



Analysis of Stratigraphic, Structural, and Production Relationships of Devonian Shale Gas Reservoirs in Meigs County, Ohio

by
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PREFACE

The following report details an analysis of Devonian shale reservoirs in Meigs County as part of a five-county study conducted from late 1985 through 1988 for the Gas Research Institute. The final project report was completed in November 1988. The overall objective of this research was to provide a standardized and usable Devonian shale database. The data included subsurface stratigraphy, well drilling, completion and production information, which would be useful to the industry for natural gas resource analyses and also to Ohio citizens and landowners.

The Meigs County study was reviewed by Dr. Arie Janssens and Dr. Paul Potter and previously edited by former Ohio Geological Survey editor Merrienne Hackathorn during the early 1990s. A previous and similar report for Lawrence County was released as Open-File Report 88-2. In light of the current, deep Ordovician shale liquids play of eastern Ohio, the shallower Devonian shales will continue to play a role as a natural gas resource, once commodity prices increase. Currently, horizontal drilling for Devonian shale resources is in its early and largely unproven stages. This shallow-subsurface geologic data also can be utilized indirectly to assist resource and structural analyses of deeper subsurface horizons.

Since this report was compiled in 1986, approximately 80 wells have been drilled to the Ohio Shale in Meigs County.[†] However, the manuscript has not been updated with these new wells, as it was determined that an update would not significantly change the maps and results of the study. Revised paleontological work reported in Pennsylvania (Harper, 1993) has resulted in moving the Devonian-Mississippian boundary to the top of the Berea Sandstone. We have not implemented this change in this report. With that stated, the maps, results, and data are made available for resource and structural assessment, both shallow and deep, and for information to interested landowners and the public at large.

Mark Baranoski and Ron Riley
February 7, 2013

[†]The J.D. Drilling Company Edison Hobstetter well (Klein lease in RBDMS) in section 26 of Sutton Twp. was the second-longest producing and greatest-volume vertical Ohio Shale well in the state. The well produced more than 700 million cubic feet of gas (mmcf) from 1945 to 2000. (The Ohio Fuel Gas Ada Hawthorne well in Lawrence County produced more than 1,600 mmcf from Ohio Shale during 1931–2011.) The Hobstetter well was plugged and abandoned in September 2001 to make way for U.S. Route 33. J.D. Drilling currently produces Ohio Shale gas from approximately 350 wells in Meigs County.

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ABSTRACT

The stratigraphy, structure, and production characteristics of the Devonian-Mississippian shale sequence in Meigs County, Ohio, have been evaluated. The Meigs County database consists of permit and completion data for 706 wells, geophysical-log tops for 586 wells, and production records for 410 wells.

The lower Huron Shale Member of the Ohio Shale is the primary Devonian unit for natural gas production in Meigs County, as it is in much of the Appalachian Basin. The Devonian shale sequence shows an eastward thickening as well as interfingering of organic shales to the west with clastic sediments to the east. Naturally completed wells have the highest cumulative production but account for less than 5 percent of the wells. Hydraulically fractured wells have the highest average initial potential but the lowest cumulative production.

Structure, isopach, isopotential, and cumulative-production maps all show a pronounced northwest-southeast trend in Meigs County. Numerous stratigraphic and structural anomalies correlate with directional trends on isopotential and cumulative-production maps; this correlation indicates that fracture systems are the primary reservoirs for natural gas in the Devonian shales. Zones of weakness in the Precambrian basement may be the ultimate cause and control on both orientation and intensity of these fractures.

INTRODUCTION

In late 1985 the Ohio Department of Natural Resources (ODNR), Division of Geological Survey began a detailed geologic analysis of Devonian shale reservoirs in southeastern Ohio (fig. 1), as part of a regional project on Devonian shales in the Appalachian Basin conducted by the Gas Research Institute (GRI) of Chicago, Illinois. The study was conducted in three phases: Lawrence County (Baranoski and Riley, 1988); Meigs County (this report); and Monroe, Noble, and Washington Counties (Baranoski and Riley, unpub. data, 1988). The primary objectives of the investigation are to (1) establish a computerized database that includes stratigraphic, production, and

completion data on the Devonian shales; (2) refine the stratigraphic framework of Devonian shales in southeastern Ohio; (3) identify the Devonian shale gas fields and pools; (4) determine relationships between production, stratigraphy, structure, and completion techniques; and (5) provide the data to industry in forms usable for developing drilling programs.

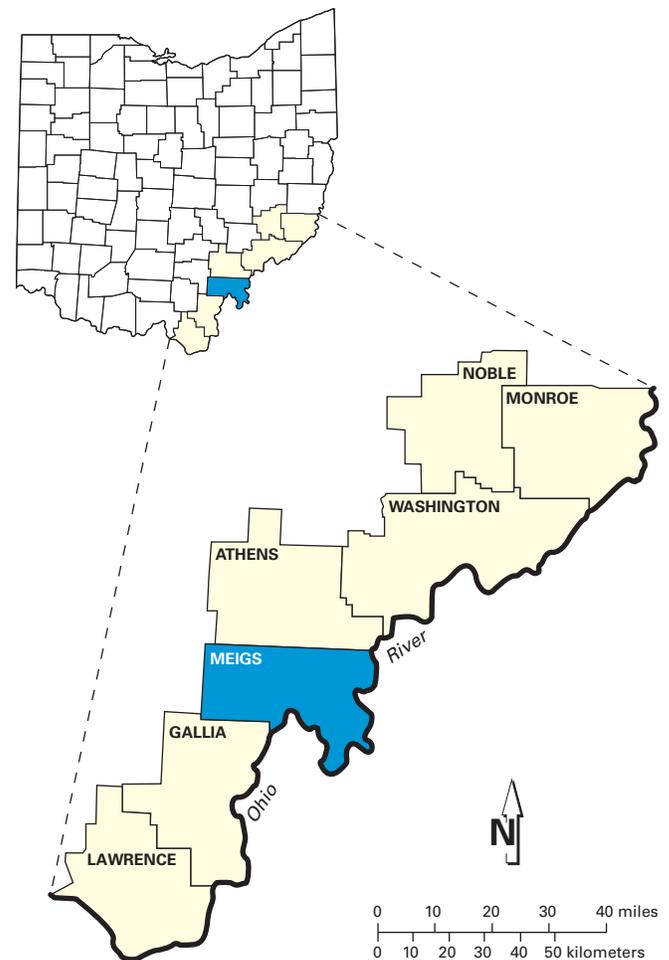


FIGURE 1. Devonian shale study areas and location of Meigs County, Ohio.

Our report presents results of the detailed analysis of the relationship of geology to production in Meigs County. The digital database developed for Meigs County was used to produce the maps and other figures in this report. The data collected for the GRI study of Lawrence, Meigs, Monroe, Noble, and Washington counties is available at no cost on the ODNR Division of Geological Survey FTP site at <ftp://ftp.dnr.state.oh.us/Geological_Survey/dev-shale/>.

The collection of production data from all available sources and the comparison to geologic factors should provide additional insight to Devonian shale exploration and help producers in the development of additional reserves. Our study complements similar Devonian shale research conducted by the geological surveys of Kentucky (Frankie and others, 1986) and West Virginia (Filer, 1985).

STRATIGRAPHY OF DEVONIAN–MISSISSIPPIAN SHALES IN MEIGS COUNTY

Previous Work

A detailed study of Devonian shales in Meigs County has not been performed in the past; however, many regional studies of Devonian shales involved records of wells in the vicinity. 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 Berea, the uppermost Devonian shales were examined by these authors. Schwietering (1970) used outcrops, sample cuttings, and geophysical logs in a regional study 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 study of Devonian shale in 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. Roen and de Witt (1984) conducted a comprehensive, regional study of Devonian shales in the Appalachian Basin.

Vast amounts of information concerning Devonian shales in the Appalachian Basin have been generated by the Eastern Gas Shales Project (EGSP) of the U.S. Department of Energy (U.S. DOE) and through research funded by the GRI. These studies have provided additional insight and a better understanding of the stratigraphy, petrology, sedimentology, structural geology, production

characteristics, and well-stimulation techniques of the Devonian shales.

Numerous regional studies of Devonian shales in Ohio (including Meigs County) have been conducted under the auspices of U.S. DOE and GRI. In a regional study sponsored by U.S. DOE, Science Applications, Inc. (1978) developed methods of increasing natural gas production from Devonian shales in the Appalachian, Michigan, and Illinois Basins. The study included a representative decline curve for a Devonian shale well in Meigs County (Science Applications, Inc., 1978, p. 67).

Schwietering (1979) prepared a regional report entitled "Devonian shales of Ohio and their eastern and southern equivalents" for the U.S. DOE Morgantown Energy Technology Center (METC), a detailed stratigraphic study that employed the use of outcrops, well cuttings, and geophysical logs to describe and correlate the stratigraphic units of the Devonian shale sequence.

Another regional study of Devonian shales in the Appalachian Basin was conducted by Potter and others (1980) for the EGSP. In this project, special emphasis was placed upon geological, geochemical, and petrologic aspects of the Devonian shales.

In a regional study for the METC, Zielinski and McIver (1981) performed geochemical analyses on more than 2,000 individual core samples and several hundred well cuttings from Devonian shale wells in the Appalachian Basin. These samples included the EGSP/OH-9 core from Meigs County (Columbia Gas, permit no. 2058, Chester Township, sec. 6) and five EGSP/OH-6 cores from adjacent Gallia County.

Cliffs Minerals, Inc. (1982) conducted a regional study of 33 EGSP cores in the Appalachian Basin that included an analysis of the lower- and middle-Huron interval in the EGSP/OH-9 well in Meigs County. Results of this core analysis indicated a N 55° E fracture trend may be responsible for the gas production from this well. The Cliffs Minerals study concluded that the fractures are limited to specific stratigraphic levels that are connected horizontally, but not vertically, over significant distances.

Gray and others (1982) studied Devonian shales in eastern Ohio as part of the EGSP. The project included stratigraphic mapping; structure mapping; mineralogic, petrographic, and geochemical characterizations; fracture and lineament analyses; and a gas-monitoring program.

Struble (1982) conducted a regional study of Devonian shales in the eastern United States sponsored by METC, a research effort that included an evaluation of stratigraphy, structure, geochemistry, fracturing, and gas production. In this study, Struble (1982, p. 309–319) outlined site-specific areas for drilling Devonian shale wells in southeastern Ohio.

More recently, the Institute of Gas Technology (1986) prepared a study for METC entitled "Porosity and permeability of eastern Devonian gas shales." The contract work involved porosity and permeability measurements

of Devonian shale cores and included an analysis of the EGSP/OH-9 well in Meigs County.

Purpose and Methods

In order to begin to evaluate the relationship between geology and natural gas production from Devonian shale wells in Meigs County, we chose stratigraphic markers, based on responses on gamma ray and neutron/density logs, which could be traced throughout the study area. The Devonian-Mississippian sequence was subdivided into mappable units (fig. 2) using these stratigraphic markers (Baranoski and Riley, 1988). Thus the internal shale stratigraphy observed is a result of contrasting radioactivity on gamma 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 (e.g., Gray and others, 1982). 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 our 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).

A cross-section network in southeastern Ohio was constructed early in the GRI project (Ohio Division of Geological Survey, 1986a) from multiple sources including geophysical logs on file at the ODNR Division of Geological Survey. Cross section B-B' from this earlier report was revised and is used in our study to illustrate the internal stratigraphy of the Devonian shales and the facies changes across the study area (fig. 3). This west–east cross section shows the basin configuration during early Mississippian time. The top of the Berea Sandstone (Mississippian) has been used as the stratigraphic datum. This contact is easily identified on geophysical logs and is present throughout the study area.

Regional Setting and General Stratigraphy

Meigs County is located in southeastern Ohio (fig. 1) and is bounded on the east by the Ohio River, which separates it from West Virginia. The topographic relief is moderate to steep, which is typical of the unglaciated, dissected surface of the Appalachian Plateau region.

Elevations at the surface range from 540 feet above sea level along the Ohio River in Salisbury Township to 1,020 feet above sea level in southeastern Salem Township. The Pennsylvanian-age Allegheny, Conemaugh, and Monongahela Groups and the Pennsylvanian-Permian-age Dunkard Group crop out at the surface and dip gently eastward. These rocks consist of a complex assemblage of sandstones, siltstones, shales, coals, and limestones that accumulated under predominantly deltaic conditions. The dominant structural features adjacent to Meigs County (fig. 4) are discussed later in the section on structure (p. 11).

The Devonian-Mississippian shale sequence of southeastern Ohio forms an eastward-thickening wedge of sediments on the western flank of the Appalachian Basin (fig. 3). Such eastward thickening into the Appalachian Basin has been documented previously in cross sections by Rich (1951), Oliver and others (1967), Heckel (1973), Gray and others (1982), and the Ohio Division of Geological Survey (1986a). Potter and others (1982) illustrate several interpretations of this wedge of Appalachian gas-bearing Devonian shales.

The stratigraphic interval investigated for our study consists of the units overlying the Onondaga Limestone (Middle Devonian) and underlying the Sunbury Shale (Lower Mississippian). A typical geophysical log from Lebanon Township illustrates the Devonian-Mississippian shale sequence in Meigs County (fig. 2). Using geophysical logs, the Devonian-Mississippian shale sequence is subdivided into the following units: the lower Olentangy Shale (in New York terminology the Hamilton Group, including the Marcellus Shale); the upper Olentangy Shale (in New York terminology the Rhinestreet Shale and Angola Shale Members of the West Falls Formation and the Java Formation, including the Pipe Creek Member); the lower unit of the Huron Shale Member of the Ohio Shale; the Chagrin Shale Member of the Ohio Shale, including the “Gordon” siltstone; the Three Lick Bed of the Ohio Shale; the Cleveland Shale Member of the Ohio Shale; the Bedford Shale; the Berea Sandstone; and the Sunbury Shale. The Marcellus Shale, the Chagrin Member, the Three Lick Bed, the “Gordon” siltstone, and the Cleveland Member exhibit significant facies variations in Meigs County (fig. 3). The Devonian-Mississippian boundary apparently lies within the Bedford Shale and cannot be precisely determined from geophysical logs.

Our detailed stratigraphic studies of the Devonian shales in Meigs County show the same broad basinwide facies variations observed by Potter and others (1982), Roen and deWitt (1984), and Etensohn (1985). Two lithologies dominate these basinwide facies of the shale sequence: black organic-rich shale and gray to greenish-gray silty shale (Baranoski and Riley, 1988). The black organic-rich shale accumulated in the moderately deep, marine, anoxic western portion of the Appalachian Basin

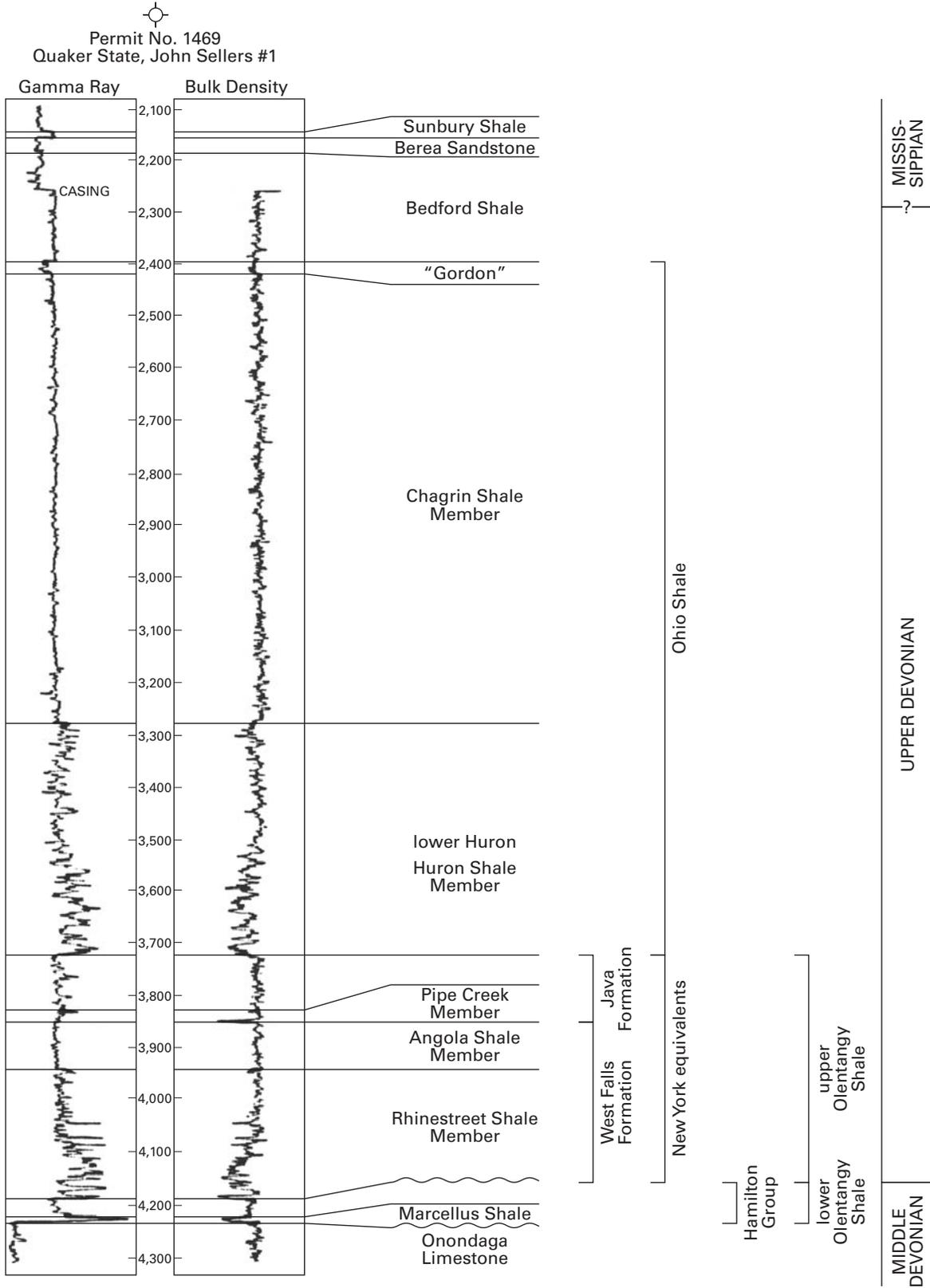


FIGURE 2. Typical log for the Devonian-Mississippian shale sequence in Meigs County, Ohio.

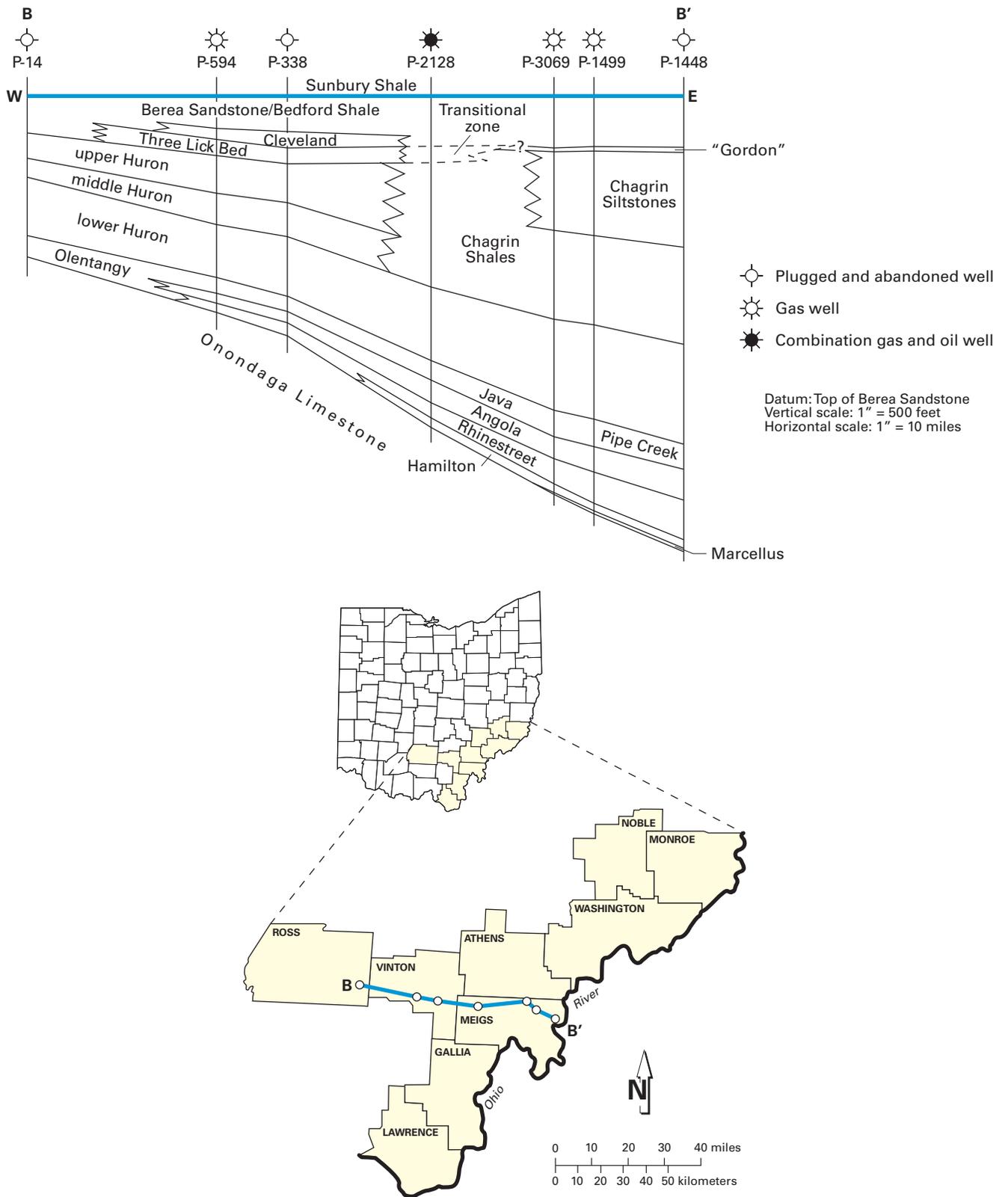


FIGURE 3. West-east stratigraphic cross section of Devonian shales in southeastern Ohio. Modified from Ohio Division of Geological Survey (1986a).



FIGURE 4. Regional structural setting and location of Ohio. Modified from Struble (1982).

(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).

Variations in terrigenous sediment 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 Devonian shale units in Meigs County show (1) the general continuity of black-shale facies along strike, (2) westward progradation of clastic sediments and resultant interfingering with black shales, and (3) eastward thickening of sediments during the Late Devonian.

Lower Olentangy Shale

The lower Olentangy Shale (Middle Devonian) is the basal stratigraphic unit of the Devonian-Mississippian shale sequence in Meigs County. The unit crops out in central Ohio and lies disconformably on the Delaware Limestone (Onondaga Limestone of this report; Tillman, 1970, p. 202). The unit appears to be conformable as it is traced into the subsurface of eastern Ohio (Schwietering, 1979, p. 16; Gray and others, 1982, p. 2.11).

In the subsurface of Meigs County, the lower Olentangy is subdivided into two units on the basis of geophysical-log characteristics. These units are equivalent to the Marcellus Shale and the Hamilton Group of New York. The Marcellus Shale is the basal unit and is easily recognized because of its relatively high gamma ray response and corresponding neutron/density porosity. The remainder of the Hamilton

Group is undifferentiated in Meigs County. Schwietering (1979, p. 19) recognized the lower Olentangy in the subsurface of eastern Ohio as gray, dark-gray, and black-shale and limestone beds. He traced the basal black shale bed into the Marcellus Shale of Pennsylvania, New York, and West Virginia; the overlying beds were traced into the Hamilton Group of New York and the Mahantango Formation of Pennsylvania and West Virginia. In Meigs County the thickness of the Marcellus ranges from 0 feet in the western portion of the county at the pinchout to 12 feet in the eastern portion. The pinchout of the Marcellus in the western portion of the county occurs along a northwesterly trend through Salisbury, Rutland, Scipio, and Columbia Townships (fig. 5). The Marcellus appears to be absent in a localized area where Bedford, Salisbury, and Chester Townships meet. The remaining portion of the Hamilton Group ranges from 20 feet thick in the western portion of the county to 40 feet thick in the east.

Upper Olentangy Shale

The upper Olentangy Shale unconformably overlies the lower Olentangy in outcrops in central Ohio (Tillman,

1970, p. 202). In the subsurface of eastern Ohio, geophysical logs show that beds equivalent to the upper Olentangy on lap westward out of the basin, possibly indicating an unconformable contact with the underlying Hamilton Group. In Meigs County, the upper Olentangy is subdivided into four mappable units, which are distal beds of the West Falls and Java Formations of New York (Gray and others, 1982). In ascending order the units are the Rhinestreet Shale Member of the West Falls Formation, the Angola Shale Member of the West Falls Formation, the Java Formation undifferentiated, and the Pipe Creek Member at the base of the Java. Total thickness of these units ranges from 240 feet in the western part of Columbia Township to 560 feet in southeastern Lebanon Township. Each unit has a characteristic log signature and can be traced into Kentucky, West Virginia, Pennsylvania, and New York (Roen and others, 1978; Schwietering, 1979). Only the Java Formation can be traced from the subsurface to the outcrop in central Ohio (Joseph Schwietering, oral commun., 1987).

The Rhinestreet Shale Member lies unconformably on the shales of the Hamilton Group in Meigs County and thins westward, pinching out in Vinton County (fig. 3). Thickness ranges from 100 feet in western Columbia

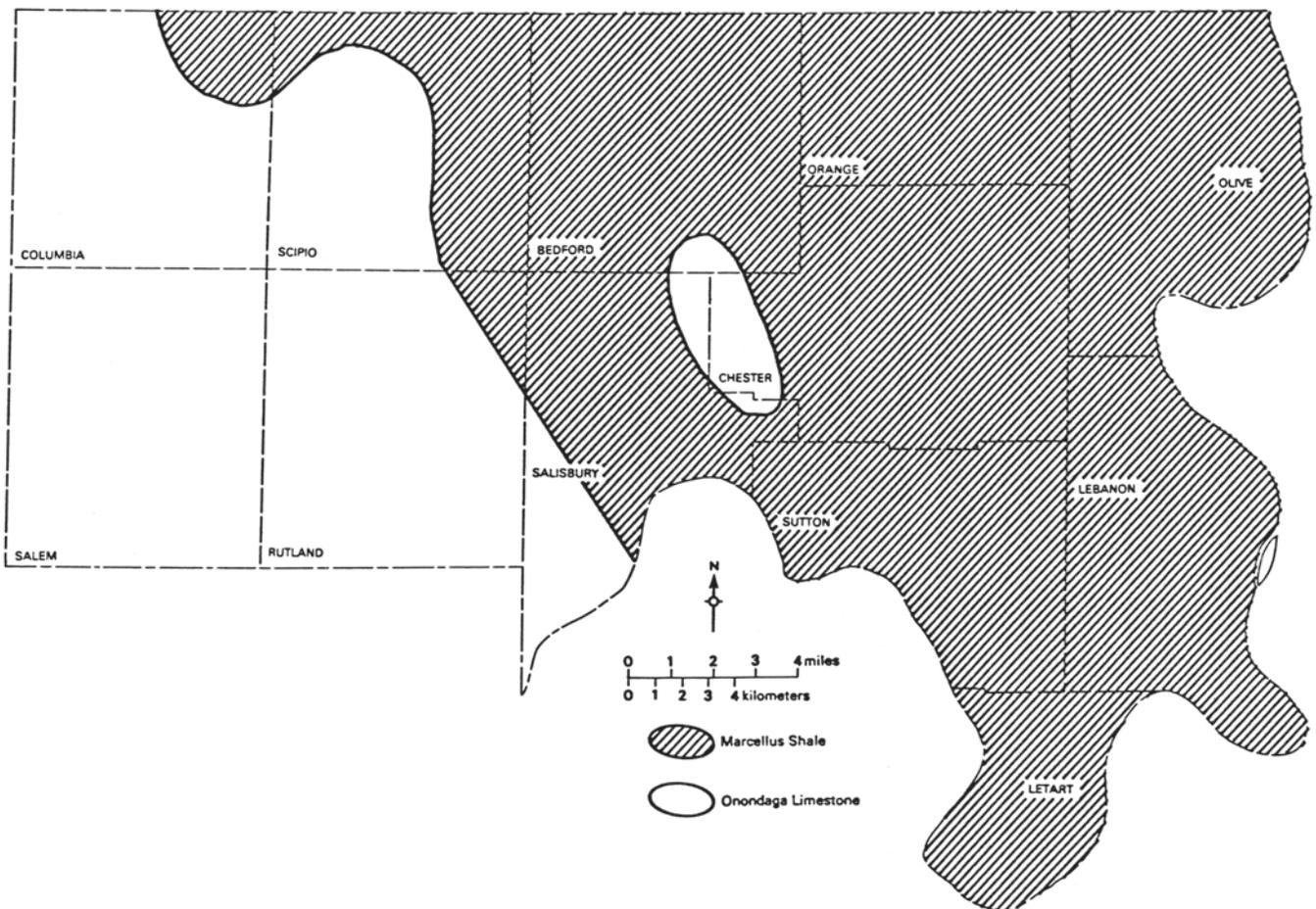


FIGURE 5. Area of occurrence of the Marcellus Shale, Meigs County, Ohio.

Township to 270 feet in eastern Lebanon Township. The unit consists of interbedded black, dark-gray, and greenish-gray shale (Dowse, 1980, p. 53). On the basis of the examination of sample cuttings and logs, the unit can be subdivided into a lower portion dominated by black shale and an upper portion dominated by gray to greenish-gray shale. The upper portion appears to be a transitional facies, equivalent to beds that grade laterally westward to black shale beds in western Meigs County and eastward to gray to greenish-gray, silty shale in West Virginia. The base of the Rhinestreet is somewhat tenuous on geophysical logs, owing to the unconformity, but is generally chosen at the base of the first black shale bed above the gray to greenish-gray shales of the Hamilton.

The Angola Shale Member conformably overlies the Rhinestreet and is easily distinguished by a very consistent low gamma ray response, which is typical of gray to greenish-gray, silty shales. The base of the unit is identified as the top of the uppermost black shale bed of the transitional facies of the Rhinestreet and can be difficult to distinguish on poor-quality logs. The top of the unit is defined by the base of a regionally persistent black shale bed, which is equivalent to the Pipe Creek Member of the Java Formation. In Meigs County, the Angola ranges in thickness from approximately 50 feet in western Columbia Township to approximately 100 feet in southeastern Lebanon Township. The unit pinches out to the west in Vinton County (fig. 3).

The Java Formation conformably overlies the Angola Member and thickens eastward. In Meigs County, the Java ranges in thickness from approximately 80 feet in the western portion of the county to 135 feet in the east. The unit consists of interbedded, brownish-black shale and gray to greenish-gray, silty shale. The gamma ray log response is generally higher than that of the underlying Angola. The Pipe Creek Member is a regionally persistent basal bed with a high gamma ray response, making the contact with the Angola easy to distinguish. The upper contact with the overlying Huron Member is gradational to a dominantly brownish-black shale with high gamma ray response, making the position of the stratigraphic top somewhat arbitrary. This contact has been chosen at the base of the lowest high gamma ray response shale of the Huron as described below.

Ohio Shale

The Ohio Shale section in Meigs County consists of the Huron Shale Member, the Three Lick Bed, the Cleveland Shale Member, and the Chagrin Shale Member and its "Gordon" siltstone bed. A number of silty shale beds of the Chagrin below the "Gordon" can be mapped as a gross facies change in eastern Meigs County. The uppermost units of the Ohio Shale contain the most significant facies variations in the Devonian shale in Meigs County (fig. 6). The Ohio Shale thickens eastward and ranges in thickness

from 1,040 feet in western Columbia Township to 1,620 feet in eastern Lebanon Township (thickness includes Bedford-Berea sequence).

Huron Shale Member

The Huron Shale Member is the basal member of the Ohio Shale and is the most widespread stratigraphic unit of the Devonian-Mississippian shale sequence. The Huron can be traced from the outcrop in central Ohio into the subsurface in eastern Ohio, Pennsylvania, West Virginia, and Kentucky (Gray and others, 1982, map no. 312). West of Meigs County the Huron Member is subdivided into three mappable units (lower, middle, and upper Huron) on geophysical-logs. In Meigs County, however, only the lower Huron can be mapped. The middle and upper Huron are not recognizable on geophysical logs because of a facies change to the Chagrin Shale Member.

The lower Huron conformably overlies the Java Formation and consists of dominantly brownish-black, organic-rich shale interbedded with lesser amounts of gray to greenish-gray, silty shale. The high organic content of the unit is characterized by a distinctive high response on gamma ray and neutron/density logs, making it easy to distinguish from the underlying Java. The top of the unit is very gradational and is chosen as the top of the uppermost brownish-black shale beneath a monotonous section of dominantly gray to greenish-gray, silty shale and siltstone as indicated by typical log response. In southeastern Lebanon Township, the unit grades eastward into a transitional facies, which consists of increasing amounts of gray to greenish-gray shale. Gamma ray response of this transitional facies is mostly less than 200 API units.

The lower Huron is the most extensive stratigraphic unit of the Huron Shale Member in eastern Ohio and thickens eastward, as do the underlying Devonian shale units. The rate of thickening increases eastward toward the axis of the Appalachian Basin. Thickness of the lower Huron ranges from 230 feet in the western part of Columbia Township to 480 feet in southeasternmost Lebanon Township. Depositional strike trends predominantly north-south. A number of strong northwest-southeast- and west-east-trending anomalies occur (fig. 7). Several of these stratigraphic features show strong correlation with lineaments, structure, and production.

Three Lick Bed

Provo (1977) originally recognized and named the Three Lick Bed of the Ohio Shale, a mappable unit in southern Ohio and eastern Kentucky. On the basis of work by Lewis and Schwietering (1971), Provo interpreted it as a western tongue of the Chagrin Shale Member. The unit conformably overlies the upper Huron and consists of interbedded, greenish-gray and brownish-black shale (Provo, 1977, p. 38). On geophysical logs the unit is

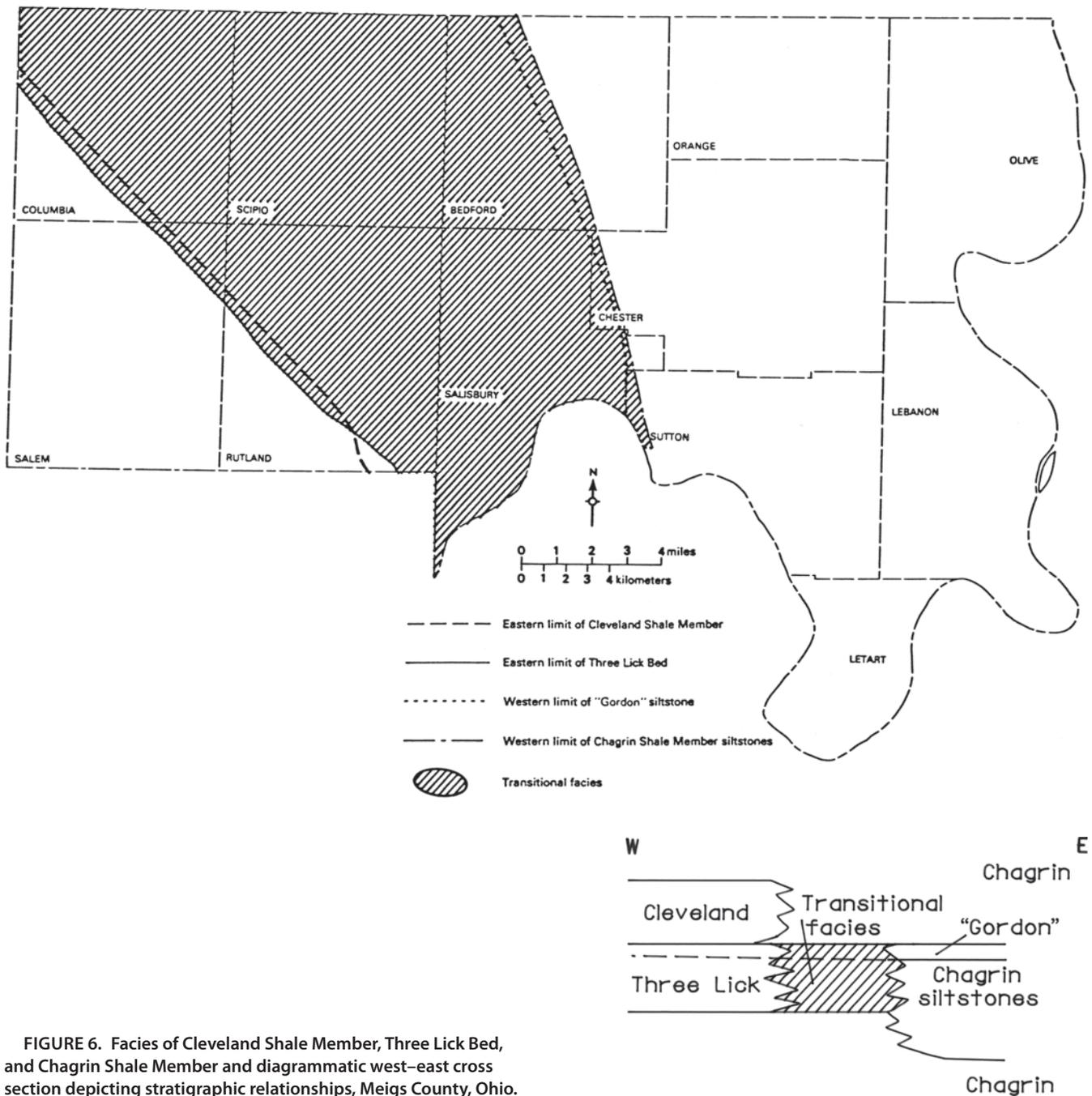


FIGURE 6. Facies of Cleveland Shale Member, Three Lick Bed, and Chagrin Shale Member and diagrammatic west-east cross section depicting stratigraphic relationships, Meigs County, Ohio.

characterized by three to four beds of low-gamma ray-response, greenish-gray shale separated by higher gamma ray-response, gray to brownish-black shale (Ohio Division of Geological Survey, 1986a). The unit can be mapped only in southwestern Meigs County. Northeastward and eastward from this area the Three Lick becomes poorly defined, apparently becoming a transitional zone to the uppermost Chagrin Member (fig. 6). Farther east, the Three Lick cannot be identified on geophysical logs because of

an absence of traceable, brownish-black shale beds. Where present, the Three Lick Bed is 60 to 70 feet thick.

Cleveland Shale Member

The Cleveland Shale Member is recognized by a high response on gamma ray and neutron/density logs. The unit consists of brownish-black, organic-rich shale (Provo, 1977, p. 34). The unit conformably overlies the Three

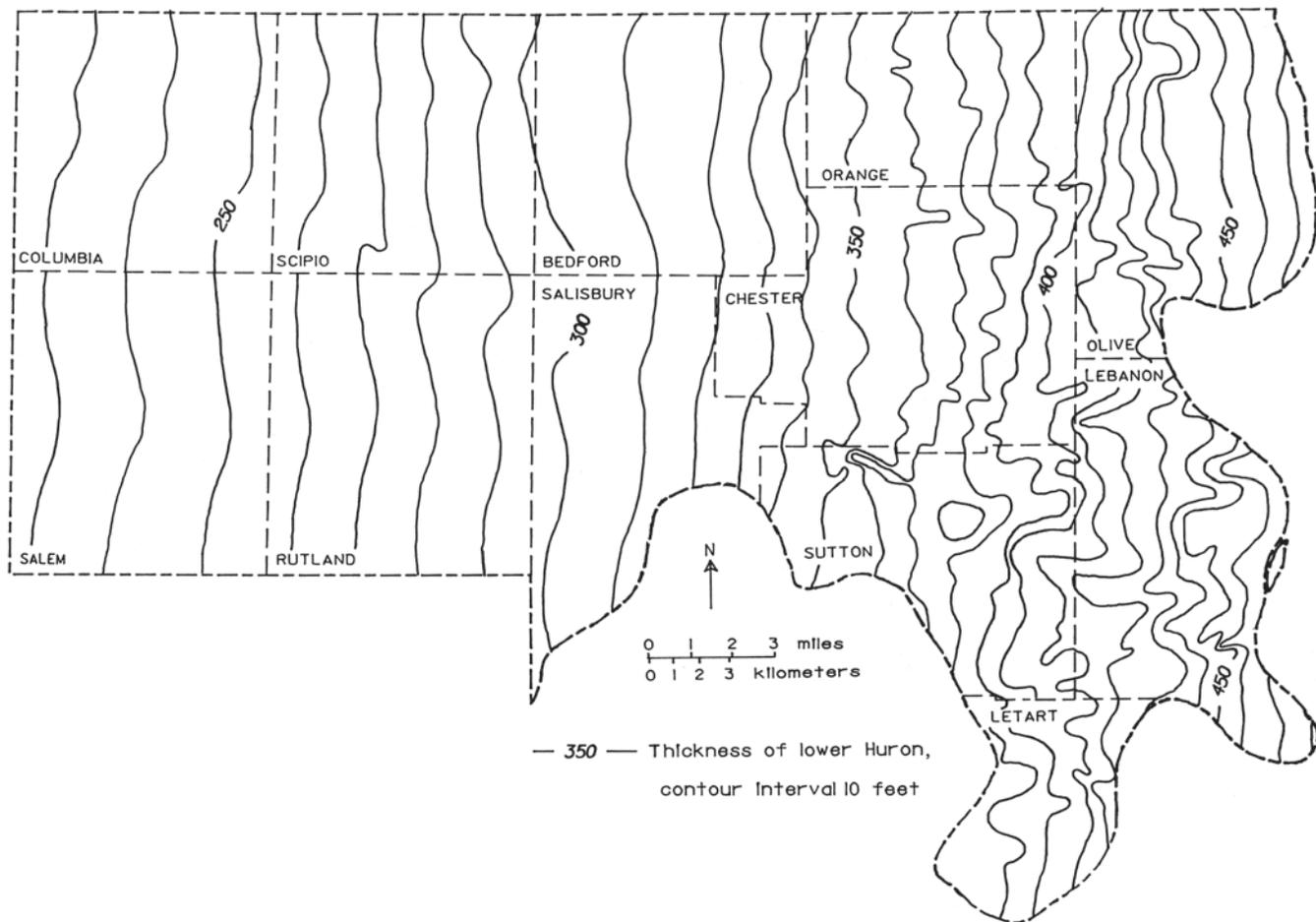


FIGURE 7. Isopach map of lower Huron Shale Member, Meigs County, Ohio.

Lick Bed, is poorly developed in Meigs County, and is present only in the southwestern portion of the county in approximately the same area as the Three Lick Bed (fig. 6). To the east the Cleveland is transitional and is replaced by gray to greenish-gray shales and siltstones of the Chagrin.

Chagrin Shale Member

The Chagrin Shale Member has an overall lower gamma ray response than that of the Huron, Three Lick, and Cleveland because of a general absence of brownish-black, organic-rich shales. The complexity of the unit makes the Chagrin very problematic when attempting to map it in the subsurface. The unit consists of gray to greenish-gray shales and siltstones, which intertongue with brownish-black shales both laterally and vertically in western Meigs County. Numerous thin siltstone beds throughout the Chagrin are indicated on geophysical logs from eastern Meigs County. The Chagrin is the thickest stratigraphic unit in the Devonian-Mississippian shale sequence and, like the underlying units, thickens eastward.

The exact thickness of the unit cannot be determined because of the difficulty in picking the base of the Bedford Shale. Thickness, including the Bedford-Berea sequence, ranges from approximately 650 feet in western Columbia Township to 1,050 feet in eastern Lebanon Township.

A significant silty unit occurs in the uppermost Chagrin, approximately 240 feet below the Berea Sandstone. The unit can be easily traced throughout the eastern portion of the county and into West Virginia and is referred to as the "Gordon" by drillers in southeastern Ohio. It appears to be equivalent to the "Gordon" siltstone, which has been identified in West Virginia (Filer, 1985). The "Gordon" is 8 to 26 feet thick in eastern Meigs County. Except for the southeastern portion of the county, there are no well-defined areas of thicker "Gordon." In Letart and Lebanon Townships the unit is slightly thicker, 16 to 26 feet. The "Gordon" appears to be equivalent to the uppermost greenish-gray shale in the Three Lick Bed of the western portion of the county. A transitional zone in which the "Gordon" is poorly developed occurs in approximately the same area of the county as the transitional zone in the Three Lick (fig. 6).

The numerous silty shale or siltstone beds present in the Chagrin throughout the eastern portion of Meigs County have been mapped only as a gross facies change in the Chagrin Member. The beds pinch out westward in approximately the same location as the transitional facies of the Three Lick, Cleveland, and "Gordon."

Bedford Shale

The Bedford Shale conformably overlies the Ohio Shale throughout Meigs County (fig. 3). The contact between the Bedford and the underlying Chagrin Member cannot be picked on geophysical logs. Where the Cleveland Member is present, the contact can be easily identified. Lithologically, the Bedford consists of red shale interbedded with gray shale and siltstone (Pepper and others, 1954, p. 26–27).

Berea Sandstone

The Berea Sandstone conformably overlies the Bedford Shale throughout the study area. Intertonguing relationships between siltstones and shales of the Bedford and Berea make it impractical to pick a contact on geophysical logs. Thickness of the Berea in Meigs County averages about 12 feet but may be up to 30 feet. Log evaluation indicates the Berea to be very silty in places. Pepper and others (1954, p. 28) described the Berea as a medium- to fine-grained, clay-bonded quartz sandstone.

Sunbury Shale

The Sunbury Shale conformably overlies the Berea Sandstone and is regionally extensive throughout Meigs County. The high gamma ray response and high neutron/density porosity of the Sunbury make the contact with the underlying Berea easily distinguished. The Sunbury is approximately 25 feet thick in Meigs County. Lithologically, the Sunbury is a bituminous black shale (Pepper and others, 1954, p. 41).

Total Devonian-Mississippian Shale Sequence

We constructed an isopach map of the total Devonian-Mississippian shale sequence using the interval between the top of the Berea Sandstone and the top of the Onondaga Limestone as recognized on geophysical logs (fig. 8). Contouring is more detailed in the eastern part of the county than in the west because of greater well control. Aside from local variations, the rate of thickening is generally uniform as the shale sequence dips eastward toward the axis of the Appalachian Basin. Thickness ranges from 1,260 feet in the western part of Columbia Township to approximately 2,180 feet in the southeastern part of Lebanon Township.

The depositional strike of the Devonian-Mississippian

sequence trends north–south with the exception of anomalous features in the eastern portion of the county. Four notable linear trends are shown on the total Devonian-Mississippian shale isopach map. The shale thickens (1) to the east in southwestern Orange Township, (2) to the southeast in southern Olive Township, and (3) to the southeast in northwestern Sutton Township. Similarly, the shale sequence thins to the southeast in southwestern Lebanon Township. These anomalous areas may be associated with structural features, such as closures, noses, and faults.

STRUCTURE OF DEVONIAN-MISSISSIPPIAN SHALES IN MEIGS COUNTY

Previous Work

Very little information has been published on the structural geology of Meigs County. The first detailed structural mapping was by Lamborn (1945a, 1945b, 1945c), who used shallow drill-hole data to contour the top of the Pittsburgh No. 8 coal (Pennsylvanian) in the Keno, Pomeroy, and Ravenswood 15-minute quadrangles. These maps indicated several southeast-plunging structural noses and troughs in eastern Meigs County. Shearrow (1971) published page-size structure maps on the Onondaga Limestone (Devonian) and Williamsport sand (Silurian) in Lebanon Township and briefly discussed the relationships between structure and gas production from the Williamsport. Gray (1981a, 1981b) constructed the first detailed structure maps (scale 1:62,500) of the county as part of the EGSP. He contoured the tops of the Onondaga Limestone and Berea Sandstone as representative of the base and top of the Devonian shale interval. The Onondaga structure map indicated low regional dip to the east-southeast. The Berea structure map indicated similar regional dip with numerous structural noses plunging to the southeast. The maps were a part of a larger study of the Devonian shales in eastern Ohio (Gray and others, 1982), and the structure of Devonian shales in Meigs County was not specifically discussed.

Numerous other studies on the structural geology of the Devonian shales of the Appalachian Basin have been published as part of the EGSP. Although these reports were not specific to Meigs County, they provide a regional overview of Appalachian Basin tectonics and an understanding of the relationships between geologic structure and shale-gas production. A summary of the EGSP structural studies and a comprehensive bibliography can be found in Shumaker and others (1982).

Purpose and Methods

We postulate that areas of higher fracture intensity in Meigs County can be delineated in part by mapping the structure on key stratigraphic horizons. Areas of high

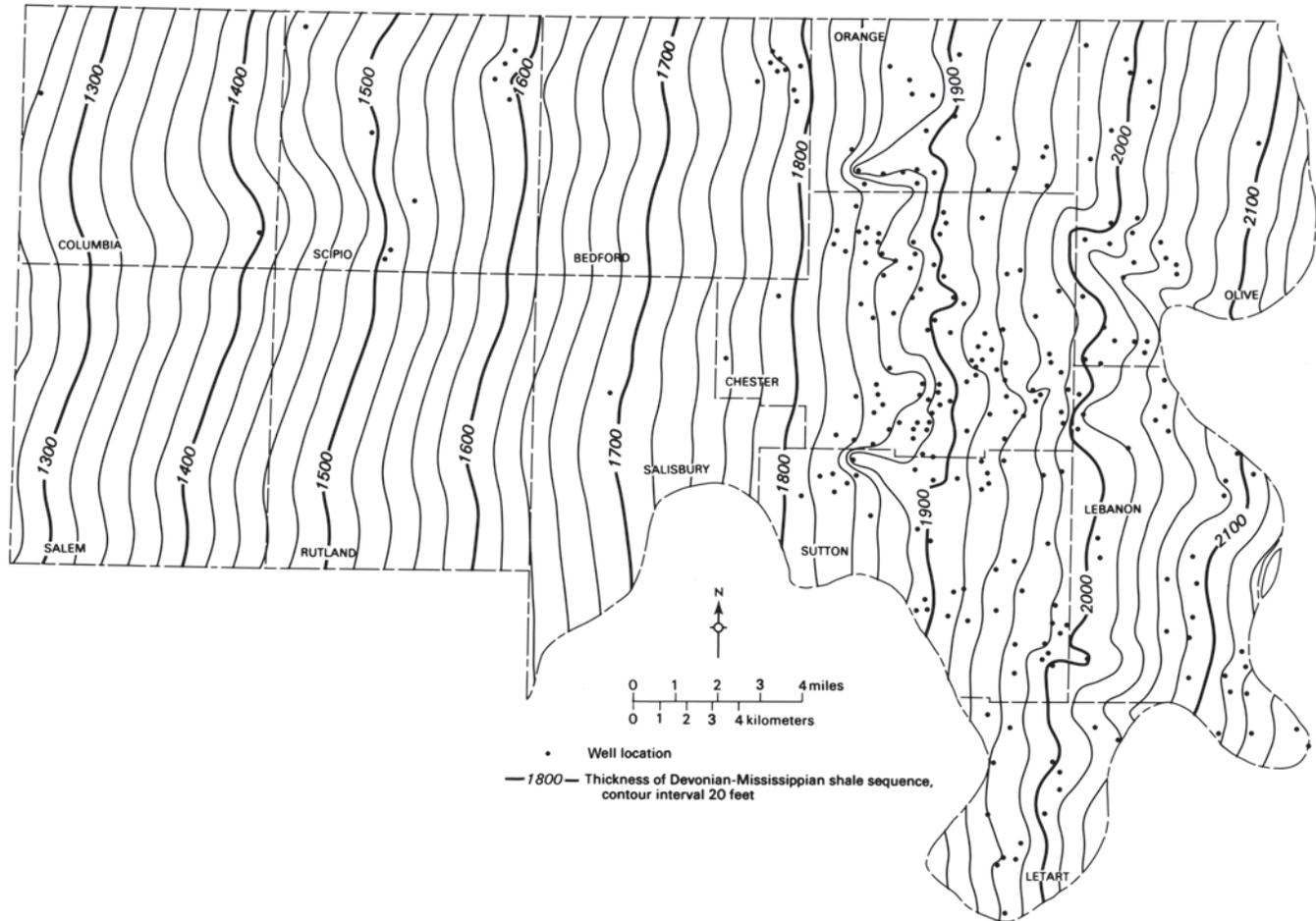


FIGURE 8. Isopach map of the total Devonian-Mississippian shale sequence, Meigs County, Ohio.

fracture density may be genetically related, in part, to the local structural geology (Stearns, 1968). The location of monoclinical structures, plunging folds, faults, and related fractures and the relative timing of their development is critical to effective exploration for natural gas. Structurally controlled geologic features and related fracture systems that have enhanced Devonian shale gas production in Meigs County have been mapped for this study.

We constructed two structure maps: one on the base of the Huron Member of the Ohio Shale and the other on top of the Berea Sandstone. Both units were deposited over broad areas of southeastern Ohio and are easily distinguishable on gamma ray and neutron/density logs. Data points were taken from geophysical well logs on file at the ODNr Division of Geological Survey. Data points considered to have inaccurate or unreliable reference elevations were not used on the maps. The accuracy of surface reference elevations as reported on well-log headers may be unreliable because of the rugged topography in most of the study area or changes in actual drilling sites after a survey was completed. (Problems

with reference elevations are an ever-present difficulty in southeastern Ohio and the Appalachian Basin as a whole.)

Data points were plotted on maps at a scale of 1 inch equals 1 mile (approximately 1:62,500) and were contoured using 20-foot intervals. Subsea data values for individual wells have been left off the maps owing to cartographic restrictions.

To minimize problems and difficulties with contouring and interpretation of the structure maps for this report, we employed the following methods. Data points were contoured using a point-to-point method, working parallel to established regional strike. For this report the investigators started first in areas of highest well density along strike, northeast to southwest, and vice versa. Departure from regional strike to more local structural trends was emphasized during the interpretation process. Anomalous or suspect data points were checked for accuracy with regard to stratigraphic units on the well log, reference elevation, and location on U.S. Geological Survey 15- and 7½-minute quadrangles. Suspect data points that could not be resolved were

disregarded. Faults were interpreted and added to the maps only where data-point value inhibited contouring with reasonable smoothness.

Regional Structural Setting

Meigs County is situated on the western flank of the Appalachian Basin within the central Appalachian Plateau physiographic province. In this portion of the Appalachian Basin, sedimentary strata dip gently east-southeast and strike north-northeast to south-southwest. Five structural features surround Meigs County: the Cincinnati Arch, the small broad folds of the Appalachian Plateau, the Rome Trough, the Cambridge Arch, and the Burning Springs Anticline (fig. 4). A brief discussion of each feature follows.

The Cincinnati Arch forms the western margin of the Appalachian Basin and is located approximately 120 miles west of Meigs County (fig. 4). It is part of an arch complex which separates the Appalachian Basin from the Michigan and Illinois Basins. The arch is not considered a true structural fold, but a broad area of nearly flat-lying strata. Positive structural relief on the arch is due to subsidence of the Precambrian basement complex in the surrounding basins (Green, 1957).

Approximately 100 miles east of Meigs County is a belt of small broad folds developed beneath the Appalachian Plateau during the Alleghenian orogeny. Rodgers (1963) viewed structures on the Plateau as resulting from "thin-skinned" deformation along decollement horizon within the Paleozoic as opposed to "thick-skinned" deformation, which involved the Precambrian basement.

The Burning Springs Anticline and Cambridge Arch are 30 miles east and northeast of Meigs County, respectively (fig. 4). The Burning Springs Anticline is considered a detachment structure that was formed by imbricated upward thrusting at the western pinchout of Salina Group evaporites (Woodward, 1959; Rodgers, 1963; Gwinn, 1964). The Burning Springs Anticline trends north-south through Pleasants, Wood, Ritchie, and Wirt Counties, West Virginia, and plunges northward into Washington County, Ohio. The Cambridge Arch trends N 20° W through Coshocton, Guernsey, Noble, and Washington Counties in Ohio. The structure plunges southeast in central Washington County, several miles northwest of the Burning Springs Anticline. Clifford and Collins (1974) and Gray and others (1982) considered the Cambridge Arch a detachment structure similar to the Burning Springs Anticline. This feature will not be discussed in detail for this report, because it is in a similar study of Monroe, Noble, and Washington Counties (Baranoski and Riley, unpub. data, 1988).

The northwestern edge of the Rome Trough is located 10 miles east of Meigs County (fig. 4). It is one of the largest faulted structural complexes within the central Appalachian Plateau. Movement of the bounding basement

blocks within the Rome Trough occurred primarily during the late Precambrian and Cambrian; subsequent movement during younger geologic ages was minimal (Harris, 1978; Donaldson and Shumaker, 1979). In eastern Meigs County and adjacent Jackson County, West Virginia, the northwestern edge of the Rome Trough has been delineated by northeast-trending gravity and magnetic anomalies (Kulander and Dean, 1978). The anomalies mark a steep gradient to the southeast at the basement level and have been considered a series of normal faults, which step down to the southeast. Reactivation of movement along these faults has taken place since the Mississippian (Harris, 1978; Donaldson and Shumaker, 1979). Such movement may have resulted in the development of fractures within the Cottageville field (western Jackson County, West Virginia) and the Big Sandy field (Kentucky-West Virginia border). Both fields overlie the Rome Trough and produce gas from fractured Devonian shales.

Structure on the Base of the Huron

Regional strike on the base of the Huron Shale Member of the Ohio Shale ranges from N 10° E to N 20° E (fig. 9). Dip averages less than ½ degree to the east-southeast, ranging from 40 feet per mile in the western portion of the county to 60 feet per mile in the east. Several localized areas of steeper dip up to 100 feet per mile exist in eastern Meigs County. Subsea elevation is -1,440 feet in the west and -3,080 feet in the east. Although the dominant strike on the base of the Huron is north-northeast, a secondary, northwest-southeast-trending structural grain has been interpreted predominantly in eastern Meigs County and is delineated by numerous southeast-plunging structural noses and troughs and associated northwest-southeast-trending faults. Along many of these faults the northeast side is down relative to the southwest side. In addition to the northwest-southeast-trending faults, subsidiary small folds and minor faults have been interpreted in eastern Meigs County. A number of small structural terraces occur parallel to regional strike in areas adjacent to faults and small folds. Except for a southeast-plunging structural nose in Scipio Township, western Meigs County lacks detailed, interpreted structural features owing to a paucity of well-control points.

Structure on the Top of the Berea

Regional strike on the top of the Berea Sandstone (fig. 10) is N 10° to 20° E, which is virtually the same as the strike of the base of the Huron Shale Member. Dip averages less than ½ degree to the east-southeast, ranging from 30 feet per mile in the western portion of the county to 60 feet per mile in the east. Several localized areas of steeper dip up to 100 feet per mile are present in eastern Meigs County. Subsea elevation ranges from -380 feet in



FIGURE 9. Structure on the base of the Huron Shale Member, Meigs County, Ohio.

the west to -1,460 feet in the east. A northwest-southeast-trending structural grain, which is oblique to regional strike, has been interpreted in the eastern half of the county. The structural grain is dominated by numerous southeast-plunging structural noses and troughs. Many of these structures have small northwest-southeast trending faults associated with them. A number of small, localized structural terraces occur parallel to regional strike in areas adjacent to the small folds and faults.

Discussion

The relationship between structure and producing shale wells in the Appalachian Basin has been summarized by Shumaker and others (1982). The principal concepts of their synthesis are:

1. Based on geologic, geophysical, and production data, there is a positive relationship between structure and highly productive Devonian shale wells.
2. Basement faults, commonly expressed as minor

surface or shallow-subsurface flexures, increase open fracturing within Devonian shales and thereby permit higher gas production.

3. Highly organic zones in Devonian shales have been the primary reservoirs; these organic zones contain open-fracture systems that impart permeability to the shale.
4. There is an interplay between basement (vertical) and thrusting (horizontal) tectonics of the Appalachian Basin and their effects on Devonian shale intervals.

These concepts can be extended to the development of structural features in Meigs County that are probably related to the vertical and horizontal movement of basement blocks along pre-existing zones of weakness in the Precambrian.

Structure maps on the base of the Huron Shale Member and the top of the Berea Sandstone (figs. 9 and 10, respectively) are very similar. Comparison of the two maps indicates that regional strike and dip are virtually the same, with the exception that dip on the Berea map is slightly less steep than that on the Huron map. The most striking

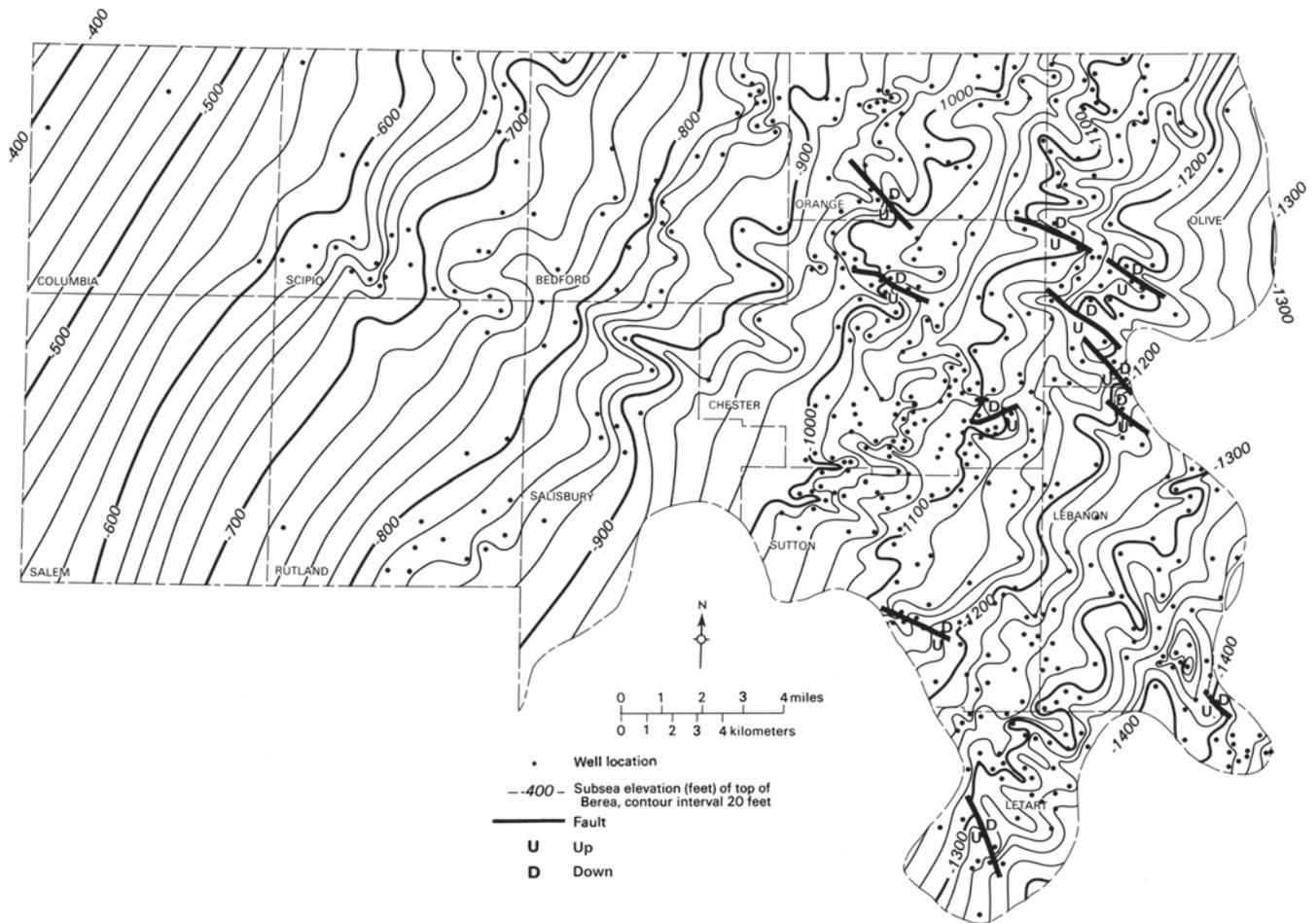


FIGURE 10. Structure on the top of the Berea Sandstone, Meigs County, Ohio.

similarity of the maps is the northwest–southeast-trending structural grain, which is more obvious on the Berea map owing to the greater well control throughout the central portion of Meigs County. Many of the structures and faults that have been interpreted on the two maps are situated in approximately the same map position. The apparent vertical to subvertical alignment of features may indicate faulting at depth. Shearrow (1971) has mapped similar-trending features on the Silurian Williamsport sandstone and Devonian Onondaga Limestone in Lebanon Township.

A number of features mapped for our report do not coincide with one another. These features may be a result of a higher degree of structural complexity, notably at the structural level of the base of the Huron, or a lack of data on either the lower Huron or Berea horizons.

The relatively flat-lying small structural terraces that have been interpreted on the maps for this report are oriented parallel to regional strike and are not related to the northwest-trending structural grain. The small terraces may have resulted from "down-to-basin" (southeast) movement of basement blocks related to the Rome Trough. Shumaker

and others (1982) demonstrated this situation in the Cottageville field, located two miles east of Meigs County in western Jackson County, West Virginia. They interpreted the Cottageville field as a fractured northeast–southwest-trending monocline that drapes over a pre-existing basement fault. The basement fault was postulated on seismic interpretation (Sundheimer, 1978). The Cottageville field produces gas from the lower Huron interval and may be an exploration model to use in Meigs County.

The northwest–southeast-trending structures cannot be explained as readily. Movement along these features may have taken place during the deposition of the Devonian shales, a theory suggested by comparing the structure maps (figs. 9 and 10) with the isopach maps (figs. 7 and 8). Several northwest–southeast-trending thickened areas are proximal to the structures in eastern Meigs County.

Subsequent movement along these northwest–southeast trends may have taken place during the Alleghenian orogeny. Rodgers (1963) postulated the presence of "conjugate sets of strike-slip faults" at the north and south ends of the Burning Springs Anticline;

the orientations “suggest that it [the block which formed the Burning Springs Anticline] moved roughly N 50° W, relative to the surrounding Appalachian Plateau” (p. 1,527). Gwinn (1964) hypothesized that “... some of the [northwest-trending] lineaments appear to reflect tear faulting ...” on the Plateau (p. 863). The northwest–southeast-trending features mapped in Meigs County appear to suggest that Rodgers' (1963) and Gwinn's (1964) northwest–southeast-trending lineaments and related strike-slip faults may have extended into Ohio. Beardsley and Cable (1983) have interpreted northwest–southeast-trending basement faults in the central Appalachian Plateau from seismic data. Consequently, the structural features in Meigs County most likely developed along pre-existing regional northwest–southeast-trending zones of weakness within the Precambrian basement complex of the Appalachian Plateau.

The Meigs County features likely did not develop as a result of decollement faulting because the Burning Springs Anticline is considered the western limit of detachment on the Appalachian Plateau. In addition, structure maps on the Williamsport sand and Onondaga Limestone in Lebanon Township (Shearrow, 1971) indicated similarly oriented features on deeper stratigraphic horizons. The vertical alignment of structures on Silurian, Devonian, and Mississippian horizons strongly suggests basement control of their development.

DEVONIAN SHALE COMPLETION AND PRODUCTION IN MEIGS COUNTY

Previous Work

The U.S. DOE and the GRI have sponsored several previous studies in Meigs County, Ohio, and adjacent counties in West Virginia. Martin and Nuckols (1976) evaluated gas production in the Cottageville Field of Jackson and Mason Counties, West Virginia. Ninety shale wells were drilled in this field between 1948 and 1950. Available production records indicated that 35 wells had an average cumulative production of 27 million cubic feet (MMcf) during the first year and 22 MMcf during the second year. Martin and Nuckols indicated that fractured Devonian shales were the main gas reservoir and that fracturing was caused by movement along reactivated basement faults along the northwestern side of the Rome Trough.

Negus-de Wys and Shumaker (1978) prepared a more detailed study of production data from the Cottageville field. The study correlated cumulative production, average annual production, initial well pressure, and production-decline data with geologic parameters. Initial-pressure trends correlated with structures mapped on the top of the Onondaga and the base of the Huron, basement magnetic trends, and fracture orientations from a Devonian shale core. Cumulative-production trends correlated with structures on the Onondaga map and fracture orientations

from the core. Production-decline data correlated with the Huron structure map, basement magnetic trends, and fracture orientations from the core.

Under the sponsorship of METC, Lewin and Associates, Inc. (1982, 1983) investigated the production mechanisms and stimulation methods in Devonian shale wells in Ohio. These studies included production-decline curves for Devonian shale wells in Meigs County, and their analyses showed that in highly fractured reservoirs, advanced stimulation techniques would produce higher gas production than conventional borehole shooting.

Science Applications, Inc. (1984) performed a multiple-well transient test program in Chester Township, Meigs County. Five Devonian shale wells were used in the program: a central, producing control well surrounded by four offset wells located within several hundred feet of the control well. A total of seventeen pressure-transient tests, consisting of single-well drawdown and buildup tests and multiple-well interference tests, were performed on the five wells. Data were collected by a computer system and were analyzed using type curves and mathematical models developed under the program. The analyses quantified key reservoir parameters of the Devonian shales in Meigs County: porosity, permeability anisotropy, dominant permeability direction, and transfer/storage coefficients. Other results of the program indicated that (1) the bottom 56 feet of the lower Huron contributed 95 percent of the gas; (2) permeability anisotropy is significant in Meigs County; and (3) computer-simulated, two-year cumulative production from a nitrogen-foam-fractured well was 38 percent greater than a conventional shot well and 60 percent greater than a high-energy-gas-fractured well.

Devonian Shale Drilling History in Meigs County

On the basis of operators' records and completion cards on file at the ODNR Division of Geological Survey, the earliest known productive Devonian shale well in Meigs County was completed in 1945 (Edison Hobstetter lease, permit no. 586, sec. 26, Sutton Township). Cumulative production for this well, which was still producing 25 thousand cubic feet per day (Mcf) as recently as 1987, was 661,386 Mcf from 1945 to 1985. Since 1945, approximately 425 Devonian shale wells have been drilled in Meigs County.

Prior to 1981, drilling activity for Devonian shale production in Meigs County was minimal, with approximately 40 wells being completed (fig. 11). Since 1981, however, over 350 Devonian shale wells have been drilled in eastern Meigs County because of an intensive drilling program by the J. D. Drilling Company. The peak of drilling activity occurred in 1984, when 228 Devonian shale wells were drilled and completed (fig. 11). By 1985, activity had decreased dramatically to only 35 Devonian shale wells.

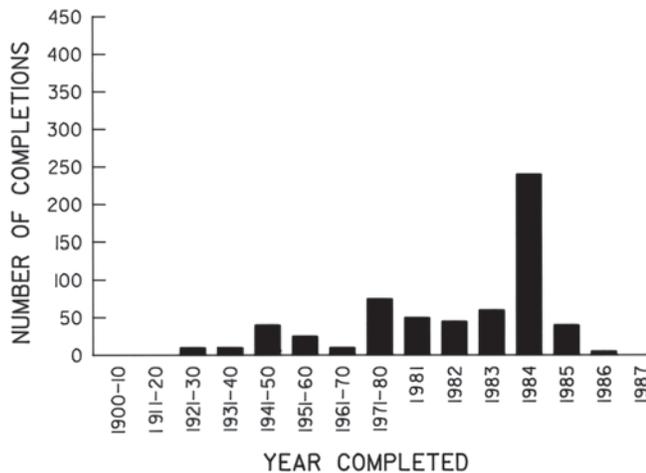


FIGURE 11. Drilling activity for Devonian shale wells in Meigs County, Ohio.

Methods of Data Collection

Completion cards¹ on file at the ODNR Division of Geological Survey were examined to determine the Devonian shale interval completed for wells in Meigs County. A record of the footage that was treated commonly is reported by the operators and noted on completion cards. If geophysical logs were not available, this footage was converted to subsea depths and compared to structure maps to determine which stratigraphic unit(s) within Devonian shales were being completed. An average initial potential (IP) was calculated for each stratigraphic interval. We used IP values taken after well stimulation throughout our report because these values are more consistently reported than natural IP values. All IP values are as reported on completion cards; none of the values have been standardized with regard to measuring device, length of time, or other engineering parameters.

Production records for Devonian shale wells were collected from five sources: (1) annual production statements on file at the ODNR Division of Oil and Gas (now Division of Oil and Gas Resources Management), (2) county auditor's reports for oil and gas properties on file at the Meigs County courthouse, (3) historical production records from Columbia Gas System Service Corporation², (4) production data accumulated by BDM Corporation for the GRI Eastern Gas Data System (EGDS), and (5) records supplied by the J. D. Drilling Company. From these five sources, 1,643 well records were collected for 410 Devonian shale wells.

¹Completion cards are presently in storage. Digital versions are available from the ODNR Division of Geological Survey website or on CD from the Geologic Records Center (614) 265-6576.

²Now NiSource, Inc.

The primary source of production data was the J. D. Drilling Company, which operates 90 percent of the Devonian shale wells in Meigs County. These data appeared to be reasonably accurate and commonly contained the "days on line" for the year. Columbia Gas System Service Corporation also provided detailed data for 19 Devonian shale wells that included the "days on line." The production data from the Division of Oil and Gas did not provide the "days on line" for annual production and thus were not as useful as data obtained from operators. County auditor's reports from the Meigs County courthouse were of little help because the data duplicated many records from the Division of Oil and Gas. All records were manually entered into a computer database, where they could be sorted and analyzed. The information provided a good database for constructing cumulative-production maps and generating decline curves.

Completion Intervals

Devonian shale wells in Meigs County were completed in either (1) small intervals within a single stratigraphic unit or (2) large intervals over hundreds of feet, covering multiple stratigraphic units. The principal operator in Meigs County, the J. D. Drilling Company, believed that the best results were obtained by completing large intervals from the top of the lower Huron to the total depth (Spence Carpenter, oral comm., 1987).

The most significant stratigraphic unit for Devonian shale gas production in Meigs County is the lower Huron, which is also the best gas-producing unit in the Devonian shale sequence in Lawrence County (Ohio Division of Geological Survey, 1986b). Similar investigations in Kentucky (Frankie and others, 1986) and West Virginia (Filer, 1985) have shown the lower Huron to be the most important Devonian shale unit. Of the 40 wells that were completed in a single stratigraphic unit, 37 were completed in the lower Huron (fig. 12). The IPs for these wells ranged from 25 Mcfd to 200 Mcfd and averaged 57 Mcfd. Two wells were completed in the Chagrin and each had an IP of 500 Mcfd. Only one well was completed in the Java and had an IP of 35 Mcfd.

There were 246 Devonian shale wells completed in multiple stratigraphic units (fig. 13). The most common interval completed in Meigs County was from the lower Huron to the Rhinestreet; 81 wells were completed in this interval. IPs ranged from 20 Mcfd to 310 Mcfd and averaged 39 Mcfd. The Chagrin to lower Huron interval had the highest IPs, which ranged from 20 Mcfd to 600 Mcfd and averaged 83 Mcfd. (Other combinations of completions in multiple stratigraphic units and their respective IPs are shown in figure 13.)

Stimulation Techniques

Prior to the mid-1970s, borehole shooting with nitroglycerine was the primary stimulation technique used on Devonian shales in the Appalachian Basin. Operators

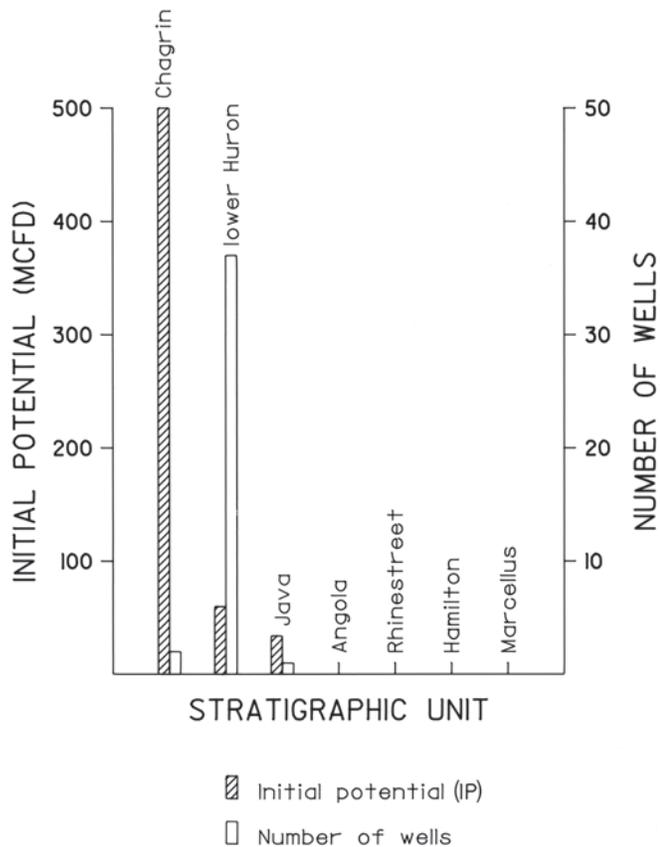


FIGURE 12. Frequency of completions reported within single stratigraphic units of the Devonian shale sequence vs. average initial potential. MCFD = Thousand cubic feet per day.

initially resisted hydraulic fracturing of the Devonian shales because of the potential formation damage at the fluid/clay interface. Such resistance was partially overcome when it was determined that a 2 percent potassium chloride solution reduced the swelling of the clays caused by clay/water reactions. Later studies showed that a 30/70 mixture of methanol and potassium chloride water further reduced the amount of clay swelling produced in the Devonian shales by hydraulic fracturing (M. E. Chenevert, unpub. data, 1977). During the late 1970s, a number of EGSP investigators experimented with various stimulation methods on Devonian shales in the Appalachian Basin, including nitrogen fracturing, massive hydraulic fracturing, foam fracturing, cryogenic fracturing, and displaced chemical explosives. Several of these newer stimulation techniques have been used in Devonian shales in Meigs County with varying degrees of success.

The primary stimulation techniques used in Meigs County for Devonian shale wells were (1) nitrogen fracturing, (2) shooting with explosives, (3) hydraulic fracturing, and (4) displaced chemical explosives (DCE) fracturing. Each method features several advantages and disadvantages (table 1). The majority of the wells in Meigs

County were drilled and completed by the J. D. Drilling Company, which utilized all of these completion techniques, thus providing a good opportunity for comparison.

Nitrogen Fracturing

Nitrogen fracturing was the most common stimulation technique and was used in 279 wells. The IPs ranged from 16 Mcfd to 600 Mcfd with an average IP of 45 Mcfd (table 1). The average two-year cumulative production for nitrogen-fractured wells was 8.3 MMcf, which was less than all other methods except hydraulic fracturing. The average cumulative production after five years was 12.1 MMcf, which was less than natural wells or those shot with explosives (fig. 14). Fifth-year production data for wells that were stimulated by DCE or hydraulic fracturing were not available for comparison.

Various combinations of nitrogen-fracture treatments have been reported in Meigs County and include (1) straight nitrogen; (2) nitrogen and acid; (3) nitrogen, acid, and sand; (4) nitrogen, water, and sand; and (5) nitrogen, foam, and sand. A comparison of the IPs of the stimulation methods using nitrogen is given in table 2. Straight nitrogen fracturing has been the most common method. The primary advantage of a straight nitrogen fracture is the absence of water, which can cause formation damage to the shale through clay swelling. A major disadvantage, however, was that no proppant can be carried by the gas. It is not clear why straight nitrogen fracturing is the most common of nitrogen methods. Straight nitrogen appears to be disadvantageous when compared to the average IP with nitrogen and acid (119); nitrogen, acid, and sand (95); and nitrogen, water, and sand (109) (table 2). Based on the number of wells completed with straight nitrogen, one might conclude that this method was most commonly used for economic reasons.

Shooting with Explosives

The second most common technique for stimulating Devonian shale wells in Meigs County was shooting with explosives. The IPs for 122 wells ranged from 15 Mcfd to 300 Mcfd and averaged 55 Mcfd (table 1). Shot wells had an average two-year cumulative production of 9.4 MMcf; after five years the cumulative production for shot wells was 2.5 times that of nitrogen-fractured wells. These cumulative-production figures were the highest of any completion technique except natural completion.

Judymite™² was the most common explosive energy source for this method and consists of gelled nitroglycerine, which is packaged with a built-in cone to give it a directional charge. Gravel or limestone commonly was used as a tamp to confine the explosive energy. The J. D.

²Reference to a trademark or patent does not constitute endorsement.

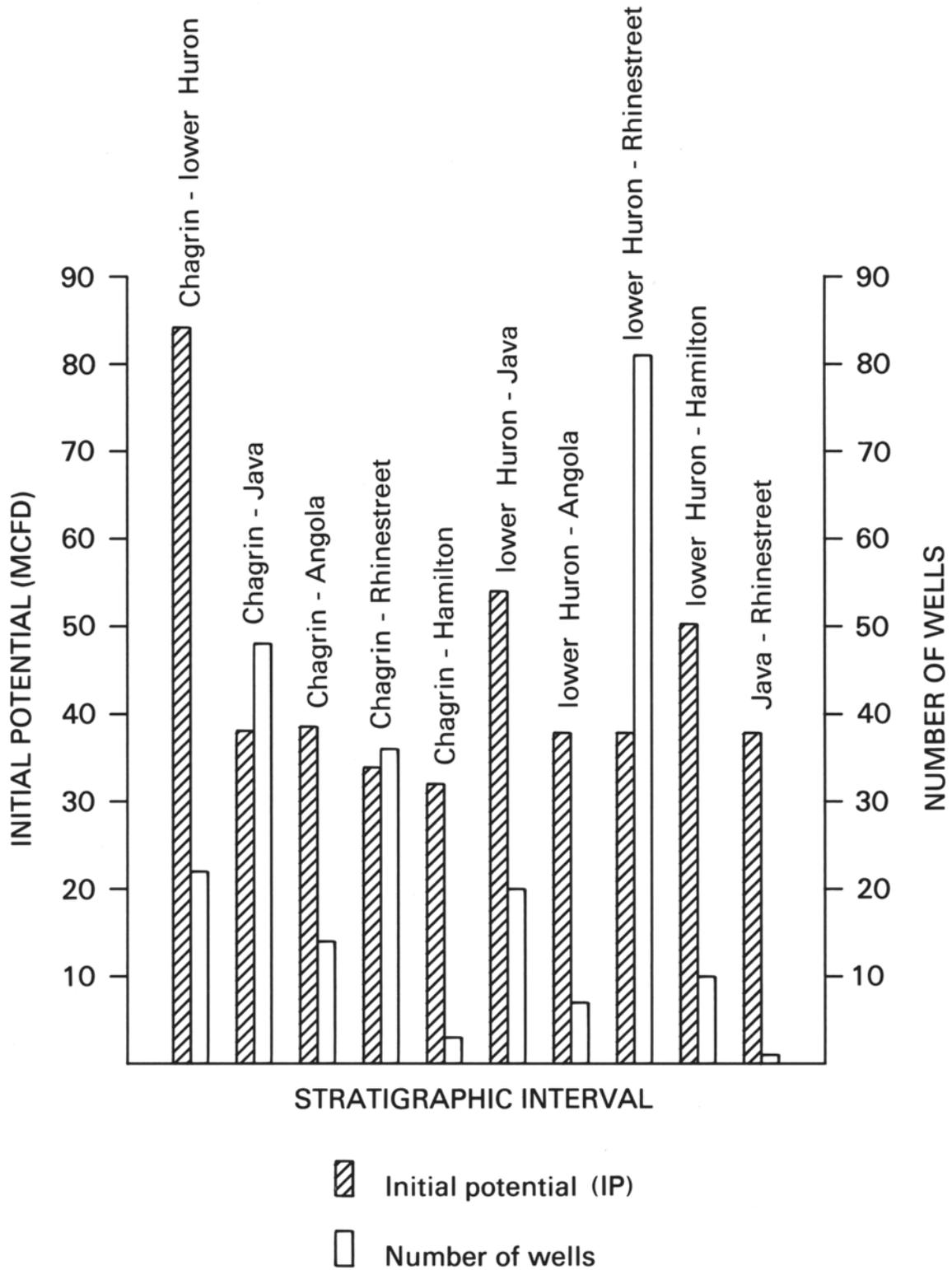


FIGURE 13. Frequency of completions reported within multiple stratigraphic units of the Devonian shale sequence vs. average initial potential. MCFD = Thousand cubic feet per day.

TABLE 1. Comparison of natural completions and the various stimulation techniques for Devonian shale wells in Meigs County, Ohio

Stimulation technique	Average initial potential (Mcf) ¹	Average 2-year cumulative production (MMcf) ²	Advantages	Disadvantages
Nitrogen fracturing	45 [279 wells]	8.3 [198 wells]	No water damage in a straight nitrogen fracture	Nitrogen alone cannot carry a proppant
Shooting with explosives	55 [122 wells]	9.4 [122 wells]	Extensive fracturing isotropically around borehole Most successful where natural fracture systems exist	Fractures propagated limited distance from borehole Extensive borehole cleanout required
Hydraulic fracturing	302 [18 wells]	4.7 [6 wells]	Highest initial potential	Fluids may cause formation damage
Displaced chemical explosives fracturing	26 [9 wells]	8.5 [9 wells]	Surface facilities and personnel not exposed to explosive hazards Fractures extend farther into formation	Requires extensive wellbore cleanout Cost is twice that of shot wells
Natural completion	130 [9 wells]	14.6 [9 wells]	Least expensive method No potential for formation damage	

¹Thousand cubic feet per day. All initial potential values are taken after treatment except for natural completion.

²Million cubic feet.

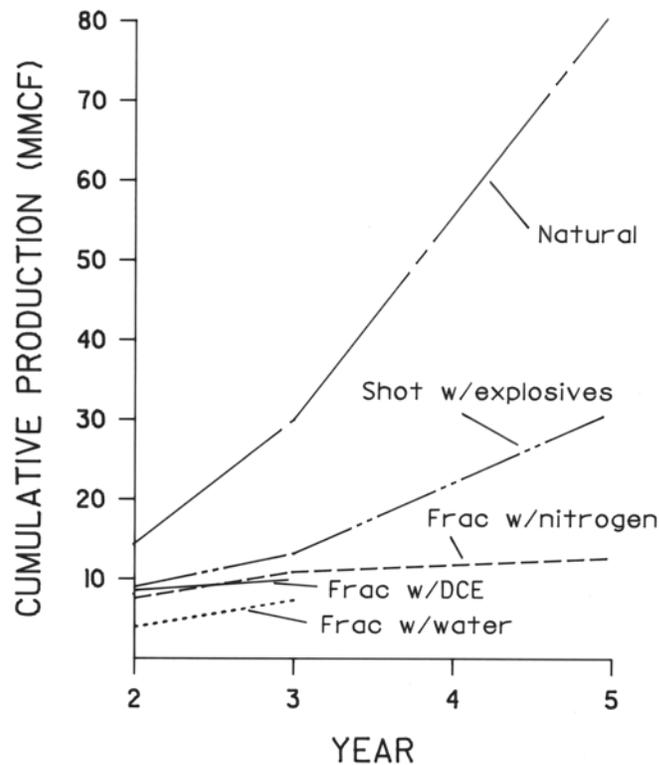


FIGURE 14. Plot of cumulative production for each stimulation technique and natural production in Meigs County, Ohio. DCE = displaced chemical explosives. MMCF = Million cubic feet.

TABLE 2. Comparison of the various stimulation techniques involving nitrogen

Stimulation technique	Number of wells	Average initial potential (Mcf/d) ¹	Range of initial potential (Mcf/d)
Straight nitrogen	258	41	20–335
Nitrogen and acid	5	119	22–310
Nitrogen, acid, and sand	3	95	17–250
Nitrogen and water	1	45	-
Nitrogen, water, and sand	8	109	16–600
Nitrogen, water, gel, and sand	1	30	-
Nitrogen, foam, and sand	2	33	27–40
Nitrogen, foam, and gel	1	15	-

¹Thousand cubic feet per day.

Drilling Company stated that the best results were obtained by shooting the explosive charge over an interval of several hundred feet from the top of the Huron to the total depth. On the basis of completion records, most operators of Devonian shale wells in the Appalachian Basin use the same technique.

The primary advantage of this method is the extensive fracture system produced isotropically around the borehole. The disadvantages are (1) the isotropic nature of the shooting limits the radial distance to which the fractures are propagated away from the borehole, and (2) extensive borehole cleanout commonly is necessary because of the crushing and caving in of rock adjacent to the borehole. Historically, explosive fracturing has been the most successful in areas with abundant natural fractures but appears to be uneconomical outside of naturally fractured areas (Horton, 1984).

Hydraulic Fracturing

Hydraulic fracturing was used in 18 Devonian shale wells in Meigs County and had the highest IPs of any stimulation treatment. IPs for hydraulic fracturing ranged from 15 Mcfd to 600 Mcfd and averaged 302 Mcfd (table 1). The two-year cumulative production for this technique was the lowest of any method at 4.7 MMcf. After three years, the average cumulative production was only 7.6 MMcf (fig. 14). This average is based on only two wells, which may explain the anomalously low cumulative production.

Six wells were reported as being fractured with water alone, and 12 were hydraulically fractured with sand as a proppant. Wells fractured with water alone had IPs ranging from 15 Mcfd to 500 Mcfd and an average IP of 230 Mcfd. Wells that used a conventional hydraulic-fracture treatment with sand as a proppant resulted in the highest IP of any stimulation method in Meigs County. These IPs ranged from 70 Mcfd to 600 Mcfd and averaged 338 Mcfd.

Hydraulic fracturing has been shown in other areas to produce higher IPs and cumulative production than

conventionally shot wells. Data from 35 shot wells and 18 hydraulically fractured wells in the Eastern Kentucky Gas Field showed that, after five years of production, hydraulically fractured wells produced nearly twice that of shot wells (Yost, 1983). In Meigs County, IPs for hydraulically fractured wells were the highest of any stimulation technique; however, the cumulative production was the lowest of any stimulation technique. The major disadvantage of this method is the potential formation damage caused by fluid/clay interaction.

Displaced Chemical Explosives

One of the more recent experimental technologies applied to stimulation treatments has been the use of displaced chemical explosives, a method that was used in nine wells in Meigs County and had the lowest IP of any stimulation technique (table 1). The IPs ranged from 12 Mcfd to 50 Mcfd and averaged 26 Mcfd. Two-year cumulative production was 8.5 MMcf, which was similar to cumulative production for nitrogen-fractured wells. After three years, the average cumulative production was 10 MMcf (fig. 14).

The displaced chemical explosive process involves the simultaneous pumping of two nondetonating chemicals into a mixer in the wellbore, where the two chemicals form a liquid explosive (Petroleum Technology Corporation, 1980). Commonly, a 200-foot column of water is used as a tamp. Petroleum Technology Corporation (PTC) patented this explosive fracturing technique as Astrofrac™ and it is reported as PTC or Astrofrac™ on completion cards.

One of the major advantages of this method is that personnel and facilities at the surface are not exposed to explosive hazards. Also, the open wellbore through the potential producing interval is filled with the explosive liquid, which is also displaced into the natural fractures of the formation. Theoretically, this procedure creates a greater gas-producing surface area connected to the wellbore and increases the probability of intersecting

nearby natural fractures. The major disadvantage is that it requires a great deal of post-shot cleanout because of the mechanical crushing of the formation. Post-shot cleanout was reported to be a significant problem with this stimulation method in Meigs County (Spence Carpenter, oral commun., 1987). Furthermore, the cost of Astrofrac™ is approximately twice as expensive as conventional gelled nitroglycerine (Petroleum Technology Corporation, 1980). The J. D. Drilling Company considered this method to be the least successful of the stimulation methods for Devonian shales in Meigs County.

Natural Completion

Nine Devonian shale wells in Meigs County were completed naturally without any stimulation treatment. The IPs for natural wells ranged from 15 Mcfd to 400 Mcfd and averaged 130 Mcfd (table 1). Wells completed naturally had an average two-year cumulative production of 14.6 MMcf, which was higher than any stimulation technique. After five years, the average cumulative production was 80 MMcf (fig. 14). The high IPs and cumulative production of natural wells suggest that operators do not stimulate those wells with good natural initial potential.

The advantages of a natural completion are that (1) it is the least expensive method for completing a well and (2) there is no potential for formation damage. There are no particular disadvantages of a natural completion; however, relatively few wells are completed without some type of stimulation.

Decline Curves

Decline-curve analysis is one of the simplest and most widely used methods for estimating gas reserves. Generally, the rate at which gas production declines indicates reservoir characteristics and determines the "payout" period for a well. Decline curves for Devonian shale gas wells typically are characterized by a period of rapid decline during the first 5 to 10 years of production, followed by a period of stabilization to the end of a well's economic life. These characteristics indicate fractured reservoirs that produce from a dual- or multiple-porosity system (Vanorsdale, 1985).

The period of rapid decline is not a desirable economic factor with conventional nonfractured reservoirs. However, with Devonian shale reservoirs this economic shortcoming is offset by a very long producing life. Many Devonian shale wells in the Appalachian Basin have been known to produce for as long as 50 years.

We constructed five decline curves using one representative well for each completion technique: natural (unstimulated), shot with explosives, nitrogen fractured, hydraulically fractured, and DCE fractured (fig. 15). An excellent spread of long-term data was available for the natural well and the shot well. The nitrogen-

fractured, hydraulically fractured, and DCE-fractured wells had production histories going back a maximum of three years.

The production of the natural well declined moderately during the first 10 years, followed by rapid decline during the 10- to 15-year period. After 15 years, production decline was very slight, indicating a period of stabilization to the end of the 30 years. Overall, the production decline of the shot well was similar to that of the natural well. Rapid decline took place during the first five years of production, followed by a long period of stabilization. A noticeable difference was that rapid decline for the shot well occurred during the first five years, compared to after 10 years for the natural well. Production data for the nitrogen-fractured well, the hydraulically fractured well, and the DCE-fractured well went back three, two, and three years, respectively. Production decline for these wells is very rapid, as indicated by the

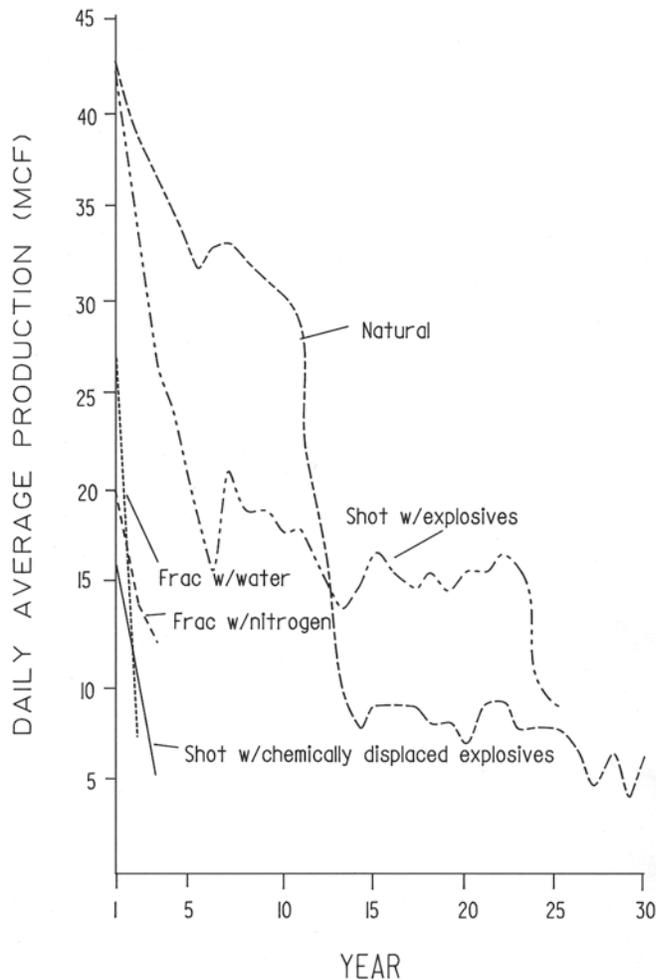


FIGURE 15. Decline curve for natural completion and each stimulation technique for Devonian shale wells in Meigs County, Ohio. MCF = Thousand cubic feet.

steep decline curves. Long-term production data were not available to provide comparisons to the shot well or the natural well.

Isopotential Map

An isopotential map (fig. 16) for Devonian shales in Meigs County was constructed using IP data from completion cards on file at the ODNR Division of Geological Survey. The IPs used for contouring were measurements taken after the well was stimulated. The IP values reported on completion cards are not standardized as to the amount of time that the tests were measured, which decreases the validity of the results. IP values greater than 50 Mcfd were contoured, and IP values greater than 150 Mcfd were patterned on the map to delineate the areas of highest gas potential. The map shows numerous northwest–southeast-trending localized areas with IPs greater than 50 Mcfd throughout eastern Meigs County. The central and western portions of the county have scattered IPs less than 50 Mcfd. Operators have not looked favorably upon these areas for production.

Cumulative-production Maps

Two cumulative-production maps were constructed: a 2-year map (fig. 17) and a 10-year map (fig. 18). The two-year period of time represents the early stages of a well's production history. A larger number of data points were used to contour the 2-year map than the 10-year map. At the 10-year mark, the well is past its greatest productive years and into a period of stabilization.

Two coarse-screening methods were applied to the production data. First, for wells where “days on line” are unknown, we assumed that production occurred for 365 days during the year reported. Records of “workovers” and temporary “shut-ins” were not available to help normalize yearly production rates. Second, only two-year or longer production was utilized. Initial inspection of the data indicated that a large portion of the database represents fewer than three years of cumulative production. Of these data, many wells only had first-year records, of which many were marginally economic to subeconomic. These wells would not provide an accurate picture of Devonian shale production in Meigs County.

Contour intervals of 10 and 30 MMcf were used on the 2-year map. Areas greater than or equal to 30 MMcf have been patterned on the map to show the highest productive areas. Contour intervals of 50 and 150 MMcf were used on the 10-year map. Areas greater than or equal to 150 MMcf have been patterned as the highest productive areas. The wells providing data for these maps are concentrated in the eastern portion of the county.

The 2-year cumulative-production map has two dominant trends: northwest–southeast and northeast–southwest. Two areas contain both northwest and northeast

trends. The 2-year map shows nine localized areas where cumulative production is greater than or equal to 30 MMcf.

The 10-year map indicates three localized areas of cumulative production greater than or equal to 150 MMcf. The three areas of high production on the 10-year map overlap with three areas of high production on the two-year map. A general paucity of 10-year data precludes the correlation with other areas on the two-year map.

Comparison of the cumulative-production maps and the isopotential map shows good correlation between areas of high cumulative production and high initial potential. A general comparison with structure maps on the top of the Berea and base of the Huron does not indicate significant correlation. Unavailability of production records precluded correlation in some areas.

LINEAMENT INTERPRETATION IN MEIGS COUNTY

We analyzed and interpreted remote-sensing data for Meigs County, specifically NASA LANDSAT multispectral-scan, band-7 satellite imagery (flown in February 1977) and synthetic aperture radar (SAR) imagery of a west-looking, near-range mosaic (flown in May 1984), both at a scale of 1:250,000. LANDSAT imagery was fair to poor. An interpretation map of the LANDSAT data was not included due to the poor quality of the imagery. On the other hand, SAR data was excellent; mosaics of the Clarksburg and Charleston 1:250,000 quadrangles were of high-quality resolution. SAR flights have not been made for western Meigs County.

Four regional trends have been interpreted from SAR data for Meigs County: (1) northwest, (2) northeast, (3) west–northwest, and (4) north–northeast (fig. 19). Aside from the lineaments, no other geologic features, such as monoclines, folds, or faults, were observed on the SAR mosaic.

A number of the lineaments on the SAR map are coincident with stratigraphic anomalies, folds, faults, and areas of high production as mapped for the Devonian shales for this report. The lineaments are proximal and parallel to a number of folds and faults on the Berea and Huron structure maps. Most notable of the trends are the northwest–southeast-trending faults and southeast-plunging folds, as well as several northeast–southwest-trending faults and northeast-plunging folds. Lineaments are proximal with two stratigraphic anomalies on the total Devonian-Mississippian and lower Huron isopach maps. The anomalies trend northwest–southeast and east–west and are located in northern Sutton and southern Orange Townships, respectively. Lineaments are proximal to most IP contours greater than or equal to 50 Mcfd. Most significant of these are northeast–southwest- and northwest–southeast-trending lineaments over an IP area greater than or equal to 150 Mcfd in northeastern Chester and southeastern Orange Townships. Several lineaments

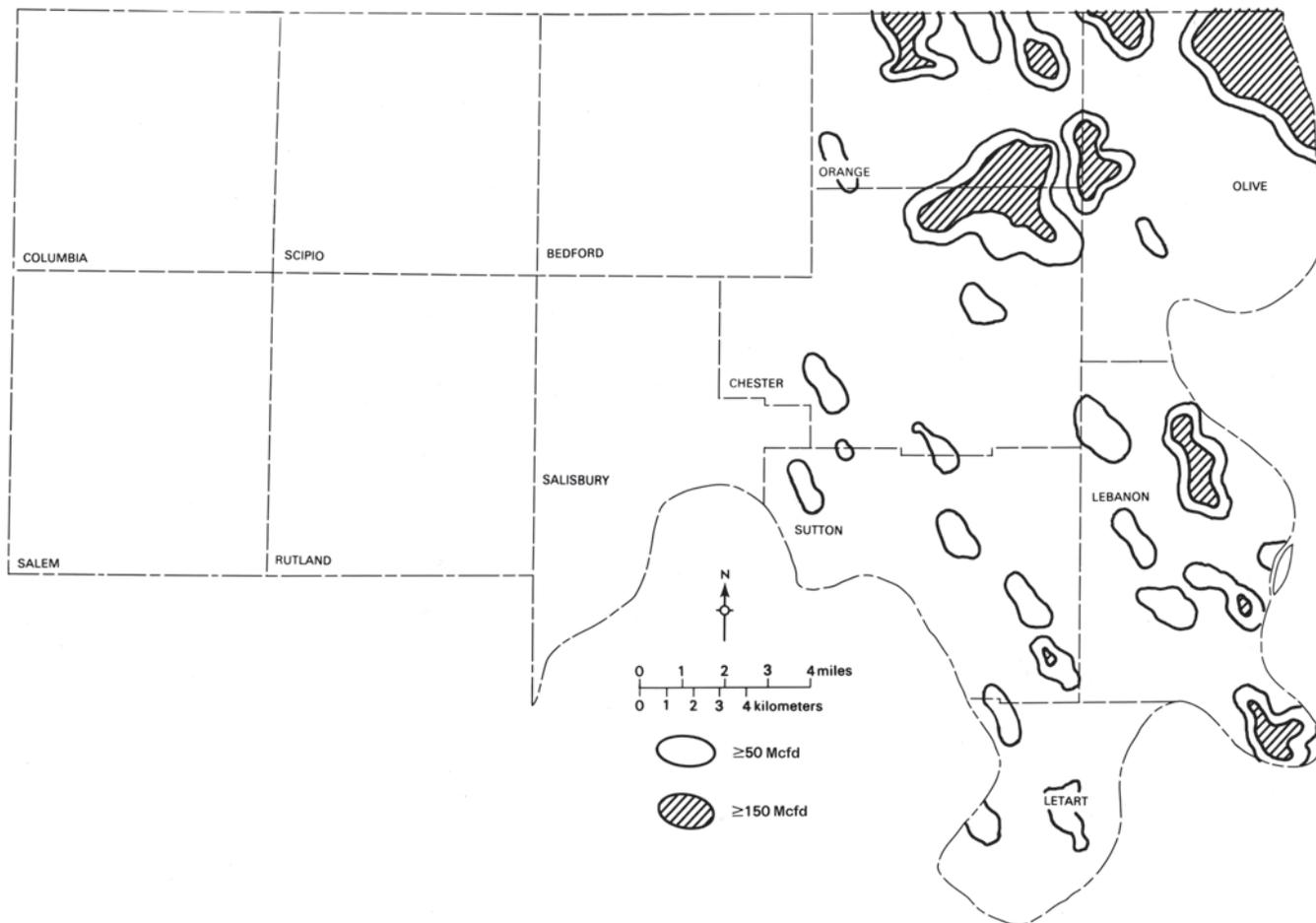


FIGURE 16. Isopotential map of Devonian shales in Meigs County, Ohio. Mcfd = Thousand cubic feet per day.

are coincidental or proximal to contour trends on the 2-year and 10-year cumulative-production maps.

CONCLUSIONS

Stratigraphic and Structural Relationships

The conclusions derived from our study of the Devonian shales in Meigs County, Ohio, should help to provide the explorationist with basic stratigraphic and structural information for the shale sequence. Several generally north–south-trending zones are present in the subsurface Devonian rocks of Meigs County. These zones define transitional facies changes from basal black shales in the west to distal turbidites in the east, as well as stratigraphic pinchouts. The structures and associated fracture systems of Meigs County most likely developed along pre-existing zones of weakness in the Precambrian basement. Maps and cross sections of the shale units in Meigs County show the following:

1. General continuity of black-shale facies along north–northeast-trending depositional strike.
2. Westward progradation of clay-rich clastic sediments and interfingering with marine black shales.
3. Eastward thickening of sediments during Late Devonian.
4. Anomalous isopach trends.
5. Fault trends, small folds, and monoclines, some of which may be associated with anomalous isopach trends.

Lineament interpretations are further evidence that fracture systems may be related to basement features at depth beneath the subsurface features on the isopach and structure maps of the Devonian shales.

Characteristics of Production

Of the following conclusions regarding characteristics of Devonian gas production in Meigs County, the first five

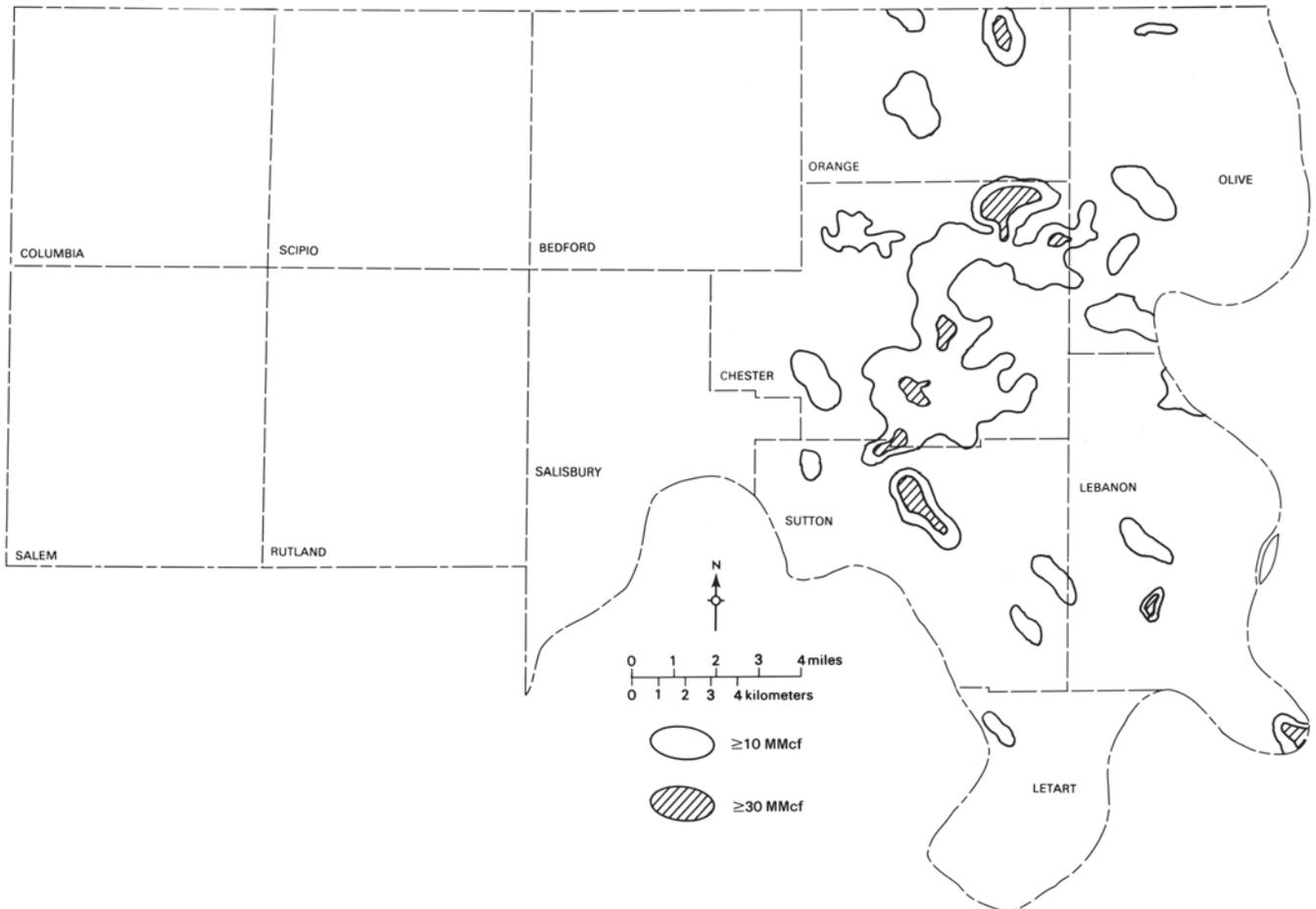


FIGURE 17. Two-year cumulative-production map of Devonian shale wells in Meigs County, Ohio. MMcf = Million cubic feet.

are observations made upon examining relationships of production data; the last four conclusions were made by comparing production characteristics to geologic factors.

1. Natural wells had the highest cumulative production.
2. Hydraulically fractured wells had the highest average initial potential (IP) but the lowest average cumulative production.
3. Decline curves for natural and shot wells show an initial period of rapid decline after 5 to 10 years, followed by a long period of stabilization. These characteristics are a result of a multiporosity system.
4. Eastern Meigs County had the highest IPs and cumulative production. Limited drilling and low IPs in western Meigs County indicated very little economic potential.
5. Localized areas with high IPs correlate with localized areas having high cumulative production after two- and ten-year periods.
6. The lower Huron was the most significant stratigraphic unit for Devonian shale gas production.
7. Devonian shale wells commonly were completed and

stimulated over hundreds of feet covering multiple stratigraphic units. The most common interval was the top of the lower Huron to total depth (Rhinestreet).

8. Fracture systems are the primary reservoir for Devonian shale natural gas. Fractures most likely developed along pre-existing northwest-southeast- and northeast-southwest-trending zones of weakness in the Precambrian basement.
9. Isopotential maps and 2- and 10-year cumulative-production data indicate localized areas of correlation with stratigraphic and structural anomalies and SAR lineaments.

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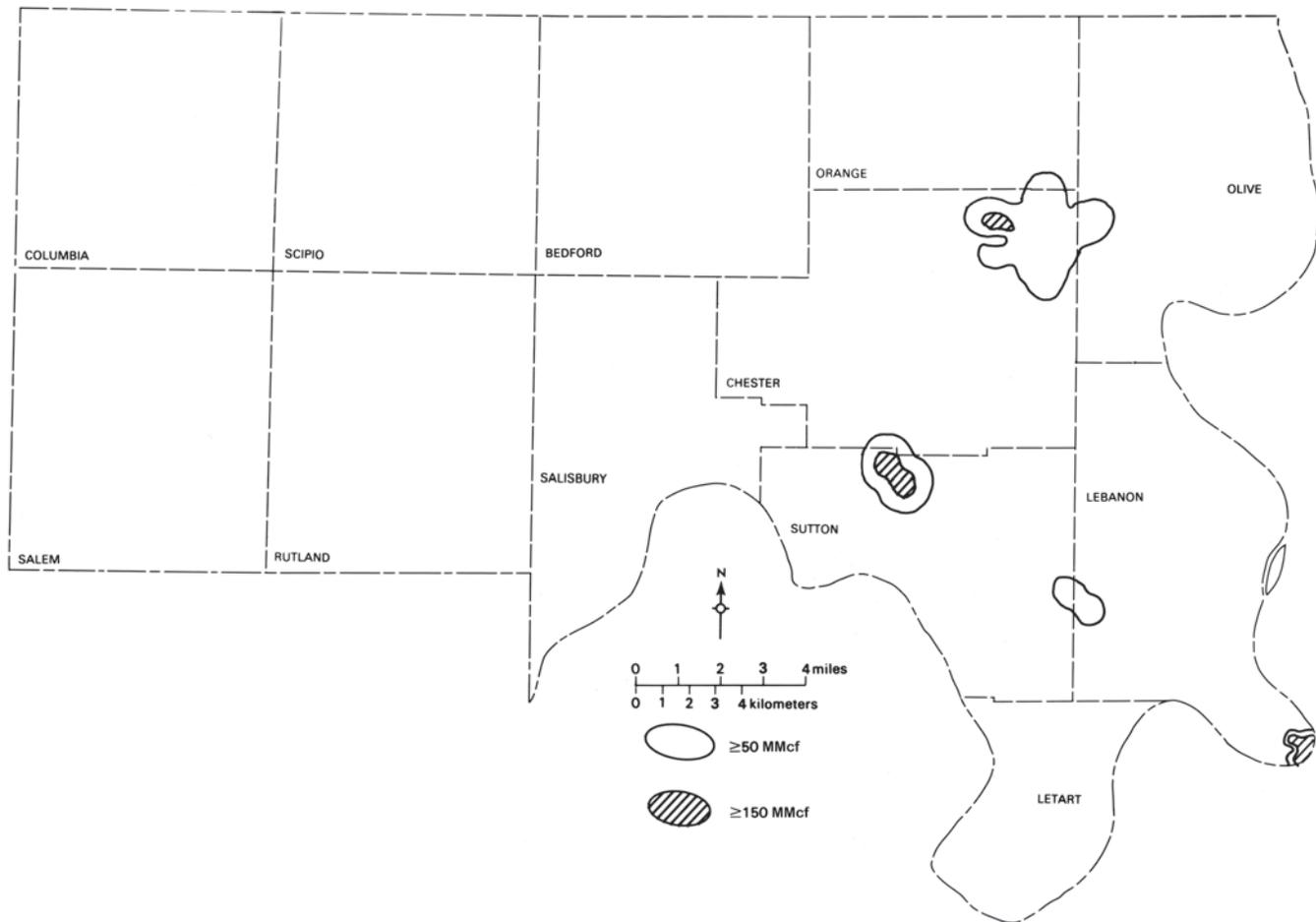


FIGURE 18. Ten-year cumulative-production map of Devonian shale wells in Meigs County, Ohio. MMcf = Million cubic feet.

and Columbia Natural Resources, Inc., which contributed production information, and to oil and gas consultants who shared ideas during this investigation. The assistance of reviewers Arie Janssens and Paul Potter is greatly appreciated.

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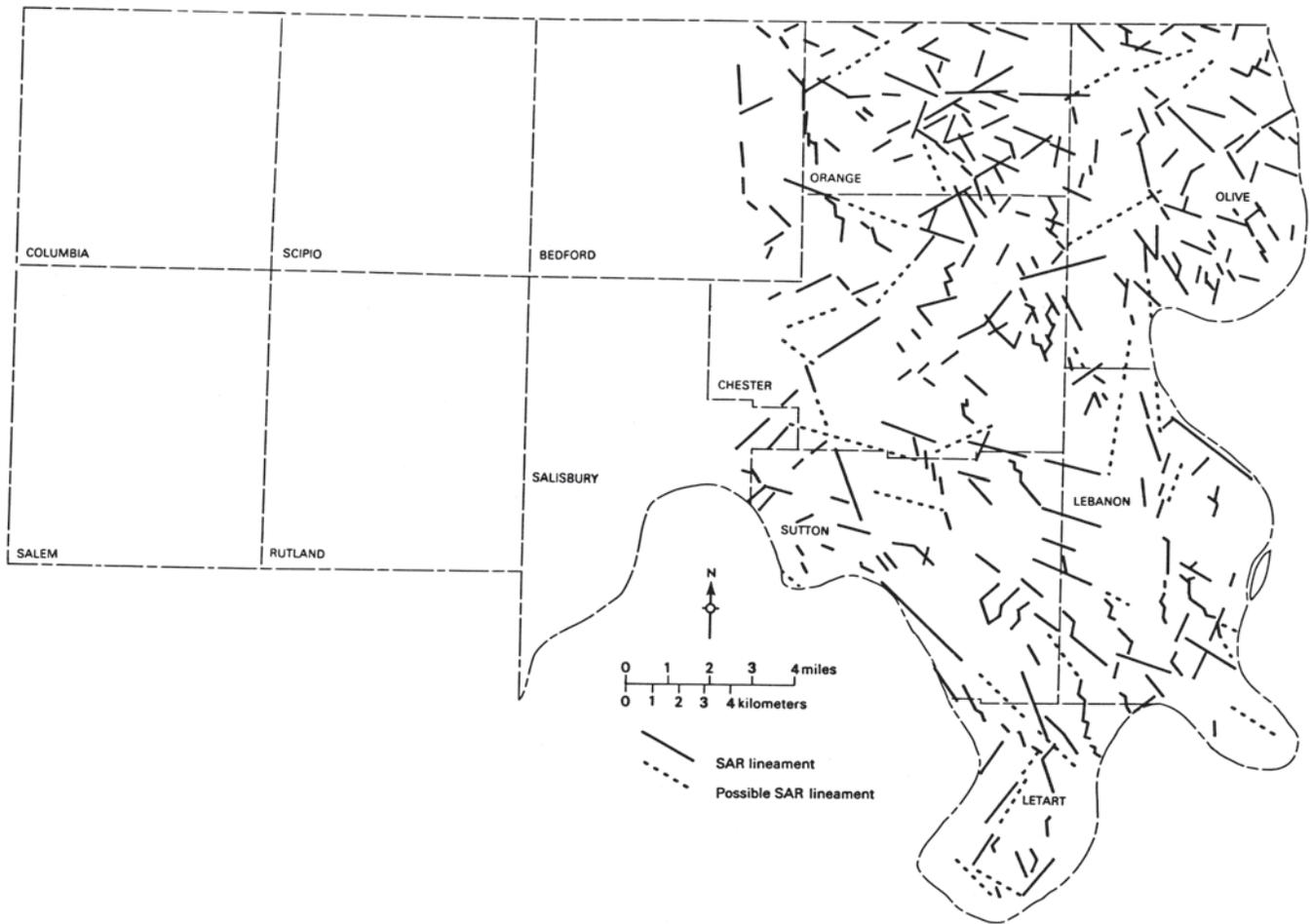


FIGURE 19. Lineaments mapped from synthetic aperture radar (SAR) imagery of eastern Meigs County, Ohio.

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