploration interest. The problem of determining the precise third-dimensional location of subsurface fracture reservoirs containing oil and gas still exists. It is hoped that the ideas presented here will stimulate future work.

CONCLUSIONS

STRATIGRAPHIC AND STRUCTURAL RELATIONSHIPS

Lawrence County is situated on a north-northeast-trending zone which defines a transitional facies change from basinal black shales in the west to far-distal turbidites in the east. The following conclusions were arrived at during

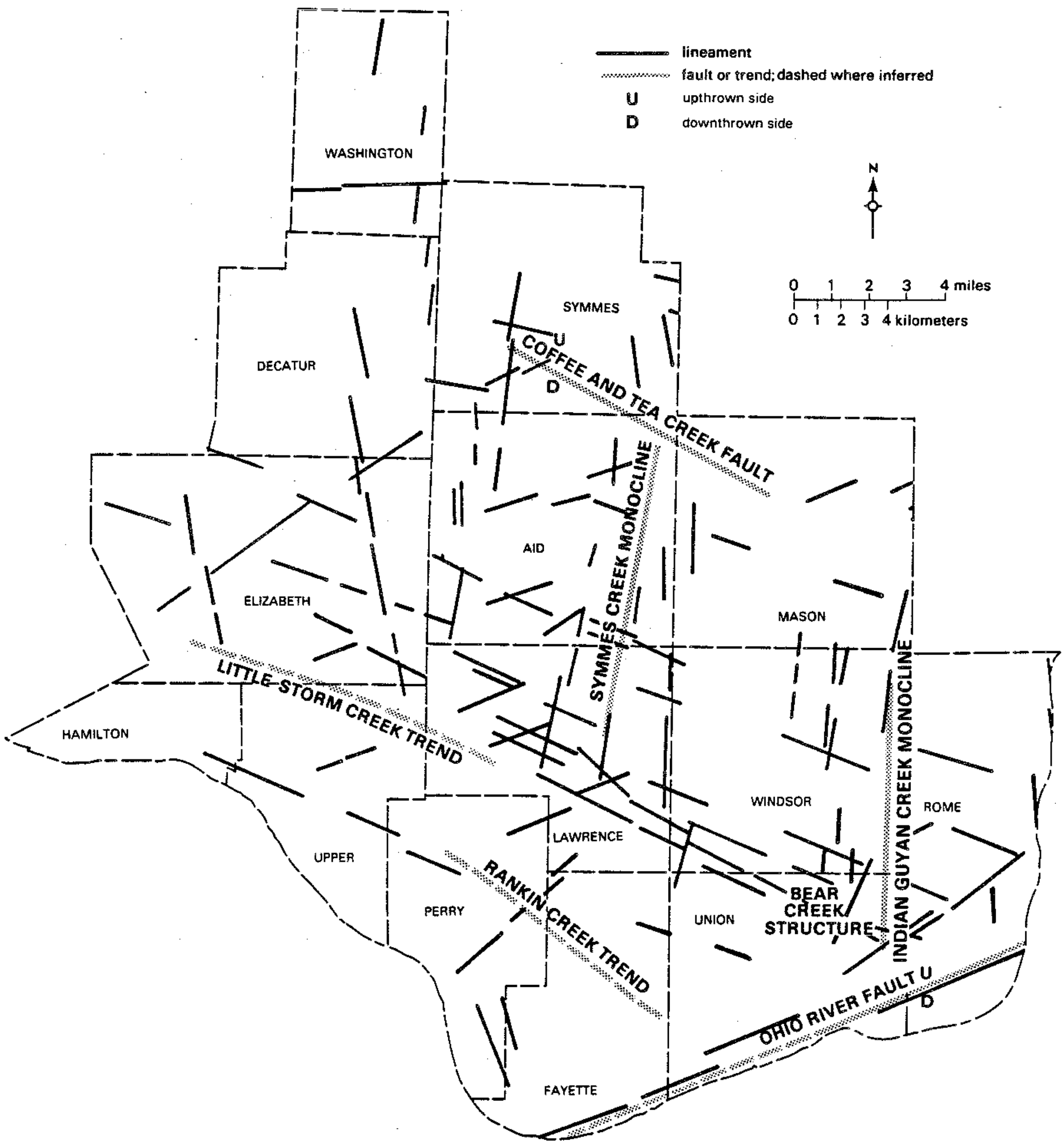

FIGURE 27.—Lineaments mapped from synthetic aperture radar imagery, Lawrence County, Ohio.

this study of Devonian shales in Lawrence County and help to provide the explorationist with basic stratigraphic and structural information that is important when exploring for natural gas from Devonian shales. The isopach maps and cross sections of the shale units in Lawrence County show (1) the general north-south continuity of the black-shale facies, (2) westward progradation of clastic sediments and resultant interfingering with black shales, (3) eastward thickening of sediments during the Late Devonian, and (4) numerous thick and thin trends. Structure maps show fault trends and structures, possibly associated with isopach trends. Lineament interpretations indicate that fracture systems may be related to basement features located beneath the subsurface features seen on the isopach and structure maps of the Devonian shales.

The isopach maps of the upper Olentangy Shale, lower, middle, and upper Huron Shale Member, Three Lick Bed, Cleveland Shale Member, and total Devonian-Mississippian shale sequence (figs. 5, 6, 7, 8, 9, 10, and 12) indicate several dominant thick trends in Lawrence County. Most significant are: (1) the Rankin Creek and Little Storm Creek Trends in Elizabeth, Upper, Lawrence, Perry, and Fayette Townships; (2) the Ohio River Fault in southeastern Rome and Union Townships; (3) the Coffee and Tea Creek Fault in northern Aid and Mason Townships; (4) the Indian Guyan Creek Monocline in Windsor and Union Townships; and (5) the Bear Creek Structure in Union Township. The remaining areas of the county have several less prominent NE-SW or NW-SE trends.

Additional stratigraphic and structural relationships have been observed; some of these warrant further study:

(1) The W-E to NW-SE thick trends in western Lawrence County possibly indicate penecontemporaneous faulting and subsequent filling with sediments during the Late Devonian.
(2) Possible subsidence along these zones of weakness (*i.e.*, faulting) may have been caused by sediment loading of the Catskill Delta.
(3) The NE-SW thick trends proximal to the Ohio River Fault observed in the middle and upper Huron, the Three Lick Bed, and the Cleveland are absent for the most part on the total Devonian-Mississippian isopach map, possibly indicating penecontemporaneous faulting and subsequent filling with sediments in the form of coalescing lobate bodies during deposition of these Upper Devonian units.
(4) The difficulty in correlating the middle and upper Huron, the Three Lick, and the Cleveland and the lobate depositional pattern on the isopach maps may indicate a facies change to the Chagrin Shale Member in eastern Lawrence County.
(5) The complexity of stratigraphic relationships in the middle and upper Huron, the Three Lick, the Cleveland, and the Chagrin indicates a transitional facies change in Lawrence County.

PRODUCTION CHARACTERISTICS

Conclusions regarding the production data are difficult to make because of the lack of reliable data. No correlation could be found between initial potential and 10-year cumulative production. Lack of correlation is probably a result of the inaccuracy of the open-flow tests. The number of wells used in the sample set for Lawrence County was insufficient for comparing the effects of different completion techniques. All of the wells used in the decline-curve analysis were shot with nitroglycerine and completed in multiple stratigraphic units. Thus, it was difficult to compare wells shot with nitroglycerine to fractured wells, or to compare wells completed in one stratigraphic unit to wells completed in multiple stratigraphic units. The following conclusions could be made based on the existing data:

(1) The lower Huron contains the highest number of shows and completions of any stratigraphic unit within the Devonian shale sequence.
(2) Scattered shows of gas have been reported within the Cleveland, Three Lick, upper Huron, middle Huron, Java, Angola, and Rhinestreet. On the basis of historical production, these stratigraphic units do not appear to have as much potential for gas production as the lower Huron.
(3) Many of the wells completed in the "Clinton" sandstone (Silurian) contain shows of gas within the Devonian shales. These areas of "Clinton" production have potential for recompletion in the shallower Devonian shale sequence.
(4) The isopotential map (fig. 20) displays localized areas of initial potential greater than 400 mcf. These isolated areas may be localized regions of fracturing which enhanced production. Three such areas of high initial potential include the Bear Creek Structure, the area surrounding the Ohio River Fault, and the Indian Guyan Creek Monocline.
(5) The cumulative-production maps (fig. 21 and 22) show a relationship between structure and production. The Bear Creek Structure is within an area of high gas production on both the three-year cumulative-production map and the 10-year cumulative-production map.
(6) Average decline curves for the sample set exhibit the standard reservoir characteristics of Devonian shale wells in the Appalachian Basin, with an initial rapid decline in production followed by a period of stabilization. These reservoir characteristics are a result of the multiporosity, multilayer system.

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